Insulation materials: Fundamentals and Applications

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Insulation Materials

Fundamentals and Applications

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Dedicated to

My Family

Preface

Since the last decades, world has seen wide spread of modern materials and corresponding functions in various kinds of applications such as: buildings, transportation, services and tools. These facilities were associated with a significant increase in fuel and electrical energy consumption. In order to reduce rapidly growing demand for energy, protect the environment resulting from the greenhouse gas emissions and pollution, and to achieve satisfaction in comfort requirements, it is necessary to develop insulation materials and improve the performance of construction elements and take advantage of clean energy and passive techniques.

In this book, some aspects of the insulation materials have been clarified telling us where technically and economically feasible, whether thermally or acoustically and also to protect buildings from external or internal moisture, which can cause damage and contamination in the building.

Thermal insulation materials are specifically designed to reduce the heat flow by limiting heat conduction, convection, radiation. The main functions are conserving energy by reducing heat loss or gain, controlling surface temperatures for comfort living and saving facilities for long time as well. Insulation done for the house helps in keeping the noise away from adjoining rooms by preventing interfering with inside or outside. The quality of the insulation materials should be chosen to satisfy balance between the economic cost and achieving the requirements of good insulation or reduce energy consumption. It has found that super thermal insulation of the building increases the cost of construction up to 20%, but this amount could be recovered as a result of lower electricity bills in a few years.

Another profit is that insulation helps in reducing the reverberations and in maintaining the right acoustic atmosphere in specialized skilled areas like recording studios, opera halls and theatres. Furthermore, buildings need insulation from moisture, rain, groundwater and surface water because the dampness causes in damage of the construction materials and releases undesired smells with the breeding of insects and mice and bring diseases. In order to choose the appropriate waterproofing it must take into accounts the nature of the ground as well as the climate.

Dielectric materials are wide used in many applications to keep safe against electrical shocks. Every electric conductor, whether it is cable, switch in a motor, transformer, etc., should carefully covered with a form of electrical insulation. To understand insulation method, it is required to present some mathematical relations in electrical engineering. Workers in nuclear facilities and X-ray labs exposed to the risk of radiation, which affects the face, hands or internal parts due to the entry of radioactive particles into the body through breathing or food. To avoid the radiation risk in this area it is necessary to know the nature of radiation and methods of isolating and comply with the instructions.

This book is intended for students, engineers, consultants, designers, researchers and those involved in the manufacturing of insulation. It uses theory and measurements to explain concepts that are important for the application, interpretation and understanding of guidance documents, test reports, product data sheets, published papers, regulations, and standards. The intention is to enable the reader to tackle many different aspects of insulation by providing a textbook easy and principle. Readers with a background can jump straight to the topic of interest in chapters. All methods, models and measurement have their limitations, but with knowledge of their strengths and weaknesses it becomes much easier to make design decisions and to find solutions for many applications. Some models are considered as theoretical procedures, while some others depend on empirical relations. Studies and debate about potential negative environmental and health impacts of insulation products have been included. However, these concerns range from detrimental health effects for the individual installer to depletion of the earth's ozone layer. So, it should take care of that and the corresponding industrial safety as well.

The author

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Thermal Insulation

1.1 Definition of Thermal Insulators

Thermal insulation materials are those materials that prevent or reduce various modes of heat transfer (conduction, convection and radiation) from the outside to the inside or the opposite direction, whether the environment temperature is high or low. This term usually used with building applications. Thermal insulation includes the use of appropriate insulation materials and design adaptations for buildings to reduce heat loss or gain. The transfer of heat is caused by the temperature difference between indoors and outdoors.

1.2 Applications of Thermal Insulation

According to American Society for Testing and Materials (ASTM) thermal insulation is one of the most used forms of insulation for businesses and homes. It is used in order to contain heat as long as possible or avoid it, thus it installed in the roof, floor and walls of a building. However, there are range of applications and conditions where thermal insulation is used, for example thermal insulation is applied to:

- Buildings
- Furnaces
- Ducts
- Refrigerators and freezers
- Water heaters and boilers
- Pipes and vessels
- Mugs and containers
- Aircrafts and spacecrafts
- Clothes
- Equipment

Figure (1.1) Applications of thermal insulation

1.3 Advantages of Thermal Insulation in Buildings

It could say that the direct and indirect benefits of using the thermal insulation in buildings are:

1. Reduce the amount of heat transmitted through the parts of the house.
2. Reduce the energy required for heating or cooling the house.
3. Make the internal temperature of the building stable, non-volatile.
4. Keep the temperature of the building elements stable thus long time life.
5. Reduce energy bills.
6. Reduce the burning of fuel in power plants.
7. Reduce the emission of greenhouse gases.

1.4 Classification of Thermal Insulators

Thermal insulators could be classified according to the structure of the materials or to the shape formed the materials, as following:

- **According to the structure**

  - Organic materials: such as cotton, wool, natural rubber and cellulose.

  - Inorganic materials: such as glasswool, rockwool, perlite, asbestos and calcium silicate.

- **According to the shape**

  - Fill (loose): this type is the most common insulator which is produced as a blanket or a roll, like: glass wool, rock wool and polyethylene (EPE or XPE). It has various degrees of flexibility as well as the ability to bend, and it could be fastened by nails.

  - Slab (panel): it is a rigid type due to the mixing with some resins, like: fiberglass, polyurethane panels, cellulose sheets and polystyrene sheets (EPS or XPS). It comes in different dimensions and thicknesses.

- Granular: a powder or grain placed in the spaces between the walls and it can be mixed with some other materials. Examples of such materials granulated cork and polymers.

- Liquid or gaseous fluids: poured or sprayed on to form the desired layer, such as polyurethane foam and epoxy.

- **According to the usage**
    - Polystyrene (EPS or XPS): it is usually used with low-temperature applications like buildings and containers.
    - Glass wool or rock wool: it is usually used with high-temperature applications like boilers and ovens, but it could be used with buildings and ducts.
    - Polyurethane: due to its efficient insulation, it is usually used with refrigerators, ducts, pipes and energy efficient buildings.
    - Calcium silicate: it is used with furnaces due to its strength and resistance to high temperature.

1.5 Commercial Insulators

The thermal insulation refers to all isolators systems and processes that reduce the heat exchange between inside and outside. Thermal insulation in buildings in hot climates is designed to prevent the entry of heat to the building. Thus, the using of thermal insulation materials reduces the heat transfer. The most important thermal insulators are glass wool, cork, polyurethane and other polymeric materials as well as evacuated panels. It should refer here that air is one of the best thermal insulators due to its low coefficient of thermal conductivity (0.025 W/m.K) and availability everywhere.

The most common insulators are:

1. Cellulose: which is made from recycled wood or waste paper and is characterized by its susceptibility to water and dust absorption.

2. Cork: this is taken from cork trees. Also, it could be made industrial from petroleum product which is called Expanded Polystyrene (EPS) or the rigid type Extruded Polystyrene (XPS). It comes as panels and used as thermal and acoustic insulators.

3. Glass wool: is an insulating material made from glass strings with a binder to give a texture similar to wool. It is a loose or fill material widely used to insulate buildings, as well as boilers.

4. Rock wool: this material is similar to glasswool but it made out of rock and used to isolate the buildings and storages.

5. Ceramic wool: is a refractory material, a particular substance that has a heat-resistant property. It primarily consists of aluminum silicate, which includes fiber made from various polycrystalline fibers and molten glass or ceramic. It is an excellent material for insulation, and can be used for numerous applications.

6. Polyurethane: is a polymer formed by reacting of isocyanate with polyol. Usually uses as insulated panel for buildings and refrigerators or foam to fill the cracks.

7. Polyethylene layers: it comes as Expanded Polyethylene (EPE) or Extruded Polyethylene (XPE). It may have a reflective layer, and then it is called as astro-foil layer. This type consists of two parts; polyethylene as bubbly air cells and a cover of aluminum foil to reflect the radiation. This insulator is good in the summer to reduce the solar gain.

8. Polycarbonate panels: These sheets are lightweight panels, and are composed of several layers to withstand the shocks with the presence of air cavities for the purposes of thermal insulation.

9. Calcium silicate: is an asbestos-free thermal insulation product that can withstand continuous high operating temperatures. Thus, it is commonly used in furnaces and oven. It is a white free-flowing powder obtained by reacting calcium oxide and silica. It has a low bulk density and high physical water absorption.

10. Evacuated panel: also called a vacuum insulated panel (VIP) is a form of thermal insulation consisting of a tight enclosure surrounding a rigid core, from which the air has been evacuated. It is used in building construction and refrigeration units. It provides better insulation performance than conventional insulation material due to less conduction, convection and radiation.

11. Reflective materials: such as aluminum panels, alu-cobond and reflective paints. These materials are used to reflect solar radiation on the exterior walls.

12. Fire retardant sheets: are wooden panels characterized by their ability to delay the fire growth in addition to the advantage of thermal insulation.

Furthermore, there are many insulation materials available for different applications such as: polypropylene, phenol, melamine and expanded rubber.

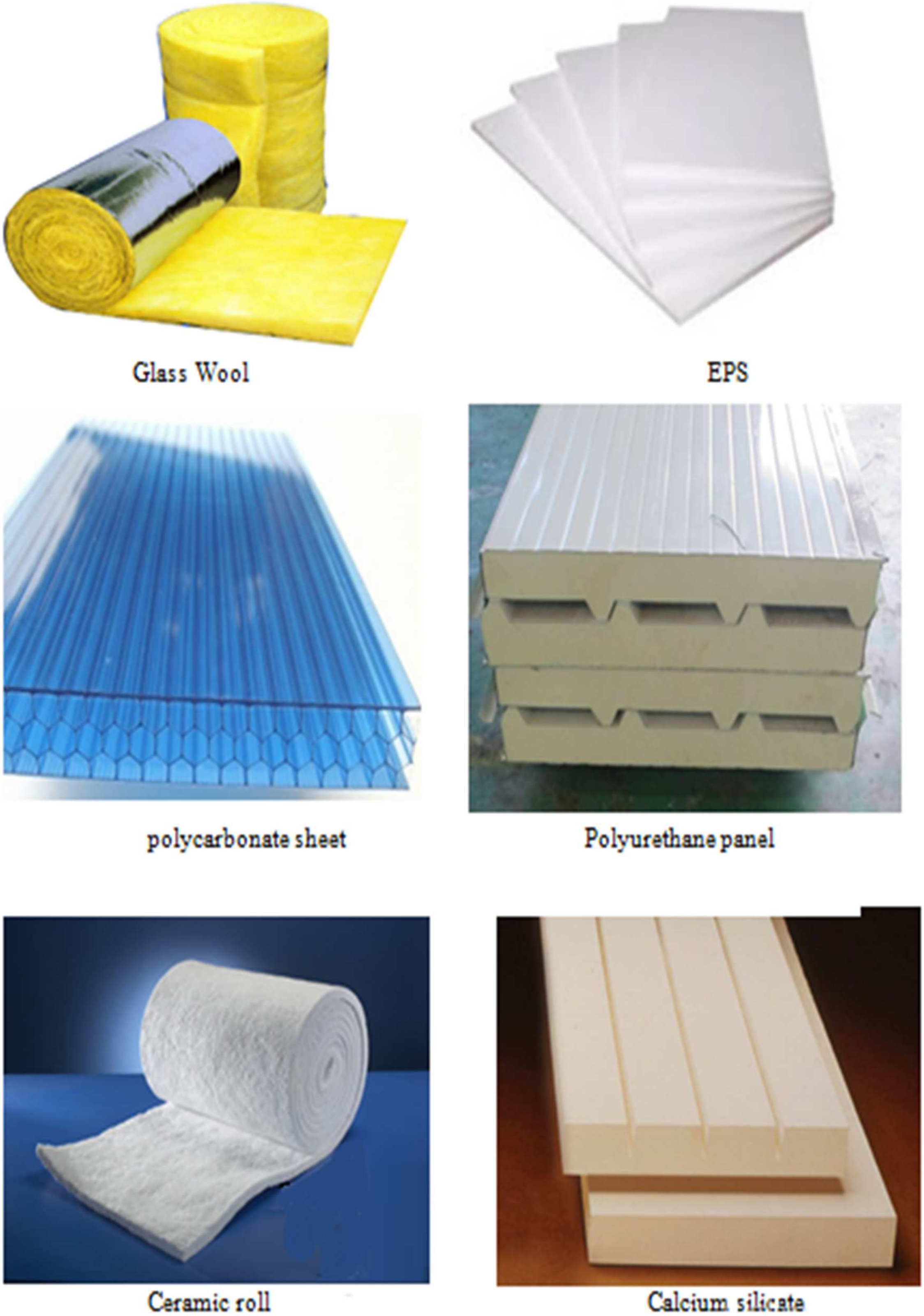


Figure (1.2) Thermal insulators

1.6 Thermal Contribution of Construction Materials

Many construction materials have been developed to minimize the energy consumption for air-conditioning. These materials could be used for walls, roof and foundation. These combinations include:

- Composite wall
- Sandwich panel
- Dry wall
- Thermostone
- Clay brick
- Hollow block with a piece of insulated material like EPS.
- Hollow block made by perlite or other low thermal conductive materials.
- Hollow core wall
- Light weight concrete (LWC) or foamed concrete

The studies show the benefits of using these construction materials instead of using common concrete blocks and bricks. For example, the comparison between thermostone as a construction material for the whole building regarding to the hollow concrete, yields that the annual electrical energy demand for a house built using the thermostone would consume 25% less energy than one built from hollow concrete. The economic analysis shows that building with thermostone can cut the annual cost of electricity by 30% as compared to buildings with hollow concrete blocks.

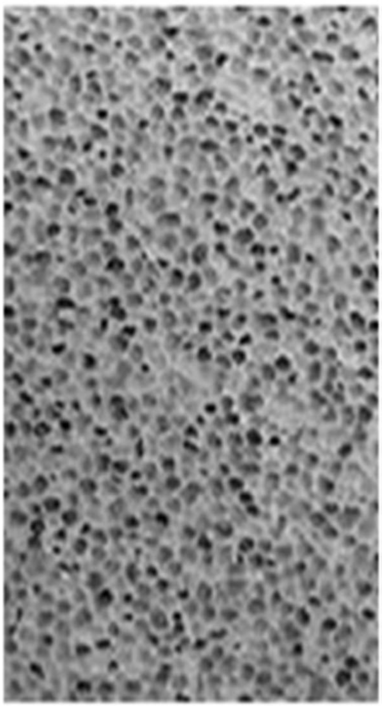
Thermostone

Sandwich Panel (PU)

Dry Wall

Composite Wall (Cellulose)

Clay Brick



LWC

Figure (1.3) Developed construction materials

1.7 Properties of Thermal Insulators

The selecting of an insulation material depends on its properties as well as the operating conditions. The coefficient of thermal conductivity is the most important property of any insulator; it indicates the resistance to heat transfer. The other thermal properties are: reflectivity, absorptivity, heat capacity, density, coefficient of thermal expansion and the coefficient of thermal bridging.

1. **Thermal conductivity**: it is the property of a material to conduct heat. Heat transfer occurs at a higher rate across materials of high thermal conductivity than across materials of low thermal conductivity. Correspondingly, materials of high thermal conductivity are widely used in heat sink applications and materials of low thermal conductivity are used as thermal insulation. The reciprocal of thermal conductivity called thermal resistivity. The unit of thermal conductivity is (W/m.K). Good insulation material should have a thermal conductivity less than (0.2 W/m.K). The coefficient of thermal conductivity can be measured by a thermal conductivity meter apparatus. Temperature is an important parameter that affects the thermal conductivity value. It is found generally increasing of thermal conductivity with the increase of temperature but within the limited temperature range depending on the climatic conditions. On the other hand, the thermal conductivity is increased with increasing of moisture content, thus less thermal resistance.

Table (1.1) Thermal conductivity for common insulators

Item	Material	Thermal Conductivity (W/m.K)
1	Astro-foil (XPE)	0.08
2	Asbestos	0.12
3	Asphalt	0.69
4	Alucobond	0.15
5	Acrylic	0.2
6	Aerogel	0.02
7	Bitumen	0.17
8	Calcium silicate	0.05
9	Cellulose	0.08
10	Coal	0.24
11	Cotton	0.04
12	Cork (EPS)	0.05
13	Ceramic fiber	0.08
14	Engine Oil	0.15
15	Epoxy	0.35
16	Glass Fiber	0.03
17	Glass Wool	0.04
18	PVC	0.2
19	Paraffin Wax	0.25
20	Plywood	0.13
21	Polycarbonate	0.19
22	Perlite	0.05
23	Polystyrene (XPS)	0.08
24	Polyurethane	0.02
25	Rubber	0.35
26	Vacuumed panel	0.007
27	Vermiculite	0.06
28	Wool	0.05

Table (1.2) Thermal conductivity for common construction materials

Item	Material	Thermal Conductivity (W/m.K)
1	Basalt	2.3
2	Block (Hollow) - 20 cm	0.5
3	Block (Hollow) – 15 cm	0.6
4	Block (Hollow) – 10 cm	0.7
5	Block (Solid)	0.9
6	Brick (Cavity)	0.4
7	Brick (Solid)	0.5
8	Concrete (Reinforced)	2
9	Concrete (Not Reinforced)	0.8
10	Cement plaster	1
11	Clay	1.2
12	Dry Wall – 10 cm	0.3
13	Granite	3
14	Gypsum	0.8
15	GRC	0.9
16	Glass	1
17	Limestone	1.5
18	Mica	0.7
19	Marble	2.2
20	Porcelain	1.5
21	Sandstone	1.5
22	Sandwich Panel – 10 cm	0.04
23	Sandwich Panel – 5 cm	0.05
24	Thermostone – 20 cm	0.3
25	Thermostone – 10 cm	0.4
26	Wood	0.15

Table (1.3) Thermal conductivity for common metals

Item	Material	Thermal Conductivity (W/m.K)
1	Aluminum (AL)	200
2	Bronze	110
3	Copper (Cu)	400
4	Iron (Fe)	80
5	Lead (Pb)	35
6	Silver (Ag)	450

Table (1.4) Thermal conductivity for common gases

Item	Material	Thermal Conductivity (W/m.K)
1	Air	0.025
2	Argon	0.015
3	Bromine	0.04
4	Carbon dioxide (CO_2)	0.014
5	Helium	0.15
6	Methane	0.03

2. **Reflectivity:** it is the ratio of reflected radiation from a surface to the total incident radiation. The factors affecting the amount of reflectivity are the color and the level of fine-tuning the surface. The following table shows values of reflectivity for some materials.

Table (1.5) Reflectivity for common materials

Material	Reflectivity (%)
Aluminum	80
Gypsum	70
Cork	45
Concrete	35
Plastic	20
Wood	17
Glass	10
Asphalt	3

3. **Absorptivity:** it is the ratio of absorbed radiation by the surface. The color of the surface affects the amount of absorption. The following table shows absorptivity values for some materials.

Table (1.6) Absorptivity for common colors

Color	Solar Absorptance
Green	0.47
Ochre	0.6
Dark Beige	0.7
Blue	0.7
Red	0.75
Brown	0.75
Dark Brown	0.83
Dark Colors	0.9
Black	0.95

4. **Heat capacity**: it is the ability of material to store the heat. The material with high heat capacity is called **thermal mass**
5. **Density:** it is the mass of matter in a certain volume. The unit is (kg/m^3).
6. **Thermal expansion coefficient:** is the amount of change in the volume of material as a result of temperature change.

Table (2.7) Thermal properties of some materials

Item	Material	Heat capacity (J/kg.K)	Density (kg/m^3)	Thermal expansion (1/K) $x10^{-6}$
1	Brick	850	1900	5
2	Concrete	900	2500	14
3	Granite	900	2750	8
4	Thermostone	750	890	16
5	Aluminum	900	2700	24
6	Iron	450	8000	12
7	Wood	1700	750	50
8	Rubber	1600	950	600
9	Marble	850	2800	8
10	Glass	600	2500	9
11	Water	4200	1000	210
12	Gypsum	1000	1500	10
13	EPS	1500	24	300
14	XPS	1900	32	200
15	Glass wool	700	24	30
16	Cellulose	1750	1200	70
17	Polyurethane	500	12	50

7. **Coefficient of thermal bridge:** which describes the amount of heat transfer in certain areas called thermal bridges. Thermal bridge is an area in the building envelope in which the highest heat transfer compared with neighboring areas, this causing the failure of building materials, the spread of moisture and mold growth. Examples of these areas:

   - The joints between the ceiling and walls
   - Link areas between windows and walls
   - Piles and foundations

8. **Moisture absorption**: The presence of water or humid air in the insulator reduces the thermal insulation value of the material and it may destruct the material rapidly. The moisture is measured by the effect of moisture absorption and permeability.

9. **Mechanical**: Such as durability, compression, tensile and shear stresses. Some insulators are characterized by strength and endurance than others. That makes sense to be used for supporting of the building beside to the goal of thermal insulation.
10. **Acoustical:** Some insulating materials may be used as acoustic insulators as well as thermal insulators.
11. **Safety:** Some insulating materials could get hurt to human during storage, installation and usage. These may cause deformities in the human body, poisoning, infections or allergies in the skin and eyes, which requires importance of knowing the chemical composition of the material and ability to interact with the environment and constitute a mold, germs and insects. There are some physical properties should be considered like the ability of combustion and sublimation.

1.8 Modes of Heat Transfer

Heat is a form of energy which transfers between bodies that are kept under thermal interactions. When a temperature difference occurs between two bodies or a body with its surroundings, heat transfer occurs. In this article, we are going to deal with the different modes of heat transfer. Heat transfers basically in three modes:

1. Conduction: is the heat transfer through a wall from the hot face to the cold one. The thermal conductivity varies from a substance to another. For example, concrete and steel have high conductivity compared to an insulating material such as cork. The amount of heat transfer by conduction depends on the temperature difference between the surfaces of the wall, wall thickness, area of surfaces exposed to heat and coefficient of thermal conductivity of the material, as well as the lag time (period of accumulated heat). This mode of heat transfer could be reduced by the using of thermal insulation materials.

2. Convection: is the transfer of heat due to the ambient air nearby the wall. where, the air molecules move from hot zone to cold zone carrying the thermal energy away and replaced by air molecules have cold temperature. This process is known as convection current. Air movement helps to increase the heat transfer rate. This mode of heat transfer could be reduced by shading and planting.

3. Radiation: is the transfer of radiant heat across a transparent medium or vacuum. The radiant heat is transferred from the hot source to the colder place, like the solar radiation across the windows or the heat that emitted from furnace walls. Reflective surfaces such as metallic foils could be used to reflect the thermal radiation and reduce heat absorption by the walls.

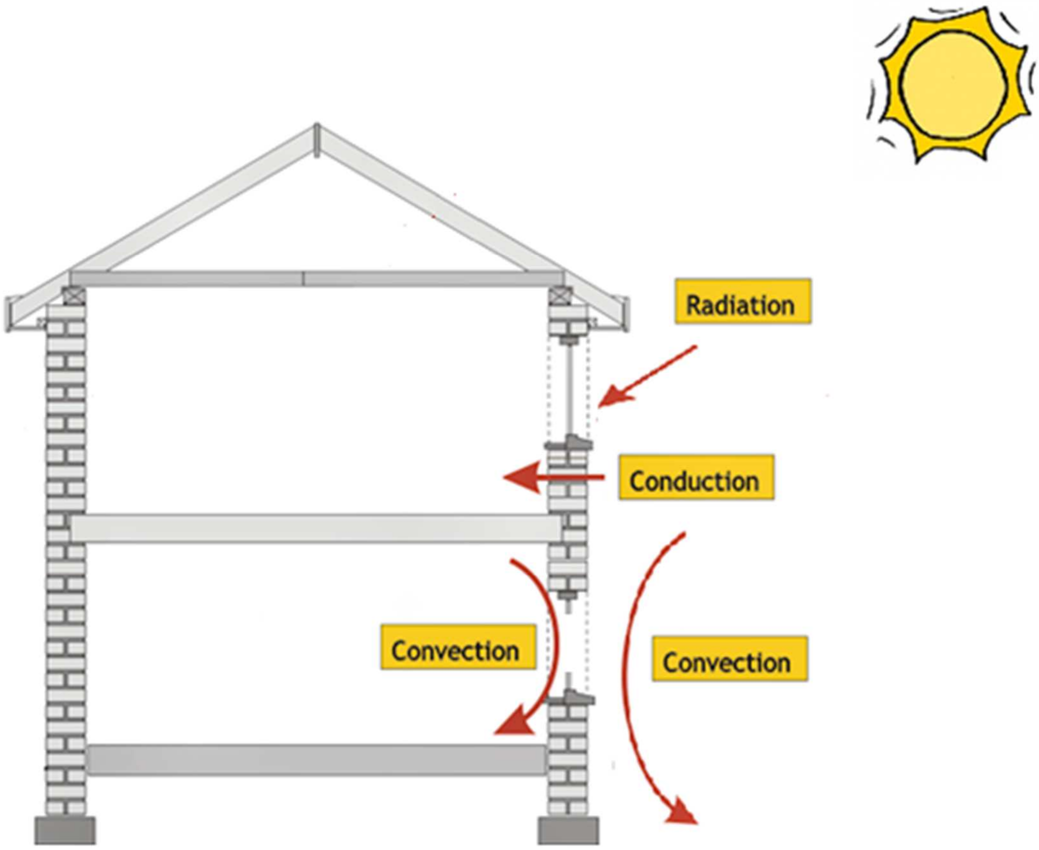


Figure (1.4) Modes of heat transfer through the building

1.9 Thermal Insulation in Buildings

Buildings could be divided in terms of the acquisition method of heat into two types, which are buildings in hot climates and buildings in cold climates. In hot climates, most of the heat is gained from the outside through walls, ceilings and windows. The thermal insulation has to be in the outer shell of the building to reduce the amount of heat gained and this consequently leads to reduce the energy demand for cooling. But in cold climates, heat is transferred from inside to out. Therefore, the insulating layers are placed inside. It is found that the heat losses through the house are as following:

- About 60% of the heat is transmitted through the ceilings and walls of the building.

- About 15% of the heat is transmitted by the windows.

- About 25% of the heat is transferred through the vents and doors of the building.

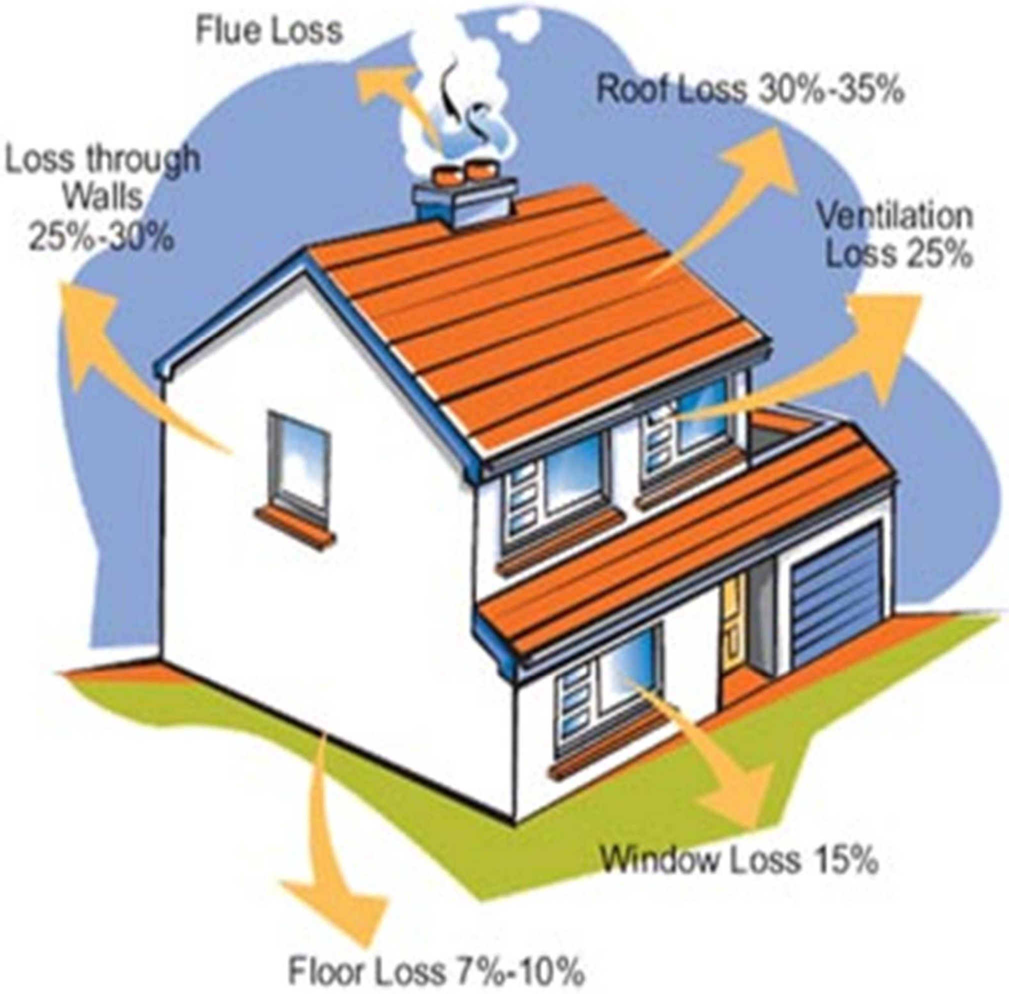


Figure (1.5) Contribution of buildings elements in heat transfer

1.10 Thermal Insulation Expression

There are some concepts must be defined before entering to the design, such as thermal resistance, overall heat transfer coefficient and thermal load.

Thermal resistance: is the susceptibility of the material to resist the heat. Thermal resistance has inverse relation with the coefficient of thermal conductivity. To find out the total resistance of the wall or ceiling, the collection of resistors for all materials should be included as well as the convection resistance adjacent to the external and internal surfaces. Dealing with these resistors exactly like that used with electrical resistors, they are either parallel or series. Resistance also called R-Value. It is worth noting that the US R-Value is about six times the SI R-Value due to the different standards.

Now assume a composite wall of two layers of materials. The resistance for each layer can be calculated by:

$$R = \frac{X}{k}$$

In case of convection presence, it is:

$$R = \frac{1}{h}$$

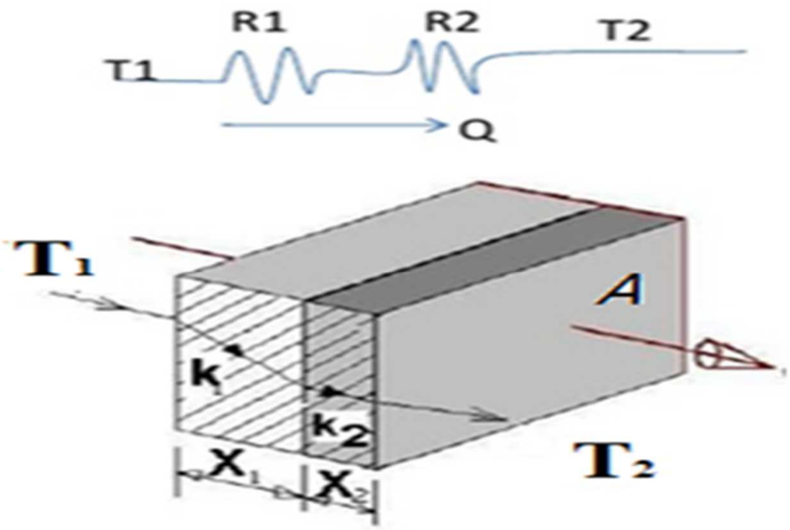


Figure (1.6) Composite wall

Overall heat transfer coefficient: is a factor used to determine the optimum thickness of the insulation material in buildings. It is also called U-Value. And it can be calculated from the following relationship:

$$U = \frac{1}{R1 + R2}$$

The amount of heat transfer through a wall is given by the following relationship:

Q = U A (T1 – T2)

Where T is the temperature of the surface, while A is the surface area. The unit of U-Value is ($W/m^2.K$). The U-Value of un-insulated wall is high up (1-5), while the U-Value of insulated wall is less than (1), while for super-insulation wall is less than (0.2). The world is moving to standardize the U-Value for residential buildings as minimum as possible toward satisfying the zero energy building.

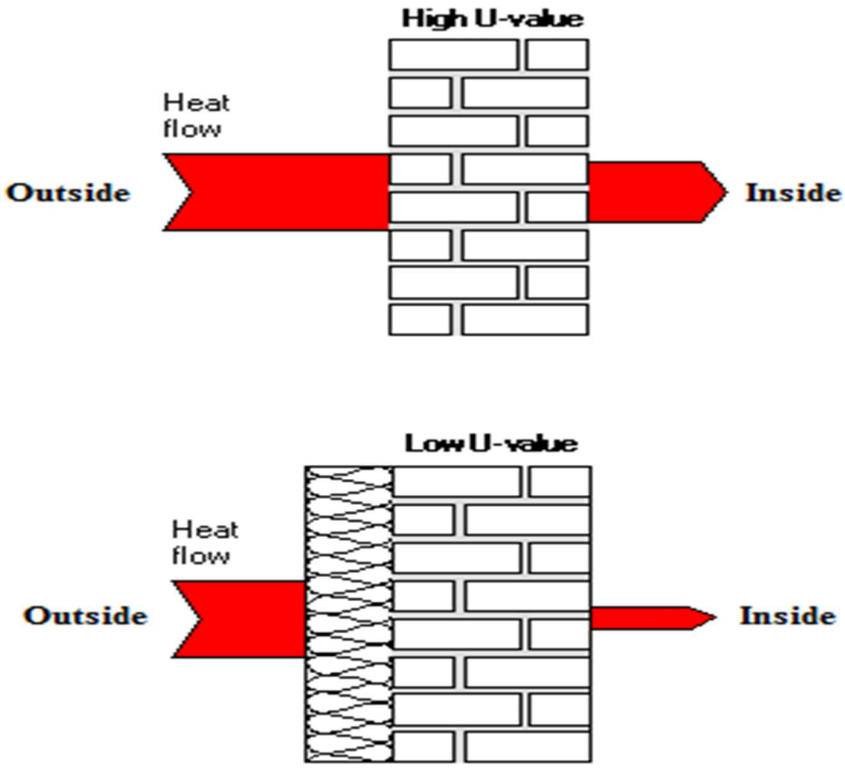


Figure (1.7) Effect of U-value in reducing the heat transfer

Thermal load: is the summation of all sources of heat on a building, such as heat loss through the structure (walls, roof and floor), solar radiation through windows, indoor-outdoor air temperature difference (ventilation and infiltration), internal heat (lighting, respiration and equipment). The total heat transfer can be calculated by:

$$Q_{Total} = Q_{Walls} + Q_{Roof} + Q_{Floor} + Q_{Windows} + Q_{Ventilation} + Q_{lighting} + Q_{Equipment}$$

Where, the product can be divided by 3600 to get the load in ton of refrigeration (TR).

1.11 Engineering Calculations

The theoretical calculation is quite systematic and easy to understand, but it is rather has a slight difference to the practical results due to some common assumptions like ignoring the floor gain or assign a constant value for the other sources of heat. However, the following are some examples to show the effect of thermal insulation in energy conservation.

<u>Example (1):</u> Heat losses through the wall in the winter

Calculate the reduction in the amount of heat transmitted through the wall shown in the figure due to the insulation. The area of the wall is 1 m^2 and the coefficients of convection heat transfer are:

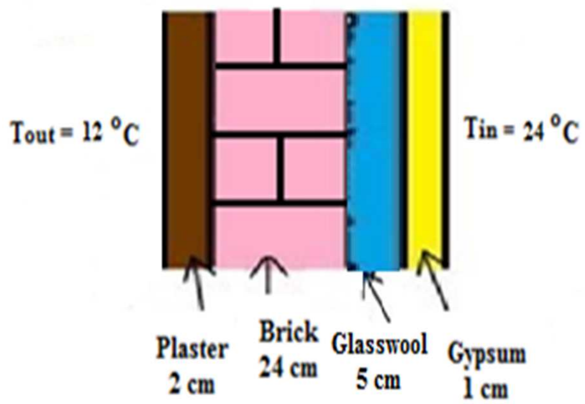
- 10 $W/m^2.K$ for external surface

- 5 $W/m^2.K$ for internal surface

Note: Values of thermal conductivity of the materials are:

$K_{plaster}=1$, $K_{brick}=0.5$,

$K_{gypsum}=0.8$, $K_{glasswool}=0.04$



<u>Solution:</u>

- **Before insulation**

Plaster R1 = x1/k1 = 0.02/1 = 0.02

Brick R2 = x2/k2 = 0.24/0.5 = 0.48

Gypsum R3 = x3/k3 = 0.01/0.8 = 0.0125

External air Ro = 1/ho = 1/10 = 0.1

Internal air Ri = 1/hi = 1/5 = 0.2

Total resistance R = R1 + R2 + R3 + Ro + Ri = 0.8125

U = 1 / R = 1.23 $W/m^2.K$

Q = U A (Ti-To) = 1.23 * 1 * (24-12) = 14.8 W

- **After insulation**

Glasswool Rg = xg/kg = 0.05/0.04 = 1.25

Total resistance R = R1 + R2 + R3 + Ro + Ri + Rg = 2.0625

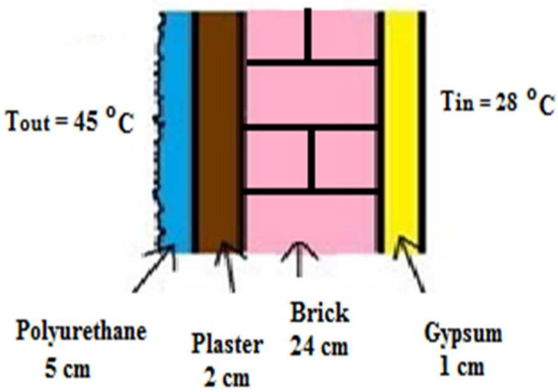
U = 1 / R = 0.485 $W/m^2.K$

Q = U A (Ti-To) =0.485 * 1 * (24-12) = 5.8 W

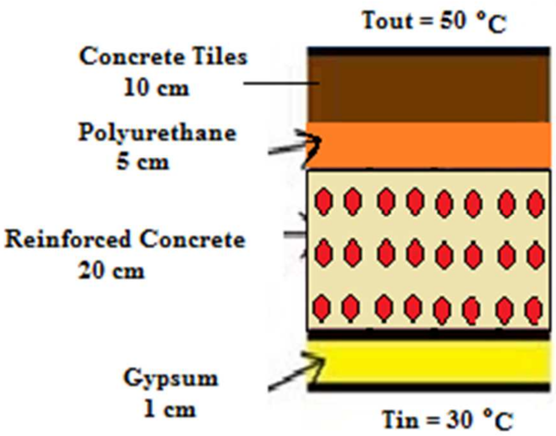
So the reduction in the heat loss = (14.8 – 5.8)/14.8 = 0.608 = 61 %

Example (2): Calculation of the heat load in summer

Calculate the size of air-conditioning device (ton of refrigeration) required to cool a room of 6 m x 4m x 3m before and after the insulation. Note that the wall and the roof materials are shown in the figures below. Neglect the effect of radiation and convection heat transfer. Add 3000 W to the total load due to the heat gained through windows, ventilation, occupants and equipment.



Wall section



Roof section

$K_{plaster}=1$, $K_{brick}=0.5$, $K_{gypsum}=0.8$, $K_{polyurethane}=0.02$, $K_{RC}=2$, $K_{concrete\ tiles}=0.8$

Solution:

- **Before insulation**

- **Walls**

Plaster R1 = x1/k1 = 0.02/1 = 0.02

Brick R2 = x2/k2 = 0.24/0.5 = 0.48

Gypsum R3 = x3/k3 = 0.01/0.8 = 0.0125

Total resistance R = R1 + R2 + R3 = 0.5125

U = 1 / R = 1.95 $W/m^2.K$

A = (6*3*2) + (4*3*2) = 60 m^2

Q = U A (Ti-To) = 1.95 * 60 * (45-28) = 1990 W

- **Roof**

  Concrete tiles $R1 = x1/k1 = 0.1/0.8 = 0.125$

  Reinforced con. $R2 = x2/k2 = 0.2/2 = 0.1$

  Gypsum $R3 = x3/k3 = 0.01/0.8 = 0.0125$

  Total resistance $R = R1 + R2 + R3 = 0.2375$

  $U = 1 / R = 4.21\ W/m^2.K$

  $A = 6*4 = 24\ m^2$

  $Q = U\ A\ (Ti-To) = 4.21 * 24 * (50-30) = 2021\ W$

  $Q_{total} = Q_{walls} + Q_{roof} + Q_{others} = 1990 + 2021 + 3000 = 7011\ W$

  Load $= Q_{total} / 3500 = 7011/ 3500 = 2$ TR

- **After insulation**

- **Walls**

  Polyurethane $Rp = xp/kp = 0.05/0.02 = 2.5$

  Total resistance $R = 0.5125 + 2.5 = 3.0125$

  $U = 1 / R = 0.332\ W/m^2.K$

  $Q = U\ A\ (Ti-To) = 0.332 * 60 * (45-28) = 338\ W$

- **Roof**

  Polyurethane $Rp = xp/kp = 0.05/0.02 = 2.5$

  Total resistance $R = 0.2375 + 2.5 = 2.7375$

  $U = 1 / R = 0.365\ W/m^2.K$

  $Q = U\ A\ (Ti-To) = 0.365 * 24 * (50-30) = 175\ W$

  $Q_{total} = Q_{walls} + Q_{roof} + Q_{others} = 338 + 175 + 3000 = 3513\ W$

  Load $= Q_{total} / 3500 = 3513/ 3500 = 1$ TR

1.12 Electricity Demand Reduction

The use of insulation keeps the indoor temperature stable as well as reduces the thermal loads and thus the amount of electricity demand. Usually, the electricity consumption is accounted in (kWh). In order to calculate the Annual Energy Demand (AED), the following equation is used:

$$\mathbf{AED = Q_{total} * N / 100}$$

Where N is the number of days under use

The amount of the annual consumption of electric power determines the building performance. The building performance factor could be calculated from the following relationship depending on the floor area:

$$\mathbf{BPF = AED / Floor\ Area}$$

The building performance factor (BPF) is used to determine the type of building in terms of energy consumption, where high-energy building consumes more than (250 kWh/m^2) per year while medium-energy building consumes an average between (100-200 kWh/m^2) per year and low-energy building consumes less than (50 kWh/m^2) per year.

