UNIT 8 PRINCIPLES OF FIRE SAFETY

Structure

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8.1 INTRODUCTION

The discovery and use of fire may be regarded as the beginning of civilization. Anthropologist Claude Levi-Straus said that primitive people became different from animals when they started cooking their food, perhaps the best use of fire one could think of! Not only in cooking, fire was used by them in crafts, in industries and in clearing forests for agriculture and new settlements. However, fire also kills people and destroys their possessions. In the present age people live among things that burn. In the homes, it could be the articles of daily use, like clothes, bedding, furniture and so on, while in the workplace it ranges from the raw materials to the semi-finished and finished products. The ignitors are their in the form of an open flame in the oven, the spark from an electrical switch or the glowing metal dropped from a welding operation. The agent bringing of them together is usually the people, ignorant, unaware or simply careless. While accurate figures are not available, it is stated that the average fire death per million in the metro cities of India is 12 and 50 for a particularly fire-prone one. It should be noted here that the record of rural areas, which remains largely unreported, is no better and on addition will push the figure further up from the estimated total of 12,000 deaths per annum. Likewise, the property loss is estimated to be 0.3% of the G.D.P which, though deceptively low, is actually a double-digit figure in billions of rupees.

In this learning unit of the subject building service, we will study the principles of fire safety and discuss how fires start, how they grow and how they spread inside and outside the buildings. It will include the physics and chemistry relating to fire, the hazards of electricity explosion and exposure as also the means of preventing, controlling and suppressing such hazards.
Objectives

After studying this unit, it would be possible for you to

- know how fires start and grow,
- understand the necessary conditions for its spread,
- analyze the theories of ignition, combustion and explosion and their control,
- know the fire-related hazards of electricity, and
- understand minituous matters connected with fire safety.

8.2 DEFINITIONS OF IMPORTANT TERMS

The definitions of the items given here are connected with fire in some way or the other and probably you know most of them. What, however, is of significance is that we will examine in some detail their relationship with the fire phenomenon. Fire for our purpose here is a chemical process in which a substance reacts with oxygen to produce heat. Elaborating further, it can be stated as an oxidation process (usually accompanied with a flame) when heated gas are given off, light is produced and radiated heat is felt.

8.2.1 Calorific Value/Heat of Combustion

All combustible materials have a calorific value, but the term is usually restricted to the fuels. It is defined as the heat given out by a given weight of the fuel/materials on complete combustion. Some materials have more calorific value per unit weight as compared to others, which make fires involving these materials quite intense and thereby difficult to control and extinguish. The calorific values of some common materials expressed in kilo Joules per kilogram (kJ/kg) are: Paper (15600-18150), Cotton (16750), Woods (17500-21000) Coals (2000-3000), Wool (20700), and Rubber (40000) and petroleum products (43000-48000)

8.2.2 Fire Load and Fire Load Density

It is defined as the total heat the combustible materials inside a building will develop when completely burnt and is obtained by multiplying the mass of the materials by their respective calorific values and thereafter adding the products. Estimated values of the fire loads (expressed as the equivalent mass of wood) per unit area of buildings in the occupied for various purposes are stated to be:

<table>
<thead>
<tr>
<th>Residences and Institutions</th>
<th>25 kg per sq mt. of Floor Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices</td>
<td>25-50</td>
</tr>
<tr>
<td>Shops</td>
<td>250 (max)</td>
</tr>
<tr>
<td>Places of Assembly</td>
<td>25-50</td>
</tr>
<tr>
<td>Factories</td>
<td>150 (max)</td>
</tr>
<tr>
<td>Storage</td>
<td>500 (max)</td>
</tr>
</tbody>
</table>

Incidentally, at some stage in all accidental fires, heat is produced by incomplete or partial combustion (oxidation). Substances of vegetable or petroleum origin contain compounds of carbon, hydrogen and oxygen or of carbon and hydrogen. The heat developed by them, whether the combustion is complete or not, depends on the amount of oxygen (air) consumed. For such substances (coal, common plastics, wood, cotton, sugar, vegetables, mineral and natural oils, etc.) the heat of combustion is approximately 3.7 kilo joules per cubic meter of air consumed and it remains constant whether the combustion is complete or not. It is for this reason; the heat developed in a fire is often restricted by the quantity of air (oxygen) that is available. Accordingly, the fire loads density (fire load per unit area) do not always represent the relative fire hazard, which is influenced by the rate of burning along with the heat produced.
Nonetheless, for classifying occupancies (according to their relative fire hazards) the fire load densities have been taken into consideration in the U.K. Thus a low rating means fire load density up to 60 kg/m²; medium, up to 125; and high, above 125. The National Building Code (Part IV containing a section on fire protection) of the Bureau of Indian Standards, however, uses a different classifying system. There, low fire hazard means a building in which there is no chance of a self-propagating fire; only danger is from panic, fumes or smoke or some external source (G₁). Medium means there could be a fire burning with moderate intensity and rapidity producing a considerable quantity of smoke, but there would be no toxic fumes or any explosion (G₂). The high hazard signifies the chance of a fire developing with extreme rapidity, giving off poisonous fumes accompanied by the threat of explosions and is marked as (G₃). According to the National Building Code, the classification has been made by considering the relative danger of the start and spread of fire, the danger of smoke or gases generated and the danger of explosion and such other occurrence endangering the lives and safety of the occupants of the buildings.

The code also recommends that the hazard of occupancy should be determined on the basis of the character of the contents and the process or operations conducted in the building provided, however, that where the combustibility of the building, the flame spread rating of the interior finish or other features of the building are such that involve a greater hazard than the occupancy hazard, the greater degree of hazards shall govern the specifications. In other words, if a concrete building used as offices contains extensive wood paneling, considerable quantities of curtains and such materials along with foam rubber (or worse, polyurethane foam) up holstered furniture, then it should be regarded as medium hazard or more appropriately high hazard.

8.2.3 Fire Resistance

Almost all materials for construction of buildings are destroyed in fire, and if not destroyed, lose the properties of which they were used in the first place. Taking this into account, the fire resistance of an element of structure is defined as the time during which it fulfills the fire safety of a building when subjected to heat and load or restraint. The National Building Code says that the fire resistance test of structures shall be done in accordance with good practice. The good practice referred to there be testing in a furnace according to the time-temperature relationship shown in Figure 8.1. It should be noted

![Figure 8.1: Time-Temperature Curve](image)
that the fire resistance is applicable to an element of structure, like column, beam, wall, etc. and is expressed in units of time, like 2 hours or 30 minutes. A material cannot have a fire resistance.

Elaborating further, it can be stated that if a structural element (say, a wall) has a fire resistance of 3 hours then it would, under the prescribed conditions in the testing furnace, not collapse due to restraint/load (integrity) not develop any crack or fissure through which hot gases of combustion find a way to the unexposed side (stability) and not be so hot on the unexposed side as to set fire to any combustible material kept in contact with it (insulation). The time-temperature relationship (temperature rise against time) in the furnace is generally as below:

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 minutes</td>
<td>540</td>
</tr>
<tr>
<td>10 minutes</td>
<td>707</td>
</tr>
<tr>
<td>30 minutes</td>
<td>847</td>
</tr>
<tr>
<td>1 hour</td>
<td>930</td>
</tr>
<tr>
<td>2 hour</td>
<td>1013</td>
</tr>
<tr>
<td>3 hour</td>
<td>1069</td>
</tr>
<tr>
<td>4 hour</td>
<td>1125</td>
</tr>
<tr>
<td>5 hour</td>
<td>1167</td>