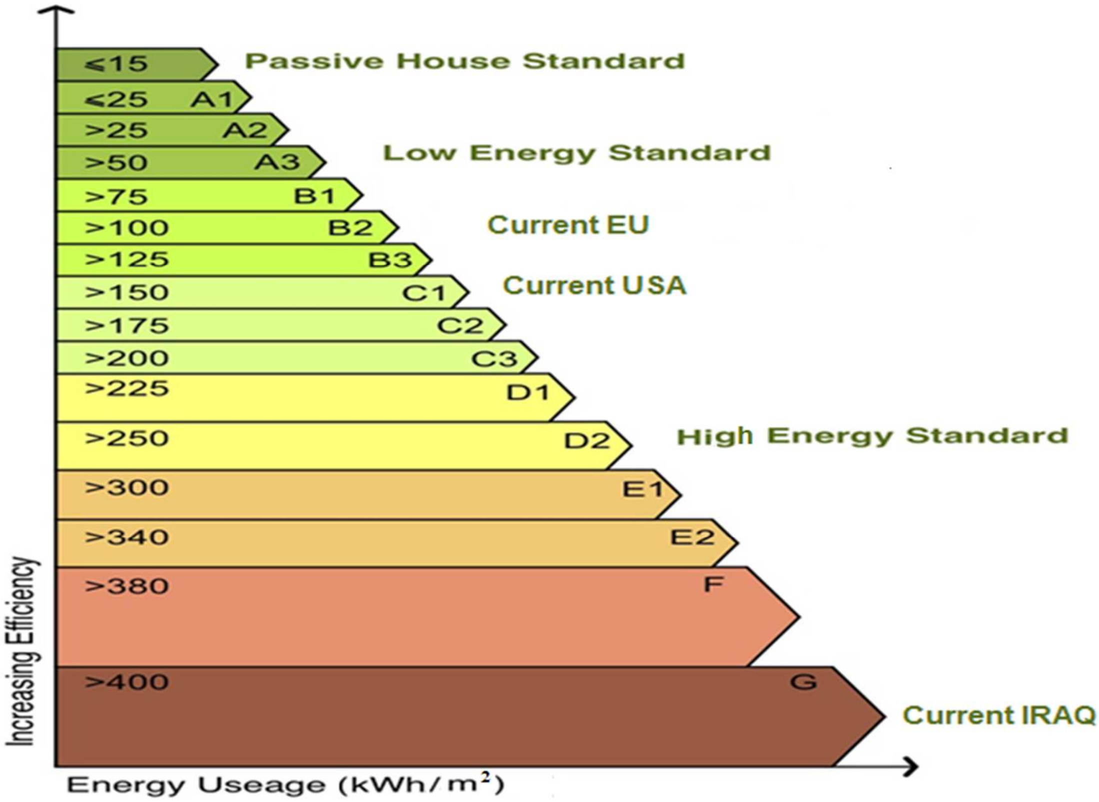


Figure (1.8) Energy classification standards

1.13 Reduce Oil Consumption

It is found that roughly about 3,000 liters of oil equivalent each year are burned to produce electricity for heating or cooling for uninsulated house. This could be saved up to 60% through the using of thermal insulation techniques. The approximate equation to determine the relationship between energy demand and the annual oil consumption in (liters/m^2) of floor area is:

Oil Consumption = 1.5 * Exp (BPF/120)

1.14 Greenhouse Effect

Greenhouse gas is any compound gas in the atmosphere that is capable to absorb infrared and keeping the heat from escaping out of the atmosphere. Greenhouse gases are responsible of the phenomenon of global warming.

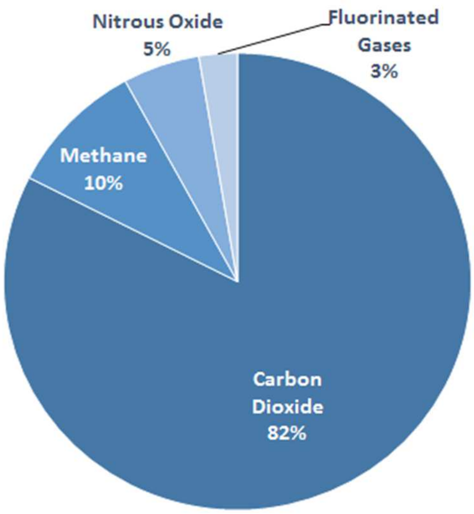


Figure (1.9) Greenhouse gases

The sector of residential building has the major impact on the increase of greenhouse gases and it is considered as the most damage to the climate. The traditional house (non-insulated) causes the emission of more than 7,000 kilograms of carbon dioxide CO_2 into the atmosphere each year. The approximate equation to determine the relationship between energy demand and the annual CO_2 emission in (kg/m^2) of floor area is:

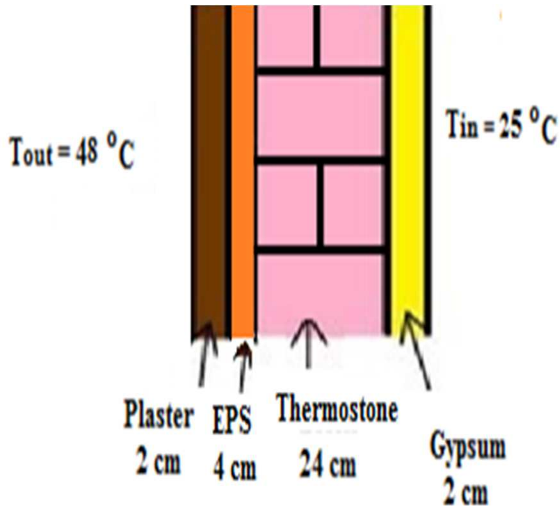
CO_2 Emission = 3.5 * Exp (BPF/120)

<u>Example (3):</u> Extra calculations for oil consumption and CO_2 emission

A house of 10 m x 5 m x 3 m dimensions has insulated walls and ceiling, as shown in the figure. Neglect the effect of radiation and convection heat transfer. Add 4000 W due to the heat gained through other sources. Calculate:

1. Total heat transmitted through the building.
2. Annual electricity consumption in the building as a result of cooling (Suppose the use of air-conditioning for 120 days).
3. Efficiency of the building.
4. Oil consumption in power plant as a result of the annual consumption.
5. CO_2 emissions in power plant.

$K_{plaster}$=1, K_{EPS}=0.05, $K_{thermostone}$=0.3, K_{gypsum}=0.8



<u>Solution:</u>

1) Heat transfer

Plaster R1 = x1/k1 = 0.02/1 = 0.02

EPS R2 = x2/k2 = 0.04/0.05 = 0.8

Thermostone R3 = x3/k3 = 0.24/0.3 = 0.8

Gypsum R4 = x4/k4 = 0.02/0.8 = 0.025

Total resistance R = R1 + R2 + R3 + R4 = 1.645

U = 1 / R = 0.608 $W/m^2.K$

A = (10*3*2) + (5*3*2) + (10*5) = 140 m^2 total area of walls and roof

Q = U A (Ti-To) = 0.608 * 140 * (48-25) = 1957 W

2) Annual Electricity Demand

Q_{total} = 1957 + 4000 = 5957 W

AED = Q_{total} * N / 100 = 5957 * 120 / 100 = 7148 kWh

3) BPF = AED / Floor Area = 7148 / 50 = 143 kWh/m^2 medium energy house

4) Oil Consumption = 1.5 * Exp (BPF/120) = 1.5 * Exp (143/120) = 5 $liters/m^2$

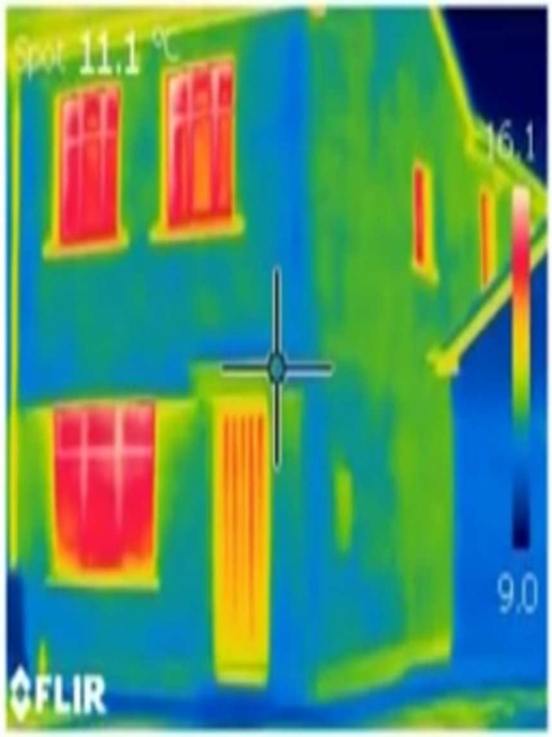
5) CO_2 Emission = 3.5 * Exp (BPF/120) = 12 kg/m^2

1.15 Thermal Images

Thermal images can be captured using thermal cameras like: FLIR, FLUKE and MSA. A thermo-graphic image is used to illustrate the difference between the well and poorly insulation levels. Heat loss through the wall is highlighted by several colors. The amount of radiation emitted increases with temperature, therefore warm objects appears in red color against blue colors for cool objects.

<u>Question:</u> Thermal images of a building have been captured in the winter, as shown in the figure below. Explain your understanding.

a. Before insulation



b. After insulation

<u>Answer:</u> In image (a), where there is no insulation, heat is transferred easily through the walls and other building elements. Thus, the outer faces close to be red and yellow. On the other hand, in image (b) after insulation, heat is accumulated inside and the outer faces have the same ambient temperature, thus appeared in blue and green.

1.16 Economical Effect

From an economical point of view, the quality of insulation materials is chosen to satisfy a balance between the reduction in energy consumption and added cost due to insulation. It has found that super insulation of the building increases the cost of construction up to 20%, but this amount would be recovered as a result of lower electricity bills in a few years. To make this process more economical, thermal insulation of the building must be chosen carefully according to the following factors:

- The amount of insulation materials (areas and thicknesses required).
- The cost of insulation materials and labor costs (installation cost).
- The amount of energy saved for suitable period of time. Hence, the money saved.

The type of climate is directly affecting the need for insulation. In different climates, the location of insulation and the reasons for insulating vary. Hot climates typically do not need the same level of insulation as cold and mild climates. Cold climates that require a lot of heating require high levels of insulation in the main areas of the home: roof, walls, floors, and basement.

There are a few alternatives to the polyurethane foam and wool products used in insulation processes. Many people believe that foam and glasswool can be hazardous to their health and for environment. Some eco-friendly insulation options are available on the market include: cellulose, sheep's wool, cork, and natural fibers.

However, the revenue of insulation (RI) equals to the cost of air-conditioning used for a certain period of time without insulation (CWO) minus the cost of air-conditioning used with insulation (CW) minus the cost of the insulation (CI).

RI = CWO – CW - CI

Insulating the home saves the average energy by 40-60% for heating and cooling. This will keep the money by 30-50%. Some countries have developed a policy to reduce the electricity bills for low-energy homes as an encouragement. The following table shows average prices of some insulators.

Table (1.8) Average costs of some common insulators

Item	Insulation Material	Cost ($/m^2) for each cm thickness
1	Alucobond	20
2	Asbestos	8
3	Asphalt	2
4	Cellulose	1.5
5	Cement	6
6	Clay	0.7
7	Coal	2
8	Cotton	3
9	Cork (EPS)	1.5
10	Glass Fiber	2.5
11	Glass Wool	2.5
12	Gypsum Plaster	3
13	Perlite	4
14	Polystyrene	3
15	Polyurethane	6
16	Rubber	2
17	Wood	15
18	Wool	8
19	Granite	18
20	GRC	10
21	Limestone	12
22	Sandstone	12
23	Marble	18
24	Basalt	12

1.17 Useful Applications

There are some tools used to obtain the contribution of thermal insulation to energy saving, fuel consumption and CO_2 emissions. The course included 2 hours of computer-lab training for the following applications:

- **Iraqi Passive House Planning Package (IPPP):** It is a visual basic based design tool that is used to find complete energy balance of passive or active buildings in Iraq. The application is very responsible for the hot climate zone of Iraq. It includes the following features:
    - Meteorological data (18 cities in Iraq)
    - Properties library for different construction materials and insulations
    - Cooling and heating load calculation for residential building
    - Electricity power consumption

- Contribution of renewable energy
- Indoor air quality and ventilation system
- Passive house standards verification
- Oil consumption
- CO_2 emission
- Cost analysis

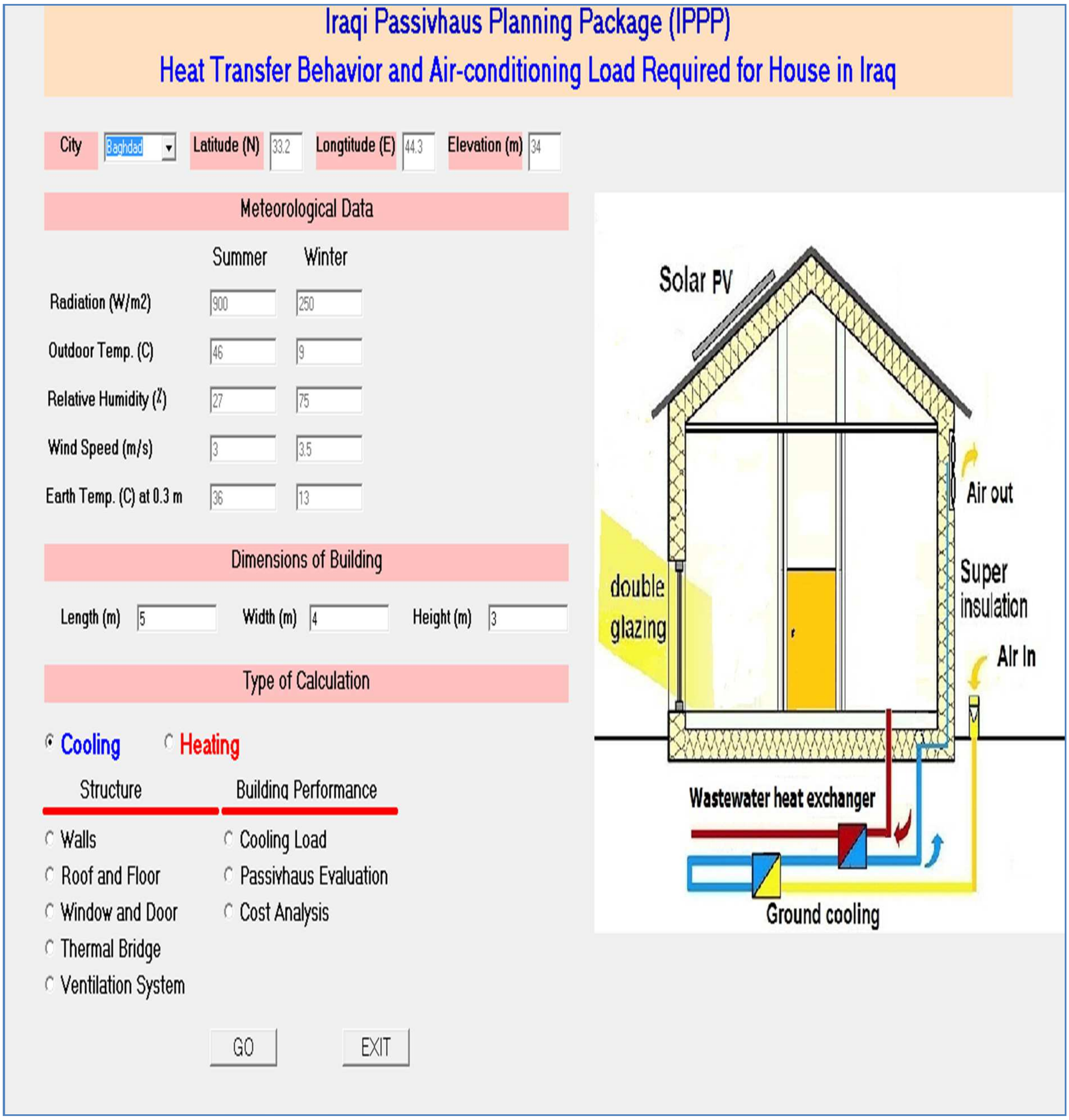


Figure (1.10) Main form of IPPP application

- **RETScreen:** is a clean energy management software system for energy efficiency, renewable energy and cogeneration project feasibility analysis as well as ongoing energy performance analysis. RETScreen 4 is an Excel-based clean energy project analysis software tool that helps to determine the technical and financial viability of potential clean energy projects. The application includes the following features:

- **Energy efficiency (EE)** models for residential, commercial & institutional buildings, & for industrial facilities & processes
- **Climate database** expanded to **4,700 ground-stations** & **NASA Satellite Dataset Integrated** within the software to cover populated areas across the entire surface of planet
- Renewable energy, cogeneration & EE models integrated into **one software file** & emerging technologies, such as wave & ocean current power added
- **Project database** providing users instant access to key data and information for hundreds of case studies & project templates
- **RETScreen file format (*.ret)** - a dramatically smaller file size (<25 KB instead of 10 MB) that is easily shared over the Internet & which allows the user to create custom databases for RETScreen
- Software & databases translated into **35 languages** that cover 2/3 of the world's population, and available at the click of the mouse

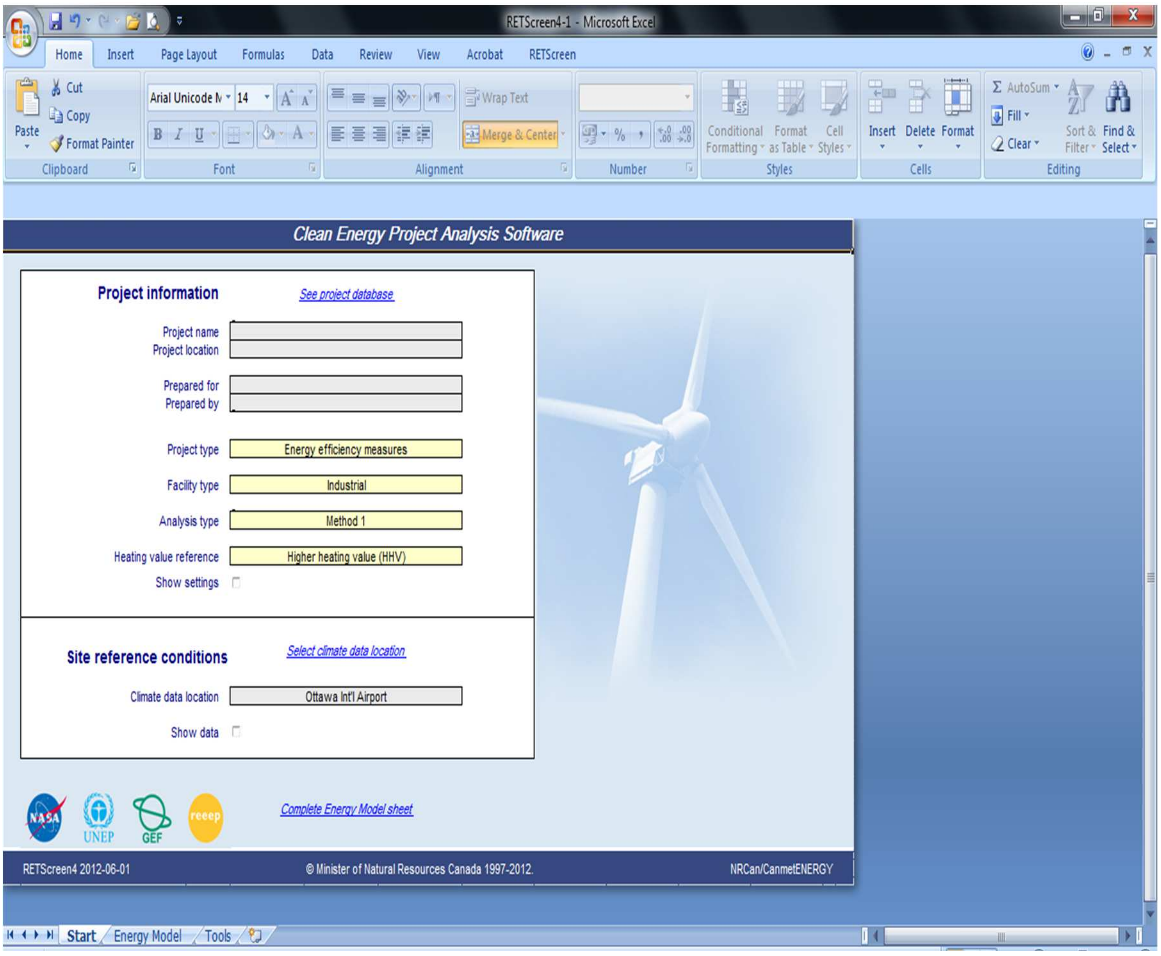


Figure (1.11) Main form of RETScreen application

- More information are available on the site: http://www.retscreen.net/

1.18 Techniques of Materials in Energy Saving

With the constantly changing environment around us, it’s important to be environmentally aware and active. It is even more important when consider how much money it could save by building a green home. The methods and ways are going about changing the home from an emission-producing powerhouse into more of a greenhouse. Everything is available in order to save energy can be implemented in creating a green space. In the long run, going green will save lots of money; the initial renovations needed to go green can sometimes be costly. Nowadays, there are many techniques to invest the natural materials and the parallel techniques in energy saving, such as: super insulation, avoiding thermal bridges, advantage of thermal mass, phase change materials, glow materials and smart materials.

1. Super insulation: is an approach to satisfy low energy building design that dramatically reduces heat loss (and gain) by using much higher levels of insulation and airtightness than normal. Super insulated buildings typically include:

- Very high levels of insulation (about 0.15 for walls and 0.1 $W/m^2{\cdot}K$ for roof in SI U-values)
- Details to ensure insulation continuity where walls meet roofs, foundations, and other walls.
- Airtight construction, especially around doors and windows to prevent air infiltration pushing heat in or out.
- Heat recovery ventilation system to provide fresh air.
- Low-e double or triple glazed windows.
- Much smaller than conventional heating system, sometimes just a small backup heater.
- Usage of renewable energy sources.

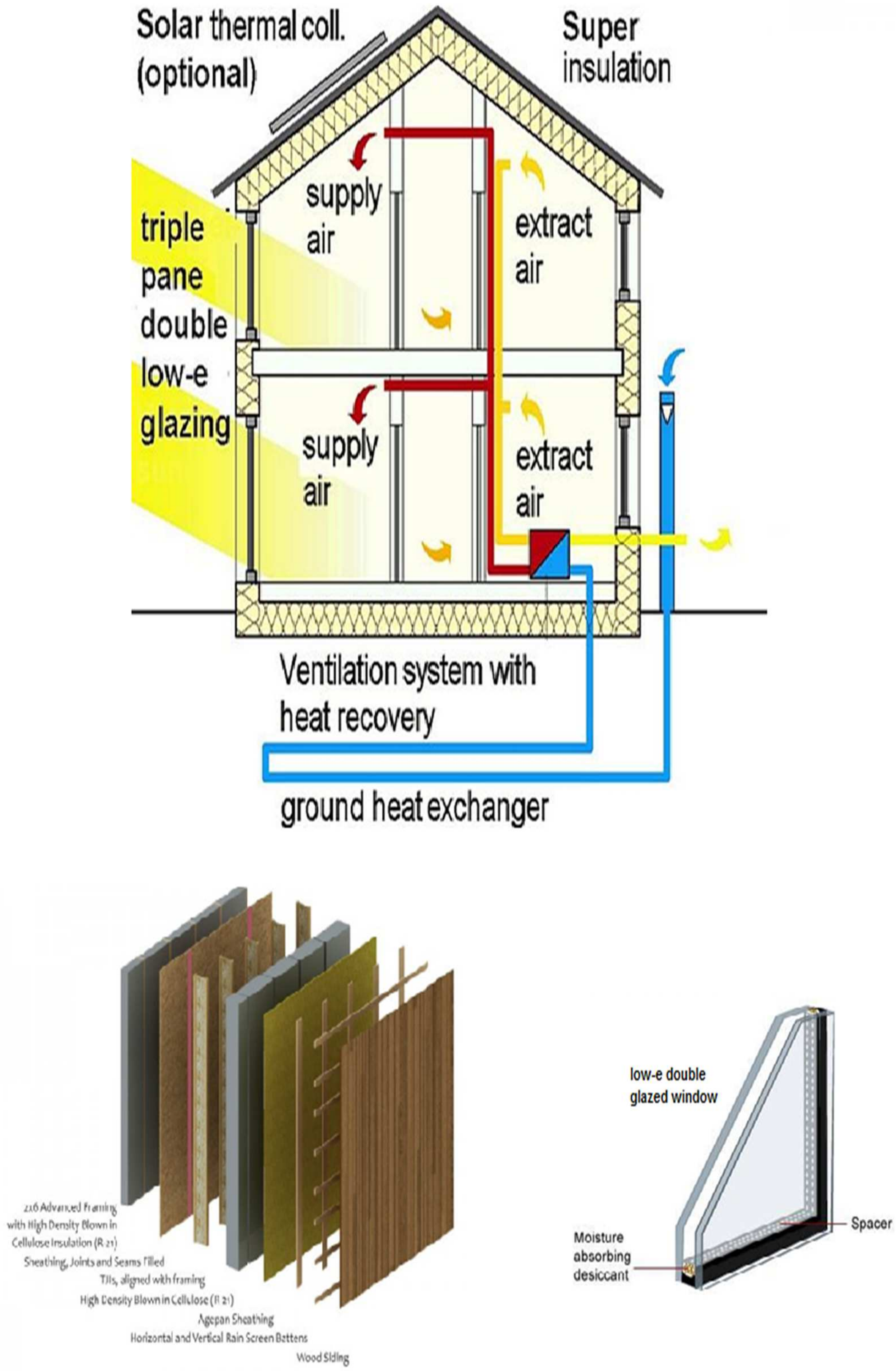


Figure (1.12) Ways to satisfy super insulation

2. Avoiding thermal bridges: in some assemblies in the building envelope heat transfers more than through the construction materials due to higher thermal conductivity. Such regions are called thermal bridges. They are clearly noticed in the junctions between windows and walls, doors and walls, walls and floors, walls and roofs and between different walls. A thermal bridge increases heat loss through the structure, and in some cases causes surface condensation or surface mould. The designer should identify and treat all thermal bridges in the construction on site using suitable thermal insulators like glasswool and EPS. However, good solutions to avoid thermal bridges for several situations are described in figure below.

Figure (1.13) Avoiding thermal bridges

3. Advantage of thermal mass: where thermal mass is a term to describe the ability of a material to absorb and store heat energy. A lot of heat energy is required to change the temperature of high density materials like concrete, bricks, tiles and stones. They are therefore said to have high thermal mass. Lightweight materials such as timber have low thermal mass. The thermal mass will absorb thermal energy when the surroundings are higher in temperature than the mass, and give thermal energy back when the surroundings are cooler, without reaching thermal equilibrium. Scientifically, thermal mass is equivalent to thermal capacitance or heat capacity, the ability of a body to store thermal energy. Thermal mass may also be used for bodies of water, machines or techniques like Trombe wall. Designers seek to find more active thermal mass like Zeolite mineral.

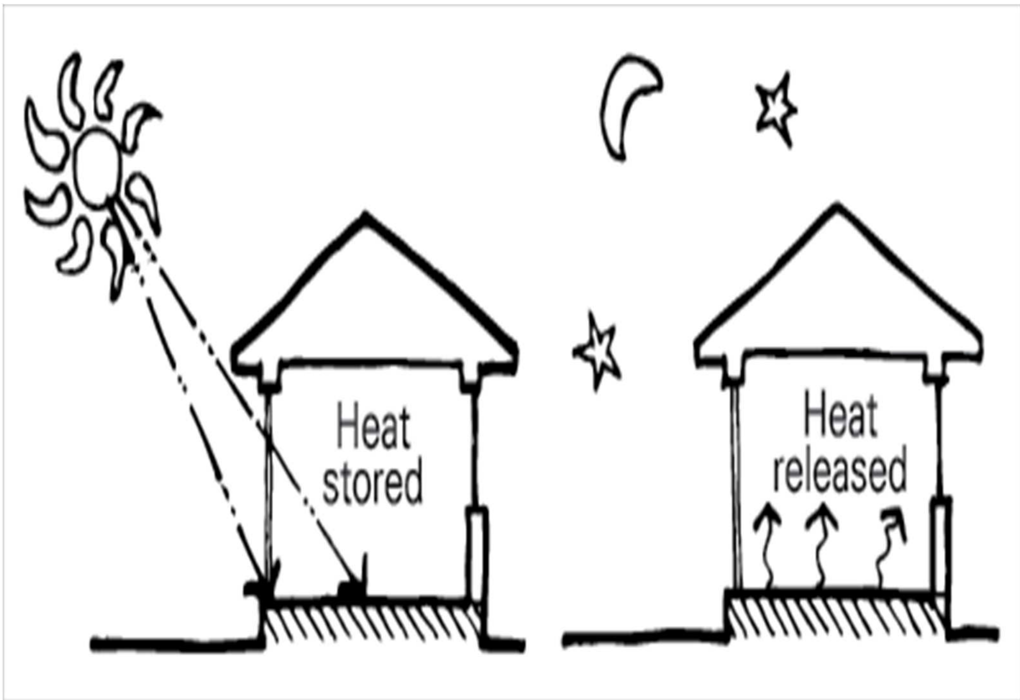


Figure (1.14) Application of thermal mass in heating

4. Phase change materials (PCM): Those materials that are consequently oscillating between liquid and solid phases, hence absorbing or releasing the heat depending on the surrounding temperature. Many substances that can act as phase change materials such as paraffin and salt hydrates. These materials could be used in moderate warm climate where the ambient air is hot at the daytime and cool nightly. In the warm daytime, this material absorbs the heat from indoor air and turns to be in the liquid state. In the cold night, the material releases the heat and turns to be in the solid state again. By repeating this process, the indoor air temperature remains stable without electricity.

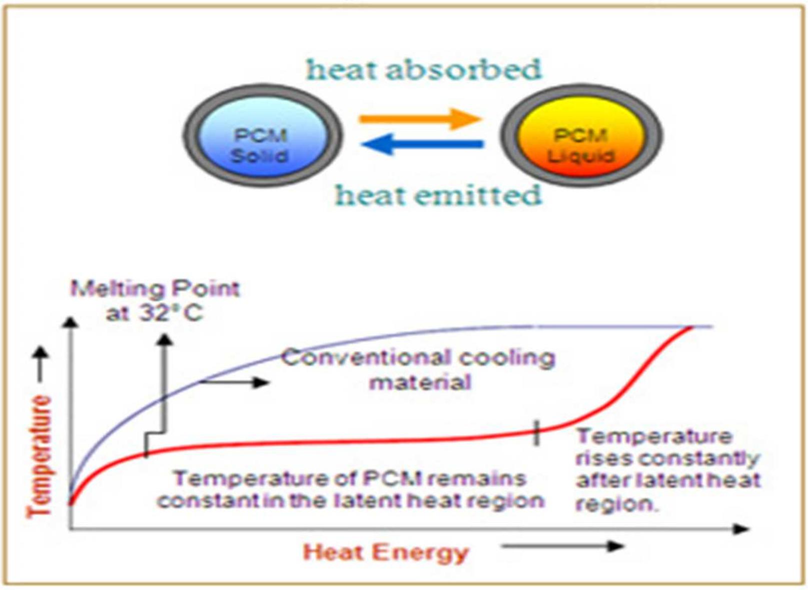


Figure (1.15) PCM behavior

National Gypsum has produced a phase change drywall with the following specifications:

- The phase change material is Micronal Paraffin
- Tiny spheres of paraffin (5-10 micrometers in diameter) are encapsulated in acrylic shells, and these are mixed with the gypsum in drywall.
- Melting temperature is 24 ^{o}C and could be operated till 32 ^{o}C.
- Heat capacity is 125 W/m^2.

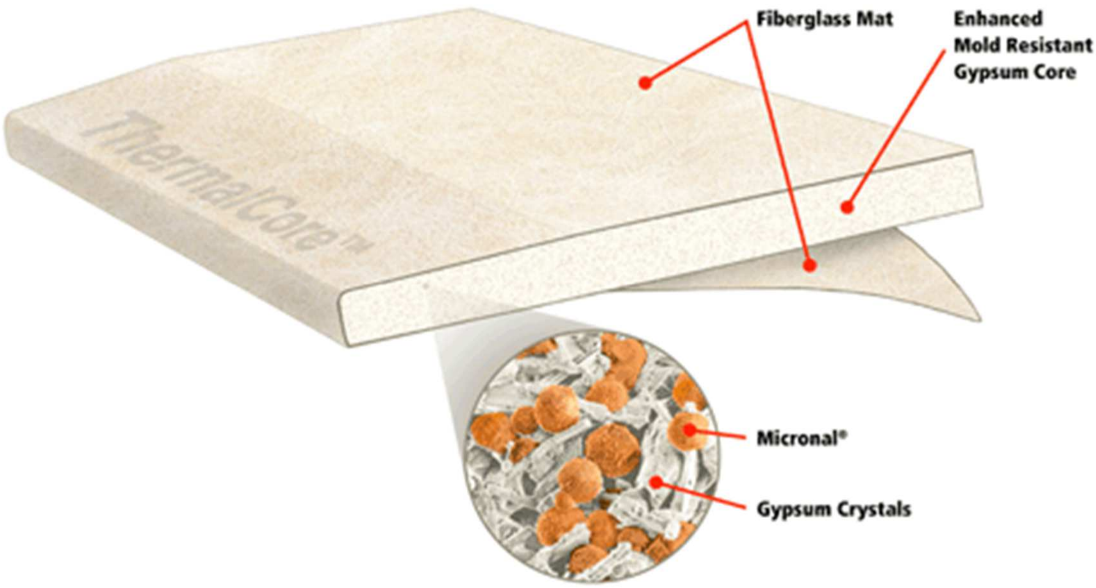


Figure (1.16) Micronal paraffin as PCM in a dry wall

5. Glow materials: in some materials, light or heat is absorbed daytime and released slowly in the form of light at night. The process is called phosphorescence. These materials are used for "glow-in-the-dark" mechanism, where particles called luminophores (phosphorescence, fluorescence, Zinc sulfide, Strontium aluminate) are mixed with the asphalt. It collects energy from the sun during daytime. At night, it emits the energy to glow the path for up to 10 hours.

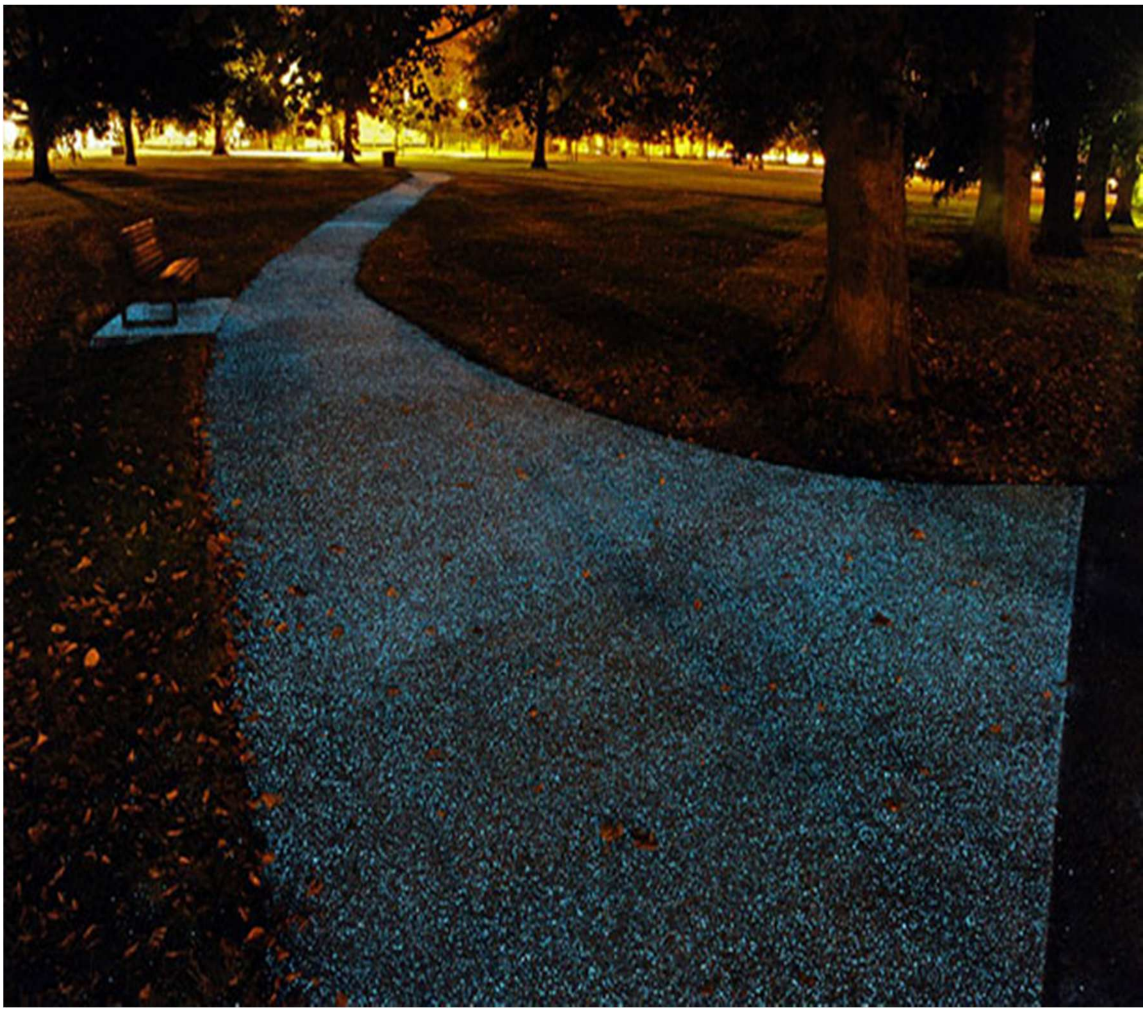


Figure (1.17) Application of glow materials

6. Smart materials: Smart materials are designed to achieve certain functions by controlling some properties of it like: temperature, moisture, electrical and stress. In the field of energy saving, companies try to design what so called "smart window" that controls the amount of light and heat that enters a space. The smart glass includes some polymers and crystals. In clear mode an electrical current is passed through the PDLC (Polymer Dispersed Liquid Crystal) interlayer which aligns the microscopic crystals along a number of parallel axes, thus allowing vision and light through the glass. When the temperature goes high it prevents the heat through in. actual thermal image shows that the smart glass acts like insulation reflecting heat back.

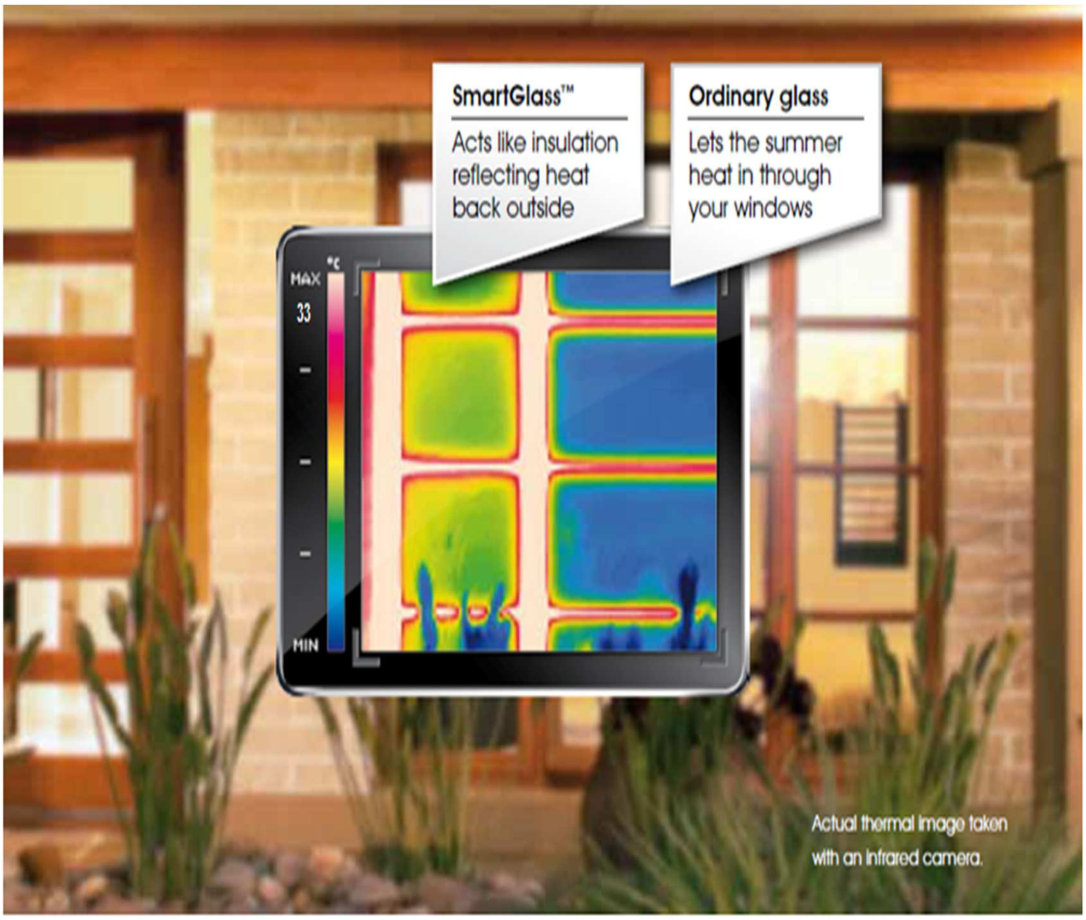


Figure (1.18) Application of smart materials

1.19 Thermal Insulation in High Temperature Applications

Thermal insulation is important in high temperature applications such as furnaces and hot pipes. The use of high temperature insulation can ensure that the heat is not transferred to the outer body, reducing the risk of burns to operators. There is a range of materials that are used as insulation materials in these applications, such as: fiberglass, calcium silicate, asbestos, perlite and ceramics.

Example (4): Insulation for furnace

A furnace wall made of brick has 24 cm thickness (k=0.5 w/m.K), as shown in the figure below. What is the thickness of asbestos (k=0.12 w/m.K) required to keep the external face of the wall less than or equal to 40 ^oC, if the heat rate is 400 W/m^2. Find also the interference temperature.

Solution:

$Q = U\,A\,\Delta T = A\,\Delta T / R$

$400 = (1)\,(900-40) / (0.24/0.5 + x/0.12)$

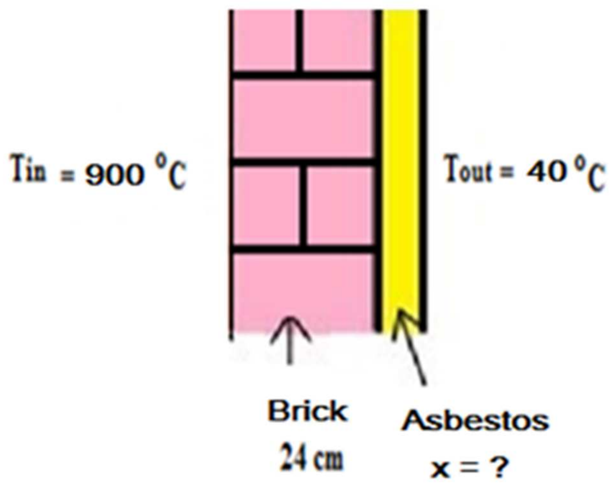
$x = 0.2$ m = 20 cm

To find the interference temperature (Tf);

$Q = U\,A\,\Delta T = A\,\Delta T / R$

$400 = (1)\,(900-Tf) / (0.24/0.5)$

$Tf = 708\ ^oC$



Example (5): Insulation for pipe

A thick-walled tube of stainless steel [18% Cr, 8% Ni, $k = 19$ W/m · °C] with 2-cm inner diameter (ID) and 4-cm outer diameter (OD) is covered with a 3-cm layer of asbestos insulation [$k = 0.2$ W/m · °C]. If the inside wall temperature of the pipe is maintained at 600°C, calculate the heat loss per meter of length.

Find also the critical thickness of the insulation if external convection heat coefficient is 5 W/m.K.

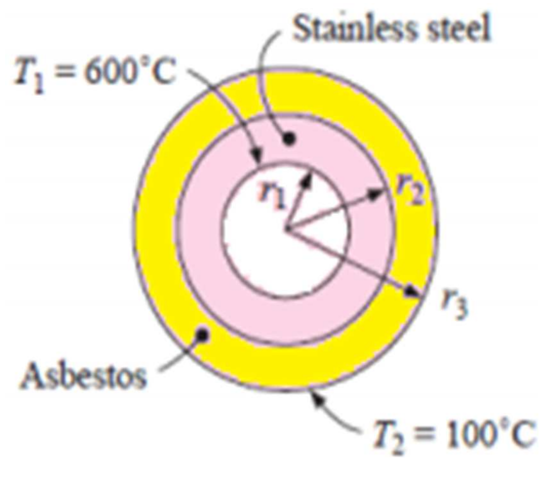
Solution:

$q = U\,A\,\Delta T = A\,\Delta T\,/\,R$

$$\frac{q}{L} = \frac{2\pi\,(T_1 - T_2)}{\ln(r_2/r_1)/k_s + \ln(r_3/r_2)/k_a} = \frac{2\pi\,(600 - 100)}{(\ln 2)/19 + (\ln \frac{5}{2})/0.2} = 680 \text{ W/m}$$

To find the critical thickness of the insulation;

$r_c = k\,/\,h = 0.2/5 = 0.04$ m $= 4$ cm



Exercises No. (1)

Q1) Complete the following sentences:

1. The polyurethane (PU) has better thermal insulation than the polyethylene (PE) due to its lower ------------- property.

2. The polystyrene is a good thermal insulator, and it could be found as expanded polystyrene (EPS) and -------------.

3. In a cold climate, the thermal insulation is covered the --------------- face of the walls.

4. In a hot climate, the thermal insulation is covered the --------------- face of the walls.

5. The material that absorbs heat in daytime and releases it overnight is called -------------.

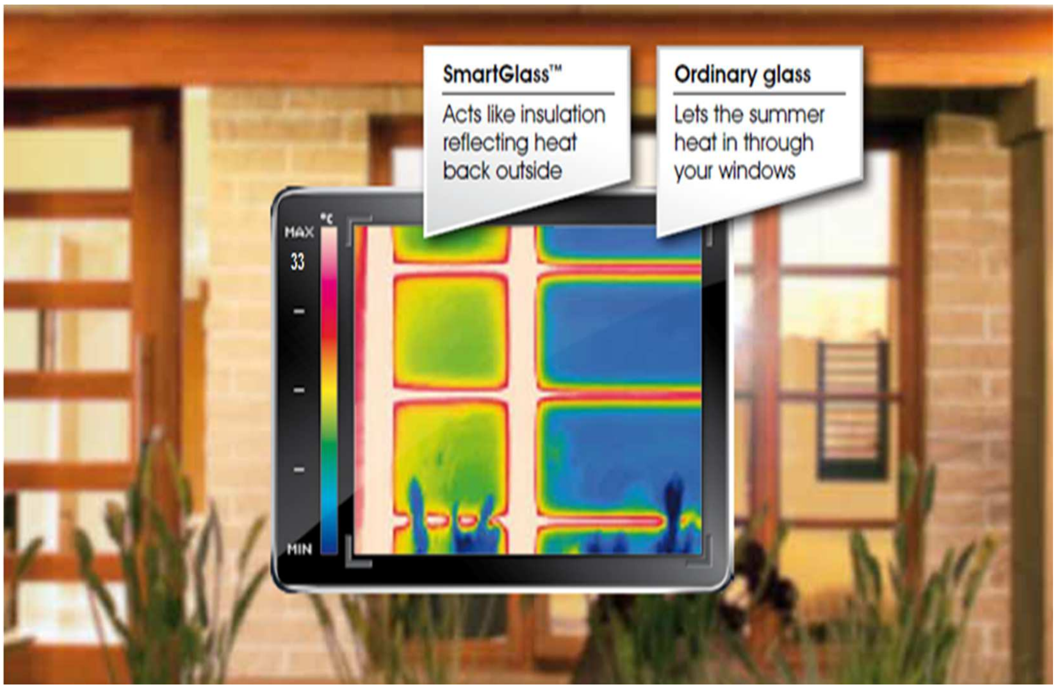
6. ------------- is a term using to describe a region in the building where the heat is transferred more than others.

7. In order to eliminate the radiation heat transfer, the thermal insulator material is covered by ---------------- layer.

Q2) What are the advantages of thermal insulation?

Q3) What are the properties that affect the performance of thermal insulator?

Q4) Thermal images of different glasses in a building have been captured outside a house in the summer, as shown in the figure. Describe the features of these images according to your understanding.



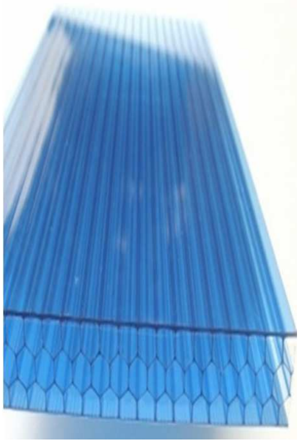
Q5) Air could not be used individually as a thermal insulator instead of solid insulators even though its thermal conductivity is low. Why?

Q6) Define the following terms: thermal mass, PCM, thermal bridge, thermal resistance, overall heat transfer coefficient, thermal load.

Q7) Select the right image for each of the following insulators:

1. Glasswool, 2. Expanded polystyrene (EPS), 3. Polyurethane panels, 4. Polycarbonate

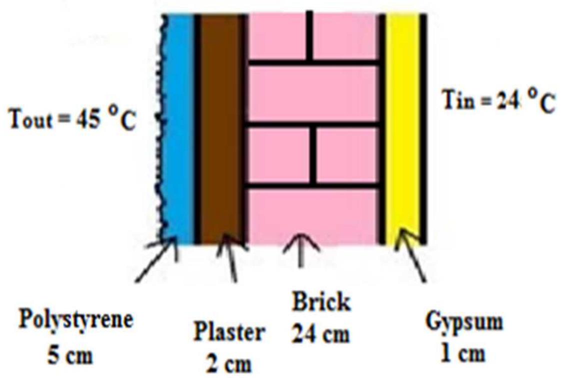




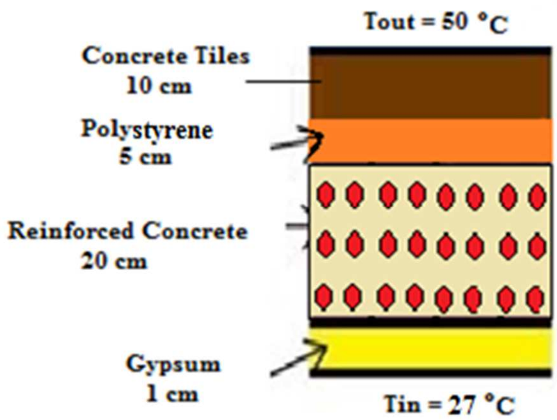

A B C D

Q8) Calculate the size of air-conditioning (tons) required to cool a room of 7 m x 4 m x 3.5 m before and after the insulation. Note that the materials of the walls and the roof are shown in the figures below. Neglect the effect of radiation and convection heat transfer. Add 3500 W to the total load due to the heat gained through windows, ventilation, occupants and equipment.

$K_{plaster}=1$, $K_{brick}=0.5$, $K_{gypsum}=0.8$, $K_{polystyrene}=0.08$, $K_{RC}=2$, $K_{concrete\ tiles}=0.8$



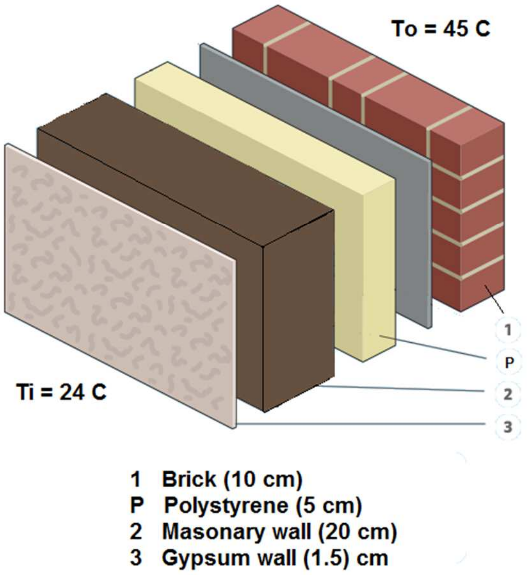
Wall section



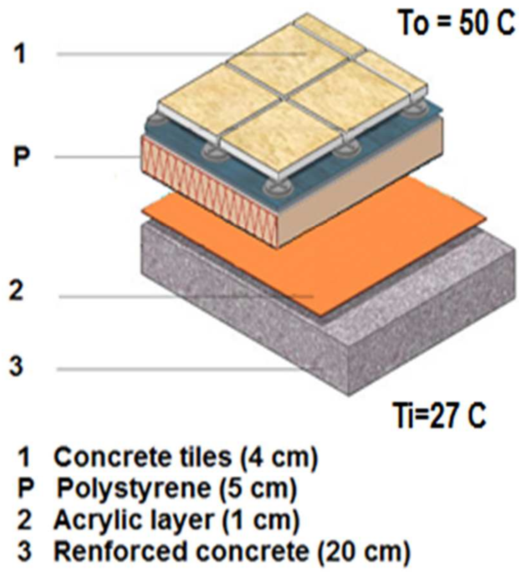
Roof section

Q9) Calculate the size of air-conditioning (tons) required to cool a room of 8 m x 5 m x 3 m before and after the insulation. Note that the materials of the walls and the roof are shown in the figures below. Neglect the effect of radiation and convection heat transfer. Add 4000 W to the total load due to the heat gained through windows, ventilation, occupants and equipment.

K_{Brick}=0.5, $K_{Masonary\ wall}$=1.2, K_{Gypsum}=0.8, $K_{Polystyrene}$=0.08, $K_{concrete\ tiles}$=0.8, $K_{Acrylic}$=0.2, K_{RC}=2



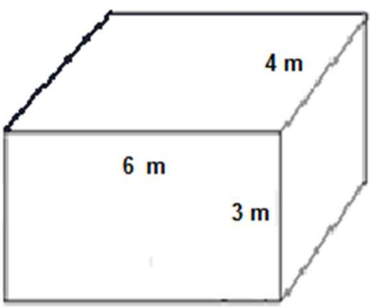
Wall section



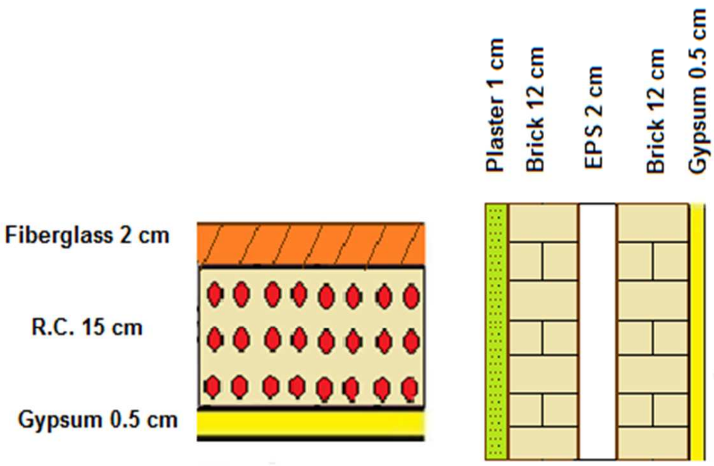
Roof section

Q10) A room of 6 x 4 x 3 m^3 has different construction materials as shown in the figure below. What is the difference in air-conditioning if EPS is replaced by air gap. The additional heat due to other sources is 3400 W. (ΔT=20 ^oC).

$K_{Plaster}$=1, K_{EPS}=0.05, K_{Gypsum}=0.8, K_{Brick}=0.5, $K_{R.C.}$=2, $K_{Fiberglass}$=0.06, K_{Air} =0.025



Room

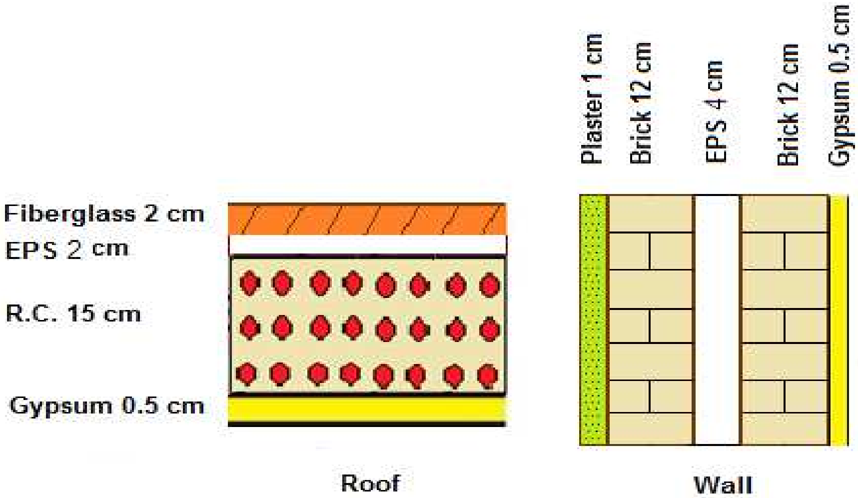


Roof

Wall

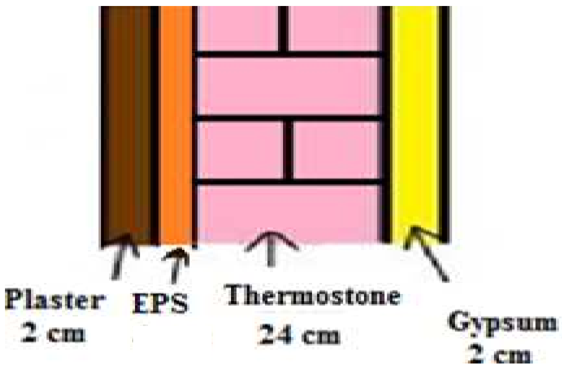
Q11) A room of 8 x 5 x 3 m^3 has different construction materials as shown in the figure below. What is the difference in air-conditioning if EPS is replaced by PU. The additional heat due to other sources is 4000 W. ($\Delta T=22\ ^oC$).

$K_{Plaster}=1$, $K_{EPS}=0.05$, $K_{Gypsum}=0.8$, $K_{Brick}=0.5$, $K_{R.C.}=2$, $K_{Fiberglass}=0.06$, $K_{PU}=0.02$

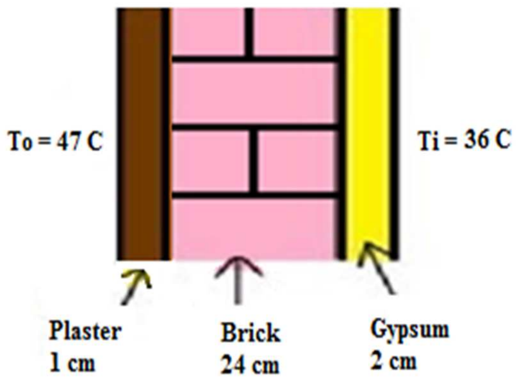


Q12) A house has composite walls, as shown in the figure. Neglect the effect of radiation and convection heat transfer. Calculate the thickness of EPS required to save the energy by 50%.

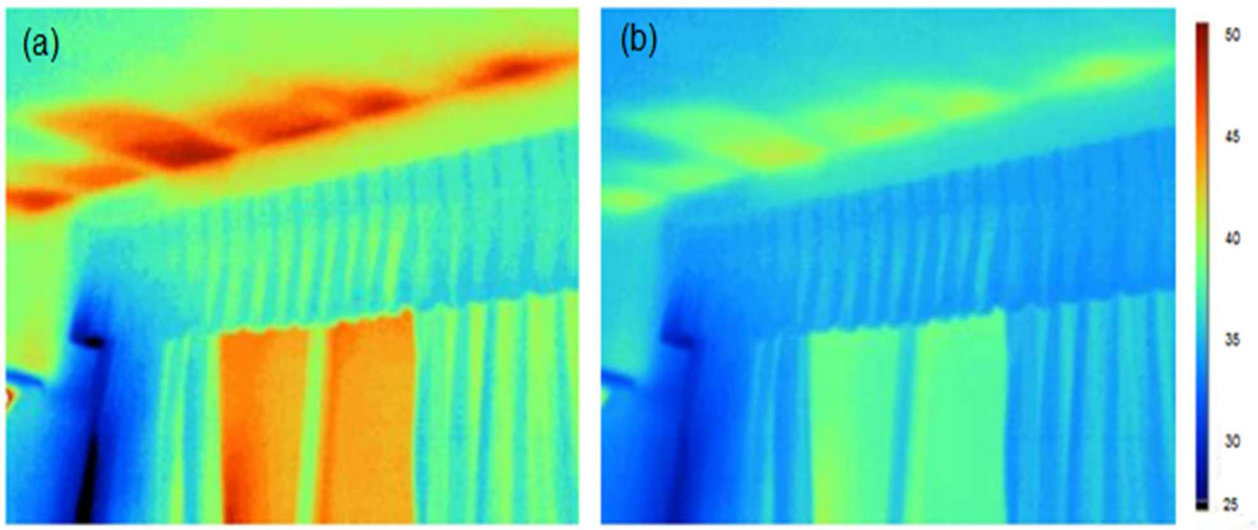
$K_{plaster}=1$, $K_{EPS}=0.05$, $K_{thermostone}=0.3$, $K_{gypsum}=0.8$



Q13) A house has a composite wall structure, as shown in the figure. Neglect the effect of radiation and convection heat transfer. What would be the internal surface temperature (Ti) after adding 5 cm of polyurethane insulation, where the energy has been saved by 60%. (Kplaster=1, Kbrick=0.5, Kgypsum=0.8, KPU=0.03)



Q14) Thermal images have been captured inside a house in the summer, as shown below. Describe them.



Chapter Two

Acoustic Insulation

Chapter Two
Acoustic Insulation

2.1 Definition of Acoustic Insulation

Acoustic insulators are those materials that prevent, reduce or absorb the sound. They are commonly referred as soundproofing materials Sound is transmitted in form of pressure waves through the air where we can distinguish various voices as well as the noise. Sound travels also through solid objects. The continuous sounds surrounding mankind may lead to nervous tension and affect the behavior and action of people. Therefore, environmental engineering identified appropriate sound levels for living and working. Since, it is easy of sound transmission through concrete parts, thus, it should always control the design of the building and select the most appropriate soundproofing materials. The insulation of building prevents the transmission of sound outside or inside and from room to another.

2.2 Architectural Procedures to Control the Acoustics

A proper architectural design helps in minimizing many costly techniques of noise control in buildings. Noise can be control by:

1. Planning methods of determining optimum home position relative to sources of external sounds such as streets, markets and factories as well as the correct orientation of windows, doors, etc.

2. Design methods for internal spaces of the building. The arrangement of rooms must be made in such a way that sensitive rooms are away from the noise and the less sensitive rooms are toward or closer to the noise source.

3. Methods of choosing perfect soundproofing material.

2.3 Objective of Acoustic Insulation

There are two main types of sound insulation in buildings: airborne insulation that produced into the air, and impact insulation that used to decrease the upper floors sounds. So the objectives of sound insulation are:

1. Prevent transmission of sound from outside or between the partitions through walls and ceiling.

2. Prevent the transmission of vibrations by machinery parts.

3. Save building materials or facilities.

4. Privacy

2.4 Procedures of Acoustic Insulation

Sound is transmitted through walls and floors by waves thus setting the structure into vibration. This vibration could be avoided by:

1. Walls: using wall tiles and insulating materials such as cork, glass wool and polyurethane foam.
2. Roof: using insulators such as plastic sheets, secondary or ceiling panels, perlite and vermiculite.
3. Dampers: some rubbers, fiberglass or certain panels could be placed under vibrating machines or inside the room. The pieces of furniture help to absorb amount of sounds.
4. Avoid acoustic bridge: it is a term describes the region that allows the transmission of sound a result of the damage in insulator or in case of absence it basically. One of these areas is the joint link between the walls and the ceiling or between the walls and floor slabs.

2.5 Classification of Materials with Respect to Sound

The incident sound upon a surface could be distributed into three main parts. The first part is reflected from the surface, the second part is absorbed by the surface while the last part is transmitted across the surface to inside. It could say that materials are divided with respect to the sound into:

1. Reflective materials: these have rigid surfaces thus reflect the majority of sound without transmission or absorption, such as ceramic tiles and glass.

2. Absorbing materials: these are quite porous such as loose materials. They interact with sound passing through them, converting the vibrations into heat. They reduce sound energy in an enclosed cavity as sound repeatedly reflects between the enclosing surfaces and passes through the sound-absorbing material many times. Each pass-through causes a small decrease in energy, with the cumulative effect being significant.

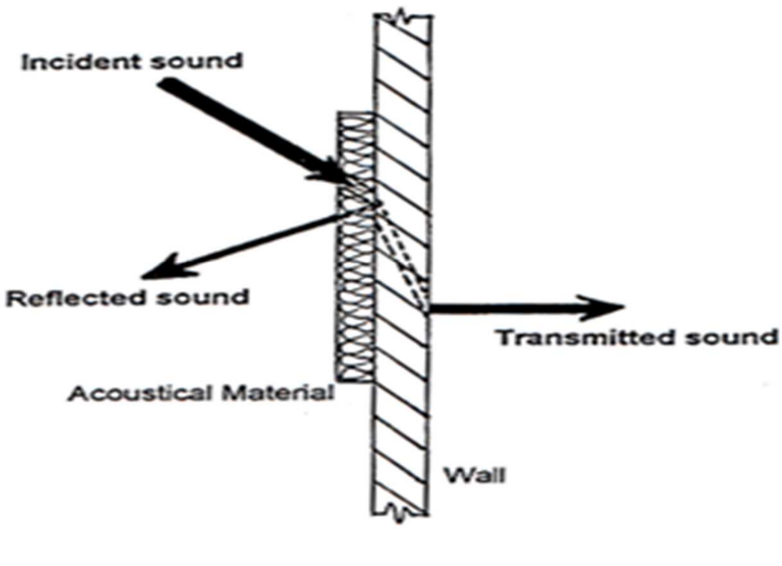


Figure (2.1) Distribution of sound

2.6 Features of Sound Absorbing Materials

Most of these materials are porous materials whether they are foamed or fibrous. Absorbing material is composed of channels, cracks or cavities which allow the sound entering the material and reflect within it. Sound energy is dissipated due to thermal loss caused by the friction of air molecules with the pore walls, and due to viscous loss caused by the viscosity of air. Usually these materials have the following structures:

a) Fully reticulated foam
b) Partially reticulated foam
c) Fully fibrous
d) Partially fibrous

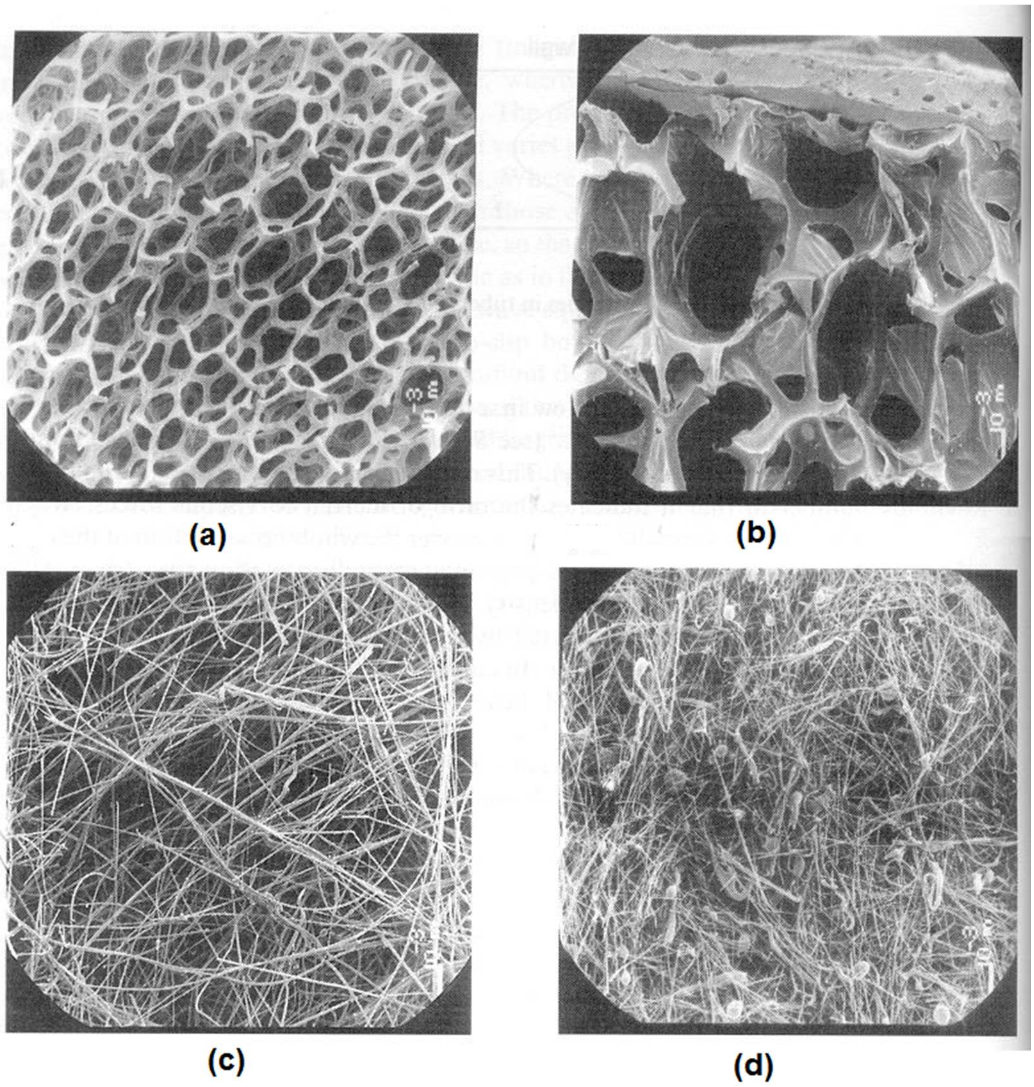


Figure (2.2) Structures of porous materials

Porous materials have different behaviors with sound depending on the frequency.

- At high frequencies (>2000 Hz), porous materials have high acoustic impedance and most of incident energy is absorbed by the pores.
- At low frequencies (100-2000 Hz), porous materials behave like stiffness layers. This leads to large reflection and little absorption.

In general, increasing the thickness provides better absorption of the wave and reflect less energy. The thickness of the materials has direct relationship at low frequency range, but it is insignificant for high frequency. Although thicker material does not prevail at higher frequency due to the coincidence dip phenomenon, it was still noticeable that at 2000Hz, the 50 mm material had almost 20% better absorption than the 10 mm material.

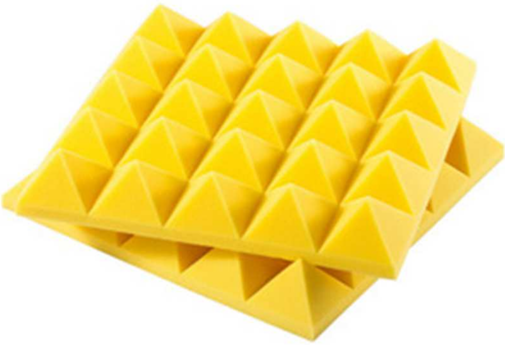
Acoustic insulator is evaluated by its α-value, acoustic absorption coefficient, which is usually between 0.5-1.0 for porous materials. This value depends mainly on some important parameters of porous materials such as:

- Porosity: The ratio of pores volume to total volume. Typical porosity is between 0.85-0.95 for effective materials. The presence of pores or voids plays a crucial role in the medium for sound wave dissipation.
- Flow resistivity: The ratio of pressure gradient across certain thickness of the material to flow velocity. Flow resistivity represents the resistance to airflow within the material. The higher the airflow resistivity, the less air permeability there is. Typical resistivity is between 2,000-50,000 Ns/m4 for porous materials.
- Bulk density: The mass of insulation material (fibrous layers) to the total volume. Density influences the acoustic impedance as the impedance determines the reflection of materials. It was found that a high density material increases the sound absorption due to the increasing of mass.

2.7 Commercial Insulators

Acoustic insulators provide acoustic treatment that reduce noise and improve the acoustic comfort for large volume spaces and buildings. These spaces create echoes, extra noise, and sound reflections. Most of these soundproofing materials come as panel or packages. They are widely used to optimize sound quality in: classrooms, music rooms, factories, airports, train stations, gymnasiums, restaurants, auditoriums, theaters, conference rooms, boardrooms, offices and open spaces. The acoustic panels, soundproofing panels, and sound baffles are either: wall mounted, ceiling mounted, curtains or hangings. The following materials are commonly available as soundproofing:

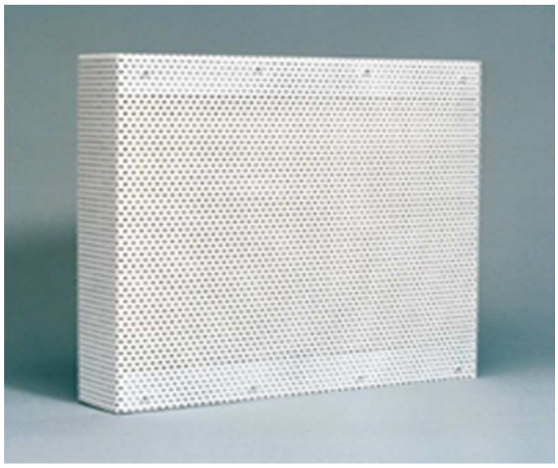
1. Acoustic tiles: these tiles have the capability of sound absorption, durability and ease of cleaning. Often, they are made of composite materials (fibers or particles mixed with granular resin) such as fiberglass, that results from the mixing of glass wool with epoxy. These tiles are used for the absorption of sounds of machines.
2. Glass wool or rock wool: they are characterized by their ability to absorb sound as well as thermal insulation. They can be mounted on the walls and ceiling. These could be used in commercial and industrial buildings.
3. Polyurethane foam: this is available in form of spray, layers and tiles.
4. Cellulose panels: which are compressed and have perforated faces.
5. Gypsum boards: it can be added to the surface.
6. Rubber: it is available in many forms like: natural rubber, industrial chloroprene (neoprene or polyisoprene) and mass loaded vinyl (MLV). These are available as layers and rolls. They usually use to absorb sound and vibrations.
7. Natural cork or synthetic cork (EPS): they are available as slabs.
8. Plastic packaging sheets: these layers are fit for ceilings in factories where large dimensions. These are resistant to dust as well as the moisture.
9. Perlite: a white color substance taken from the volcanic rocks and it is a good insulator for sound and heat. It gives the surface a reliable fire-resistant. It is used to insulate ceiling and walls.
10. Viscoelastic damping compound (VDC): a viscous resin fast to dry, used in flooring damping, absorption of the noise as well as to absorb the vibrations of machinery parts and ducts.
11. Fabrics, leather, carpet and sponge materials.
12. Metallic panel: it is similar in work to the silencer where it dissipates the undesired sounds and then absorbs it by internal acoustic insulation materials such as fiberglass.



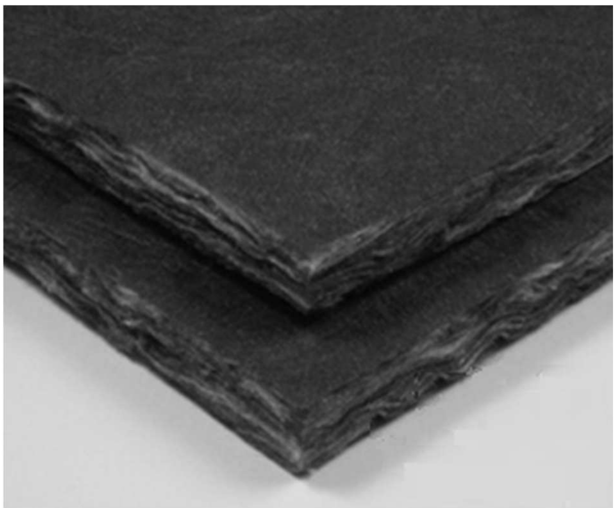
Polyurethane (32 kg/m^3)

Rock wool (60 kg/m^3)

Acoustic tiles (1250 kg/m^3)



Metallic panel



Fiberglass (48 kg/m^3)

Mass loaded vinyl (16 kg/m^3)

Figure (2.3) Sound insulators

2.8 Applications of Soundproofing

Sound can transmits through walls, floors, ceilings, windows, doors, openings, and more. Soundproofing aims to reduce transmitted sound and absorb the noises in many applications, especially:

- Residential buildings
- Working offices
- Theatres and studios
- Airports
- Gymnasiums
- Industrial places

Soundproofing for residential building and working office requires insulation for the walls to reduce the noises. If the walls are constructed from concrete or heavy materials, then soundproofing would be unnecessary. Note, that thermal insulation that installed in advance can play as absorptive sound materials so no need for acoustic insulation. For multi-floors building, the floor should be insulated by rubbery materials to reduce impact transmission. For theaters, airports and sport halls, the following procedure is required:

- Cover the walls by acoustic panels.

- Use rubber pads for the floor.

- Use ceiling baffles to dissipate the sounds.

- Seal the openings by suitable weather strips.

Below are general tips to reduce transmission of exterior noise into a building;

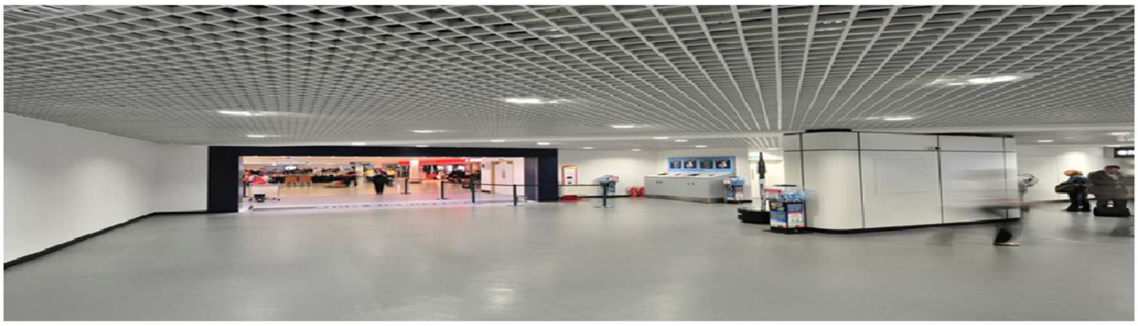
- Replacing of prime windows and doors.
- Installing acoustical storm windows.
- Adding wall and attic insulation.
- Baffling the ceiling.
- Modifying ventilation access.

a. Resedential building

b. Classroom

c. Recording studio

d. Theatre



e. Airport

Figure (2.4) Applications of soundproofing

2.9 Acoustical Engineering

Sound is a kind of mechanical energy. Sound travels from one place to another in the form of pressure waves occurring vibrations in the air and building materials. Because of the longitudinal motion of the air particles, there are regions in the air where the air particles are compressed together and other regions where the air particles are spread apart. These regions are known as compressions and rarefactions, respectively. The compressions are regions of high air pressure while the rarefactions are regions of low air pressure, as shown in figure below. The sound does not move in a vacuum but only in a medium. The science of acoustics describes the source of the sound, its transmission and sensing of it.

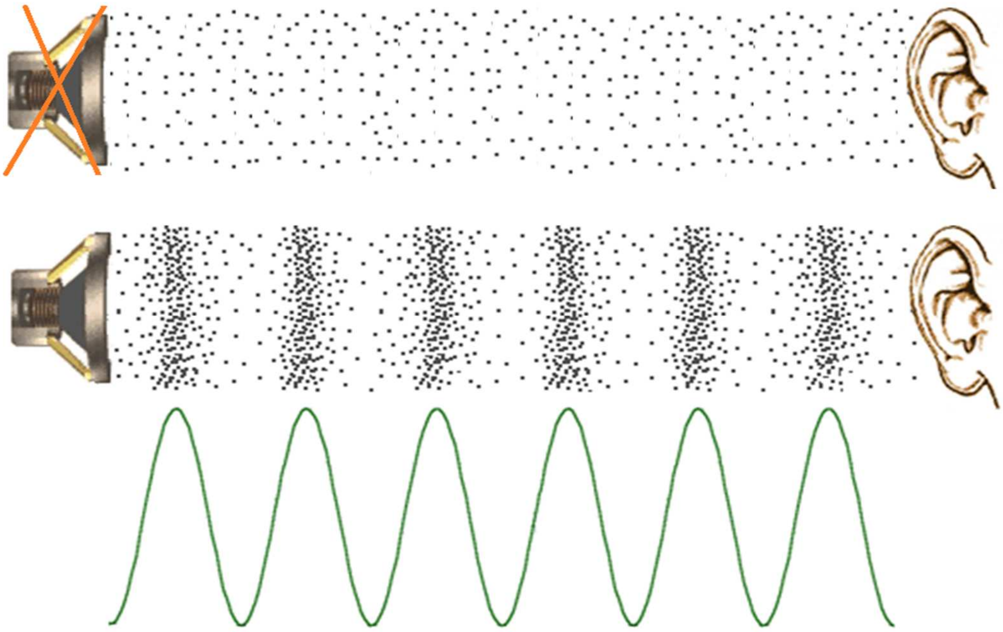


Figure (2.5) Regions of compressions and rarefactions by sound

There are some basic definitions in the acoustics science, including:

Type of sound: it is the property that distinguishes between different types of sounds. For example: the voice of a man, an animal, a machine, etc.

Quality of sound: it is the property that characterized the pitch change to the same source. It depends on the frequency of sound waves which characterized the loudness of sounds, such as the difference between the sound of men and women and the difference between mature and young voices, as well as sound in joy and sorrow.

Pitch: is the subjective response to frequency. Low frequencies are identified as "low-pitched", while high frequencies are identified as "high-pitched". As few sounds of ordinary experience are of a single frequency (for example, the quality of the sound of a musical instrument is determined by the presence of many frequencies other than the fundamental frequency), it is of interest to consider what determines the pitch of a complex note.

Sound velocity: also called the speed of sound which is the distance travelled per unit time for a sound wave as it propagates through an elastic medium. Sound waves travel slowly through gases, faster through liquids, and fastest through solids. At 20 °C, the speed of sound in air is 343 m/s. The relationship between the speed of sound, its frequency, and wavelength is given by:

$$V = f\,\lambda$$

In fluid dynamics, the speed of sound in a fluid medium (gas or liquid) is used as a relative measure for the speed of an object moving through the medium. The ratio of the speed of an object (u) to the speed of sound (a) in the fluid is called "Mach number". Objects moving at speeds greater than 1 Mach are said to have supersonic speeds.

$$M = u / a$$

$$a = \sqrt{\gamma\, R\, T}$$

Where γ is the heat index of air (1.4), R is the air constant (287.1 J/kg.K) and T is the medium temperature in (K).

Sound frequency: it is the number of times that air particles fluctuate per second as a result of sound energy passed. It is expressed in the unit of Hertz (Hz). Most of the sounds that we hear are a mixture of frequencies. Sound waves are classified into:

1. Infrasonic: waves that have less than 20 Hz frequency.
2. Sonic: waves that have frequencies between 20 Hz and 20,000 Hz.
3. Ultrasonic: waves that have frequencies above 20,000 Hz.

Sound power: it is the energy carried by the acoustic wave in a period of time. And it is measured in watts.

Sound intensity: it is the property that differentiates between sounds in terms of being high or low. Mathematically, it is the amount of acoustic energy on a unit area. Human ear can feel a sound has 10^{-12} W/m^2 intensity as minimum. The highest intensity of sound within earshot is 1 W/m^2. So, $\mathbf{I_{ref} = 10^{-12}\ W/m^2}$

Sound Intensity Level (SIL): The sound intensity value is too small and it is difficult to compare with, so it is looking for a value more acceptable like (Decibel) which is symbolized by (dB). The lowest sound level value is zero dB. The sound level could be accounted from the relation:

$$\mathbf{SIL = 10 \log (I/I_{ref})}$$

Based on that, the sound is classified in terms of the level of intensity to:

- 0 - 40 dB : Quiet
- 40 - 80 dB : Noisy
- 80 - 120 dB : Very noisy
- > 120 db : Intolerable

Sound pressure: it is the change of atmospheric pressure in a region as a result of the passage of sound. The less sound pressure feeling by human ear is about $2x10^{-5}$ Pa and this is called the hearing threshold. At a pressure of about 20 Pa the ear starts feeling of pain.

Sound Pressure Level (SPL): it is a value similar to the sound intensity level, and also measured in decibels. It is calculated from the relation:

SPL = 20 log (P/P_{ref})

Table (3.1) Properties of some sound sources

Sound sources (noise) Examples with distance	Sound pressure Level L_p dB SPL	Sound pressure p N/m² = Pa Sound field quantity	Sound intensity I W/m² Sound energy quantity
Jet aircraft, 50 m away	140	200	100
Threshold of pain	130	63.2	10
Threshold of discomfort	120	20	1
Chainsaw, 1 m distance	110	6.3	0.1
Disco, 1 m from speaker	100	2	0.01
Diesel truck, 10 m away	90	0.63	0.001
Kerbside of busy road, 5 m	80	0.2	0.000 1
Vacuum cleaner, distance 1 m	70	0.063	0.000 01
Conversational speech, 1 m	60	0.02	0.000 001
Average home	50	0.006 3	0.000 000 1
Quiet library	40	0.002	0.000 000 01
Quiet bedroom at night	30	0.000 63	0.000 000 001
Background in TV studio	20	0.000 2	0.000 000 000 1
Rustling leaves in the distance	10	0.000 063	0.000 000 000 01
Hearing threshold	0	0.000 02	0.000 000 000 001

2.10 Sound Transmission

It means the ability of sound to move across the building from one part to another. There are several ways of sound moving which are:

- Airborne transmission: it referred to the sound transmitted through windows and openings. These can be processed by good sealing.
- Impact transmission: it means the voices of people movement as well as of the machines on the upper floor. These can be treated by absorbing layers and dampers such as carpet and rubber.
- Flanking transmission: it means the sound transmission through the parts of the building (concrete, metal, wood or glass). These are processed using insulating materials. Any part of the building has a number represents the amount of resistance to the permeability of sound called transmission loss.

Transmission loss: is a measure of the sound difference in decibels through the barrier. For example, if we have a sound of 100 decibels on a side of the wall. Then we measured this sound on the other side and we found it is 55 dB. Then we say that the wall has 45 dB transmission loss. The higher value indicates good resistance and good acoustic insulation. This value varies depending on the frequency of the sound source.

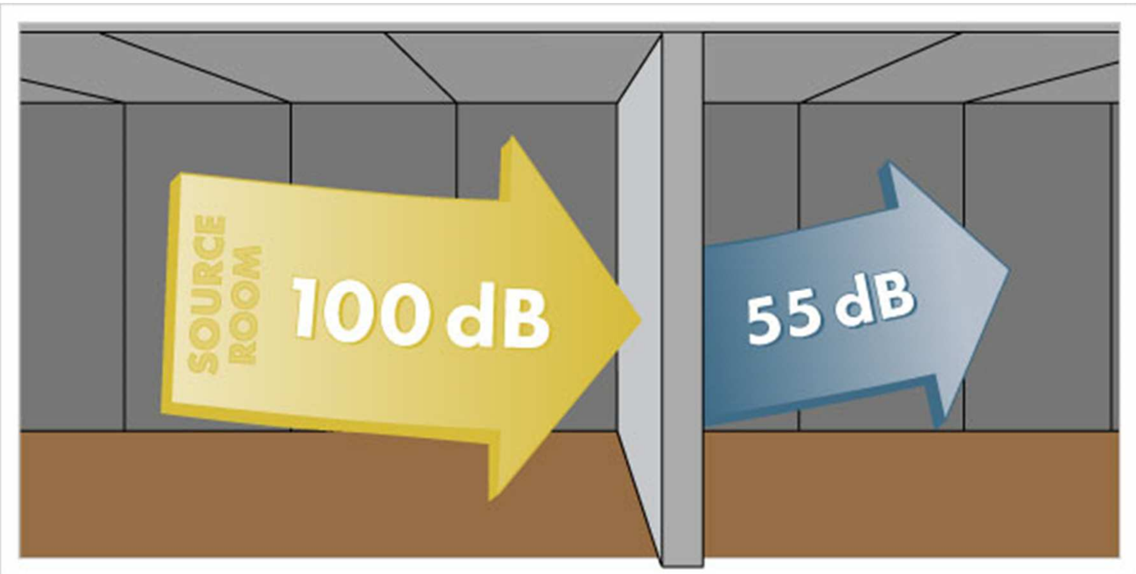


Figure (2.6) Transmission loss

Sound Transmission Class (STC): is the amount of transmission loss through a barrier or a wall at a sound frequency of 500 Hz. Sound transmission class is a key factor in the design and represents an indication of the building element performance to resistance the sound transmission through it.

Table (2.2) STC values of some building elements

Partition type	STC
Single glass window	27
Double glass window	30
Single layer of 1 cm drywall on each side, wood studs, no insulation (typical interior wall)	33
Single layer of 1 cm drywall on each side, wood studs, fiberglass insulation	39
10 cm hollow CMU (Concrete Masonry Unit)	44
20 cm thermostone wall with plastering for both sides	44
Double layer of 1 cm drywall on each side, wood studs, batt insulation in wall	45
Single layer of 1 cm drywall, glued to 15 cm lightweight concrete block wall, painted both sides	46
15 cm Hollow CMU (Concrete Masonry Unit)	46
20 cm hollow CMU (Concrete Masonry Unit)	48
25 cm hollow CMU (Concrete Masonry Unit)	50
20 cm hollow CMU (Concrete Masonry Unit) with 5 cm Z-Bars and 1 cm drywall on each side	52
20 cm concrete floor with plastering for both sides	53
Single layer of 1 cm drywall, glued to 20 cm dense concrete block wall, painted both sides	54
20 cm hollow CMU with 5 cm wood Furring, 5 cm fiberglass insulation and 1 cm drywall on each side	54
24 cm brick wall with plastering for both sides	54
Double layer of 1 cm drywall on each side, on staggered wood stud wall, batt insulation in wall	55
Double layer of 1 cm drywall on each side, on wood stud wall, batt insulation	59
Double layer of 1 cm drywall on each side, on wood/metal stud walls (1 cm space), double batt insulation	63
20 cm Hollow CMU with 8 cm Steel Studs, fiberglass Insulation and 1 cm drywall on each side	64
20 cm concrete block wall with 1 cm drywall on steel stud walls, each side, insulation in cavities	72

2.11 Sound Absorption

Any substance has the ability to absorb sound in addition to its ability to reflect the sound. The energy absorbed is converted into heat. Sound absorption factor is a value describes the ability of sound absorption. The absorbance in porous materials is more than in dense solids.

Coefficient of sound absorption: is the ratio between the energy absorbed by the surface to the total energy incident up on the surface. The parameter is denoted by the symbol (α).

Table (2.3) Coefficients of sound absorption at differente frequences

Material	Frequency (Hz) 125	250	500	1,000	2,000	4,000
Acoustic Panels	0.15	0.3	0.75	0.85	0.75	0.4
Brick	0.024	0.024	0.03	0.04	0.05	0.07
Carpet	0.05	0.1	0.3	0.25	0.3	0.35
Concrete	0.01	0.01	0.02	0.02	0.02	0.03
Curtains	0.05	0.12	0.15	0.27	0.37	0.5
Fiberglass	0.38	0.89	0.96	0.98	0.81	0.87
Wood Floor (joists)	0.15	0.2	0.1	0.1	0.1	0.05
Glass	0.03	0.03	0.03	0.03	0.02	0.02
Gypsum board	0.3	0.1	0.05	0.04	0.07	0.1
Plaster	0.3	0.3	0.1	0.1	0.04	0.02
Plywood on 2" Batten	0.35	0.25	0.2	0.15	0.05	0.05
Wood Panel	0.1	0.11	0.1	0.08	0.08	0.11

Note: It can be seen from the table above that the absorption coefficient of the material varies with the source frequency. In some cases, taking the average of these values is preferred and this is what so-called Noise Reduction Coefficient (NRC) which is commonly used to describe the value of the absorbance of the insulating material.

Table (2.4) Noise reduction coefficient of some insulating materials

Material	NRC
Acoustic tiles	0.8-0.9
Polyurethane	0.8-0.9
Mass vinyl	0.75
Glass wool	0.7
Asbestos	0.6
Mineral wool	0.65
EPS, XPS	0.3-0.4
Rubber	0.2

Absorption capacity: it represents the amount of acoustic units that can be absorbed by the barrier or the wall. Sound absorption unit is called (Sabin). The absorption capacity depends on the space area and absorption coefficient according to the relationship:
$C = \alpha \times A$

2.12 Noise Reduction (Attenuation)

The total amount of reduction in the acoustic energy as a result of reflection and absorption when moving from a room to another or abroad is called the noise reduction. This amount is expressed in the relationship:

$NR = TL + 10 \text{ Log } (C/A)$

Where:

TL is the loss transmission of the walls

C is the absorption capacity of the room

A is the area of the separation wall

Note: in the design usually suppose a sound frequency value of 500 Hz which is still within the range of the voices of people and cars, as shown in the figure below.

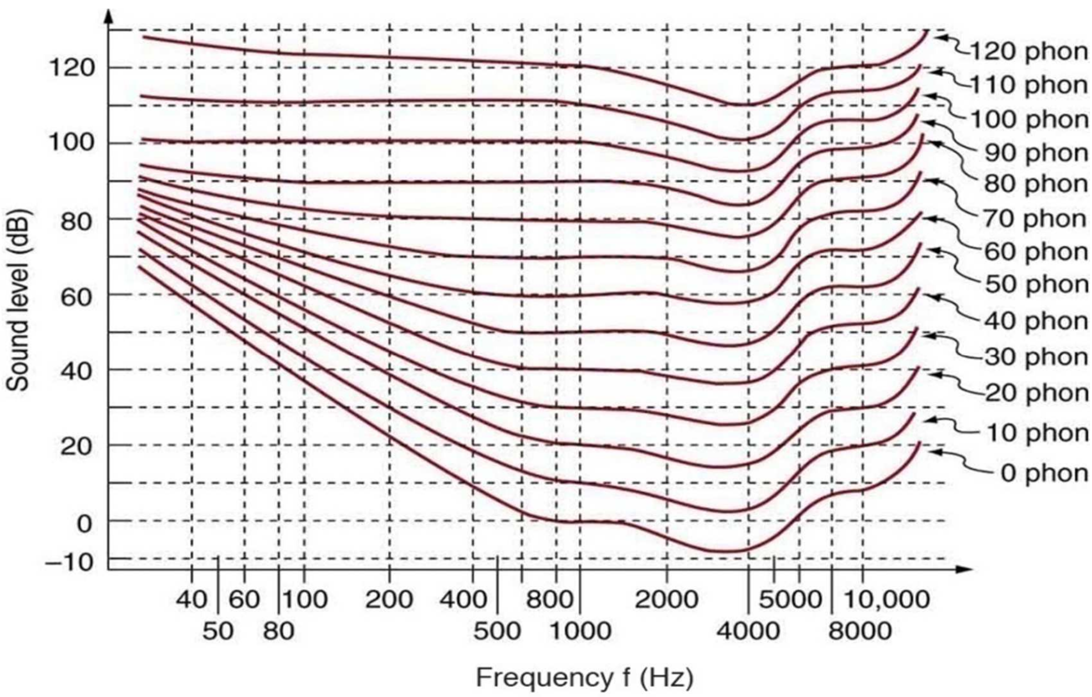


Figure (2.7) Relation between sound level and frequency

- So it could say that: **TL = STC**

- In case of high ranges of frequencies, then it is acceptable to use the correction chart as shown in the figure below.

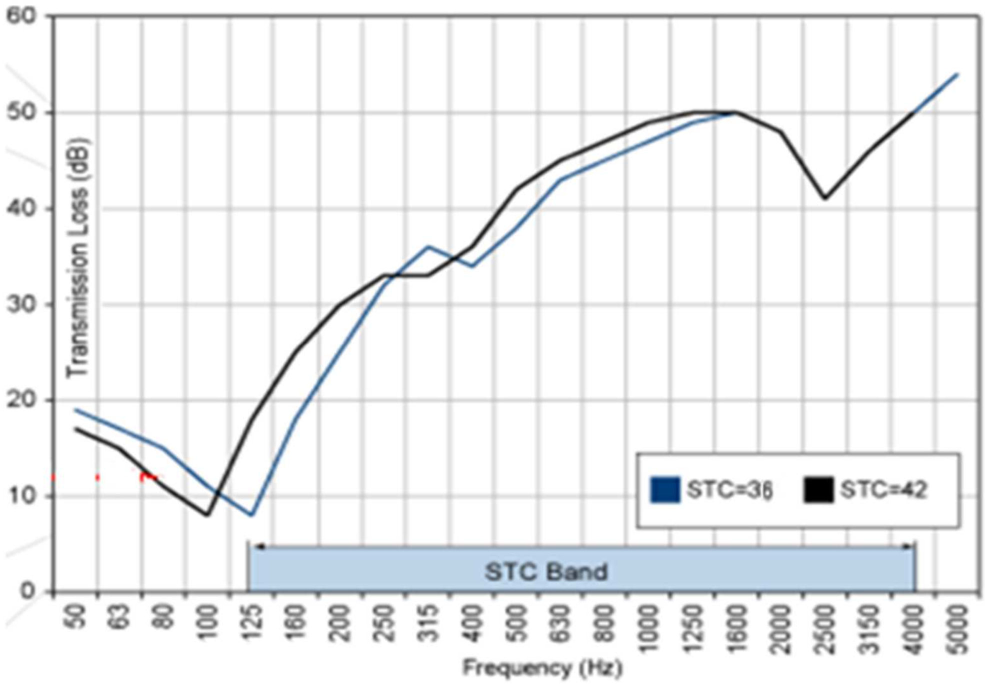
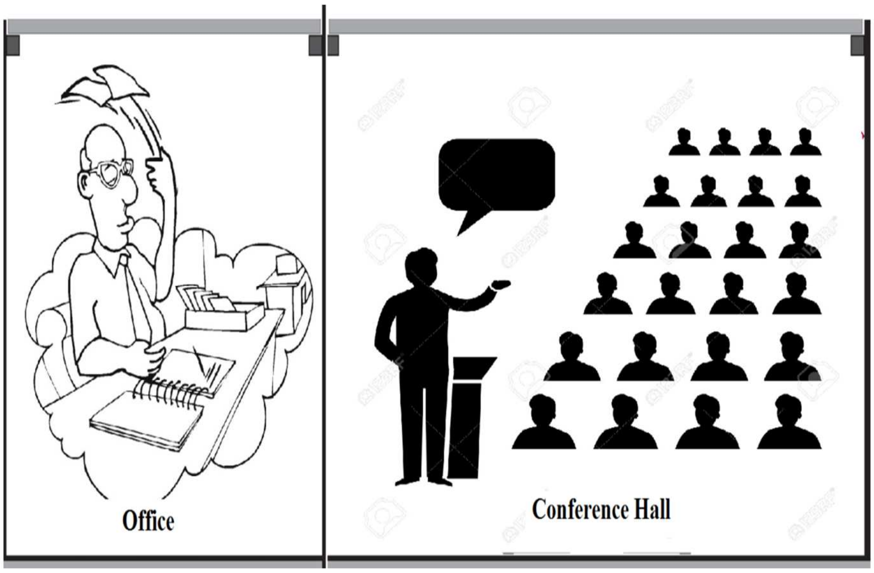


Figure (2.8) Correction of STC values for many sound frequencies

2.13 Engineering Calculations

The problems chosen for the design are assigned for one type of sound transmission which is the pure transmission from one room to another. It is required at the first to know the dimensions of the room and the specification of the materials used. The acoustical calculation provides a quick overview of the acoustics in a room, whether how much of sound is absorbed by structure elements and the rest absorbed by the separated wall or transmitted to other room. The acoustical calculation gives a precise overview of absorption capacity, transmitted sound as well as other relevant information about acoustics. Further corrections are required practically to ensure reliable results. In this section the area of: walls, ceiling and floor are calculated and multiplied by their absorption coefficient. Doors and windows may be ignored to simply the problem. The calculation is repeated after the insulation, where the insulator material is usually added to the separated wall. Here are some examples to show the effect of acoustic insulators.

Example (1): A conference hall of 10 m x 6 m x 3.5 m, has 3 walls of gypsum (α=0.05), a big facade of glass (α=0.03), ceiling of plastic tiles (α=0.1) and floor of carpet (α=0.3). An office is located next door to the hall, as shown in the figure.



Find:

a) Total absorption for the conference hall. (Absorption of furniture=20 Sabins)

b) Noise reduction for the office room. (STC of the separated wall is 48)

c) Total absorption for the conference hall if the separated wall is covered by acoustic tiles (NRC=0.9)

d) Noise reduction for the office room after insulation. (STC of the separated wall becomes 54)

Solution

a)

- Walls (gypsum) $A = 10*3.5+6*3.5*2 = 77\ m^2$

$C = \alpha \times A = 0.05*77 = 4$ Sabins

- Wall (glass) $A = 10*3.5 = 35\ m^2$

$C = \alpha \times A = 0.03*35 = 1$ Sabin

- Ceiling (plastic tiles) $A = 10*6 = 60\ m^2$

$C = \alpha \times A = 0.1*60 = 6$ Sabins

- Floor (carpet) $A = 10*6 = 60\ m^2$

$C = \alpha \times A = 0.3*60 = 18$ Sabins

$C_{total} = C_{walls} + C_{ceiling} + C_{floor} + C_{furniture} = 4+1+6+18+20 = 49$ Sabins

b) NR = TL + 10 Log (C/A) = 48 + 10 Log (49/21) = 52 dB

c) Acoustic tiles A = 6*3.5 = 21 m^2

C = NRC x A = 0.9*21 = 19 Sabins

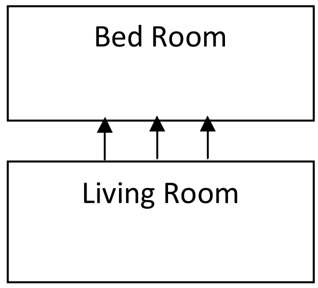
C_{total} = 49+19 = 68 Sabins

d) NR = TL + 10 Log (C/A) = 54 + 10 Log (68/21) = 60 dB

Therefore, it is an excellent insulation.

Example (2): A living room of 6 m x 5 m x 3 m has the following features:

Element	Material	α
Walls	Plywood	0.2
Ceiling	Gypsum	0.05
Floor	Carpet	0.3



If the sound source in living room is 70 dB, what is the sound level at the upper room:
1- Before insulation.
2- After insulating the ceiling by 5 cm glasswool (NRC=0.7).
Take into account that STC of the roof without insulation is (48) and with insulation is (54). There is an additional absorption due to the furniture (15 Sabins).

Solution

1-Befor insulation
- Walls (plywood) A = 6*3*2+5*3*2 = 66 m^2
  C = α x A = 0.2*66 = 14 Sabins
- Ceiling (gypsum) A = 6*5 = 30 m^2
  C = α x A = 0.05*30 = 2 Sabins
- Floor (carpet) A = 6*5 = 30 m^2
  C = α x A = 0.3*30 = 9 Sabins

$C_{total} = C_{walls} + C_{ceiling} + C_{floor} + C_{furniture}$ =14+2+9+15 = 40 Sabins
NR = TL + 10 Log (C/A) = 48 + 10 Log (40/30) = 50 dB
Sound level = Sound source – NR = 70 – 50 = 20 dB

2-After insulation
- Glasswool A = 6*5 = 30 m^2
C = NRC x A = 0.7*30 = 21 Sabins
C_{total} = 40+21 = 61 Sabins
NR = TL + 10 Log (C/A) = 54 + 10 Log (61/30) = 57 dB
Sound level = Sound source – NR = 70 – 57 = 13 dB

2.14 Effectiveness of Absorption in Porous Materials

Energy dissipation occurs due to acoustic pressure fluctuations at the surface which pump air into and out of the material. Friction between the air flow and the tortuous passages of the material dissipate energy by friction to be heat. Materials in this category include glasswool, foam and fabric. The variation of absorption coefficient with frequency for a porous material is shown in figure below. The effectiveness depends on the thickness, relative to the sound wavelength. In order to be effective (nearly anechoic) at a given frequency, the material thickness must equal to at least ¼ of the wavelength.

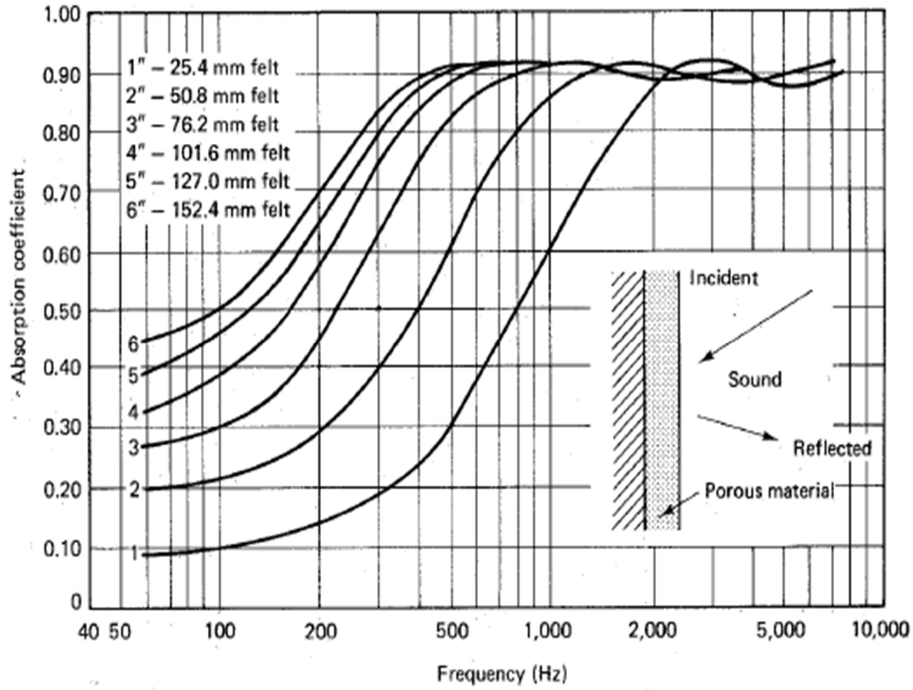


Figure (2.9) Variation of absorption coefficient with frequency for a porous material

<u>Example (3):</u> Determine the thickness of a porous material suitable for 500 Hz sound.

<u>Solution:</u>

λ = V/f = 343/500 = 0.686 m

Thickness = ¼ of the wavelength = ¼ (0.686) = 0.171 m = 171 mm

From the figure, the material with 171 mm will absorb as maximum as 92% of the sound.

2.15 Reverberation Time

The reverberation time (RT) is the duration that sound requires dropping to a certain low level (usually 60 dB below its original level) such that suitable acuity of the hearing to the observer. The reverberant sound in an auditorium dies away with time as the sound energy is absorbed by multiple interactions with the surfaces. The time for reverberation depends upon the intensity of the sound was to begin with, the dimensions of the hall and the reflective surfaces. The reverberation time can be modeled to permit an approximate calculation. The choice of the relative intensity to use is of course arbitrary, but the 60 dB range is about the range of dynamic levels for orchestral music. The optimum reverberation time for a medium-sized, general purpose auditorium that is used for both speech and music is 2 seconds. A classroom should be much shorter, about 1 second or less. For a recording studio it must be a minimum time (less than 0.5 second) for clarity of recording.

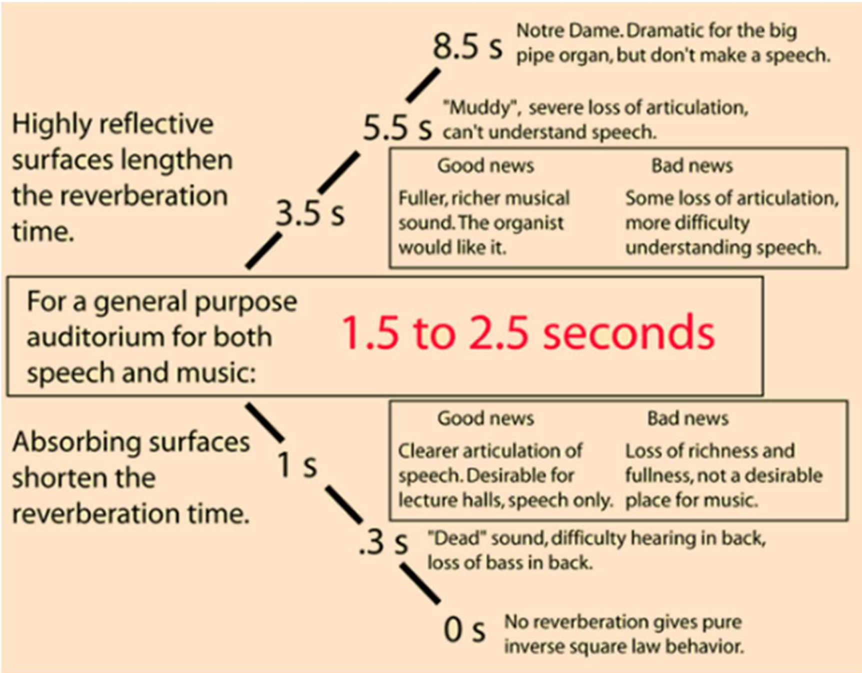


Figure (2.10) Estimated reverberation time for many applications

Designers usually attempt to satisfy a reverberation time between (1.5-2.5) seconds for music and orchestra halls, as shown in the table below.

Table (2.5) RT-values of some famous halls in the world

Auditorium	RT in seconds at 500 Hz
Royal Festival Hall, London	1.5
Severance Hall, Cleveland	1.7
Opera House, San Francisco	1.7
Carnegie Hall, New York	1.8
Symphony Hall, Boston	1.8
Musikvereinsaal, Vienna	2.0
Concertgebouw, Amsterdam	2.1
Royal Albert Hall, London	2.5

However, approximate reverberation time under 60 dB reduction can be calculated from the Sabine formula:

RT = 0.16 V / C

Where:

C = Total absorption capacity

V = volume of the space

Example (4): What is the reverberation time for a space of 6x6x5 m^3 where the ceiling and walls have 0.1 absorption coefficient, while the ground is carpet (α=0.3). Then make an evaluation according to the result, whether it is suitable as a classroom or a music hall.

Solution:

C_{walls} = 0.1 x (6x5x4) = 12 S

$C_{ceiling}$ = 0.1 x (6x6) = 3.6 S

C_{floor} = 0.3 x (6x6) = 10.8 S

C = C_{walls} + $C_{ceiling}$ + C_{floor} = 26.4 S

V = 6x6x5 = 180 m^3

RT = 0.16 V / C = 0.16 x 180 / 26.4 = 1.09 s

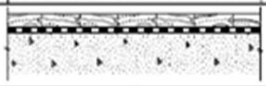
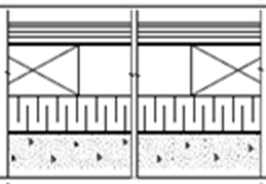
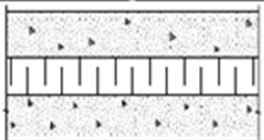
According to the result, the design is suitable as a classroom not a hall.

2.16 Controlling the Impact Sound through Floors

An impact source, such as those created by footsteps or the moving of an object, sets up vibrations directly on the floor, and spread it out over to the lower parts through construction materials. Hence, floors should be insulated to reduce both impact and airborne sounds. There are two principal ways of providing an acceptable finished floor surface or topping by using:

1. **Resilient layers (flexible):** this way is used with concrete floors by layering a vinyl or carpet. Recently, the attenuation of impact sound could be measured depending on the level of impact insulation class (IIC). The higher the IIC, the better the attenuation of impact. A 50 dB usually considered the minimum rating for occupant satisfaction in residential buildings. Table below gives approximate IIC ratings for a 150-mm-thick concrete slab with various kinds of toppings.

Table (2.6) Approximate IIC ratings for a 150-mm-thick concrete slab

Item	Sketch	Topping	IIC
1		None, or ceramic or marble tiles	28
2		Vinyl flooring	35-40
3		Hardwood flooring	30-35
4		9-mm-thick hardwood on 6-mm-thick resilient layer	45-50
5		16-mm plywood or OSB on 40- x 90-mm wood strapping on 25-mm mineral fibre board	50-55
6		35-mm concrete on 25-mm mineral fibre board	60-65
7		Carpet and underlay	75-85

2. **Floating floors:** this way is usually used with ceramic tiles floor which consist of a slab of rigid material supported on a mat or pad. The main idea behind the damping of floating floor is the mass-spring system. The frequency of the system dominates the vibrations due the impact, thus less frequency is seeking to get better impact insulation. The frequency in (Hz) of such system is given by:

$$f = 160\sqrt{\frac{s}{m}}$$

Where:

s is the dynamic stiffness in (MN/m^3)

m is the surface mass in (kg/m^2)

The resonance frequency is acoustically the most important factor of floating floors. In order to have good impact sound insulation, the resonance frequency should be as low as possible. The goal is achieving f < 100 Hz. The resonance frequency of the floating floor can be lowered by decreasing the dynamic stiffness of the material or increasing the mass of the layer. Tests show that the stiffness of insulation material preferred to be less than 40 MN/m^3 when it is used under a floating concrete floor in apartment building, as shown in the figure below.

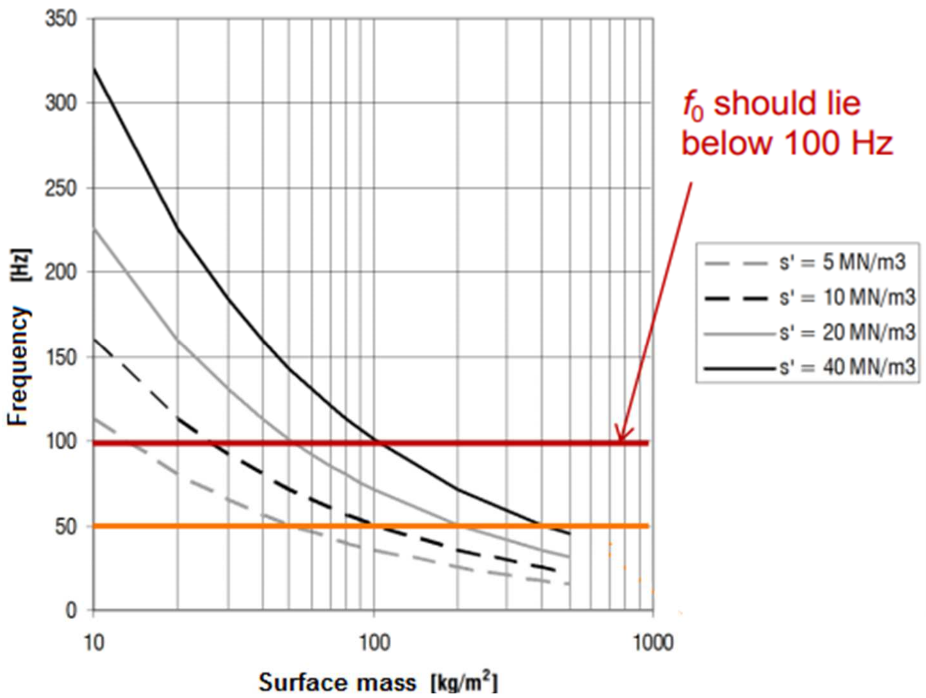


Figure (2.11) Selecting the stiffness of floating material

However, the dynamic stiffness of insulation materials (PU foam, EPS, rock wool, etc.) is in the range of 5-45 MN/m^3. Average values of stiffness for some insulation materials are shown the table below.

Table (2.7) Dynamic stiffness for some insulation materials

Material	Dynamic stiffness (MN/m^3) For 5 cm thickness
Polyurethane	5
EPS	12
Glass wool, rock wool	15
PEVA	32
Epoxy (Elastic)	40
Rubber, MLV	45

Example (5): which one of the following materials is suitable to control the impact sound for apartment building.

Material	Dynamic stiffness (MN/m^3) For 5 cm thickness	Surface mass (kg/m^2)
EPS	12	40
Rockwool	15	10
Rubber	40	60

Solution:

Use $f = 160\sqrt{\frac{s}{m'}}$

EPS f= 88 Hz

Rockwool f= 196 Hz

Rubber f= 130 Hz

EPS is suitable because it satisfies a frequency less than 100 Hz.

2.17 Controlling the Transmission across the Windows

Windows generally provide less sound insulation than the surrounding walls. Carefully placing and sizing windows may reduce outdoor noise. Multi-glazing, perimeter sealing and weather stripping are improving the sound transmission loss. The most common types of standard operable windows now being installed in residential construction are casements, horizontal sliders, vertical sliders and awnings. In an open position, casements and awnings can deflect external noise into the living space. They should be planned to open away from the dominant noise direction so there is some noise reduction from deflection. Acoustical data about windows typically assumed that the composition of the glazing was the primary influence on sound transmission properties. STC ratings for typical windows vary from 25 to 40 depending on type, glazing, frame and airspace as shown in table below.

Table (2.8) STC for typical windows

Composition	Note	STC
Glass 3 mm	Regular type	25
Glass 3 mm; airspace 19 mm; glass 3 mm	Standard thermo-pane used in aluminum casement windows	28
Glass 5 mm; airspace 38 mm; glass 5 mm	Glazing composition designed for a sealed window or for the most economical sliding window	32
Glass 6 mm; airspace 9 mm; glass 8 mm	Maximizes acoustical performance of aluminum, wood, PVC windows	40

2.18 Noise Pollution in Industrial

The steady increase in the noise level result in a permanent damage in the auditory system, as well as some attendant symptoms like: reducing the heart rate, changing in blood pressure and difficulty of breathing. As the psychological impact on the individual worker, protrudes through the change the style of his sleep, thus accompanying fatigue in the body which will affect the production efficiency of the working. If the worker is exposed to a continuous noise (80 dB) during the period of his work, then that will lead to loss 15 dB approximately in his hearing threshold during several years (i.e., he loses the level of whisper). The sound level is measured using a device called sound level meter, as shown in the figure below.

Figure (2.12) Sound level meter

The prevention of noise pollution satisfying the industrial safety conditions required in the lab, factory and warehouse. So, it must follow these steps:
1. Use suitable damper for high-vibration machines.
2. Use soundproofing for the purpose of absorption and dispersion of sounds.
3. Use of ear protectors as a prerequisite for workers.

Hearing protection or other means must reduce the noise levels to 85 dB on an eight-hour time-weighted basis. However, OSHA has established permissible noise exposure limits to help avoid the standard threshold shifts in working, as shown in the table.

Table (2.9) Noise exposure limits

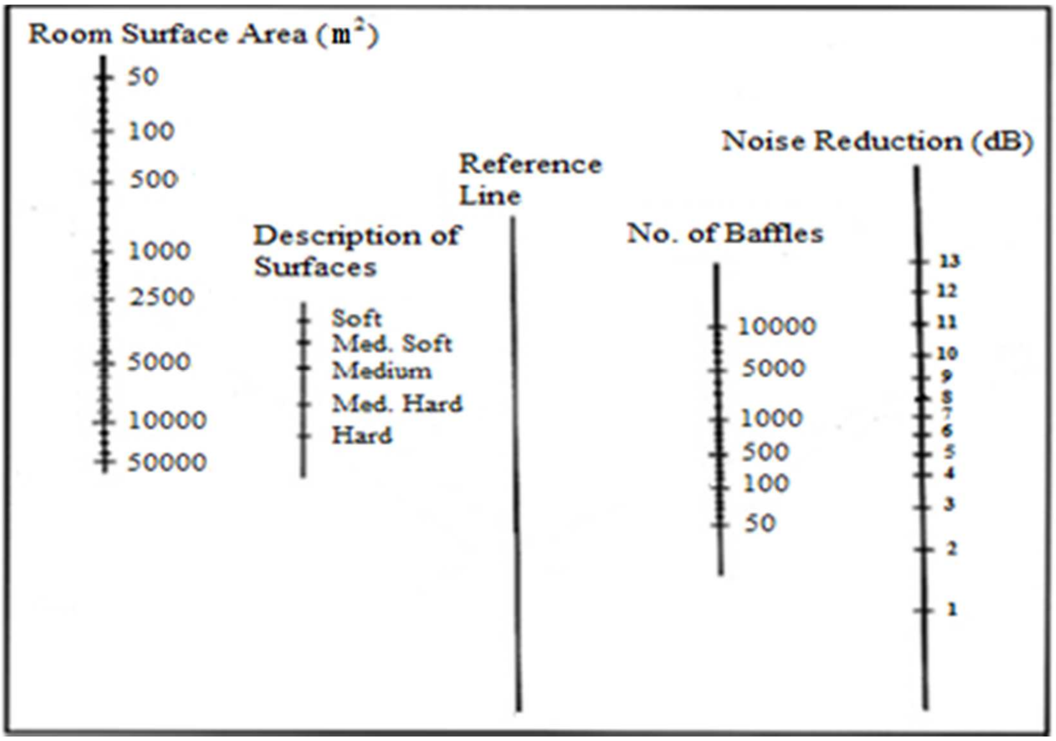
Noise Level	Exposure Limit
90 dBA	8.0 hours
92 dBA	6.0 hours
95 dBA	4.0 hours
97 dBA	3.0 hours
100 dbA	2.0 hours
102 dBA	1.5 hours
105 dBA	1.0 hours
110 dBA	30 minutes
115 dBA	15 minutes

Vibration pad (Neoprene or vinyl) **Viscoelastic compound**

Noise control baffles (fiberglass) **Curtain**

Figure (2.13) Noise dampers and baffles

Example (6): Noise control baffles of PVC are used to reduce the overall noise level in a factory of (12m L x 6m W x 3.5m H) where they are suspended above the noise source. Walls are made from concrete; ceiling is wooden, while the floor is covered by a carpet. Find number of baffles that required to reduce the noise by 10 dB. Use the nomogram chart below.



Solution:

1. Determine the total surface area:

12 x 3.5 x 2 = 84 (walls)
6 x 3.5 x 2 = 42 (walls)
12 x 6 x 1 = 72 (ceiling)
12 x 6 x 1 = 72 (floor)
Total Area = 270 m^2

2. Point the area on the chart.

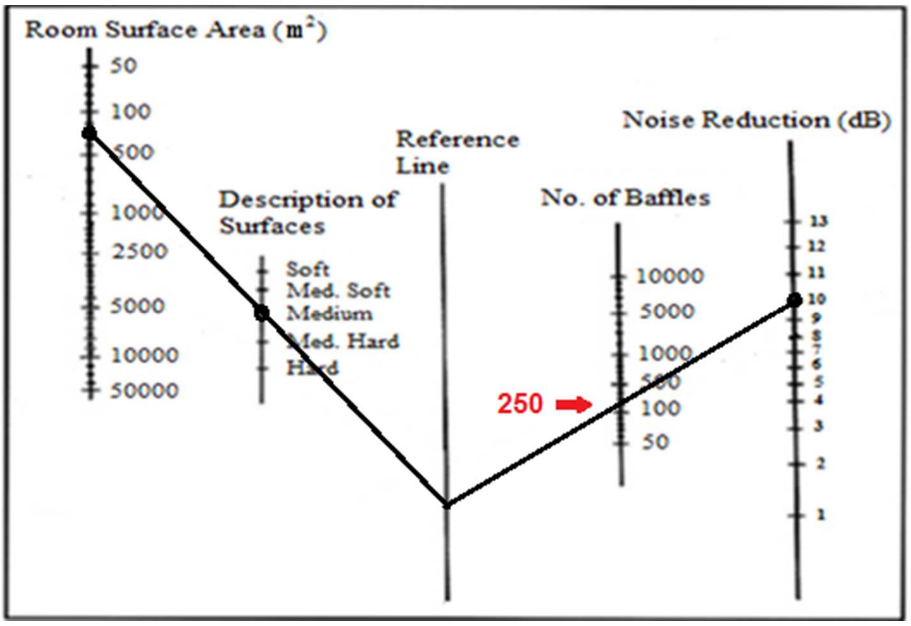
3. Select (medium) to describe the surfaces because there are 2 absorptive surfaces (wood & carpet). And point that on the chart.

Note: Hard surface are: concrete, brick, marble and gypsum. Absorptive surface are: wood and carpet.

Term	Description
Hard	6 hard surfaces
Med. Hard	5 hard surfaces and 1 absorptive
Medium	4 hard surfaces and 2 absorptive
Med. Soft	3 hard surfaces and 3 absorptive
Soft	2 hard surfaces only or even one

4. Connect (area=270) and (medium) on the chart. Extend the line to connect the reference line and then reflect it to reach noise reduction line at (10 dB).

5. Now, you can determine number of baffles required which is approximately (250).



2.19 Combining Noise Sources

Often in the factory, there are combinations of noises and sounds from many sources are observed and they contribute to the total sound pressure as following:

$$p_t^2 = p_1^2 + p_2^2 + \cdots$$

Where (p) is the sound pressure.

<u>Example (7)</u>: The noise level measured at a particular location in a factory for three machines operating nearby are measured. The three sound pressure levels were (a) 90 dB, (b) 88 dB and (c) 85 dB. Determine the effective SPL in the design.

<u>Solution:</u>

$SPL = 20 \log (P/P_{ref})$, $P_{ref} = 2x10^{-5}$ Pa

a) $90 = 20 \log (P_1/2x10^{-5}) \rightarrow P_1 = 0.632$ Pa

b) $90 = 20 \log (P_2/2x10^{-5}) \rightarrow P_2 = 0.502$ Pa

c) $90 = 20 \log (P_3/2x10^{-5}) \rightarrow P_3 = 0.356$ Pa

$$p_t^2 = p_1^2 + p_2^2 + p_3^2$$

$P_t = 0.882$ Pa

$SPL_t = 20 \log (0.882 /2x10^{-5}) = 92.2$ dB

2.20 Measuring the Acoustic Performance of the Materials

a. Absorption coefficient

The absorption coefficient of the material can be determined using a "standing wave tube" (also called "impedance tube"). It uses a small sample (typically 4" diameter) and has limited validity and usefulness due to the small sample size and the difference between a true normal incidence condition, and the actual incidence conditions (nearly random) seen in most real installations. But it is still useful for comparison purposes. The diameter of the tube must be smaller than ½ wavelength to insure plane wave sound propagation. A 4" tube is good up to about 3300 Hz. For higher frequencies, a smaller diameter tube is used.

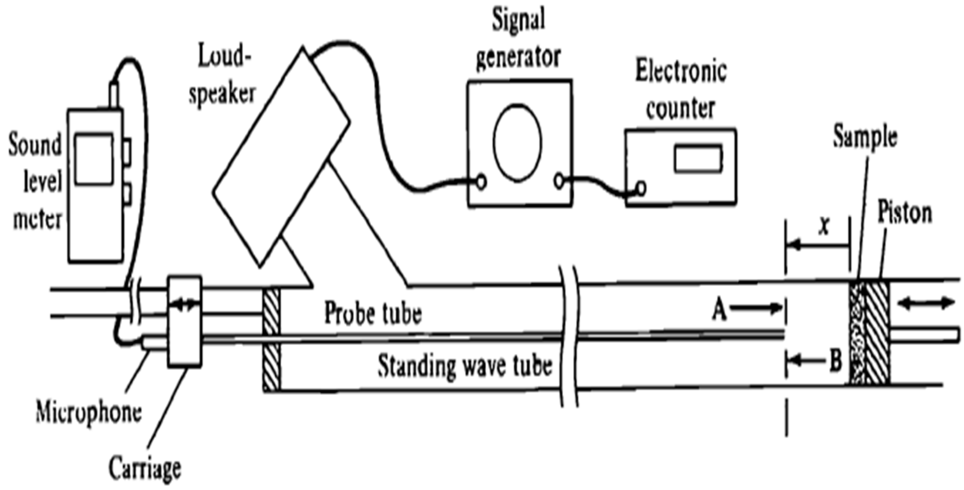


Figure (2.14) Impedance tube for measuring the absorption coefficient

b. Noise reduction coefficient

The manufacturers are required to declare the noise reduction coefficient of their products. The way to determine the coefficient is to test the material for various frequencies and calculate the average value. It is required testing rooms that have a dividing wall with a cutout (for example 30 cm by 40 cm) to insert the insulation layer. On one side there is a sound source, and on the other side there is a sound level meter. Now turn on the sound source at a certain frequency (for example 1000 Hz) without insulation and measure the sound reading on the other side (for example 86.4 dB). Now put the insulation material (for example 2 cm polyurethane) and take another reading (for example 63.3 dB). Hence, the sound drop (d) is 23.1 dB. To determine the coefficient of sound reduction (C), for the recent sound drop, use the following formula:

$$C = 1 - 10^{-\left(\frac{d}{20}\right)}$$

$$C = 1 - 10^{-\left(\frac{23.1}{20}\right)} = 0.93$$

Therefore, the coefficient for this material combination at 1 kHz is (0.93). This test should be repeated for different frequencies (125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, and 4 kHz). Once the tests are done at the different frequencies, a table like the following can by illustrated. The average value at different frequencies is (0.92) which is the NRC.

Frequency	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Drop (dB)	19.4	21.6	22.0	23.1	22.9	22.1
Coefficient	0.89	0.92	0.92	0.93	0.93	0.92

c. Sound transmission class

A usual method that is used in the laboratory for the determination of the transmission loss needs two rooms (source and receiving) with an opening in between. Each room may have about 9 ft. high, 12 ft. wide, and 16 ft. long. The opening between the two rooms is 7 ft. high by 5 ft. wide. The tested wall or panel should be fitted upon the opening. The measurements are taken at different frequencies, for example: 125, 250, 500, 1000, 2000, and 4000 Hz. Sound transmission class (STC) can be calculated by taking the obtained values over the range of 125 Hz to 4000 Hz and plotted on a graph. If the fitted graph is closest to have 56 dB at 500 Hz, then the wall is said to have an STC rating of 56.

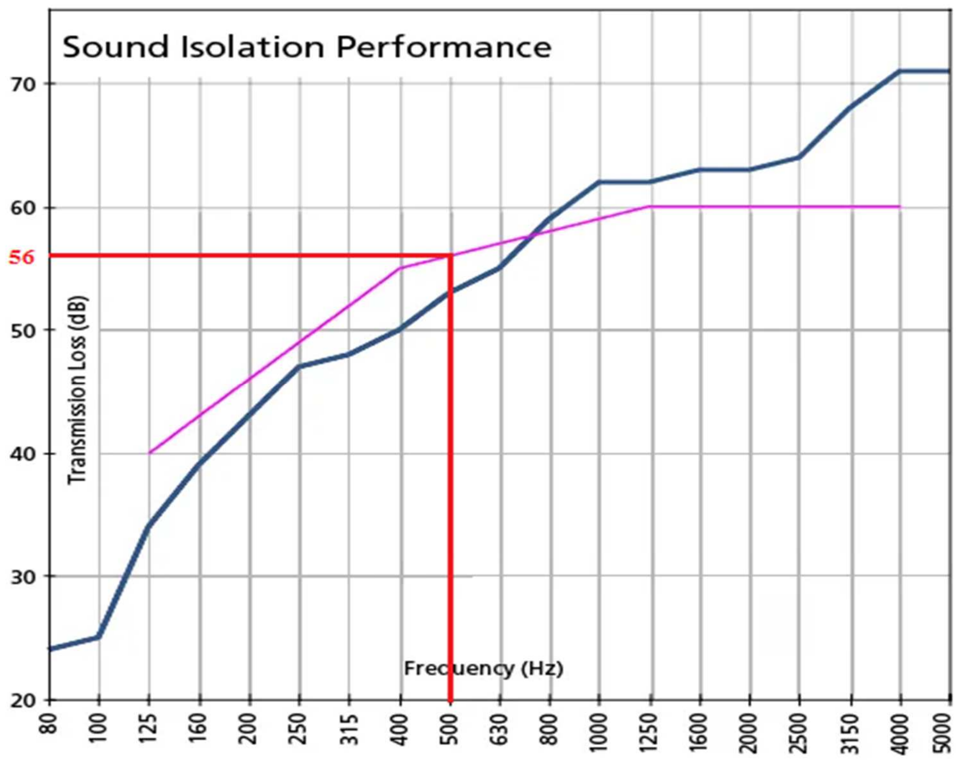


Figure (2.15) Finding the STC of a wall

2.21 Reducing of Earthquake Effects on Buildings

Earthquake directly affects ground shaking and turns to vibration across the building and may cause damage to the structure. Special techniques are required to design buildings to remain undamaged in a severe earthquake. This may render the building non-functional after the earthquake, which may be problematic in some structures, like hospitals, which need to remain functional after the earthquake. Two basic technologies are used to protect buildings from damaging earthquake effects, which are:

i. Base Isolation:

The idea behind base isolation is to isolate the building from the ground in such a way that earthquake waves are not transmitted up through the building, or at least greatly reduced. The main feature of the base isolation technology is that it introduces flexibility in the structure.

- The common type of base isolation is the fixed pad, as shown in figure below. In this case, the isolators are designed with the foundation to absorb energy and thus add damping to the system. As a result, a robust masonry or reinforced concrete building becomes flexible. Several commercial brands of fixed pad isolators are available in the market, and many of them look like large rubber pads. These isolators are suitable for low buildings or medium-rise buildings rested on hard soil underneath; high-rise buildings or buildings rested on soft soil are not recommended.

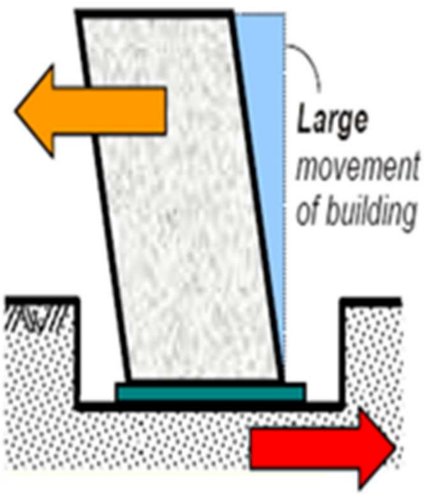


Figure (2.16) Fixed pad base isolation

- Another concept of base isolation is building resting on frictionless rollers, as shown in figure below. When the ground shakes, the rollers freely roll, but the building above does not move. Thus, no force is transferred to the building due to shaking of the ground; simply, the building does not affected by the earthquake.

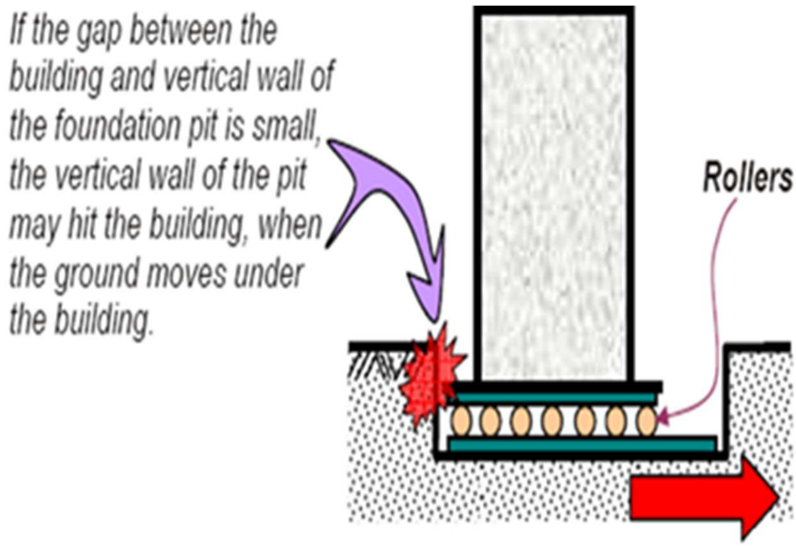


Figure (2.17) Rolling base isolation

- Pendulum bearings are seismic base isolation systems based on the principle of a pendulum. They allow the structure to become horizontally displaced during an earthquake, with seismic energy being dissipated by the friction between various moving components. See figure below.

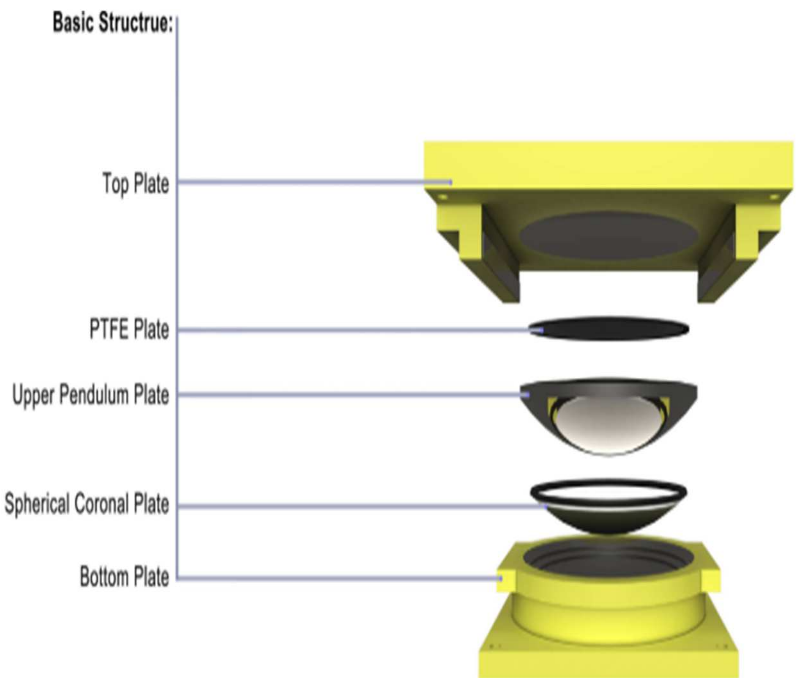


Figure (2.18) Pendulum bearing

ii. ***Seismic Dampers:***

These are special devices introduced in the building to absorb the energy provided by the ground (much like the way shock absorbers in motor vehicles absorb the impacts due to undulations of the road). When seismic vibrations are transmitted through them, dampers absorb part of energy by the hydraulic fluid and only little impact is transmitted to the building. Common types of seismic dampers are: viscous dampers (energy is absorbed by silicone-based fluid passing between piston-cylinder arrangement), friction dampers (energy is absorbed by surfaces with friction between them rubbing against each other), and yielding dampers (energy is absorbed by metallic components that yield). See the figure below for different modes of dampers.

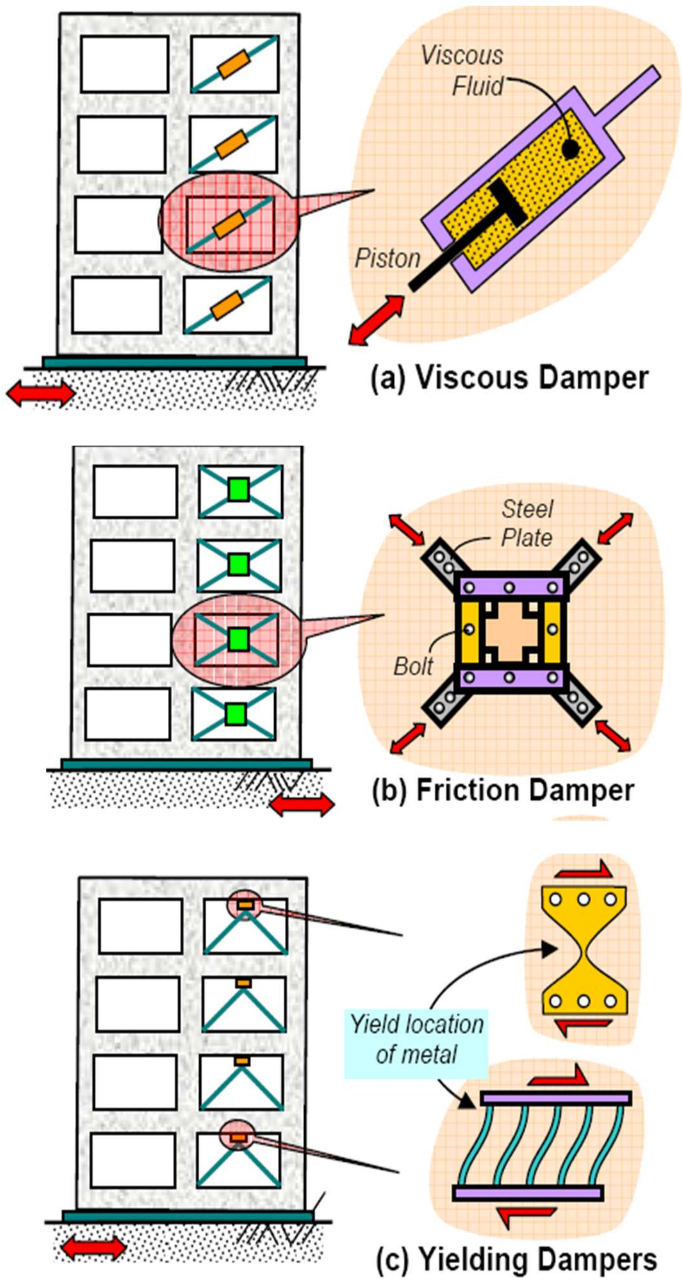


Figure (2.19) Seismic dampers

Exercises No. (2)

Q1) Complete the following sentences:

1. ----------- is a measure of the sound difference through the barrier.

2. Fiberglass could be used for sound insulation; it is composed from glasswool mixed with ------------.

3. ----------- is a viscous resin fast to dry, used in damping, noise absorption as well as to absorb the vibrations of machinery and ducts.

4. In the acoustic design, it is supposed a sound frequency value of ---------- which is still within the range of the voices of people and cars.

Q2) Select the correct answer:

1. Sound transmits through the parts of the building by impact and -------------.

Choices: A. Radiation B. Airborne C. Conduction D. Flanking

2. Sound insulator usually covers ---------- surface of the wall.

Choices: A. Inner B. Outer C. Both D. None

3. A material used in acoustic insulation made of recycling tires is -----------.

Choices: A. MLV B. EPS C. VDC D. PCM

4. Polyurethane has better acoustic insulation than that of EPS due to its high -----------.

Choices: A. NRC B. Hz C. SL D. STL

5. Brick wall has better acoustic insulation than that of drywall due to its high -----------.

Choices: A. AAC B. NRC C. STC D. Strength

6. Acoustic absorption coefficient of a certain material could be measured using ---------.

Choices: A. Impedance tube B. SL meter C. Thermometer D. Intensity meter

7. Sound intensity could be measured using a device called -----------.

Choices: A. Impedance tube B. SL meter C. Thermometer D. Intensity meter

8. Minimum acoustic power that affects the hearing is -----------.

Choices: A. 10 W/m^2 B. 1 W/m^2 C. 10^{-2} W/m^2 D. 10^{-12} W/m^2

9. The sound absorption capacity is measured by a unit called -----------.

Choices: A. dB B. W/m^2 C. Sabin D. K

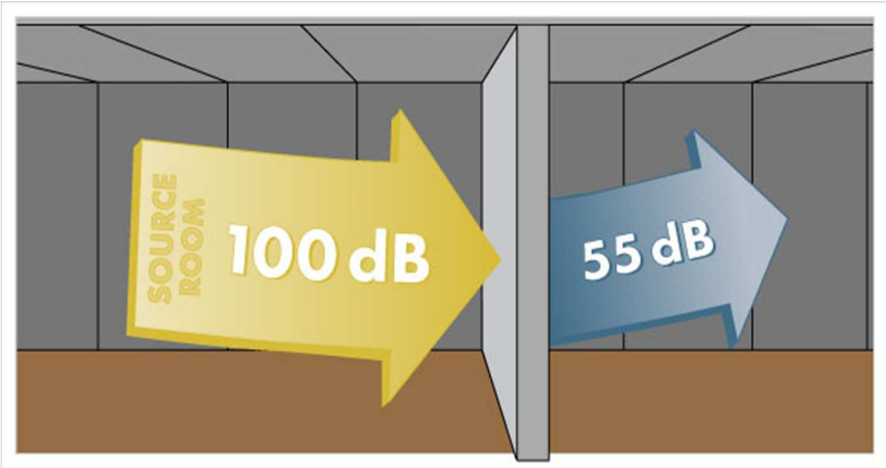
10. Acoustic insulator converts part of the absorbed sound to ------------.

Choices: A. Electricity B. Light C. Magnetic D. Heat

Q3) Classify the sound-proofing materials and give examples of each type.

Q4) What steps should be followed to prevent the noise pollution in industrial?

Q5) What can you understand from the figure?



Q6) A studio hall of 8 m x 6 m x 4 m, has 3 walls of wood (α=0.1), a big facade of glass (α=0.03), ceiling of polyurethane panels (NRC=0.9) and floor of carpet (α=0.3). An office is located next door to the hall. Absorption of furniture=5 Sabins.

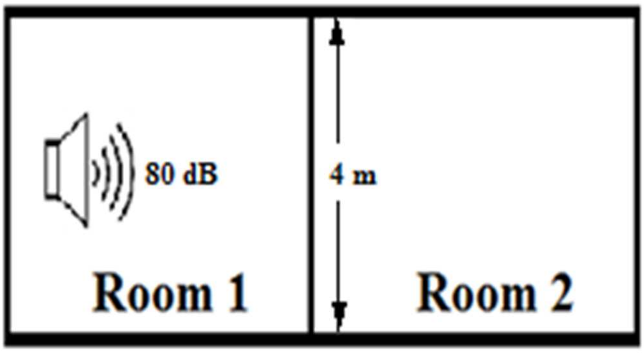
Find:

a) Noise reduction for the office room if STC of the separated wall is 46.

d) Noise reduction for the office room after insulation if the separated wall is covered by acoustic tiles (NRC=0.7) and STC of the separated wall becomes 52.

Q7) Room (1) of 5 m length, 4 m width and 3 m height has the following features:

Element	Material	α
Walls	Brick	0.03
Ceiling	Concrete	0.02
Floor	Wood	0.1



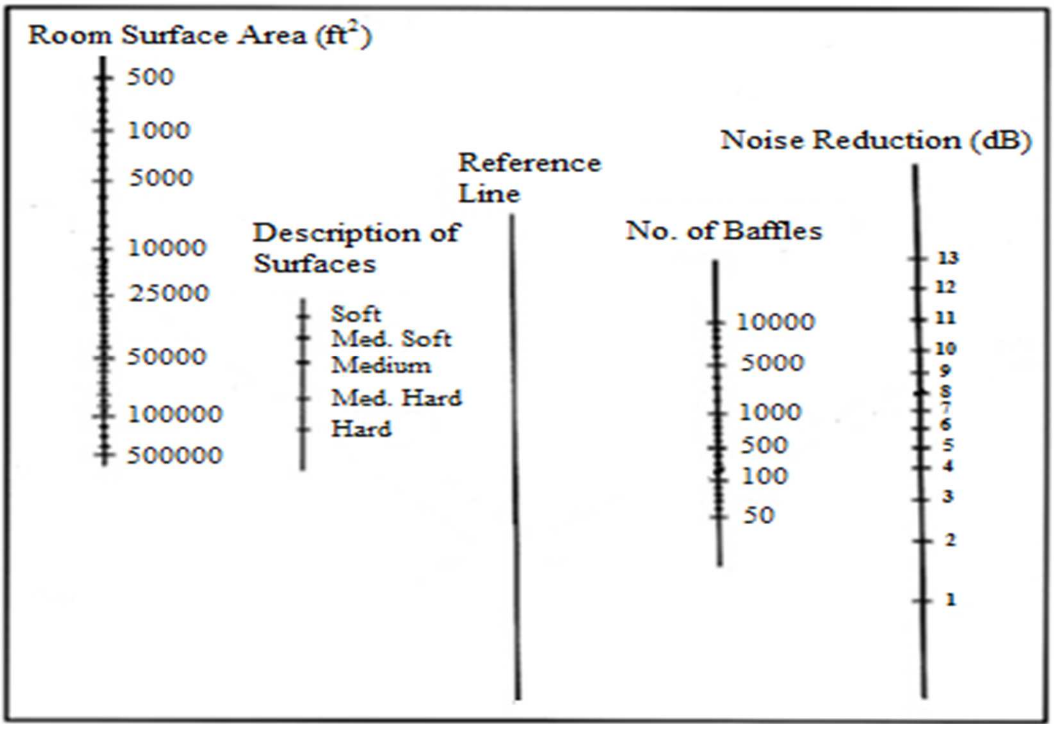
There is an additional absorption due to the furniture which is 15 Sabins. What is the sound level at room (2) for the following cases:

A- Before insulation.

B- After insulating the separating wall by 2 cm polyurethane (NRC=0.9).

Take into account that STC of the wall without insulation is (50) and with insulation is (56).

Q8) Noise control baffles of polyurethane are used to reduce the overall noise level in a generator warehouse of (40' L x 20' W x 12' H), and they are suspended around the noise source. Walls and floor are concrete, while ceiling is wood. Determine number of baffles required to reduce the noise by 10 dB.



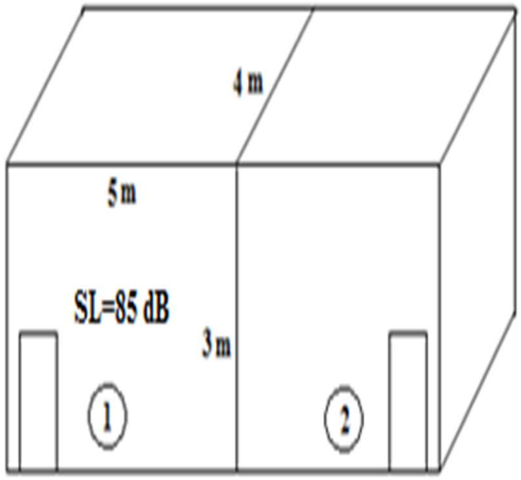
Q9) Room (1) of 5 m length, 4 m width and 3 m height has the following features:

Element	Material	α
Walls	Wood	0.1
Ceiling	Plastic	0.05
Floor	Ceramic	0.01

10 persons (C=0.5 S for each person)

Furniture (C=12 S)

Dissipation to outdoor (C=3 S)



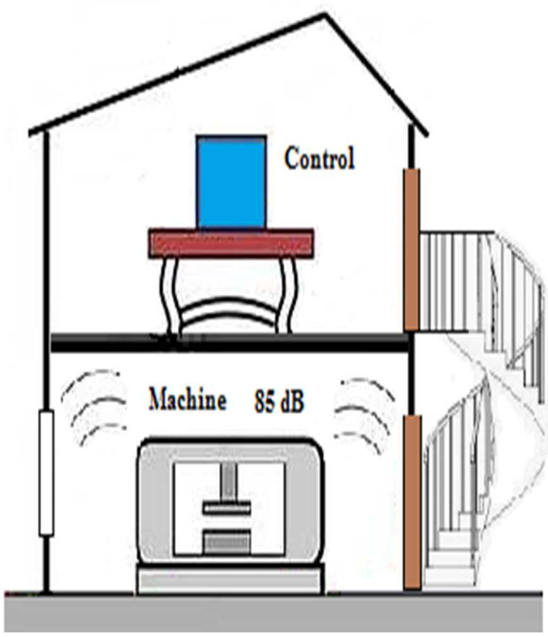
Determine the sound level at room (2) for the following cases:

A- Before insulation. (STC of the separated wall is 50 dB)

B- After insulating the separating wall by 1 cm EPS of NRC=0.5 (STC of the separated wall is 53 dB).

Q10) A machine room of 6 m x 5 m x 3 m has the following features:

Element	Material	α
Walls	Gypsum	0.05
Ceiling	Wood	0.1
Floor	S. Rubber	0.6



What would be the sound level at the upper control room:

1- Before insulation (STC of the ceiling is 39).

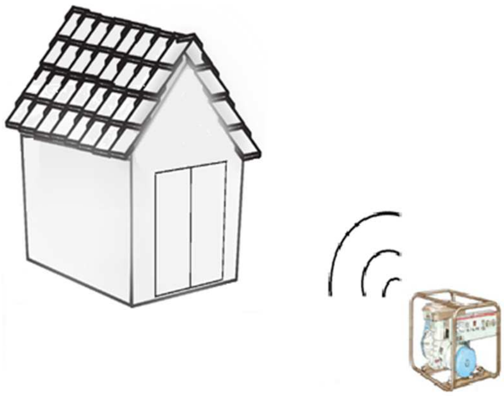
2- After insulating the ceiling by 5 cm EPS (NRC=0.5) and STC of the ceiling will be (47).

Take into account that dissipation due to airborne transmission and furniture is 15 Sabins.

Q11) A generator is located outdoor a warehouse (10 m away) in front of the external wooden door, as shown in the figure below. Measuring the sound level during the running of the generator was (93 dB). The absorption of sound by the atmosphere is (0.8 dB/m). Neglect the sound transmission across the walls and windows. Calculate:

1. Noise reduction across the door to the inside without insulation.
2. Thickness of the door insulating material required to achieve (35 dB) inside.

Type	Description	STC
A	Door without insulator	20
B	Door with 5 mm insulator	30
C	Door with 10 mm insulator	40
D	Door with 15 mm insulator	50
E	Door with 20 mm insulator	60



Q12) A space of 16 m long x 8 m wide x 5 m high, has the following materials:

Walls: gypsum board (NRC = 0.05)

Ceiling: Fibrous board (NRC = 0.15)

Floor: Wooden board (NRC = 0.1)

Find the reverberation time, and evaluate the room according to the result.

Chapter Three
Waterproofing Insulation

Chapter Three
Waterproofing Insulation

3.1 Waterproofing

All buildings need insulation from moisture, rain, groundwater and surface water because the dampness causes in damage of the construction materials and releases undesired smells with the breeding of insects and mice and bring diseases. The walls that exposed to the rain without sufficient amount of sunlight are more susceptible to dampness.

3.2 Effect of Dampness

The effect of dampness is clearly noticed in the following results:

- Damage of building materials and elements of the house.

- Efflorescence of the walls, floor and ceiling.

- Damaging the paint.

- The failure in the timber used and wooden décor.

- Corrosion of metallic parts.

- Proliferation of fungi and unhealthy situation for users in the building.

- The moisture content in an insulation material leads to increase its thermal conductivity. This reduces the performance of thermal insulation up to 50%.

Figure (3.1) Effect of dampness

3.3 Causes of Dampness

It is important for basements and foundations to be waterproof especially in areas where the groundwater is high because the water in the soil is likely to exert hydrostatic pressure on the basement floor and walls. Generally dampness is accused by:

1. Rain water: The rain water has the ability to penetrate the roof of the building, especially for poor surfaces and absence of gutters. Rain could penetrate the windows in absence of overhangs.

2. Surface water: This means river, sea or pond. The water mixes with the soil close to the building and forming a clay then moisture seeps to the foundations or inside through the capillary action. The capillary action is the ability of water to transport through the small pores of the material with the help of the forces of adhesion and cohesion. The capillary action occurs in porous materials like sponge, brick, concrete and many construction materials.

3. Underground water: The accumulated water under the earth's surface could be transmitted through the pores of the soil by the capillary action and ascend to the foundations or inside hence damage the structural materials used in the building. It could even overflowing into the building.

4. Condensation: It is noticed in winter days a layer of dew formed on the window or even wall, and this phenomenon is called "condensation". The accumulated moisture on windows, walls, ceiling and floor seeps into the parts of the house after a period of time and leads to the fragility of construction materials and the appearance of rust, mildew and odors.

5. Poor sewage drainage: When wastewater gathers under the building and it was hard to flow downstream because of some restrictions then dampness could be occurred in the nearby elements of the building.

6. Modern construction: The walls newly constructed remain in the wet state for a certain period.

Capillary action: is the ability of water to transport through the small pores of the material due to the forces of adhesion and cohesion. The capillary action occurs in porous materials like sponge, brick, concrete and many construction materials.

3.4 Types of Waterproofing Insulators

The purpose of waterproofing materials is to prevent the water as well as the moisture and keep it away from building elements. In order to choose the appropriate isolator of humidity it must take into account the nature of the ground (concrete, stone, clay, metal) as well as the climate (dry, wet). The method is characterized by the development of the insulation layer or membrane resists water pressure and using materials to prevent leakage of water or moisture into building elements. The main types of waterproofing materials are:

- **Bitumen:** It is a black material made from the rest of the distillation of crude oil. Bitumen is very common in waterproofing isolation because of its cheapness compared to the other insulating materials in addition to its flexibility and resistance to the proliferation of fungi and insects. Bitumen is available in drums where it should be heated to about 80 degrees to melt. The most famous types are:

  - Liquid of bitumen which is used to fill the cracks in the concrete or roof tiles. Sometime, adhesive is added to the resin components and it is called "mastic". Bitumen could be used as paint (1-2 mm) for the foundations and walls that are in a direct contact with the soil.

  - Solid of bitumen (asphalt) which is used for paving of the street after mixing with sand and stones.

  - Flancoat: a waterproofing material of bitumen used for coating surfaces of concrete in contact with the soil to prevent the dampness. It is effective and easy to use and does not need any mixing with any compound. It does not need to melt, where a brush or a roll is used to paint the surfaces. Often, it is available in black, but there are many other colors.

  - Bitumen rolls: These layers have the excellent isolating and waterproofing capability. They are made of bitumen and sometimes covered by a reflective metallic sheet to reflect the heat. The bitumen layer commonly used to insulate the ceiling or walls and it is available in (3, 4 and 5 mm) thickness.

- **Acrylic:** It is a water resistant material and frequently used for waterproofing of the building roof and the floor of swimming pool. This material is composed of polyester fibers submerged in a liquid resin of polyacrylonitrile, where the required surface should be painted (many layers) and exposed to air to dry quickly and becomes a flexible insulating layer. This substance has a high susceptibility adhesion to various building materials. It is long-life and environment-friendly material.

- **Waterproofing liquid:** This liquid is made from the mixing of paraffin's wax with volatile oil. The waterproofing liquid is used to spray or paint the required surfaces.

- **Epoxy:** A polymeric material sticky and has rapid solidification used to process the holes and cracks.

- **Cement:** In case of free of impurities, cement could be a good resistant insulator. Cement is available as:

  - Portland cement: the increasing of the amount of cement in cement-sand mixture increases the resistance.

  - White cement: it is used to fill the separations in marble tiles for bathrooms and balconies.

- **Fiberglass:** It is a hard kind that results from mixing the glasswool with the epoxy. It is characterized by high resistance to the water therefore used in tank construction. Glasswool could be also mixed for the purposes of strengthening bitumen waterproofing layer.

- **Sheets or layers:** Surfaces could by isolated using many layers like:

  - Polyethylene membrane: Polyethylene is a flexible material that resists moisture and is often found in a very thin layer.

  - Rubber sheets

  - Extruded polystyrene (XPS) layers.

  - Layers of Mass Loaded Vinyl (MLV).

  - Nylon: It can be used between different parts of the building or between the layers of insulators, as well as to cover the foundations.

  - Metallic sheets: slabs, roofs and walls could be covered by a tiny layer of metallic sheet such as copper and aluminum plates. These metals are commonly used to make water storages.

- **Shingle:** These tiles have good isolation and used to cover the inclined surfaces and remove the accumulated water. A shingle is made of durable material like brick, stone or composite material and has a beautiful appearance.

- **Asbestos:** It is ceiling panels characterized by light weight and resistance to water, heat, fire, acids and fungi. The asbestos panel is often used in roofing but it is prohibited recently due to its harmful effect to the body health and environment.

- **Rocks:** Such as marble and granite. They are characterized by hard surfaces so a high resistance to the water. Marble is commonly used as floor tiles in kitchens and bathrooms. These rocks could be used to make the statues.

Asphalt **Bitumen paint** **Shingles**

Acrylic

Bitumen rolls **Polyethylene membrane**

Figure (3.2) Waterproofing materials

3.5 Practical Waterproofing Treatments

The following procedures are assigned for some building elements like:

A. Waterproofing of foundation

1. Paint foundation surface using bitumen paints (or any suitable waterproofing) to prevent water transport and to provide adhesion between the concrete and insulation layer.

2. Put a layer of tarpaulin to protect the foundation from direct contact with water.

3. Put a layer of thermal insulator.

4. Fill the neighboring land to the foundation by stones to resist the permeability of the water as much as possible (see the figure below).

B. Waterproofing of walls

1. Paint wall surface using bitumen paints to prevent water transport and to provide adhesion between the wall and insulation layer.

2. Put a layer of tarpaulin, to protect the walls from direct contact with water, starting from the underground to prevent dampness path to the top.

3. Put a layer of thermal insulator.

4. Finishing works by a layer of mortar or marble.

C. Waterproofing of roof

1. After the casting of concrete, surface should be cleaned and the cracks should be treated carefully using grout or epoxy.

2. Provide appropriate inclination towards the gutters and treating the cumulative area by a layer of cement.

3. Paint concrete surfaces using bitumen paints to provide adhesion between the concrete and the insulation layer.

4. Put a layer of waterproofing material.

5. Put a layer of thermal insulating material.

6. Put a layer of soil and then covering with impervious tiles or insulating membrane such as acrylic.

Note This procedure can be applied to other waterproofing applications such as swimming pools with similar procedures.

Figur (3.3) Waterproofing of foundation

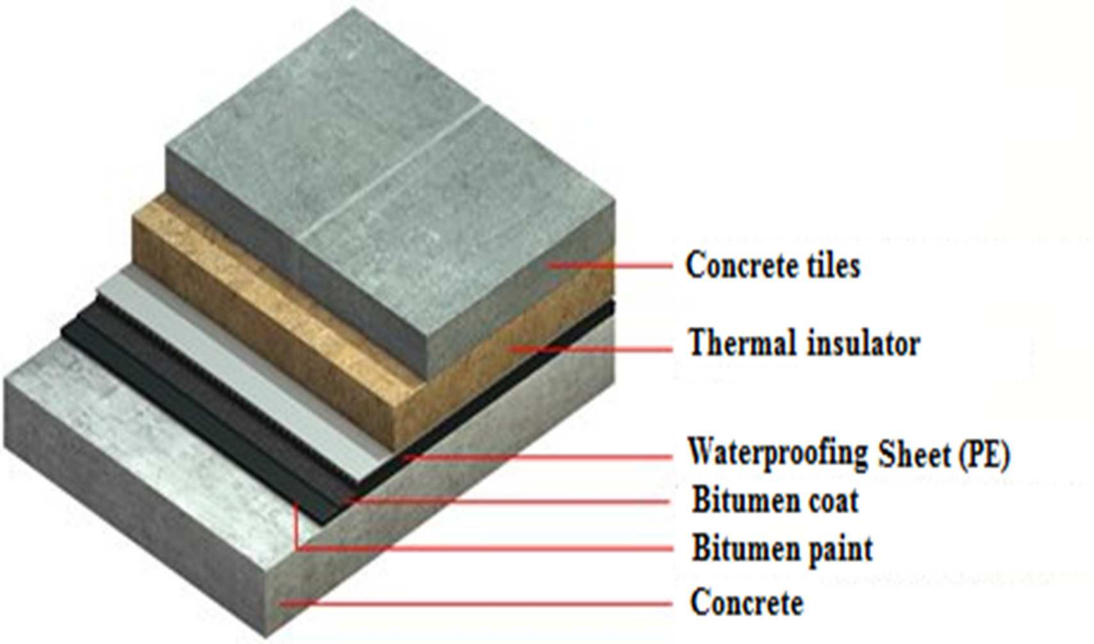


Figure (3.4) Waterproofing of roof

3.6 Waterproofing for Huge Structures

In some huge applications (dams, tanks, tunnels and bridges), where water may be in a contact with structure body, it is required to use cementitious waterproofing which is a highly flexible cement-polymer based waterproofing, designed to protect the concrete that exposed to high concentrations of water and chemicals like (sulfuric compounds). The key benefit of this waterproofing is:

- The product comes in a package
- The product is two-component combination, usually (cement-acrylic)
- The product is easily applied by brushing or spraying to the contact surfaces
- 2 mm coating provides good anti-carbonation cover
- Waterproof resistance is up to 15 bar of positive pressure and 3 bar of negative pressure
- The elongation > 100%
- High resistance to carbon dioxide and chloride ion diffusion
- Requires to cure for 24 hours
- Potable water certified
- Environmentally friendly product. No solvents and no VOC's

Figure (3.5) Waterproofing for a huge tank

3.7 Engineering Calculations of Water Transfer

One of the primary roles of all waterproofing systems is the control of the movement of water whether this is by keeping water in, out, off, or even letting it through. The controlling of water required to know some properties and understand the difference between permeability and porosity. Porosity is the amount of holes and permeability is how well the holes are connected. Generally there are three ways may water transfer through the building element, which are:

1. Water transfer under hydrostatic pressure: in this category, the water is transfer under certain pressure. The term permeability is appeared as dominated parameter. It is an indication of liquid ability to pass through a material under the pressure effect. In another way, it is a measure of the allowability of a porous material to pass the liquids. It is the inversion of the resistance, and its unit is Darcy (D). The Darcy can be converted in term s of area to:

1 Darcy ≈ 10^{-12} m^2

However, a medium with a permeability of 1 D permits a flow of 1 cm³/s of a fluid with viscosity 1 cP under a pressure gradient of 1 atm/cm acting across an area of 1 cm². Typical values of permeability range as high as 100,000 mD for gravel, 1 mD for sand, 0.1 mD for concrete, 0.005 mD for marble and as less as 0.001 mD for granite.

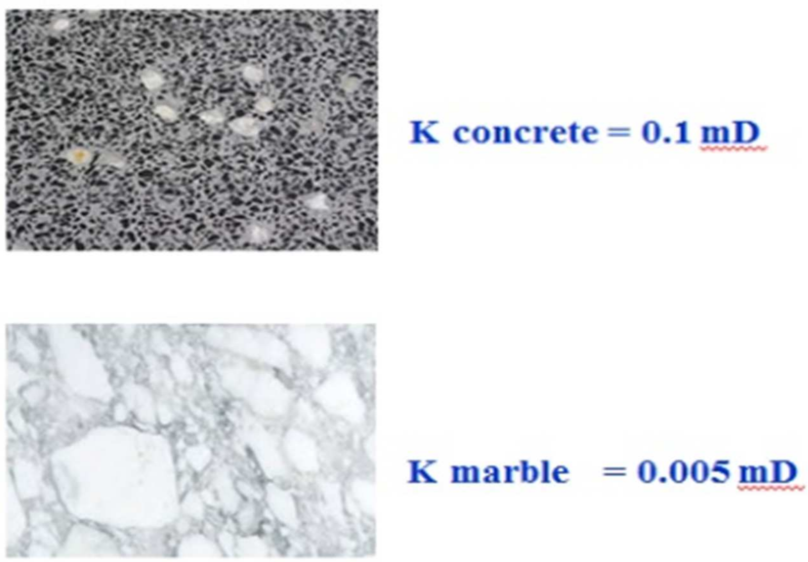


Figure (3.6) Difference between the permeability of concrete and marble

The following table shows the values of permeability for some materials.

Table (3.1) Values of water permeability for some materials

<table>
<tr><td>Unconsolidated Sand & Gravel</td><td colspan="2">Well Sorted Gravel</td><td colspan="3">Well Sorted Sand or Sand & Gravel</td><td colspan="4">Very Fine Sand, Silt, Loess, Loam</td><td colspan="4"></td></tr>
<tr><td>Unconsolidated Clay & Organic</td><td colspan="4"></td><td colspan="2">Peat</td><td colspan="3">Layered Clay</td><td colspan="4">Unweathered Clay</td></tr>
<tr><td>Consolidated Rocks</td><td colspan="4">Highly Fractured Rocks</td><td colspan="3">Oil Reservoir Rocks</td><td colspan="2">Fresh Sandstone</td><td colspan="2">Fresh Limestone, Concrete</td><td colspan="2">Fresh Granite</td></tr>
<tr><td>κ (milliDarcy)</td><td>10^8</td><td>10^7</td><td>10^6</td><td>10^5</td><td>10000</td><td>1000</td><td>100</td><td>10</td><td>1</td><td>0.1</td><td>0.01</td><td>0.001</td><td>0.0001</td></tr>
<tr><td>Strength</td><td colspan="4">Pervious</td><td colspan="4">Semi-Pervious</td><td colspan="5">Impervious</td></tr>
</table>

In order to determine the discharge of the liwuid across the material under the pressure effect, the velocity of the liquid in a permeable material is given by:

$$v = \frac{\kappa}{\mu}\frac{\Delta P}{\Delta x}$$

Where:

υ = flow velocity through the medium (m/s)

k = coefficient of permeability of the medium (m^2)

μ = dynamic viscosity of the fluid (Pa·s)

ΔP =Applied pressure difference (Pa)

Δx = thickness of the bed of the porous medium (m)

The the discharge in (m^3/s) is given by:

$Q = \upsilon . A$

Example (1): A swimming pool of 60 m^2 has a concrete floor of 10 cm thickness and exposed to 20 kPa pressure difference of water. Determine the discharge of water across the concrete. (μ of water = 0.001 Pa.s) (k of concrete = 0.01 miliDarcy). What will be the difference if granite is used (k of granite = 0.001 miliDarcy).

Solution

- In case of concrete

$$v = \frac{\kappa}{\mu}\frac{\Delta P}{\Delta x} = (0.01 \times 10^{-3} \times 10^{-12}/0.001)\,(20000/0.1) = 0.2 \times 10^{-8} \text{ m/s}$$

$Q = \upsilon \times A = 0.2 \times 10^{-8} \times 60 = 12 \times 10^{-8}$ m^3/s

- In case of granite

$\upsilon = (0.001 \times 10^{-3} \times 10^{-12}/0.001)\,(20000/0.1) = 0.02 \times 10^{-8}$ m/s

$Q = \upsilon \times A = 0.02 \times 10^{-8} \times 60 = 1.2 \times 10^{-8}$ m^3/s

2. Water transfer by sorption: this is the tendency of water to rise into porous materials by capillary action. Thus, no water pressure is required. The quantity of water absorbed into the material by capillary action is given by:

$$\boldsymbol{V = A\, S\, \sqrt{t}}$$

Where
V = accumulated volume by absorption (m^3)
A = wetted area (m^2)
S = Sorptivity of the material ($m/\sqrt{min}$)
t= time (min)

Table (3.2) Values of water sorptivity for some materials

Material	S ($mm/\sqrt{min}$)
Stone	0.15
Concrete	0.2
Block	0.5
Brick	1.1
Cement	1.5
Gypsum	3.5
Soil	40

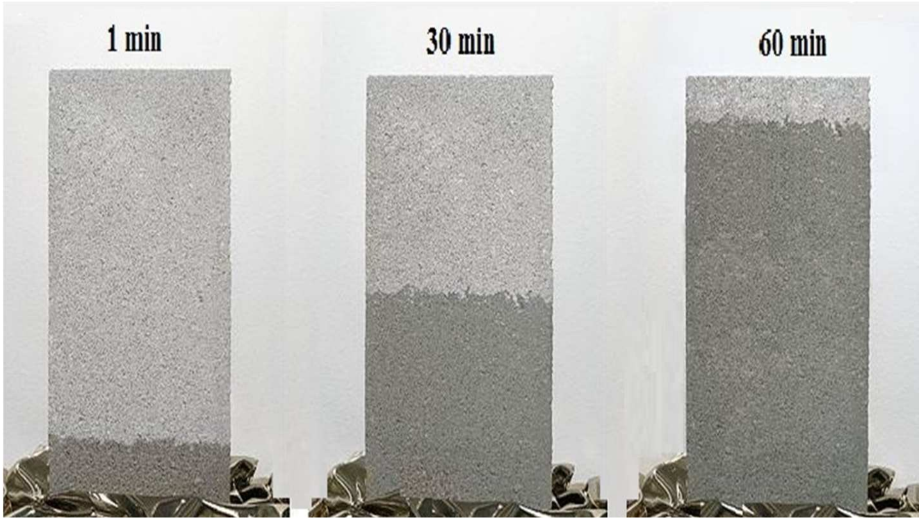


Figure (3.7) sorption in concrete (s=1.6 mm/√min)

Example (2): Brick wall (S=1.1 $mm/\sqrt{min}$) of 5 m width, 3 m high and 25 cm thickness is attached to underground water. What would be the dampness level for a period of one month, if the water touches 10 cm of the foundation height. What is the difference if impervious brick (S=0.1 $mm/\sqrt{min}$) has been used.

Solution:

$V = A\,S\,\sqrt{t}$ = (5 x0.1) x 1.1 x 10^{-3} x $\sqrt{30\ x\ 24\ x\ 60}$ = 0.114 m^3

Water rise = V / A = 0.114 / (5x0.25) = 0.091 m

It means that the water will rise approximately 9 cm after a month.

3. Vapor flow: it refers to the humidity of the ambient air. Air always contains an amount of water as vapor, and the relative humidity is a term used to describe this amount. At 0% RH there is no water in the air and at 100% RH the air if full of water where condensation will occur. However, as air heats up, it can hold more water; therefore a relative humidity measurement is accompanied by a temperature. The term "vapor pressure" is the pressure exerted by the molecules of water vapor in the air. A considerable amount of vapor can be transported through construction materials (like concrete), and the direction of flow is from high vapor pressure to low vapor pressure due to the process of diffusion. Diffusion is simply described as flow of species (liquid, gas or dissolved ions) from a location of high concentration to low concentration (or more precisely from high chemical potential to low chemical potential). It is important to note that water vapor does not necessarily move from high relative humidity to low relative humidity as illustrated in the figure bellow where water flows from the higher vapor pressure side to the lower side. The actual flow of moisture in an exterior concrete building wall is much more complex owing to the effect of heating and cooling.

Understanding the vapor flow is essential when applying waterproofing treatment to unbalanced vapor pressure gradient. Therefore "vapor barrier" is commonly used to protect building elements. A vapor barrier (or condensation barrier) is any material (typically a plastic sheet) used for damp proofing to resist the diffusion of moisture through wall, ceiling and floor assemblies of buildings, and to prevent interstitial condensation. Technically, many of these materials are only vapor retarders as they have varying degrees of permeability. Vapor barrier is usually applying to the internal face of a building wall in a cold climate or to the external face of a building wall in a hot climate. As a general rule of thumb the barrier should be placed on the upstream face, otherwise the vapor pressure or (water) will act to damage and blister the membrane and building element as well.

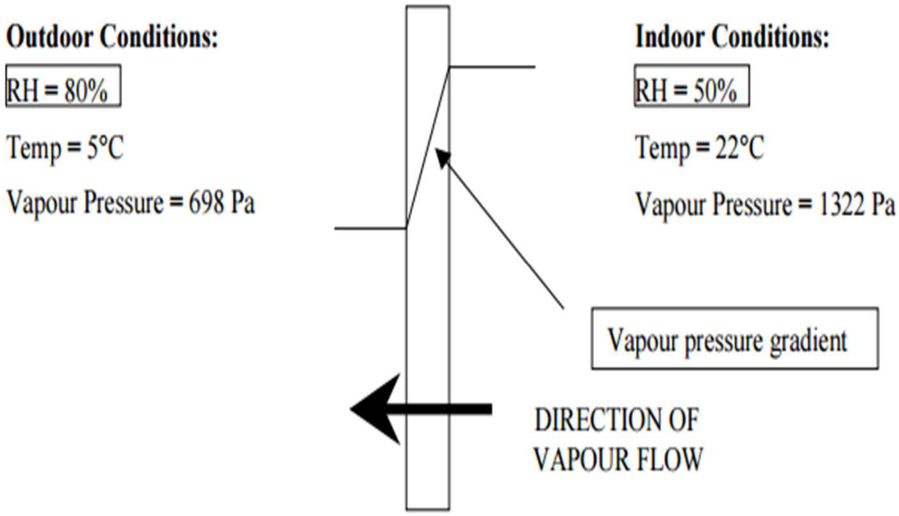


Figure (3.8) Direction of vapor flow in cold weather

The moisture transfer can be expressed by:

$$\frac{\partial w}{\partial t} + \nabla \cdot (\rho_a v \omega) + \nabla \cdot \left(-\delta_v \frac{\partial p_v}{\partial x_i} \right) + \nabla \cdot \left(D_l \left(\frac{\partial p_s}{\partial x_i} + \rho_w g \right) \right) = 0$$

There are different driving potentials in this equation, including humidity, vapor pressure, and suction pressure; as well as some effective parameters like: density, velocity, permeability and conductivity. It is difficult to solve this question by using more than one driving potential.

Exercises No. (3)

Q1) Complete the following sentences:

1. --------- is used to pave the street after mixing with sand and stones.

2. Acrylic is a good waterproofing material which composed of polyester fibers submerged in a liquid resin of -----------.

3. ---------- is an indication of liquid allowability to pass through a porous material in (Darcy) unit.

4. --------- is a plastic sheet used to resist the diffusion of moisture through the walls.

Q2) Select the correct answer:

1. The most common waterproofing materials is:

Choices: A. EPS B. Fiberglass C. Bitumen D. Cement

2. Fiberglass is composed from glasswool and

Choices: A. Polyester B. Epoxy C. Latex D. Nylon

3. The tendency of water to rise into materials by capillary action is:

Choices: A. Permeability B. Sorptivity C. Absorptivity D. Permittivity

Q3) What are the effect of dampness?

Q4) What are the commercial types of waterproofing insulators?

Q5) Explain the practical waterproofing process required for the foundation.

Q6) Explain the practical waterproofing process required for the roof.

Q7) What is the capillary action? How could calculate the quantity of water absorbed by capillary action.

Chapter Four

Electrical Insulation

Chapter Four

Electrical Insulation

4.1 Introduction to Electrical Insulation

Insulators are used in many applications; to wrap electrical cables or in electrical equipment to separate electrical conductors. The term insulator is also used more specifically to refer to supports that used to attach electric power transmission lines to towers and poles. They support the weight of the suspended wires without allowing the current to flow through the tower to ground. An electrical insulator is a material whose internal electric charges do not flow freely, and therefore make it nearly impossible to conduct an electric current under the influence of an electric field. This contrasts with other materials which conduct electric current more easily. A perfect insulator does not exist, because even insulators contain small numbers of mobile charges (charge carriers) which can carry current.

Figure (4.1) Applications of electrical insulators

4.2 Classification of Materials

It is known that any substance contains a number of molecules and atoms. These atoms have some electrons in the outer orbit called "free electrons". Due to the ease expelled of the free electrons from the external orbit and make it move easily to another atom, and so on creating a flow of electrons called "electrical current". Materials are classified according to its ability to conduct electricity to:

1. Conductors

A conductor is a material that allows the flow of electrical current in one or more directions. The mobile charged particles are usually the electrons. Conduction materials include metals (copper, aluminum, iron, etc), electrolytes, superconductors, semiconductors, plasmas and some nonmetallic conductors such as graphite and conductive polymers. Copper has a high conductivity and it used for many applications, such as building wire, motor windings and busbars. Because of its ease of connection by soldering or clamping, copper is still the most common choice for most light-gauge wires. Aluminum has higher conductivity than copper, but it has some problems. Where, it can form a resistive oxide that makes wires unable to terminate heat. Aluminum can creep, slowly deforming under load, eventually causing device connections to loosen, and also has a different coefficient of thermal expansion. However, aluminum wires could be used for low voltage distribution, such as buried cables and service drops, require use of compatible connectors and installation methods to prevent heating at joints. Aluminum is also the most common metal used in high-voltage transmission lines, in combination with steel as structural reinforcement. Silver is more conductive than copper, but due to cost it is not practical. However, it is used in specialized equipment, such as satellites.

2. Semiconductors

Semiconductors are crystalline or amorphous solids with higher resistance than typical conductors but still much lower than insulators. Their resistance decreases as their temperature increases, which is behavior opposite to that of a metal. So, their conducting properties may be adopted in useful ways (such as in diodes and transistors) by doping of impurities into the crystal structure to reduce its resistance. Doping is important to increase the number of charge carriers within the crystal. When a doped semiconductor contains mostly free holes, then it is called "p-type", and when it contains mostly free electrons, then it is known as "n-type". Many pure elements and some compounds display semiconductor properties like silicon, germanium, compounds of gallium, and mixtures of (arsenic, selenium and tellurium). It is important here referring to the term "energy gap" which is the energy required by an electron to move from valence band to conduction band. This is equivalent to the energy required to free an outer shell electron from its orbit to become a mobile charge carrier, able to move freely within the solid material. The energy gap is a major factor determining the electrical conductivity of a solid. Substances with large band gaps are generally insulators, those with smaller band gaps are semiconductors, while conductors either have very small band gaps or none, because the valence and conduction bands overlap.

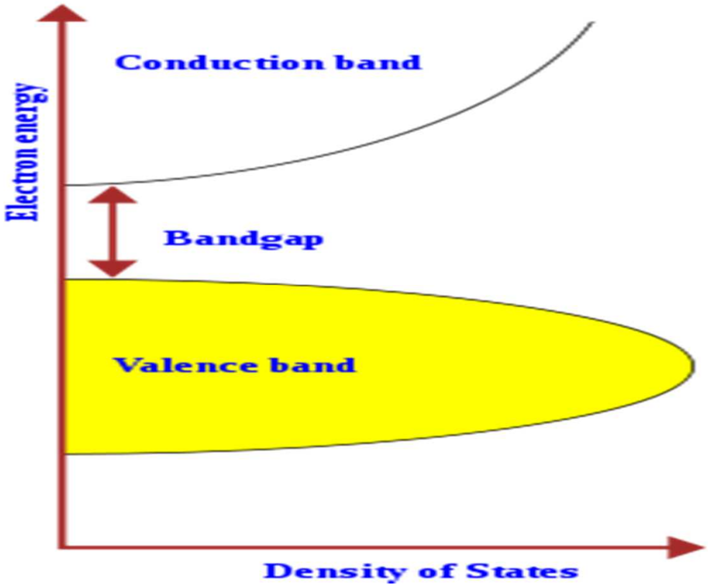


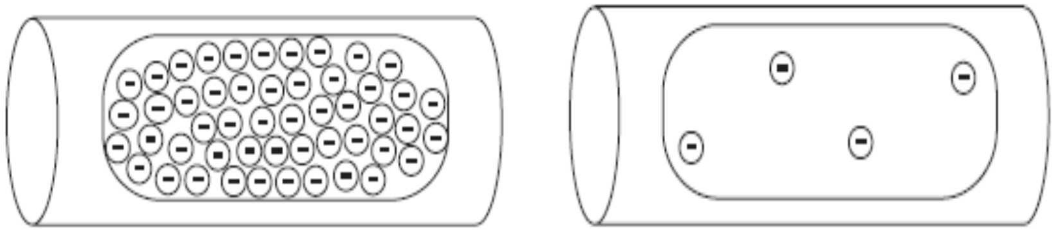
Figure (4.2) Semiconductor energy structure

Table (4.1) Energy gap for common semiconductors and insulators

Material	Symbol	Energy gap (eV) at 25 °C
plastics	-	6-10
Silicon dioxide	SiO_2	9
Ceramics: Aluminum oxide (Al_2O_3) Mullite ($3Al_2O_3 \cdot 2SiO_2$) Forsterite (2MgO · SiO2) Beryllium oxide (BeO) Aluminum nitride (AlN)	-	4 - 8
Diamond	C	5.5
Silicon nitride	Si_3N_4	5
Gallium nitride	GaN	3.4
Gallium phosphide	GaP	2.26
Copper oxide	Cu_2O	2.1
Gallium arsenide	GaAs	1.43
Silicon	Si	1.11
Germanium	Ge	0.67
Lead sulfide	PbS	0.37

3. Insulators

Those materials do not allow the flow of electric current, such as: wood, plastic, quartz and ceramic. The main reason of the ability of these materials to restrict the electrical flow is that the atomic structure contains a very small number of free electrons midwife to move.



Conductor **Insulator**

Figure (4.3) Comparison between electrical conductor and insulator

It may understand the following from the figure:

• Material that contains a plenty of free electrons becomes a "conductor".

• Material that contains few of free electrons becomes an "insulator".

The electric field still active even in an insulating material, where an imbalance occurs and the positive charges attract to the electric field while the negative charges displace away. This separation between electrical charges generates the so-called "dipole" and the corresponding process called "polarization". The insulator that can be polarized by an applied electric field is called "dielectric material".

The term dielectric is the combination of two words; 'dia' and 'electric', which means opposite to electrical conduction. The electrical conductivity of a perfect dielectric is zero. A dielectric material does not conduct elasticity but it stores and dissipate the electrical energy similar to an ideal capacitor. Dielectrics are categorized based on the type of molecule present in the material. There are two types of dielectrics: polar dielectrics and non-polar dielectrics. In polar dielectrics, the center of mass of positive particles does not coincide with the center of mass of negative particles. Here the dipole moment exists. The molecules are asymmetrical in shape. When the electric field is applied the molecules align themselves with the electric field. When the electric field is removed random dipole moment is observed and the net dipole moment in the molecules becomes zero. Examples are H2O and CO2. In the non-polar dielectrics, the center of mass of positive particles and negative particles coincide. There is no dipole moment in these molecules. These molecules are symmetrical in shape. Examples of non-polar dielectrics are H2, N2 and O2.

4.3 Properties of Dielectric Materials

Some of the main properties of a dielectric material are: resistance, permittivity, polarization, susceptibility, dispersion, relaxation and tenability.

1. Resistance: is the ability of the material to repel the electrical current. The resistance of a given conductor depends on the material it is made of and on its dimensions. For a given material, the resistance is given by:

$$\boldsymbol{R = \rho \frac{L}{A}}$$

ρ = the resistivity of the material (ohm.m)
L = length of the wire (m)
A = cross-sectional area of the wire (m^2)

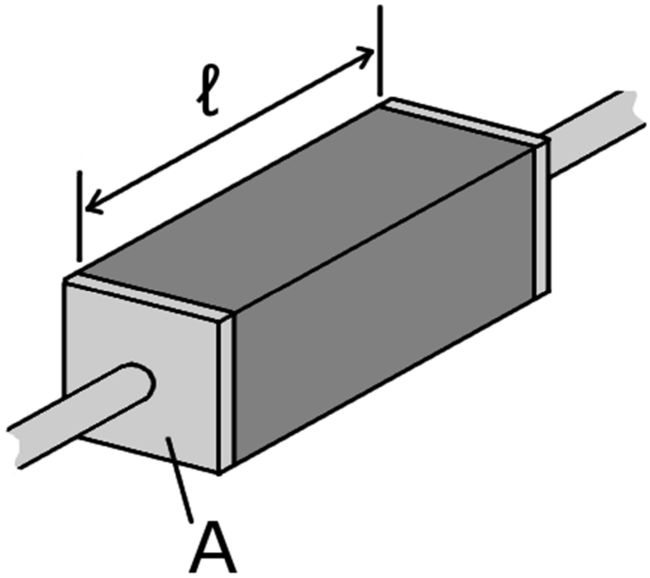


Figure (4.4) A piece of resistive material

Resistivity is the property that distinguishes the insulators, where insulators have higher resistivity than semiconductors or conductors. Some materials such as glass, paper and Teflon, which have high resistivity, are very good electrical insulators. A much larger class of materials, even though they may have lower bulk resistivity, are still good enough to prevent significant current from flowing at normally used voltages, and thus are employed as insulation for electrical wiring and cables. Examples include rubber, polymers and most plastics.

Table (4.2) Resistivity for common materials

Material	ρ (Ω·m) at 25 °C	Material	ρ (Ω·m) at 25 °C
Carbon (graphene)	1.00×10^{-8}	GaAs	1.0×10^{-3} to 1.0×10^{3}
Silver	1.5×10^{-8}	Germanium	4.6×10^{-1}
Copper	1.7×10^{-8}	Water	2.0×10^{-1} to 2.0×10^{3}
Aluminum	2.8×10^{-8}	Silicon	6.4×10^{2}
Tungsten	5.6×10^{-8}	Wood (damp)	1.0×10^{3} to 1.0×10^{4}
Zinc	5.9×10^{-8}	Plastics	1.0×10^{8} to 1.0×10^{16}
Nickel	6.9×10^{-8}	Rubber	1.0×10^{10} to 1.0×10^{13}
Iron	1.0×10^{-7}	Ceramics	1.0×10^{12} to 1.0×10^{14}
Tin	1.1×10^{-7}	Glass	1.0×10^{11} to 1.0×10^{15}
Lead	2.2×10^{-7}	Air	1.3×10^{16} to 3.0×10^{16}
Titanium	4.2×10^{-7}	Quartz	7.5×10^{17}
Mercury	9.8×10^{-7}	Polyethylene terephthalate (PET)	1.0×10^{21}
Carbon (amorphous)	5.0×10^{-4} to 8.0×10^{-4}	Teflon	1.0×10^{23} to 1.0×10^{25}

2. Permittivity: is a measure of how an electric field affects a dielectric medium. In other words, the permittivity of a medium describes how much electric field is generated per unit charge in that medium. More electric flux exists in a medium with a low permittivity because of polarization effects. The best insulator is that which has a large permittivity. Since the increasing of the permittivity leads to increase the capacitance of the material, hence it could say that the permittivity increases the ability of the insulation to absorb more amounts of electrical charges and avoid the transfer of energy. Permittivity relates to the ability of material to resist an electric field. In SI units, permittivity (ε) is measured in farads per meter (F/m).

Permittivity is directly related to electric susceptibility, which is a measure of how easily a dielectric polarizes in response to an electric field, as following:

$$\varepsilon = (1 + \chi)\, \varepsilon_0$$

χ = electrical susceptibility

ε_0 = vacuum permittivity (8.85×10^{-12} F/m)

In engineering applications, permittivity is often expressed in relative, rather than in absolute terms. The relative permittivity of the material is also called the "dielectric constant", thus:

$$\varepsilon_r = \varepsilon / \varepsilon_o$$

ε_r = relative permittivity of the material

ε = absolute permittivity of the material

Table (4.3) Relative permittivity (dielectric constant) for common materials

Material	ε_r
Vacuum	1.0
Air	1.0006
Conductive polymers	2-12
Wood	2-6
PTFE/Teflon	2.1
Polypropylene	2.2-2.36
Polyethylene	2.25
Polystyrene	2.4-2.7
Carbon disulfide	2.6
Polyimide	3.4
PVC	3.8
Paper	3.85
Silicon dioxide	3.9
FR-4	4.0
Concrete	4.5
Pyrex	4.7
Glass	3.7-10
Salt	3-15
Rubber	7
Diamond	5.5-10
PVDF	9-13
Graphite	10-15
Silicon	11.7
Water (200 ^oC)	34.5
Water (20 ^oC)	80.1
Water (0 ^oC)	88
Lead Zirconate Titanate (PZT)	500 - 6000
Calcium Copper Titanate (CCT)	1000 - 100000

3. Polarization: is the ability of insulating material to undergo the separation between electrical charges and forming the dipole. Polarization is the amount of dipole moment per unit volume. Polarization in dielectric materials are affected mainly by two parameters: temperature and frequency. It is noticed that polarization in some materials like ceramics are higher than that of others like polymers, due to the ability of a material to have many ways of polarization. The following polarization types are available:

1. Electronic: due to the displacement between electrical charges (+ve and -ve), like in PE and PTFE.

2. Ionic: due to the displacement between ions (cations and anions), like in PVC and rubber.

3. Molecular: due to the shifting between polar molecules, like in Methyl Chloride and Fiberglass.

4. Space (Interfacial): due to the shifting between some elements in the materials when there is an accumulation of charge at the interface, like in Al2O3 and TiO_2.

Thus the total polarization is the summation of all these types.

Total polarization = Electronic Pol. + Ionic Pol. + Molecular Pol. + Space Pol.

All insulators become electrically conductive when a sufficiently large voltage is applied that leads to extracts the electrons away from the atoms. This is known as "breakdown voltage". The expression of voltage drop per unit length is known as "dielectric strength", which is the maximum voltage that an insulating material can withstand under ideal conditions without breaking down. This is measured in (V/m).

Table (4.4) Dielectric strength for common materials

Material	Dielectric Strength (MV/m)
Air	3.0
Alumina	13.4
Glass	9.8 - 13.8
Silicone oil, mineral oil	10 - 15
Polystyrene	19.7
Polyethylene	19 - 160
Neoprene rubber	15.7 - 26.7
Distilled water	65 - 70
Fused silica	25–40
Waxed paper	40 - 60
PTFE ,Teflon	20 - 173
Mica	118
Diamond	2000
Vacuum	10

4.4 Purposes of Dielectric Materials

There are many types of dielectric materials used in different electrical systems for various purposes. Some materials used for electrical insulation in wirings, tools and devices like: plastics, rubber, wood, ceramics, glass, cellulose paper, and oils. Some others used for electrical charging in capacitors or piezoelectricity applications like: crystals, ceramics and polymers.

4.5 Applications of Dielectric Materials in Insulation

Some applications of dielectrics rely on their electrically insulating properties rather than ability to store charge, so high electrical resistivity and low dielectric loss are the most desirable properties here. The most obvious of these uses is insulation for wires, cables etc., but there are also applications in sensor devices. For example, it is possible to make a type of strain gauge by evaporating a small amount of metal onto the surface of a thin sheet of dielectric material.

4.5.1 Wiring

Conductor wire, usually made of copper or aluminum, should be insulated electrically and physically, within the cable. Insulators could be found in many forms: solid, semi-solid and foam. Plastics, rubbers and epoxy are commonly used to cover the electrical wires.

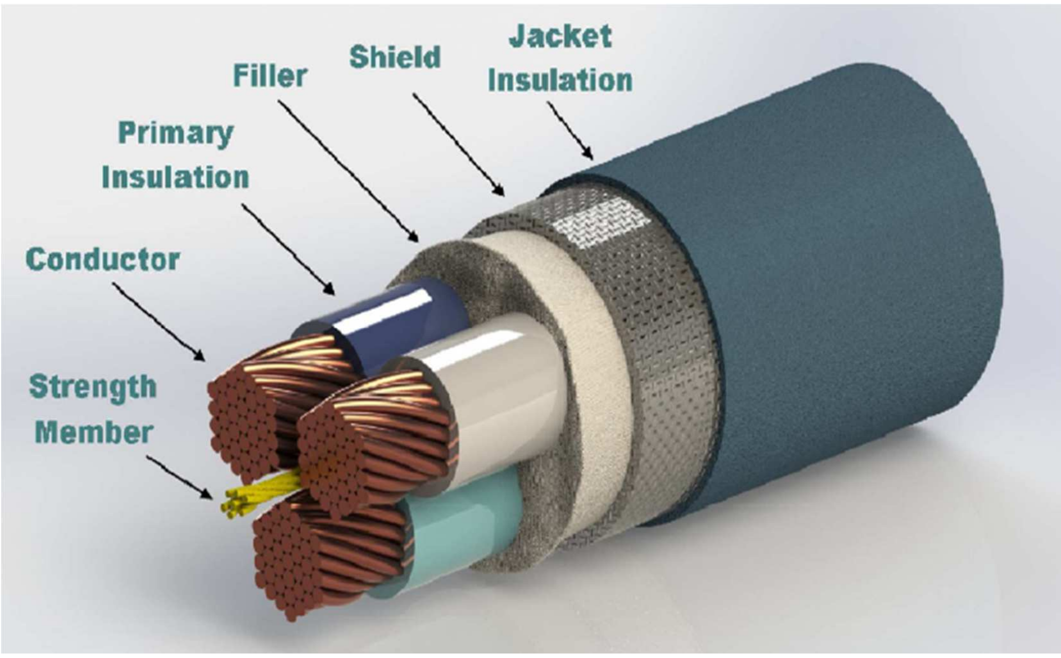


Figure (4.5) Insulation of wire

Electrical wires usually have many layers such as: primary insulation, filler and jacket.

a. **Primary insulator:** is a flexible material used to insulate the conductors and prevent any contact. Alternative polymers could be used like thermoplastic and thermoset materials. Thermoplastic materials used for electrical insulation are: PVC, HDPE, PP, PEEK, PTFE, PET, PES, PEI, ECTFE, PBT and FE. While thermoset materials are: Neoprene, rubber, SBR and EPDM.
b. **Filler:** is a material used to fill the gap between insulated wires and the jacket. Usually they are filled with: foam like (PU), textile or just air. For heavy cables, the filler could be covered by a metallic sheathing (shield) for strengthening.
c. **Jacket**: is the external shell of the cable usually made from solid materials like: Neoprene, rubber, PVC and HDPE. Jacket used to:
   - protect the internal components of the cable physically.
   - protect from environmental impacts and from flame.
   - improve the cable appearance.

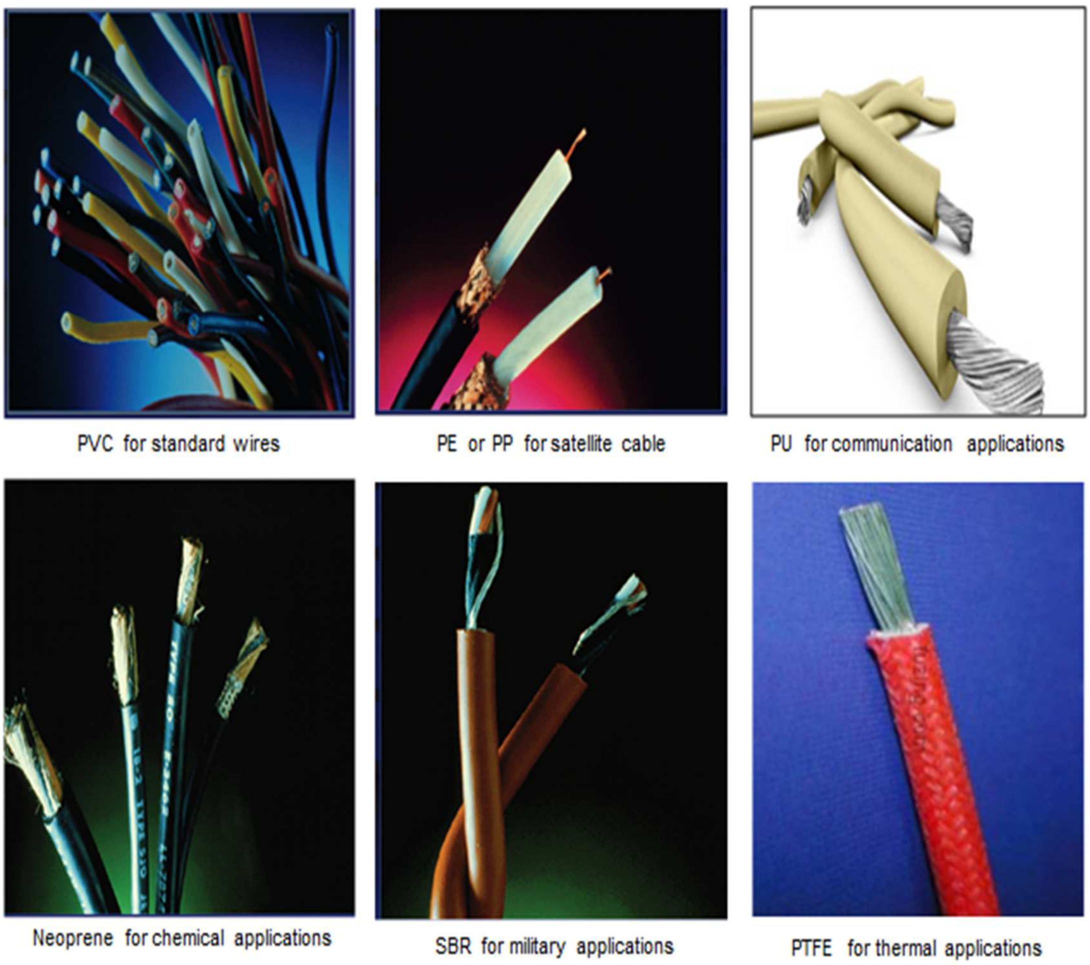


Figure (4.6) Some materials used for wiring insulation

Selecting the insulation: the insulation material should consider the following specifications in design:

- Electrical: working voltage, dielectric strength, dielectric constant and velocity propagation.
- Physical: density, tensile strength, flexibility, temperature rating and flammability.

However, for cable with voltage ratings of:

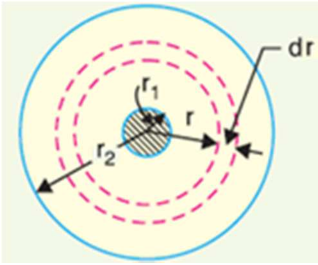
- Low voltage (up to 1000 V), PVC and any plastic insulators are sufficient.
- High voltage (up to 11 KV), XLPE and rubber insulators are sufficient.
- Super voltage (up to 33 KV), oil-paper and EPDM insulator are sufficient.
- Ultra high voltage cable (more than 33 KV), silicon and ceramic insulators are sufficient.

Cables have to withstand temperature extremes in different applications such as: electronic devices, food and ice-cream machines, heaters, ovens and industrial process equipment. These applications can subject the cable to continuous-use temperatures as low as −30°C and as high as 200°C. Each type of insulation is assigned for a certain operating temperature or the maximum temperature reached by the wire. The following table gives the limit or maximum operating temperature for each type of insulation.

Table (4.5) Maximum operating temperature for several insulators

Material	Maximum operating temperature (^oC)
PVC, PP	80
HDPE, LDPE, PA	90
Butyl Rubber, neoprene	100
EPDM	150
Silicone-based rubber	180
PTFE	200
Fiberglass	400
Ceramics	>1000

Insulation thickness for underground cables: the conductor should be provided by a suitable thickness of insulation material to prevent current leakage. Consider a single-core cable of conductor radius (r_1), total radius with insulation (r_2), cable length (L) and insulation resistivity (ρ). Note that the path of electrical leakage is radial from the center to the surface Therefore, the resistance of a portion of insulating material is:



$$R = \int_{r1}^{r2} \rho \, \frac{\text{Length}}{\text{Area}}$$

$$R = \int_{r1}^{r2} \rho \, \frac{dr}{2\pi\, r\, L}$$

$$R = \frac{\rho}{2\pi\, L} \ln(\frac{r_2}{r_1})$$

Where, the insulation resistance should be between 100-500 MΩ for high working currents.

Example (1): A single-core cable has a conductor diameter of 1 cm and 2 km length. Find the thickness of insulation required. Use a rubber with resistivity of 5×10^{12} Ω.m and insulation resistance of 234 M Ω.

Solution:

$$R = \frac{\rho}{2\pi\, L} \ln(\frac{r_2}{r_1})$$

$$234 \times 10^6 = \frac{5 \times 10^{12}}{2\pi \times 2000} \ln(\frac{r_2}{r_1})$$

$r_2/r_1 = 1.8$

$r_2 = 1.8 \times r_1 = 1.8 \times (1/2) = 0.9$ cm

Thickness of insulation = $r_2 - r_1 = 0.9 - 0.5 = 0.4$ cm

Insulation thickness for simple wires: usually a standard wire gauge table is used for localized wires conjugated with a simple formula according to certain code. However, this formula offers minimum insulation thickness for wires. For household applications, the insulation needs to be much thicker to protect against any leakage or breakage due to sharp objects, bending and abrasion. So, the wires in the home should have an insulation thickness many times greater than the minimum calculated value.

Table (4.6) Standard wire gauges

Max Current [Amperes]	Area [mm^2]	AWG
302	107	0000 (4/0)
239	85	000 (3/0)
190	67.4	00 (2/0)
150	53.5	0 (1/0)
119	42.4	1
94	33.6	2
75	26.7	3
60	21.2	4
47	16.8	5
37	13.3	6
30	10.5	7
24	8.37	8
19	6.63	9
15	5.26	10
12	4.17	11
9.3	3.31	12
7.4	2.62	13
5.9	2.08	14
4.7	1.65	15
3.7	1.31	16
2.9	1.04	17
2.3	0.823	18
1.8	0.653	19
1.5	0.518	20
1.2	0.41	21
0.92	0.326	22
0.729	0.258	23
0.577	0.205	24
0.457	0.162	25
0.361	0.129	26
0.288	0.102	27

Example (2): A copper wire assigned to withstand maximum of (220 V & 12 A) single phase application. Determine critical radius of the conductor as well as the thickness of the insulation. Use the table below and the formula:

$$t = r\,[\exp(V\,F\,/\,r\,E) - 1]$$

Where E is the dielectric strength and F is the safety factor (10)

Solution:

From the table, at 12 A: $A_{wire} = 4.17\ mm^2 = \pi r^2$

r = 1.15 mm radius of conductor

For such simple application wire, PVC insulation is suitable; with a dielectric strength of about 14 MV/m.

t = r [exp(V F / r E) - 1]

$t = 1.15\,[\exp(220x10 / 0.643x10^{-3} \text{ x } 14x10^{6})-1] = 0.32$ mm thickness of insulation

4.5.2 Overhead Transmission Lines

The transmission towers must be equipped with appropriate electrical insulators; at the points of installing the transmission lines, to prevent the leakage of electric power from the high voltage lines to the ground. The requirements for electrical insulation:

- Mechanical strength to withstand the expected stresses.
- Insulation quality under the worst environmental conditions.
- Completely free of impurities and pores.
- Resistant to internal puncture and flashover.

Figure (4.7) Overhead transmission lines

The insulation has two basic functions:

1- Electrical function: it provides full electrical insulation between electrical conductors and towers.

2 - Mechanical function: hanging the electrical lines, bearing mechanical forces and in all expected weather conditions.

Overhead lines usually deal with many types of insulators, such as:

a. Porcelain insulators: these insulators have high electrical insulation. Porcelain is produced by firing, at high temperature, some mixtures such as: kaolin, feldspar and quartz. The material withstands high temperature and high strength, where the dielectric strength of this material reaches 60 kV/cm and the tensile force is 500 kg/cm^2. The porcelain insulator could be found in forms of pin and long rod.

b. Glass insulators: glass insulators are made of silicon and have high dielectric strength up to 140 kV/cm. Glass is characterized as transparent, which has many advantages like the possibility to notice any impurities or cracks and do not heat too much when exposes to sunlight. While, the disadvantage is that glass suffers of condensation thus limitation of using in wet areas. Glass insulation is found in form of pin only.

c. Plastic and rubber insulators: these insulators are made of composite plastics and rubbers. They have limited dielectric strength but characterized by light weight as (1/30) compared to the porcelain type. The other advantages are: the reduction of pollution, and easily installation on the towers. On the other hand, their prices are still high. These insulators are found in form of long rod only.

Figure (4.8) Materials of insulators used for overhead lines

There are several types of insulation discs could be used for overhead lines.

1. **Pin type**: this type is supported on a forged steel pin which is secured to the cross arm of the supporting structure. Pin type could be used with maximum voltage of 33 kV.
2. **Suspension type**: a suspension insulator consists of a number of separate insulator disc units connected with each other by metal lines to form a flexible string or chain. This type could be used with voltage higher than 33 kV, and can withstand 1800 kg tension force.

3. **Strain (tension) type**: strain or tension insulators are design for handling mechanical stresses at angle positions where there is a change in the direction of the line or at termination of the lines.

4. **Long rod type**: it is made of porcelain or rubber and used when the voltage is very high. The length of the chain may be more than one meter.

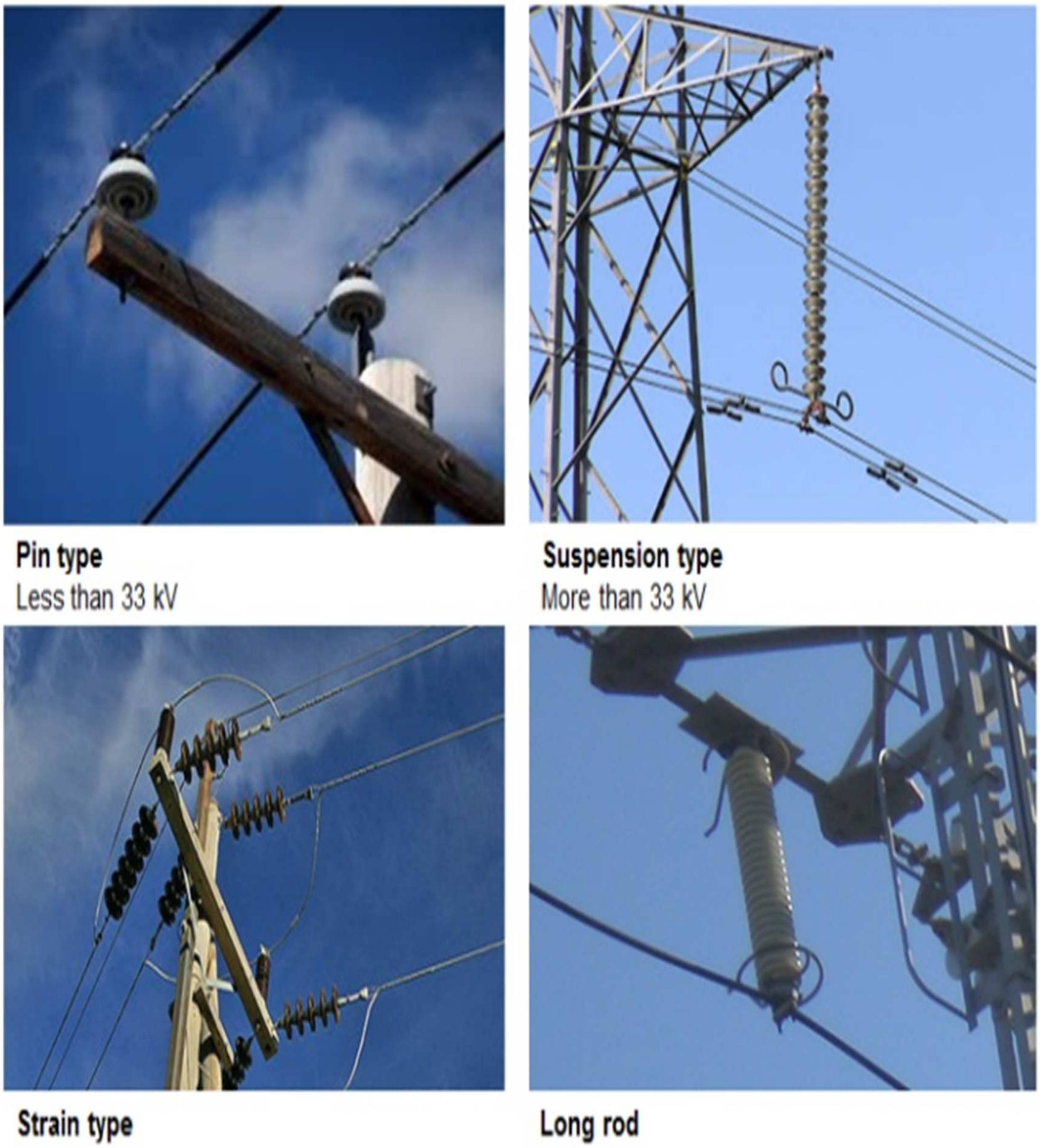


Figure (4.9) Types of discs

Shapes of discs according to the usage are:
1. Standard insulation: It is used in low-pollution areas. The lower surface of the insulator is designed with a few turnings.
2. Anti-Pollution: It is suitable for high pollution areas, which contributes to reduce pollution by increasing creepage distance without increasing the length of the chain.
3. Anti-fog: Used in areas where there is active fog where there are many turnings to increase the condensation.
4. Desert: It is used in desert areas where the surface of the insulator is open and flat to prevent accumulation of dust on it.

Figure (4.10) Shapes of discs

The selection of insulation discs depends on the working voltage and distance operated. Electricity is transferred through power lines from the generating station to the distribution station. For the purpose of reducing power loss, the voltage is raised to the highest value using the transformer. The standard voltages for long-distance transmission lines are from 11 kV to 400 kV. Therefore the number of insulating discs (insulation series) must meet the balance between electrical insulation and mechanical failure opportunities as well as the cost of insulation. Each material has a table showing the optimal number for certain conditions.

Table (4.7) Working voltage of overhead transmission lines for different distances

Distance (KM)	No. of Phases	Standard working voltage (KV)
Upto 8	3	6.6
Upto 16	3	11
Upto 64	3	33
Upto 116	3	66
Upto 240	3	132
Upto 480	3	220
Upto 800	3	400

- The minimum number of discs per suspension string for 400KV, 220 KV, 132 KV, 66 KV and 33 KV shall be 24, 15, 10, 5 and 3 respectively.
- For typical systems, this would be:

  11 Kv: 1 disc

  Up to 33 KV: 2-3 discs

  Up to 69 KV: 4-6 discs

  Up to 115 KV: 7-9 discs

  Up to 138 KV: 10-12 discs

  Up to 230 KV: 13-18 discs

  Up to 345 KV: 19-23 discs

  Up to 500 KV: 24-28 discs

Example (3):

Calculate the number of insulated discs per suspension string required to overcome working voltage of overhead lines between Baghdad and Kirkuk (280 km) in a wet region, where (SF = 2.5). Use the table.

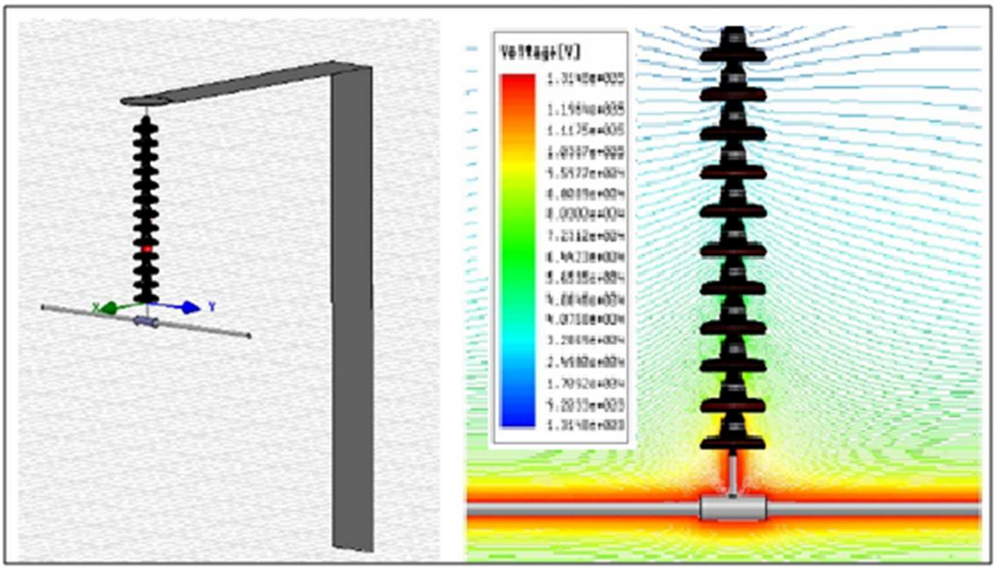
No. of units (Disc)	Power frequency withstand voltage	
	Dry KV(rms)	Wet KV(rms)
1	78	45
2	135	80
3	185	115
4	235	150
5	275	185
6	315	225
7	365	260
8	415	295
9	455	330
10	495	360
11	530	395
12	580	440
14	630	480
15	680	530
16	730	580

Solution:

From distance table, working voltage = 220 KV

Safety voltage = 220 x 2.5 = 550 KV

So, from the table, No. of discs = 16



Distribution of electrical voltage on the insulation discs: Let us assume that there is a series of five-disc insulators, as shown in the figure below, where each insulator is considered as a capacitor of capacity (C) and a further capacitor is considered between the hanging metal and the tower of capacity (C1), as shown below:

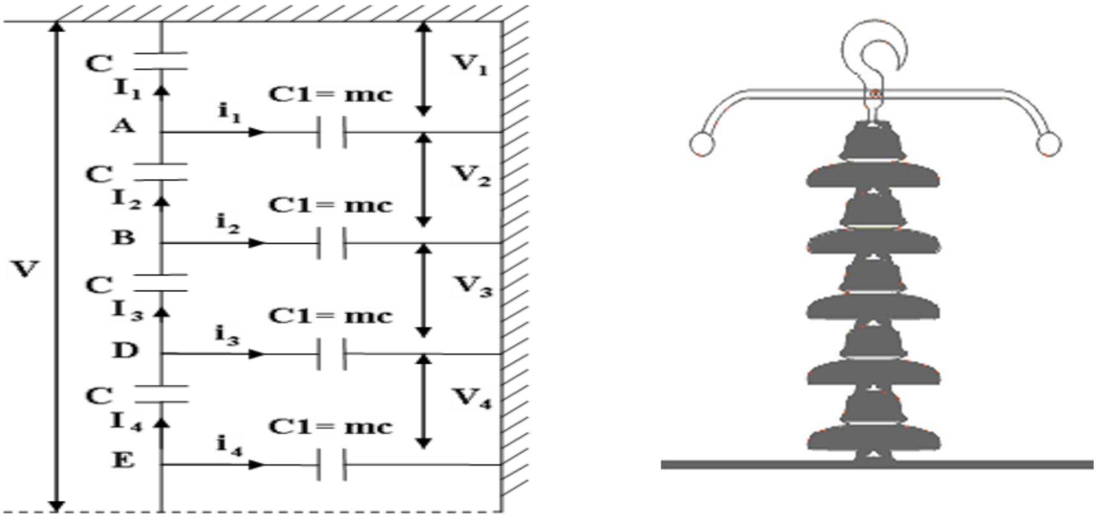


Figure (4.11) Distribution of electrical voltage on the discs

From Kirchhoff's circuit law;

$V2 = V1\ (1 + m)$ ------------- (1)

$V3 = V1\ (1 + 3m + m^2)$ ------------- (2)

$V4 = V1\ (1 + 6m + 5m^2 + m^3)$ ------------- (3)

$V5 = V1(1 + 10m + 15m^2 + 7m^3 + m^4)$ ------------- (4)

It is clear that the disk connected to the electrical line has a higher voltage than the voltage on the next dish. This behavior is similar for upper discs until reducing the voltage on the tower arm disc to zero.

$V = V1 + V2 + V3 + V4 + V5$ ------------- (5)

$V = V1\ (5 + 20m + 21m^2 + 8m^3 + m^4)$ ------------- (6)

Note that (V) is the potential difference of the phase, while the potential difference of the line is ($V_{line} = 1.732$ V).

Example (4): A 3-phase power transmission line installed on a tower using a series of five discs. Find the voltage on each disc if (m = 0.1).

Solution:

$$V = V_1(5 + 20m + 21m^2 + 8m^3 + m^4)$$
$$V = V_1(5 + 20(0.1) + 21(0.1)^2 + 8(0.1)^3) + (0.1)^4)$$
$$V = V_1(5 + 2 + 0.21 + 8 \times 10^{-3} + 1 \times 10^{-4})$$
$$\therefore V = V_1\,(7.2181)$$
$$\therefore V_1 = 0.1386\,V$$
$$V_2 = V_1(1 + m)$$
$$V_2 = 0.1386\,(1 + 0.1)\;V$$
$$V_2 = 0.1386\, \times 1.1\;\;V$$
$$\therefore V_2 = 0.15246\,V$$
$$V_3 = V_1(1 + 3m + m^2)$$
$$V_3 = 0.1386\,(1 + 3(0.1) + (0.1)^2)\;V$$
$$V_3 = 0.1386 \times 1.31\;\;V$$
$$\therefore V_3 = 0.1815\,V$$
$$V_4 = V_1(1 + 6m + 5m^2 + m^3)$$
$$V_4 = 0.1386(1 + 6(0.1) + 5(0.1)^2 + (0.1)^3)\;V$$
$$V_4 = 0.1386 \times 1.651\;\;V$$
$$\therefore V_4 = 0.2288\,V$$
$$V_5 = V_1(1 + 10m + 15m^2 + 7m^3 + m^4)$$
$$V_5 = 0.1386(1 + 10(0.1) + 15(0.1)^2 + 7(0.1)^3 + (0.1)^4)\;\;V$$
$$V_5 = 0.1386 \times 2.1571\;\;V$$
$$\therefore V_5 = 0.2987\,V$$

4.5.3 Transformers

Insulating oils are used in transformers and some electrical equipment. These oils have two primary functions: electrical insulation and cooling. In order to be effective, Oil must have low viscosity and high resistance against oxidation and impurities. Transformer oil is usually a bright yellow liquid with a density of about 0.88 mm / cm^3 at 15° C and its cooling value is 11 times greater than that of air, and its volume expansion coefficient is 0.00075 cm^3 / cm^3.

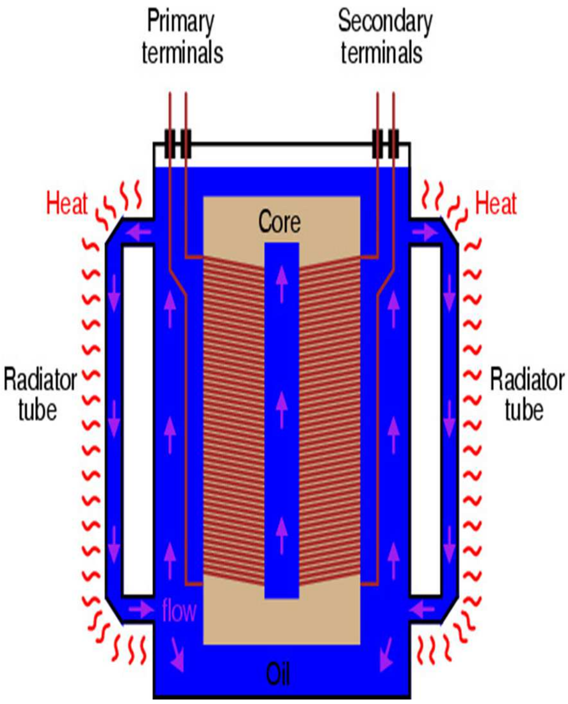


Figure (4.12) Electrical transformer

Characteristics of insulating oil:

1. Dielectric Strength: The oil used for 11 kV should have dielectric strength of 30 kV / 2.5 mm at least and for 66 kV should be at least 50 kV / 2.5 mm.

2. Viscosity: The lower the oil viscosity the better heat transfer from the heart of the transformer to the outside, but should not be too much liquidity because the oil vapor is flammable if exposed to any flame. The maximum evaporation rate is 1.6% for eight hours of work.

3. Flash point: The temperature at which the oil vapor ignites when exposed to flame. The British specifications set the minimum temperature of 145 °C.

4. Density: The density should not exceed 0.895 g/cm^3 at 20 °C.

5. Oxidization: The oxidation of oil causes a deposition that inhibits the cooling process. The oil is tested at 120 °C and for 75 hours with copper as a catalyst. The acceptable percentage of deposition is (0.4mg.KOH/g) which is approximately 1% deposition. The neutral volume can be measured by dissolving the oil with a mixture of methanol and toluene. The acceptable neutral volume is 0.03 mg/kOH/g. The oil should be free of sulfur.

6. Water content: water affects oil solubility and leads to pollutants and oxidation. Water content shall not exceed 40 ppm.

4.5.4 Powder Coating

Powder coating technology is recognized as a superior method of applying a protective finish on numerous shapes and sizes, as opposed to wet applications. One approach that is effectively used as a high dielectric insulator on copper or aluminum conductors is epoxy powder coating. It is used to ensure consistent insulation barrier due to its durability. The surface should be clean and dry prior to the powder application.

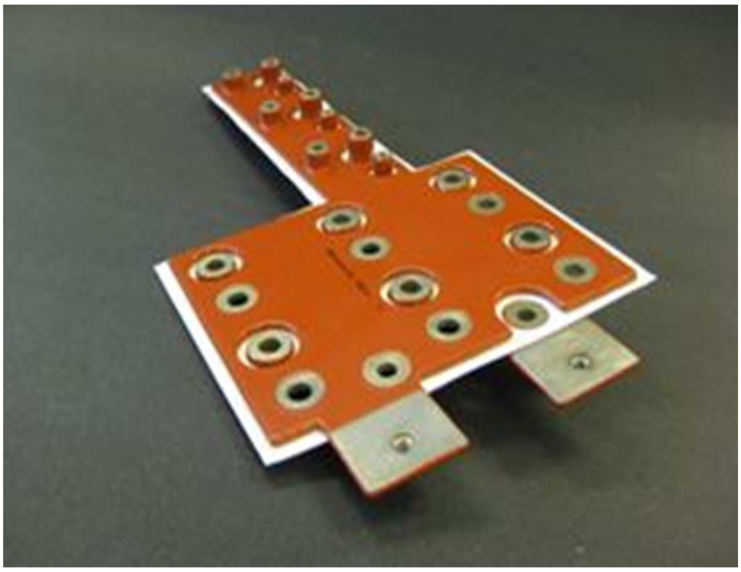


Figure (4.13) Electrical board coated by epoxy

4.5.5 Insulating Varnishes

Organic varnishes and solvent-less resins are widely used for motor winding because they offer:

- Dielectric insulation.

- Bonding to the winding wire.

- Protection against moisture and corrosion.

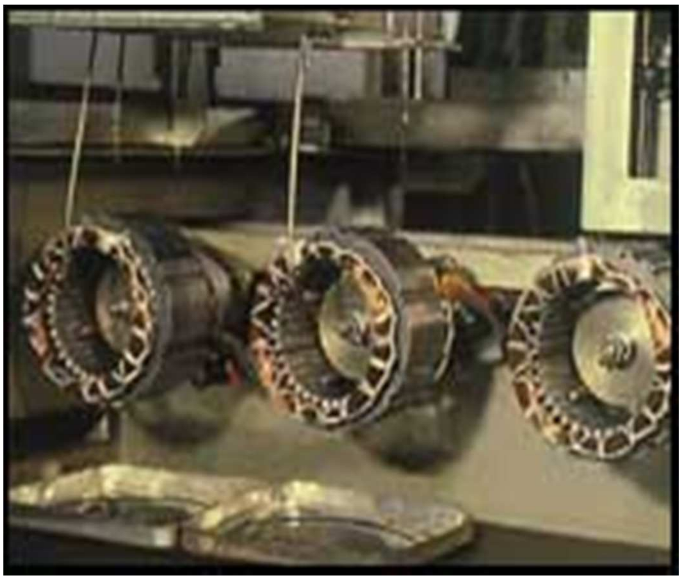


Figure (4.14) Electrical motors insulated by varnish

4.6 Applications of Dielectric Materials for Energy Storage

A major use of dielectrics is in fabricating capacitors. These have many uses including storage of energy in the electric field between the plates, piezoelectricity, filtering out noise from signals as part of a resonant circuit, and supplying a burst of power to another component.

4.6.1 Capacitors

A capacitor is a passive two-terminal electrical component used to store electrical energy in the form of an electrostatic field. It consisting from two electrical conductors (plates) separated by a dielectric material that can store energy by polarization. The conductors are metal foils or conductive electrolyte. A dielectric could be glass, ceramic, plastic film, air, vacuum, paper, mica or oxide layer.

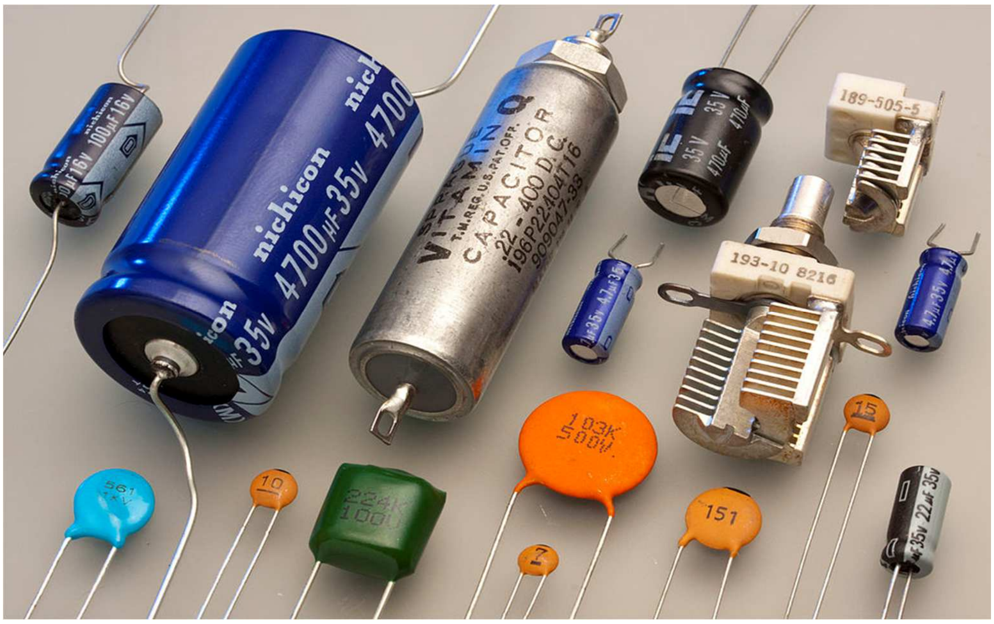
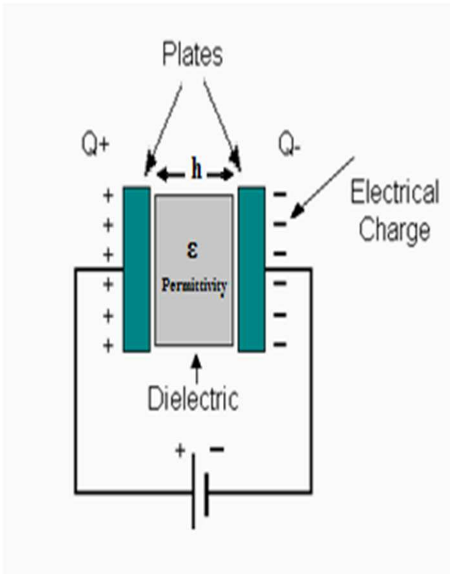


Figure (4.15) Electrical capacitors

There two common types of capacitors are:

a. Parallel Plates

The formula of capacitance (C) for parallel plates capacitor of a gap distance (h) can be derived as following;



$C = Q / V$

Where:

Q = Electric charge (coulomb)

$V = D\,h / \varepsilon$ (voltage for parallel plates)

So,

$C = Q\,\varepsilon / D\,h$

But,

$D = Q / A$ (density of field in coulomb/m^2)

Thus,

$C = A\,\varepsilon / h$

Example (5): It is required to manufacture a capacitor of $17x10^{-9}$ coulomb/m^2 field density under 2.4 V between plates of 1 cm x 2 cm area and spaced 3 mm apart. Select a proper dielectric material for this capacitor.

Solution:

V = D h / ε

or

ε = D h / V

= $17x10^{-9}$ x 3 $x10^{-3}$ / 2.4

= 21.25 $x10^{-12}$ F/m

εr = ε / εo

= 21.25 $x10^{-12}$ / 8.85×10^{-12} = 2.4

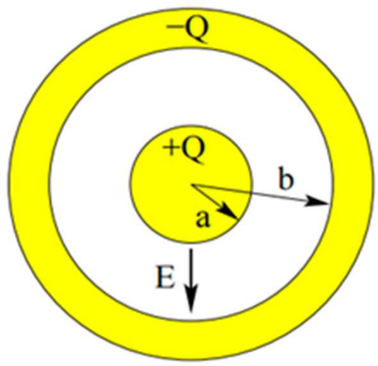
From permittivity table, the dielectric material is polystyrene.

Material	Dielectric constant
Vacuum	1.0
Air	1.0006
Conductive polymers	2-12
Wood	2-6
PTFE/Teflon	2.1
Polypropylene	2.2-2.36
Polyethylene	2.25
Polystyrene	2.4-2.7
Carbon disulfide	2.6
Polyimide	3.4
Silicon dioxide	3.9
FR-4	4.0
Concrete	4.5
Pyrex	4.7

b. Cylindrical

The formula of capacitance (C) for cylindrical capacitor of a length (L) can be derived as following;

C = Q / V



Where:

$$V\,(r) = \int_a^b \frac{Q}{2\pi\epsilon L}\,\frac{dr}{r}$$ (voltage for cylindrical)

$$V = \frac{Q}{2\pi\epsilon L}\ln(b/a)$$

Thus,

$$C = \frac{2\pi\epsilon L}{\ln(b/a)}$$

4.6.2 Piezoelectric Materials

Piezoelectricity is the appearance of electrical voltage across the sides of a material (such as crystal, ceramic and polymer) when it subjected to a mechanical stress, due to the change of polarization. The potential difference (V) generated in a piezoelectric material by the applied force (F) could be expressed by:

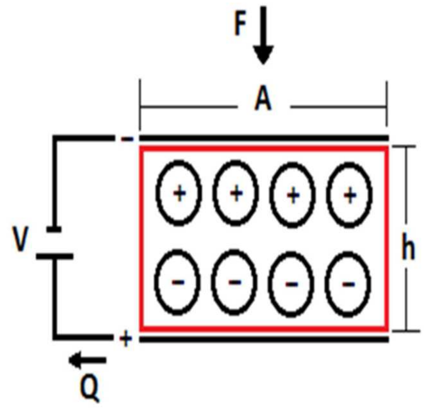
$V = (F/A)\ h\ G$

Where,

A = Subject area (m^2)

h = Thickness (m)

G = Axial piezoelectric voltage coefficient (Vm/N)



Ferroelectric materials: some piezoelectric materials show a spontaneous polarization without mechanical stress due to a non-vanishing electric dipole moment associated with their unit cell. If the dipole moment can be reversed by the application of an electric field, the material is said to be ferroelectric, such as PZT, $BaTiO_3$ and $PbTiO_3$. All ferroelectric materials are piezoelectric, however, not all piezoelectric materials are ferroelectric. Ferroelectric materials have many properties and they are widely used in many applications. These include:

- ferroelectric hysteresis (used in nonvolatile memories)
- high permittivity (used in capacitors)
- high piezoelectric effects (used in sensors, actuators and resonant devices)
- high pyroelectric coefficients (used in infra-red detectors)
- strong electro-optic effects (used in optical switches)
- anomalous temperature coefficients of resistivity (used in electric-motor overload-protection circuits).

Pyroelectric materials: those materials that generate a temporary voltage when they are heated or cooled, such as: most of piezoelectric materials and all of ferroelectric materials. However, not all pyroelectric materials are ferroelectric. Where, at a temperature T > Tc (Curie point), the crystal does not exhibit ferroelectricity, while for T < Tc it is ferroelectric.

Example (6): A piezoelectric ceramic material is used in sport shoes to produce electricity. The material has 35 mm diameter and 0.6 mm thickness. The weight of the human body is assumed as 70 kg. By neglecting the planar polarization, calculate the generated voltage and energy. Note: $\varepsilon r = 2250$, $G = 22.5\text{x}10^{-3}$ V.m/N.

Solution:

$A = \pi / 4 * (0.035)^2 = 9.62\text{x}10^{-4}\ m^2$

$F = 70 * 9.81 = 686.7$ N

$V = (F / A)\ h\ G = (686.7 / 9.62\text{x}10^{-4}) * (0.6\text{x}10^{-3}) * (22.5\text{x}10^{-3}) = 9.64$ v

$\varepsilon = \varepsilon r \text{ x } \varepsilon o = 2250 * 8.85\text{x}10^{-12} = 2\text{x}10^{-8}$ F/m

$C = \varepsilon\ A / h = (2\text{x}10^{-8}) * (9.62\text{x}10^{-4}) / 0.6\text{x}10^{-3} = 3.2\text{x}10^{-8}$ F

$E = 0.5\ C\ V^2 = 0.5 * (3.2\text{x}10^{-8}) * (9.64)^2 = 148.7\text{x}10^{-8}$ J

Exercises No. (4)

Q1) Complete the following sentences:

1. The separation between electrical charges in electrical insulator generates the so-called -----------.

2. An effective electrical insulator that is used as a powder coating on metallic surfaces is -----------.

3. A capacitor usually consists of two electrical plates separated by ------------ to store energy.

4. The dielectric material that commonly used for primary wiring insulation is ----------.

5. The dielectric material that commonly used for sockets and switches is ----------.

6. The dielectric material that commonly used in the transformers is ---------.

7. OPL discs have two functions: electrically as insulators and -------- as supporters.

8. For the first or the last OPL tower, ---------- type arrangement should be used for insulating discs.

9. The materials that commonly used for piezoelectricity are ----------.

Q2) Select the correct answer:

1. Which type of insulator is used on 132 kV transmission lines?
   A. Pin type
   B. Shackle type
   C. Discs type
   D. Strain type
2. Porcelain is produced by firing at high temperature of which of these mixtures?
   A. Kaolin
   B. Feldspar
   C. Quartz
   D. All of these
3. What is the dielectric strength of porcelain?
   A. 55 kV/cm
   B. 60 kV/cm
   C. 75 kV/cm
   D. 80 kV/cm
4. Where is the strain type of insulators used?
   A. Low voltage overhead lines
   B. Dead ends
   C. Change in direction of the transmission lines
   D. Both (B) and (C)

5. Strain type insulator is similar to which type of these insulators?
   A. Pin type
   B. Shackle type
   C. Suspension type
   D. Long rod type
6. Which type of insulators is mainly used for low voltage overhead lines?
   A. Pin type
   B. Strain type
   C. Suspension type
   D. Long rod type
7. What is the maximum voltage which the pin type insulator can be used with?
   A. 22 kV
   B. 33 kV
   C. 66 kV
   D. 132 kV

Q3) What are the properties of dielectric materials.

Q4) What is the difference between dielectric constant and dielectric strength?

Q5) What is electrical susceptibility? Prove that x=0 for vacuum.

Q6) What are the layers usually used to insulate wires?

Q7) What are the main insulator types used for overhead transmission lines?

Q8) Compare between insulators for different OPL voltages.

Q9) What are piezoelectric materials, ferroelectric materials and pyroelectric materials?

Q10) Which one of these materials is the best dielectric, and why?

Material	Energy Gap (ev)
SiO_2	9.2
Al_2O_3	6.5
GaN	3.4

Q11) It is required to manufacture a capacitor of 14×10^{-9} coulomb/m^2 field density under 3 V between plates of 1 cm x 2 cm area and spaced 4 mm apart. Select (from the table) the proper dielectric material used for this capacitor. Then find the capacitance.

Material	ε_r
Vacuum	1.0
coal	1.5-2.0
PTFE/Teflon	2.1
Polypropylene	2.2-2.4
Polystyrene	2.4-2.6
Carbon disulfide	2.7

Q12) Calculate the number of insulated porcelain discs required to withstand the overhead lines between Baghdad and Kut (170 km). Use SF = 2.6

Distance (km)	No. of Phases	working voltage (KV)
Upto 8	3	6.6
Upto 16	3	11
Upto 64	3	33
Upto 116	3	66
Upto 240	3	132
Upto 480	3	220
Upto 800	3	400

No. of units (Disc)	Safely voltage (KV)		
	Glass	Porcelain	Polymer
1	78	45	35
2	135	80	65
3	185	115	95
4	235	150	100
5	275	185	125
6	315	225	185
7	365	260	235
8	415	295	265
9	455	330	315
10	495	360	330

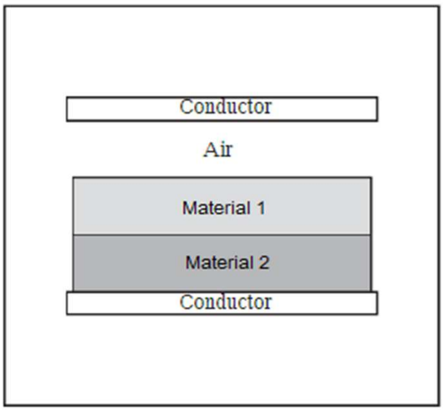
Q13) Calculate the number of insulated discs required to overcome working voltage of 66 KV in a dry region and determine the suitable insulation material if the safety factor is 2.9 and the length of each disc is 18 cm. Note: The total height of the discs should not exceed 100 cm.

No. of units (Disc)	Safely voltage (KV)		
	Glass	Porcelain	Polymer
1	78	45	35
2	115	80	65
3	145	115	95
4	185	150	100
5	255	185	125
6	315	225	185
7	365	260	235
8	415	295	265
9	455	330	315

Q14) A square parallel plate capacitor with plate area of 100 cm2 has plate separation of 3mm. The airspace between the plates is partially filled by two 1 mm thick dielectric slabs, as shown in the figure. One slab has a constant of 2.5 and the other slab has a constant of 4. Compute the capacitance of the system.

Note: for parallel slabs;

$$\epsilon = \frac{1}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}+1}$$



Q15) A single-core cable has a conductor diameter of 2.5 cm. Find the thickness of insulation required for kilometer length. Use a rubber with resistivity of $4.5\text{x}10^{12}$ Ω.m and insulation resistance of 495 M Ω.

Chapter Five

Radiation Insulation

Chapter Five
Radiation Insulation

5.1 Introduction to Radiation

It is known that various electromagnetic waves and particles emitted from radioactive sources have direct and indirect effects on living organisms, where many symptoms could be happened when expose to radiation more than allowed. Workers in nuclear facilities and X-ray labs exposed to the risk of external, which affects the face, hands or internal exposure due to the entry of radioactive particles into the body through breathing and food. To avoid the radiation risk in this area it is necessary to know the nature of radiation and methods of isolating and comply with the instructions for the prevention of it as mentioned in this chapter.

5.2 Definition of Radiation

Radiation is an energy released as electromagnetic waves and has many forms, such as: light, ultraviolet and infrared or small particles from radioactive materials like alpha, beta and gamma. The source of this radiation is universe, sun, nuclear reactors, industrial and laboratory applications. Some substances found in the earth are also characterized by radiation. There is a little radioactivity within the body. Electromagnetic waves consist of photons; shortest waves are gamma rays while the longest are radio waves.

5.3 Classification of Radiation

Radiation could be classified according to its danger as following:

1. Non-Ionizing Radiation: Examples of this radiation light, infrared, ultraviolet and radio waves. This type of radiation is safe usually.

2. Ionizing Radiation: Such as cosmic rays, gamma rays, alpha particles and beta particles. It is dangerous because of its ability of ionizing.

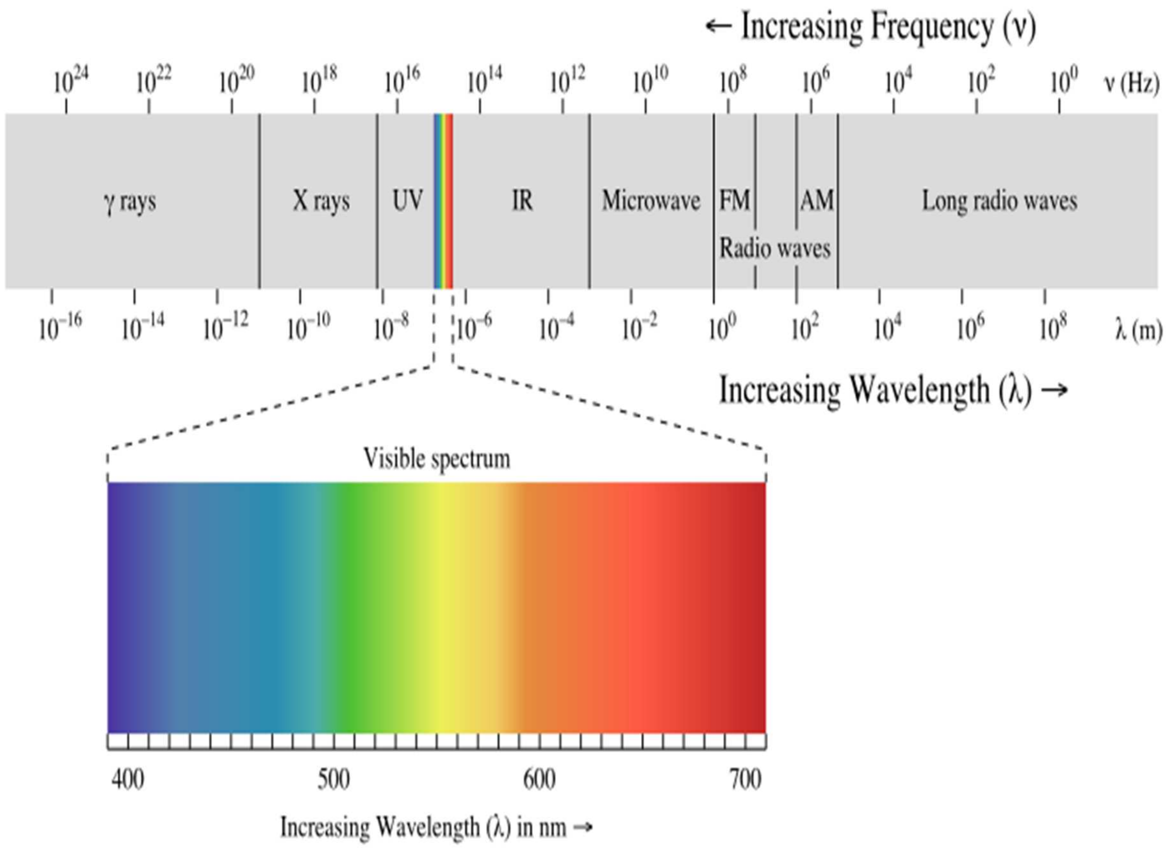


Figure (5.1) Electromagnetic waves

5.4 Non-Ionizing Radiation

The sources of these rays are sun or industrial applications. These rays are not inherently dangerous, but when prolonged exposure to it has caused cases of discomfort or headaches queasiness or dryness of hair and sometimes minor skin burns. Clothes, sunglasses and shading protect us from these rays. The forms of non-ionizing radiation are:

1. **Light (visible spectrum):** it is a very useful radiation. It provides the light and control many biological functions such as: strengthen of bone tissue, maintain the blood pressure, diabetes level, cholesterol level and psychological comfortable. It has a big role in the growth of plants by photosynthesis.

2. **Infrared:** it is very useful where provides the warmth and used for many applications like: night vision, short-range wireless communications and remote sensing.

3. **Ultraviolet:** it is a useful radiation except one band of it. These rays help to provide the body with vitamin (D). There are many application of UV like: water and medical sterilization, reducing the yellowing with newborns. The long exposure to UV harms the skin and the eye. It is worth to refer that that these rays are the cause of damaging plastics and insulating polymeric materials because of their ability to destroy the chemical bonds.

4. **Radio waves:** such as the broadcasting of radio, television, telecommunications and microwave wavelengths. Despite the benefits of these rays in the transfer of information, they have some harmful effects on humans, especially on the nervous side and the senses.

5.5 Ionizing Radiation

It includes rays or particles come from the sun, the universe or radioactive elements (such as radium, uranium, plutonium, thorium, iodine, potassium, zircon, phosphor and radon). The radiation that is emitted from these sources could ionize the medium, which means detaching the electrons from atoms. The forms of ionizing radiation are:

1. Alpha particles: alpha particle is emitted from the nucleus during the decay. It consists of two protons and two neutrons (i.e. similar to the nucleus of the helium atom) so alpha has positive electrical charge. These particles lose energy quickly as soon as leaving the radioactive element. Hence, the penetration of alpha particles to the skin is weak, and it could be blocked by a thick paper. The risk of alpha particles appeared when enter to the internal parts of the body by breathing, eating or wounding.

2. Beta particles: These particles are emitted from the nucleus during the decay. It is noticing, during the breakdown of neutrons, that beta particles may be produced either as electrons (negative charge) or as positrons (positive charge), or in sometimes whole neutrons are emitted to the outside. Beta has more penetration force than alpha, and some beta particles can penetrate the skin and damage it. It also causes harmful effects if entered to the body. Beta radiation could be blocked by a piece of wood or a layer of aluminum (10-20 mm).

3. Gamma rays: This type of radiation represents the energy generated by the disintegration that is occurred within the nucleus. The emission of alpha and beta particles pushes the nucleus to the stability phase, hence emits energy (photons) out in the form of gamma rays. There is a kind of gamma rays called annihilation radiation which is produced from the combination of electrons and positrons. this radiation is one of the most dangerous types of radiation and has very high penetrating force, where it can easily penetrates the human body and absorbed by the tissues. It could be blocked by a barrier of concrete or a layer of lead (4-12 mm).

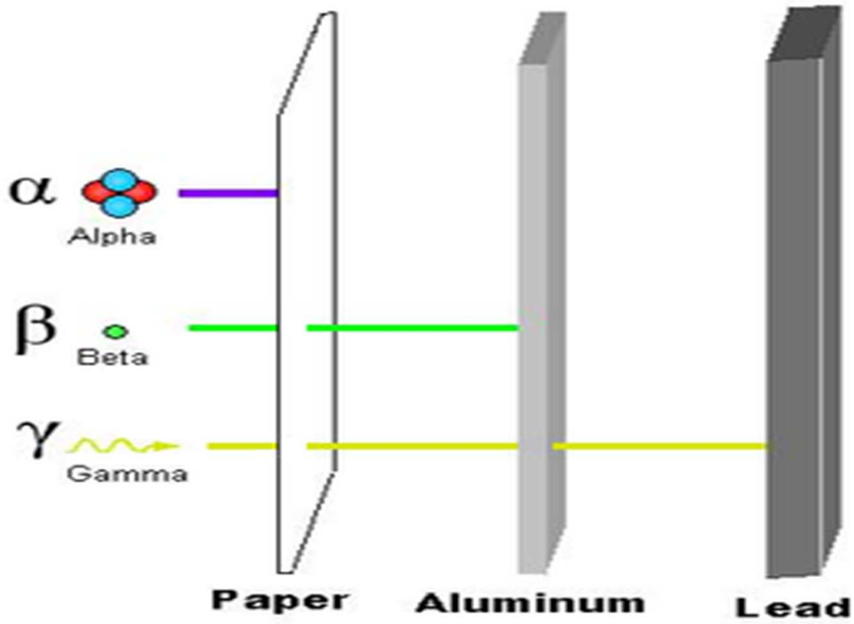


Figure (5.3) Shielding for some types of radiation

4. X-rays: These rays are similar to gamma rays in terms of features but differ in the source, where X-rays emitted from the outside of nucleus (transportation of electrons between the energy levels), while gamma rays are emitted from the inside of nucleus. Penetration force and permeability of these rays are less than that of gamma rays, where it could be blocked by a thin layer of lead (1-3 mm).

5. Cosmic rays: These are high-energy particles coming from the space. Mostly, this radiation is dissipated through the upper layers of the atmosphere, but a few percent in. This dangerous radiation could be blocked by a layer of composite materials or chemical compounds.

5.6 Radioactivity

Most of the chemical elements have the same number of neutrons and protons in the nucleus. In some elements the number of neutrons is greater than the number of protons, so that be unstable and called radioactive isotopes. These isotopes emit small particles from the nuclei such as alpha particles, beta particles and gamma rays. Over time, these elements are transformed into other elements less weight and have various chemical and physical characteristics. The emitted particles and rays are considered as ionizing radiation. The characteristics of radioactive isotopes depend on the type of radiation emitted, energy of radiation and its half-life.

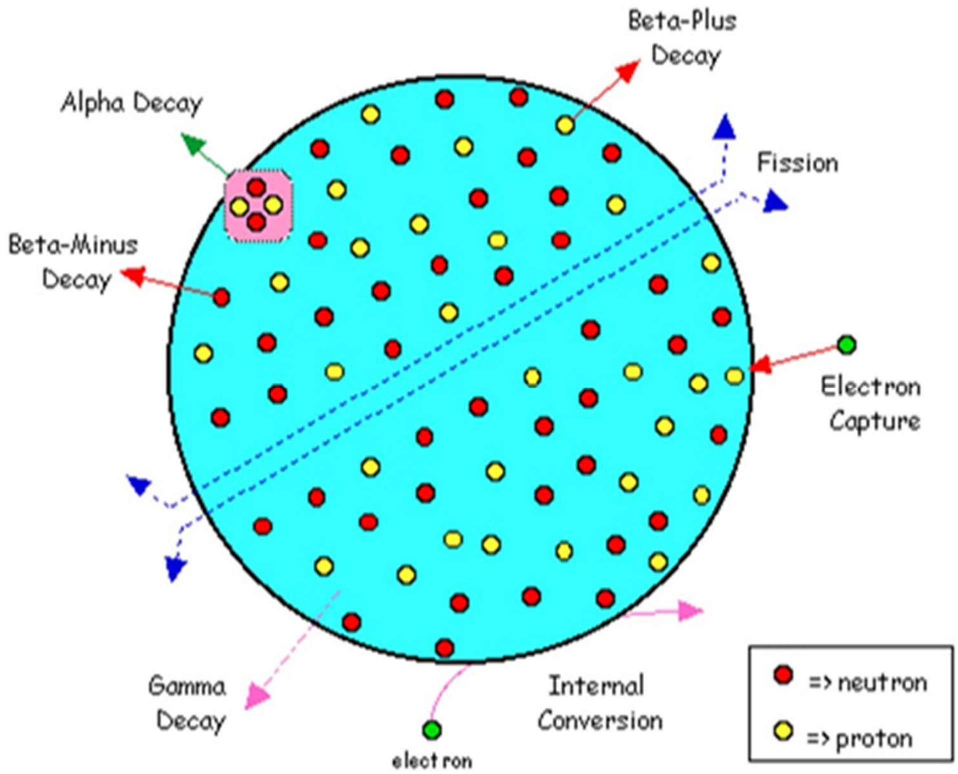


Figure (5.2) Disintegration of the radioactive isotope

Half-Life: It is the time needed to disintegrate half of atoms of a radioactive element, hence reducing the activity by half. For example, the half-life of (iodine -131) is 8 days while the half-life of (radium -226) is 1600 years.

5.7 Risks of Ionizing Radiation

The ionizing radiation could ionize the medium, which means detaching the electrons from atoms. The Ionizing of the constituent elements of the biological material of the recipient's body causes the increase or decrease in the size of the cell or fragmentation, hence the formation of toxic compounds that may move to other parts of the body, leading to serious damage. These effects are appeared either early or later in the form of symptoms or disease like cancerous diseases in addition to the hereditary effects of genetic influences. Workers in radiation facilities may get internal or external exposure. Internal exposure to ionizing radiation occurs when inhaling or swallowing radionuclides or entry into the bloodstream. External exposure occurs when radioactive materials attached to the skin. The type of damage is inflicted by the amount of radiation dose to the body according to the level of exposing. Usually the risks of radiation are: skin redness, burns, hair loss, syndrome of radiation, bleeding, infertility and cancer in some cases.

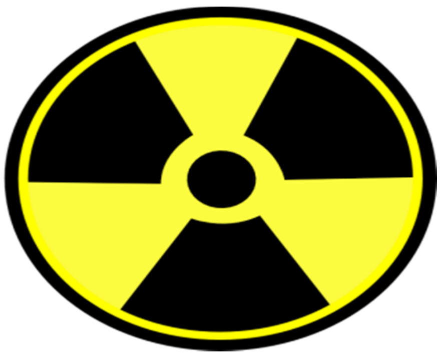


Figure (5.4) Warning sign for ionizing radiation

5.8 Radiation Measuring

Radiation intensity is measured in a unit called Sievert, denoted as (Sv) and consists of 100 Rem. Human may expose to a dose of radiation that is measured using an instrument called radiation meter, as shown in the figure, which often works within the limits (0.1 - 200 μSv/h).

Figure (5.5) Radiation meter

5.9 Means to Minimize the Risk of Radiation

Person who is working in the field of radiation may expose to a dose of radiation depending on the nature of the work. The commitment to the following aspects is very important to reduce the risk of radiation.

1. **Time of exposing**: radiation is less dangerous in the case of reducing the exposure time (time spent by the person beside the radiation source). The maximum exposure limit allowed to the human is (0.05 Sv/yr) according to the recommendations of international councils such as (ICRP) and (USNRC). In order to calculate the amount that is permitted to those working in the field of radiation, the exposure limit is divided by the total working time. Hence, for 8 hours and 360 days, the allowed limit is 17 µSv/h.
2. **Exposure distance:** the increasing of distance far from the radiation source will reduce the intensity of the radiation (inverse relationship) according to the inverse-square law as following:

   $$\mathbf{I_1\, L_1^2 = I_2\, L_2^2}$$

   Where:

   I = Intensity of radiation

   L= distance away from the source

3. **Shielding: r**adiation could be reduced using barriers consisting of metals or materials have the ability to either absorb the radiation and convert it to heat or reflect it. For each type of radiation there is appropriate barrier setting according to the intensity and the energy of radiation.

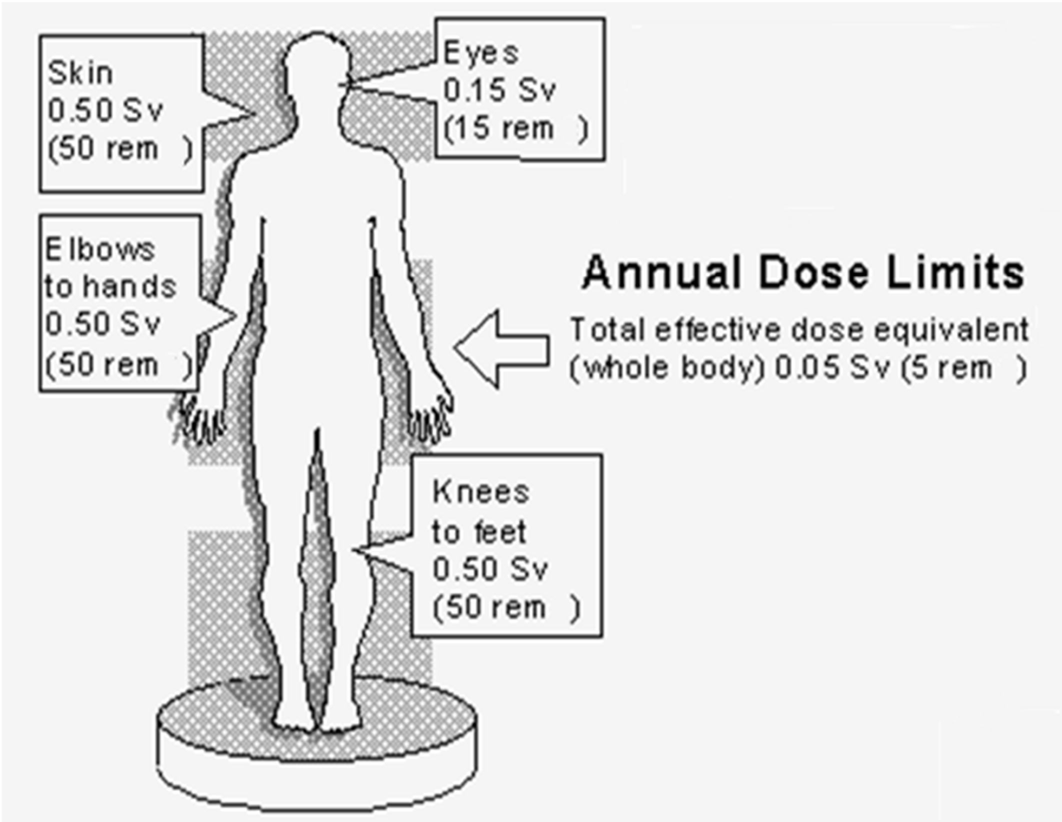


Figure (5.6) Exposure limits

5.10 Linear Attenuation Coefficient

Also called beam attenuation coefficient, is a characteristic indicates how easily a material can be penetrated by a beam (radiation) of electromagnetic waves or particles. A large attenuation coefficient means that the beam is quickly attenuated (weakened) as it passes through the medium, and a small attenuation coefficient means that the medium is relatively transparent to the beam. Simply, the linear attenuation coefficient is the susceptibility of a material to reduce the radiation. It has the symbol (μ) and has the unit (cm^{-1}). The following table shows the value of the linear attenuation coefficient for some materials.

Table (5.1) Attenuation coefficient in (cm^{-1}) for a range of gamma-rays

Material	Energy (keV)		
	100	200	500
Carbon	0.335	0.274	0.196
Aluminum	0.435	0.324	0.227
Iron	2.72	1.09	0.655
Copper	3.8	1.309	0.73
Lead	59.7	10.15	1.64

It is noticed that, the value of linear attenuation coefficient decreases with the increasing of radiation energy (eV) passing through the material, as shown in the figure below.

- More values for different elements are available on the site:

http://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html

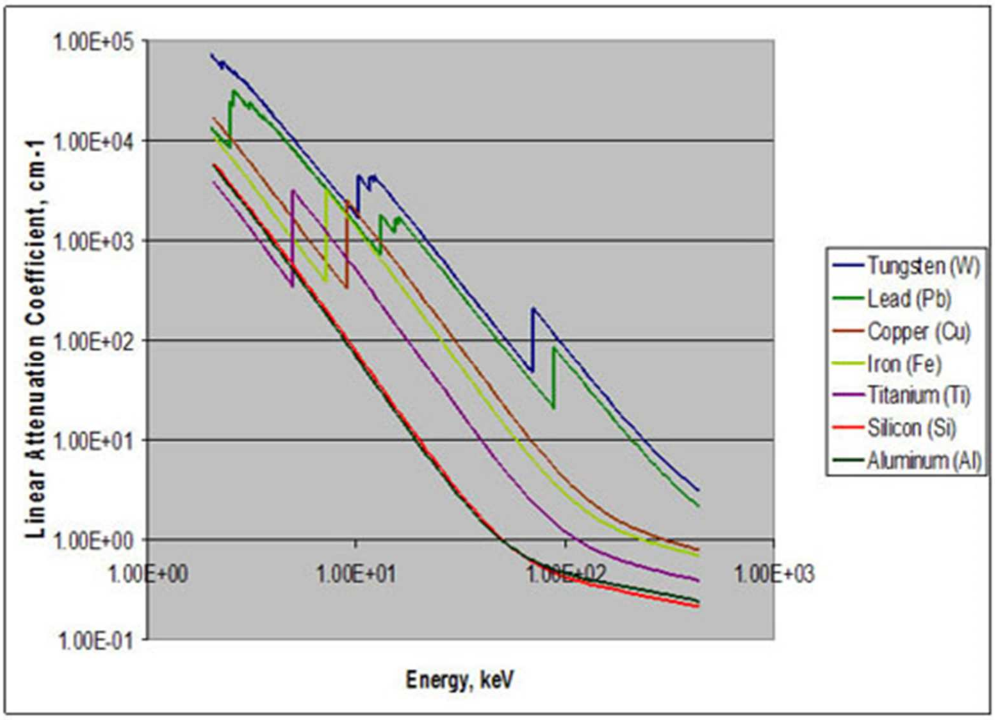


Figure (5.7) Values of linear attenuation coefficient of some materials

Half value layer: is the thickness of the material that satisfies half reduction of radiation (ie, attenuated by 50%). It is measured in centimeters and symbolized as (HVL). The following table shows some HVL for some elements.

Table (5.2) HVL in (cm) for a range of gamma-rays

Material	Energy (keV)		
	100	**200**	**500**
Carbon	2.07	2.53	3.54
Aluminum	1.59	2.14	3.05
Iron	0.26	0.64	1.06
Copper	0.18	0.53	0.95
Lead	0.012	0.068	0.42

5.11 Calculation of Radiation Attenuation

Beer-Lambert Law could be used to calculate the amount of attenuated radiation (gamma rays and rays) exit from the barrier, as following:

$$I = I_o\, e^{-\mu x}$$

Where;

I = radiation intensity behind the barrier

I_o = radiation intensity in front of the barrier

μ = linear attenuation coefficient

x = thickness of the barrier

<u>**Example (1):**</u> The intensity of 500 keV gamma-rays has measured at a zone and it was 25 μSv/h. What would be the intensity after using a shield of 8 mm lead. (μ=1.64 cm^{-1})

<u>**Solution:**</u>

$I = I_o\, e^{-\mu x}$ = 25 exp (-1.64*0.8) = 6.73 μSv/h

Since the intensity is less than 17 μSv/h, therefore it sounds good.

Example (2): Three materials: aluminum (8 cm), iron (4 cm) and lead (0.4 cm) have exposed to 18 µSv/h at 200 keV. Determine the best shield.

Solution:

$$I = I_0 e^{-\mu x}$$

Material	µ (cm^{-1})	Thickness (cm)	I (µSv/h)
Aluminum	0.324	8	1.35
Iron	1.09	4	0.23
Lead	10.15	0.4	0.31

In this case, iron has the minimum attenuation, so it is the best shield.

Example (3): What thickness of copper is required to reduce the radiation intensity by 10%. Assume 200 keV.

Solution:

From HVL table for copper at 200 keV:

HVL = 0.53 cm

HVL means reduction by 50% so,

%	X
50	0.53
10	?

X = 10 * 0.53 / 50 = 0.106 cm

Example (4): In the x-ray lab, a source of 60 keV radiates 1000 µSv (0.5 m beside the focal spot). What is the radiation intensity behind monitoring glass shielded by 1 mm tungsten (µ=58.5 cm^{-1}) at 2 m far from the source.

Solution:

$I_1 L_1^2 = I_2 L_2^2$

$1000 (0.5)^2 = I_2 (2)^2$

I_2 = 62.5 µSv radiation at 2 m

$I = I_0 e^{-\mu x}$ = 62.5 exp (-58.5*0.1) = 0.18 µSv behind the shield

5.12 Applications of Radiation Insulation

1. Nuclear power plant

The main part of the nuclear plant is the reactor which contains the units of nuclear fuel (uranium, thorium, plutonium or iodine). Since there are series of nuclear fissions, hence the reactor is surrounded by a thick wall of concrete and steel to retain high vapor pressure and to prevent radiation leakage (particles) to the outside. It should also cover the surfaces in direct contact with the nuclear explosions by a layer made of highly absorbent material to neutrons, such as cadmium alloy. The energy emitted (photon) is absorbed by the water which encloses the reactor. This energy leads to boil the water which is taken to the turbine to generate electricity.

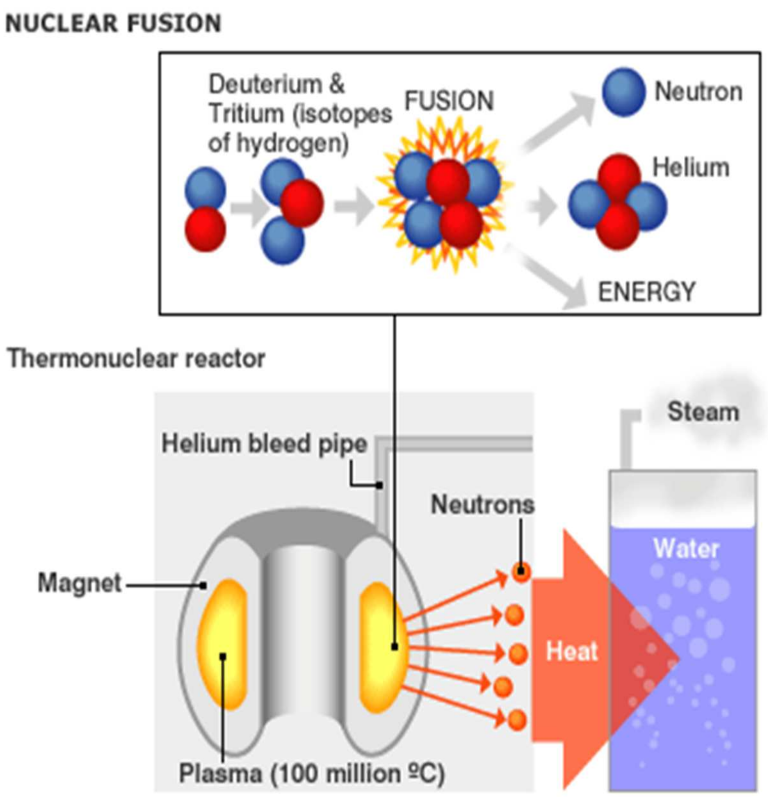


Figure (5.8) The fusion in nuclear power plants

2. Radioactive waste

It means the remnants of nuclear plants or it is related to chemical anti-armor weapons. The problem of radioactive waste emerged several decades ago, it was found that these materials remain effective and radiate particles that could be absorbed by nearby plants and insects and then transmit to humans and infect the internal parts. However, there are several ways to keep the danger of these substances, including:

a. Storing in plastic barrels into the ground and in the desert areas.

b. Storing in concrete tanks surrounded by salt or gypsum.

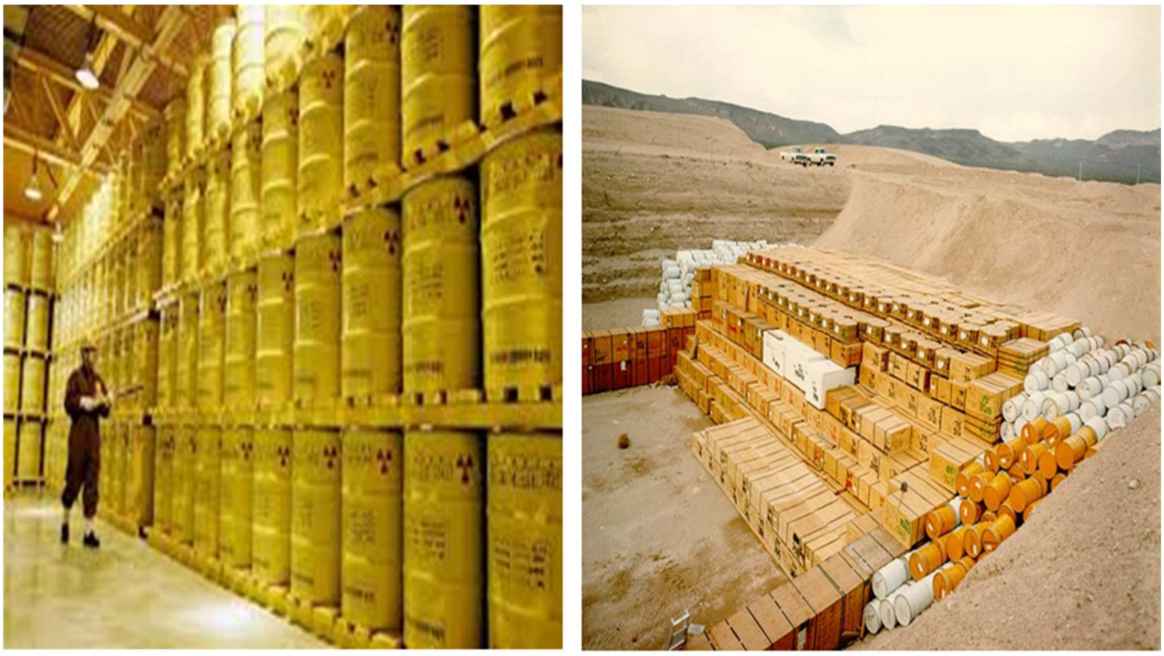


Figure (5.9) The storing of radioactive waste

3. X-ray lab

In hospitals, it should pay some attention to the X-ray lab. It should offer a private room for X-ray capturing without any internal windows. Wall should be built from brick or concrete, but if there is an internal separator, door or control window, then it should be isolated by a layer of lead (2 mm). X-ray tube should be placed at least half meter far from the body.

4. Airplane

Recently, the external parts of the aircraft are replaced by composite materials in order to reduce weight and cost. This procedure increases the risk of radiation because the attenuation coefficient of polymeric material is very weak. To process this problem, a deposition of a thin layer of lead is required, or intercalation small grains of absorbent materials (such as bromine) within the composite material.

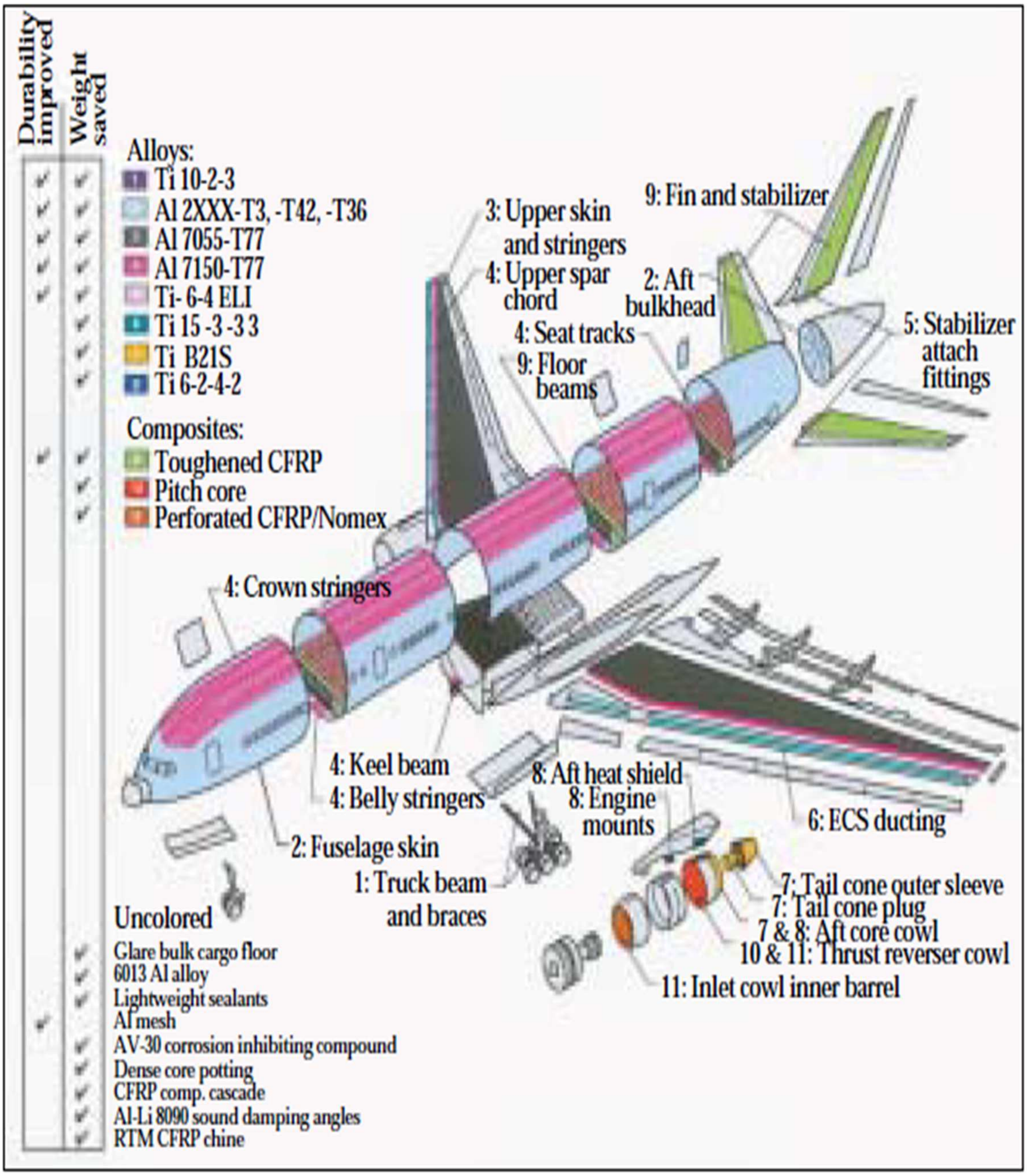


Figure (5.10) Materials used in airplane

5. Spacecraft

Spacecraft is exposed to high-energy gamma rays, cosmic rays and particles. So, it should use accurate shielding materials. External shells are covered by alloys of high z-materials such as: lead, tungsten, gold, vanadium and titanium. For the inner layers, usually use materials with high hydrogen such as lithium-hydride. In addition to the prevention of radiation, shields must enclose some magnetic parts made of ferromagnetic materials such as (iron, nickel and cobalt). The providing of magnetic field protects the craft against solar hurricanes and cosmic rays.

5.13 Advanced Techniques in Shielding

The use of composite materials technology in radiation barriers is common because of the economic and qualitative benefits. The following table shows some composite materials used in radiation shields and their applications.

Table (5.3) Composite materials used in radiation shielding

Material	Description of composite	Density (g/cm^3)	Application
Pb6	Anhydride (polymer+Pb+W+Ti)	5.6	Nuclear
Jxa	Polyamide (polyamer+Pb+W+Gd)	3.4	Nuclear
GFRP	Glass fibers	2	Airplane
P100+Br	Graphite-epoxy intercalated by bromine	1.7	Airplane
Kevlar or Vectra	hydrogenous using liquid-crystal polymer (LCO)	1.6	Airplane, spacecraft
Nomex or Aramid	Aramid polymers	1.5	Airplane, spacecraft
Interlayer	Polyamide without any dense absorber elements	1.4	Radioactive waste
Dibutyl Sebacate	Organic ester	0.9	X-ray lab

5.14 Protective Garments

Radiation shielding garments are generally used to protect workers and occupants in nuclear, industrial and medical application from direct and indirect radiation during diagnostic imaging in hospitals, clinics and dental offices. Radiation shielding garments include x-ray aprons, vests, kilts, skirts and thyroid shields. Radiation shielding material options including standard lead, lead composite and non-lead shielding materials, as following:

1. Standard lead: This kind of garment manufactured with 100% lead. Lead is a chemical element in the carbon group with the symbol Pb and atomic number 82. Lead is a soft, malleable and corrosion-resistant material. The high density of lead (11.34 grams/cm^3) makes it a useful shield against X-ray and gamma-ray radiation. Lead, in its pure form, is brittle and cannot be worn as apparel. To transform pure lead into a wearable garment it is mixed with additives (like vinyl) to make it flexible. The lead then layered to the desired thickness to achieve the required lead equivalency and incorporated into the radiation shielding garment.
2. Lead-based composite: It is a mixture of lead and other light weight radiation attenuating metals or materials, reducing the weight by up to 25% compared to standard lead garment. The lead composite blend includes a mixture of lead, tin, rubber, PVC and other proprietary attenuating metals.
3. Non-lead shielding material: or lead-free garment is made from other types of attenuating metals including tungsten, antimony, bismuth and tin or other elements. Non-lead garments are recyclable and safe for non-hazardous disposal.

When choosing x-ray aprons, some important factors should be considered like:

- Attenuation: this deals with the intensity of incident radiation or dose exposure allowed.
- Equivalency: There are typically three standard levels of lead equivalency protection for radiation shielding garments including 0.25 mm, 0.35 mm and 0.5 mm.
- Peak kilovolts: The definition of peak kilovolt is the maximum electrical potential across an x-ray tube during an exposure; it is expressed in kilovolts like (80 kVp, 100 kVp and 120 kVp).

Figure (5.11) X-ray apron

Exercises No. (5)

Q1) Complete the following sentences:

1. In order to process the risk of radiation in airplanes, it is necessary intercalation small grains of absorbent materials such as ------- within the composite material.

2. --------- rays are emitted from the inside of nucleus due to the decay of particles.

3. --------- rays are emitted from the outside of nucleus due to the transportation of electrons between the energy levels.

4. Spacecraft is exposed to high-energy rays and particles. So, external shells are covered by alloys of high z-materials such as --------------.

Q2) Choose the correct definition.

1. Particle that emitted from the inside of nucleus due to the decay of neutrons.

A. Alpha B. Beta C. X D. Gamma

2. Particle that emitted from the inside of nucleus and has 2 neutrons and 2 protons.

A. Alpha B. Beta C. X D. Gamma

3. The best ionizing radiation insulator among all.

A. Steel B. Tungsten C. Aluminum D. Wood

4. An indication of the susceptibility of a material to reduce the radiation.

A. Half-life B. Radioactivity C. Resistance D. Attenuation coefficient

5. The thickness of a material required to reduce the radiation by 50 %.

A. Half-life B. lead equivalent thickness C. HVL D. Attenuation coefficient

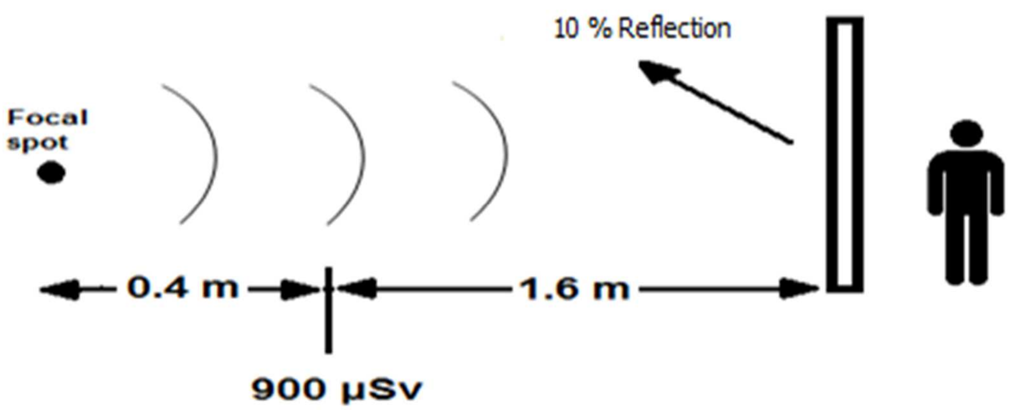
Q3) Gamma rays cannot penetrate the atmosphere even though they have high energy while light can do that, why?

Q4) Prove the relationship: HVL = 0.693 / μ

Q5) In the x-ray lab, a source of 100 keV radiates 800 µSv (0.5 m beside the focal spot). What is the radiation intensity behind monitoring glass shielded by 0.5 mm tungsten at 2 m far from the source?

Material	**Linear attenuation coefficient (1/cm)**		
	100 keV	**200 keV**	**500 keV**
Fe	2.72	1.09	0.655
Cu	3.8	1.309	0.73
Pb	59.7	10.15	1.64
W	62.8	12.2	1.84

Q6) In the x-ray lab, a source of 100 keV radiates 900 µSv (0.4 m beside the focal spot). What is the radiation intensity behind a monitoring glass shielded by 0.8 mm lead (μ=59.3 cm^{-1}), as shown in the figure below.



Q7) A source of cosmic rays radiates 50 μSv outside airplane windows, as shown in the figure below. What is the radiation intensity inside the airplane cabin if the glass is shielded by 0.1 mm lead (μ=10.15 cm^{-1}).

Chapter Six

Fireproofing Insulation

Chapter Six

Fireproofing Insulation

6.1 Introduction to Fireproofing

Most fatal fires occur when people are asleep in their homes, or aboard their offices. Residential fires may occur due to cooking, smoking, electrical shocks, or gas leakage. It could kill many people every day as smoke can lull a person into a deep slumber. Fire protection has since evolved into a branch discipline of engineering where it can be described as the application of science and engineering principles to protect people and their environments from the destructive effects of fire and smoke. As it relates to the petrochemical industry today, simply stated, fireproofing serves to maintain the structure of the building stable and for other applications as well like steel members and vessel/pipe supports for a defined period of time when the elements are exposed to a fire. In practice, owners, in association with fire protection specialists, typically identify risks and design safeguards that aid in preventing, controlling and mitigating the effects of a fire.

When thinking about fire protection, it is generally looking for two models: Active Fire Protection (fire suppression systems and fire alarms) and Passive Fire Protection (fire barriers and space separation). Active fire protection is characterized by items or systems that require a certain amount of motion and response in order to work. These means and methods include fire suppression and fire detection. Fire suppression can be either manually operated systems like fire extinguishers, fire sprinklers or piping systems. Fire detectors can be systems such as fire detectors and smoke alarms. On the other hand, passive fire protection includes preventing the fire and minimizing the effect of burning, or slowing the spread of fire by breaking up the fire into component sub-sets thus controlling the fire spread. These procedures limit building damage and provide more time for personnel evacuation. The focus of this chapter will be on the passive systems using suitable fireproofing materials, how they work and the evaluation of structural components, once these materials have been applied and the components put into service for extended periods of time.

Practical fireproofing building can prevent extreme tragedies by using materials that are relatively fire-resistant. Fire-resistant materials should not be confused with fire-retardant materials. Whilst a fire resistant material is one that is designed to resist burning and withstand heat, fire retardant materials are designed to burn slowly. The key is to construct a building in which a fire would take effect slowly, allowing the occupants plenty of time to escape.

Reflective rockwool　Fire-resistant mortar　Silicone based polymer

Figure (6.1) Examples of fireproofing materials

6.2 Types of Fireproofing Materials

Fireproofing material could be classified according to its strength, functionality, and availability to:

1. Fire-resistant materials (used in building parts)

- Glass wool and rock wool
- Gypsum boards
- Asbestos
- Perlite boards
- Proplex Sheets
- Calcium silicate
- Brick

- Concrete
- Intumescent paint
- Glass
- MgO Panels

2. Fire-retardant materials (used in textiles manufacturing)

- PBI
- Aramids
- Coated nylon
- Carbon foam
- Polyhydroquinone - dimidazopyridine
- Melamine
- Modacrylic
- Wool
- Leather

6.3 Application of Fireproofing

Fireproofing is a passive fire protection measure, and can be used for many applications, like structures, pipelines and tanks. Applying a certification listed fireproofing system to certain structures allows them to have a fire-resistance rating. An item classed as fireproof is resistant in specified circumstances, and may burn or be rendered inoperable by fire exceeding the intensity or duration that it is designed to withstand. However, fireproofing materials could be applied generally in: construction, metallic structure, electrical contacts, traffic tunnels, air-conditioning ducts, pipes and pressure vessels.

1. **Construction:** such as; walls, timber battens, wooden door and windows. Concrete and gypsum are good examples of fireproofing material in construction and they are designed specifically to be fire resistant. Recently, many incorporated chemical additives may be used such as fiberglass that makes the board more dimensionally stable when it is exposed to high heat.
2. **Metallic structure:** Fire resistance can be sprayed on the steel to provide heat resistance. Sprays are divided into "wet Spray" or "dry spray" materials, describing how the material is mixed and applied. This is clearly evident in new airports, shopping malls, hotels, sports stadiums, etc. Intumescent coatings or

paints are used to coat steel structure where it reacts under the influence of fire and swell to many times their original thickness, producing an insulating layer that protects from the effects of the fire. Intumescent material is generally accomplished with three components: mineral acid catalyst, typically ammonium polyphosphate (APP), carbon, typically pentaerythritol or dipentaerythritol, and blowing agent, typically melamine.

Figure (6.2) Fireproofing structural steelwork

3. **Electrical contacts:** such as; switches, cable trays and control joints. Fire Protect Putty Pads have been developed to maintain the fire resistance and acoustic integrity of plasterboard partitions, where plastic electric socket boxes have been fitted. They also make a significant contribution to the reduction of air leakage and reduce infiltration load, thus energy costs and carbon emissions. These pads are usually made of silicon based polymers.
4. **Traffic tunnels:** Traffic tunnels may be traversed by vehicles carrying flammable goods, such as petrol, liquefied petroleum gas and other hydrocarbons, which are known to cause a very rapid temperature rise and high ultimate temperatures in case of a fire. Where hydrocarbon transports are permitted in tunnel construction and operations, accidental fires may occur, resulting in the need for fireproofing of traffic tunnels with concrete linings. Traffic tunnels are not ordinarily equipped

with fire suppression means, such as fire sprinkler systems, thus it is very important to control hydrocarbon fires by active fireproofing materials like fire-resistant cement and ceramic tiles.

5. **Air-conditioning ducts and service penetrations:** For this application, companies have developed ultimate fireproofing materials based on innovative mineral wool or rock wool, which offer:
   - Optimum fire resistance times for ductwork (up to 2 hours).
   - Lightweight (up to 3 times lighter than conventional solutions).
   - Ease of installation.
6. **Pipes and pressure vessels:** Fireproofing is employed in refineries and petrochemical plants to minimize the escalation of a fire that would occur with the failure of structural supports and the overheating of pressure vessels and pipes. This section is for the materials and construction of fire resistant casings to pipes. The thickness of fire proofing cover shall not be less than the requirement for two hours fire rating. The following type of casing is approved: Gunite, prefabricated cementitious board and intumescent coatings. Gunite is a mixture (usually cement-sand) applied for a pressure vessel, producing a dense hard layer of concrete covering it. Gunite is the most widely used method for fireproofing of pipes. The reinforcing fabric shall be 50 mm thickness and 1-2 mm steel galvanized, with a clearance of not less than 20 mm from the face of the member.

6.4 Contemporary Ways of Fireproofing

Recently, many fireproofing mixtures and solutions have been used and they are available and affordable commercially. Fireproofing spray is primarily used to protect rigid structural elements including columns, beams, metal beams, and some steel joists from the effects of heat generated during a fire. The technical name for applied fireproofing spray is Sprayed Fire-Resistive Material (SFRM). It is used as part of a building's passive fireproofing strategy. Spray applied fireproofing has thermal and acoustical properties and controls condensation.

Passive fire protection products, such as fireproofing, is used to delay (or even prevent) the failure of steel and concrete structures that are exposed to the high temperatures found during a fire. They do this by thermally insulating the structural members to keep them below the temperatures that cause failure. Fire spray may also provide acoustical treatment and thermal insulation for large areas where the structural members and metal

columns are left exposed. Spray fireproofing is not suitable for surfaces exposed to moisture or high humidity levels. The moisture and humidity will deteriorate the products. In addition, the moisture may cause mold growth.
SFRM is composed of cement or gypsum and often contains other materials like mineral wool, quartz, perlite, or vermiculite. The gypsum or cement makes up the majority of the solution and is selected because it hardens as it dries. The other materials are used to help lighten the solution or to add air as in insulator. Chemical hardeners are sometimes used to either speed up hardening or to make the final fireproofing harder than normal. Applied fireproofing is available as a wet or dry spray formula. The fireproofing is generally delivered as a dry powder in bag, which is then mixed with water in the field. Proper lung and eye protection is required during mixing and application.
The following figure shows a typical spray fireproofing applied on steel columns and beams.

Figure (6.3) Application of fireproofing spray

Exercises No. (6)

Q1) Select the correct answer:

1. Fireproofing materials could be:

Choices: A. Retardant B. Resistant C. Both D. None

2. One of the common fire-resistant materials is:

Choices: A. PVC B. Glass C. Wood D. EPS

3. One of the common fire-retardant materials is

Choices: A. PVC B. Oil C. Wood D. Aramid

4. The fireproofing material that is commonly used around electrical sockets is:

Choices: A. EPS B. PVC C. Ceramic D. Sand based polymer

5. One of the best fireproofing materials is:

Choices: A. Cement B. Perlite C. Sand D. Gypsum

Q2) Classify the types of fireproofing materials.

Q3) What are the main applications that require fireproofing?

Q4) Discuss the nature of intumescent materials used for metallic structure.

Q5) What is SFRM? Explain briefly.

Answers

Chapter One

Q1)

1. Thermal conductivity
2. Extruded polystyrene (XPS)
3. Internal
4. External
5. Phase change material (PCM)
6. Thermal bridge
7. Reflective

Q2)

1. Keep the indoor temperature stable
2. Reduce the energy required for heating or cooling the house
3. Keep the building materials from thermal stress
4. Reduce energy bills
5. Reduce the burning of fuel in power plants
6. Reduce the emission of greenhouse gases

Q3) Thermal conductivity, reflectivity, absorptivity, heat capacity, density, thermal expansion, thermal bridge coefficient, strength, moisture content, safety

Q4) For ordinary glass, heat is transferred to the inside easily so the glass still cold and it appears in blue. Smart glass restricts the heat flow so turn hot and appears in red and yellow.

Q5) Heat could be transferred in three modes: conduction, convection and radiation. Air has a good resistance to conduction but it can easily transfer convection and radiation, thus it is undesired in comparison to solids.
Q6)

PCM: a material that consequently oscillate between solid and liquid states. It absorbs heat in daytime and releases it overnight such as paraffin and salt hydrates.

Thermal mass: a material with high heat capacity, thus high energy storage such as concrete, rocks and water.

Thermal bridge: is an area in the building envelope in which the highest heat transfer compared with neighboring areas, this causing the failure of building materials, the spread of moisture and mold growth.

Thermal resistance: is the ability of the material to obstruct the heat flow. It is calculated by dividing the thickness per the thermal conductivity of the material.

Overall heat transfer coefficient: is the factor that is used to determine the optimum thickness of the insulation material in buildings. It is also called U-Value. It is the inverse of total thermal resistance.

Thermal load: is the summation of all sources of heat on a building, such as heat loss through the structure (walls, roof and floor), solar radiation through windows, indoor-outdoor air temperature difference (ventilation and infiltration), internal heat (lighting, respiration and equipment).

Q7) Glasswool (B), EPS (D), PU (A), PC (C)

Q8) 2.67 TR, 1.62 TR

Q9) 3.66 TR, 1.92 TR

Q10) 1.68 TR, 1.56 TR

Q11) 1.83 TR, 1.52 TR

Q12) 4 cm

Q13)28 C

Q14) Images have been captured in the summer, where figure (a) is before insulation where heat is transferred to the inside easily, while figure (b) is after insulation where the heat is eliminated outside.

Chapter Two

Q1)

1. Sound transmission loss (STL)
2. Epoxy
3. VDC
4. 500 Hz

Q2)

1. Flanking
2. Inner
3. MLV
4. NRC
5. STC
6. Impedance tube
7. SL meter
8. 10^{-12} W/m^2
9. Sabin
10. Heat

Q3)

1. Reflective materials: these have rigid surfaces thus reflect the majority of sound without transmission or absorption, such as ceramic tiles and glass.
2. Absorbing materials: these are quite porous such as loose materials. They interact with sound passing through them, converting the vibrations into heat.

Q4)

1. Use suitable damper for high-vibration machines.
2. Use soundproofing for the purpose of absorption and dispersion of sounds.
3. Use of ear protectors as a prerequisite for workers.

Q5) STL = 45 dB

Q6) 50.8 dB, 57.7 dB

Q7) 27 dB, 19 dB

Q8) 250

Q9) 31 dB, 27 dB

Q10) 44 dB, 35 dB

Q11) 28 dB, 15 mm

Q12) 2.3 s

<u>Chapter Three</u>

Q1)

1. Asphalt
2. Poly acrylonitrile
3. Permeability
4. Condensation barrier

Q2)

1. Bitumen
2. Epoxy
3. Sorptivity

Q3)

1. Damage of building materials.
2. Efflorescence of the walls, floor and ceiling.
3. Damaging of the paint.
4. The failure in the timber used and wooden décor.
5. Corrosion of metallic parts.
6. Proliferation of fungi and unhealthy situation for users in the building.
7. This reducing the performance of thermal insulation.

Q4) Bitumen, acrylic, epoxy, grout, fiberglass, ceramics

Q5)

1. Paint foundation surface using bitumen paints (or any suitable waterproofing) to prevent water transport and to provide adhesion between the concrete and insulation layer.

2. Put a layer of tarpaulin to protect the foundation from direct contact with water.

3. Put a layer of thermal insulator.

4. Fill the neighboring land to the foundation by stones to resist the permeability of the water as much as possible (see the figure below).

Q6)

1. After the casting of concrete, surface should be cleaned and the cracks should be treated carefully using grout or epoxy.

2. Provide appropriate inclination towards the gutters and treating the cumulative area by a layer of cement.

3. Paint concrete surfaces using bitumen paints to provide adhesion between the concrete and the insulation layer.

4. Put a layer of waterproofing material.

5. Put a layer of thermal insulating material.

6. Put a layer of soil and then covering with impervious tiles or insulating membrane such as acrylic.

Q7) Capillary action: is the ability of water to transport through the small pores of the material due to the forces of adhesion and cohesion. The capillary action occurs in porous materials like sponge, brick, concrete and many construction materials. The quantity of water absorbed into the material by capillary action is given by:

$$\boldsymbol{V = A\,S\,\sqrt{t}}$$

Chapter Four

Q1)

1. Dipole
2. Epoxy
3. Dielectric material
4. PVC
5. ABS
6. Oil
7. Mechanical
8. Strain
9. Ceramics

Q2)

1. Discs type
2. All of these
3. 60 kV/cm
4. Both (B) and (C).
5. Suspension type
6. Pin type
7. 33 kV

Q3)

1. Resistance: Ability of the material to repel the electrical current.
2. Permittivity: Ability of the material to store electrical energy for an electric field.
3. Polarization: Ability of the material to undergo the separation between electrical charges.

Q4)

Dielectric Constant: The relative permittivity of a material with respect to vacuum.

Dielectric Strength: The maximum electric voltage that an insulating material can withstand without breaking down. It is measured in (V/m).

Q5) Electric susceptibility (x): is a measure of how easily a dielectric polarizes in response to an electric field, as following:

$$\varepsilon = (1+x)\,\varepsilon_o$$

But, $\varepsilon = \varepsilon_o \varepsilon_r$

$\varepsilon_o \varepsilon_r = (1+x) \varepsilon_o$

$\varepsilon_r = 1+x$

But, for vacuum $\varepsilon_r = 1$,

Hence, $x = 0$

Q6)

1. Primary insulator: is a flexible material used to insulate the conductors and prevent any contact.
2. Filler: is a material used to fill the gap between insulated wires and the jacket.
3. Jacket: is the external shell of the cable usually made from solid.

Q7) Pin type, suspension type, strain type and long rod type.

Q8)

Low voltage	Medium voltage	High voltage
Pin-type	Suspension-type	Suspension-type
1 disc	2-6 discs	More than 8 discs
Plastic, rubber or ceramic	Ceramic, porcelain or glass	Ceramic, porcelain or glass
Used for supply lines	Used for distribution lines	Used for main transmission lines

Q9)

1. Piezoelectric materials: those have electrical voltage across the sides of a material when it subjected to a mechanical stress, such as crystals, ceramics and polymers.
2. Ferroelectric materials: some piezoelectric materials show a spontaneous polarization without mechanical stress, such as PZT, $BaTiO3$ and $PbTiO3$.
3. Pyroelectric materials: those materials that generate a temporary voltage when they are heated or cooled, such as: most of piezoelectrics and ferroelectrics.

Q10) SiO_2 because of its high energy gap.

Q11) From table, the material is (PTFE/Teflon). C = 0.935 pF

Q12) No. of discs = 10

Q13) Glass with 5 discs.

Q14) C = 54 pF

Q15) 1.25 cm

Chapter Five

Q1)

1. Lead
2. Gamma
3. X
4. Titanium

Q2)

1. Beta
2. Alpha
3. Tungsten
4. Attenuation coefficient
5. HVL

Q3) When Gamma rays pass through the atmosphere; they ionize matter when they collide with it. So, they dissipate their own energy in those collisions. On the other hand, light is not absorbed by the molecules and atoms in the atmosphere, so it reaches the ground level easily.

Q4)

$I = I_o \text{ Exp } (- \mu x)$

$0.5 \times I_o = I_o \text{ Exp } (- \mu \text{ HVL})$
$\text{Ln } (0.5) = - \mu \text{ HVL}$
$\text{HVL} = 0.693 / \mu$

Q5) 2.16 µsv

Q6) 0.28 µSv

Q7) 40.6 µsv

<u>Chapter Six</u>

Q1)

1. Both
2. Glass
3. Aramid
4. Sand based polymer
5. Perlite

Q2)

1. Fire-resistant materials (used in building parts)
2. Fire-retardant materials (used in textiles manufacturing)

Q3) Fireproofing materials could be applied in: construction, metallic structure, electrical contacts, traffic tunnels, air-conditioning ducts, pipes and pressure vessels.

Q4) Intumescent paints are used to coat steel structure where it reacts under the influence of fire and swell to many times their original thickness, producing an insulating layer that protects from the effects of the fire. Intumescent material is generally accomplished with three components: mineral acid catalyst, typically ammonium polyphosphate (APP), carbon, typically pentaerythritol or dipentaerythritol, and blowing agent, typically melamine.

Q5) Sprayed fire-resistive material (SFRM) is a primarily fireproofing spray used to protect rigid structural elements including columns, beams, metal beams, and some steel joists from the effects of heat generated during the fire. SFRM is composed of cement or gypsum and often contains other materials like mineral wool, quartz, perlite, or vermiculite.

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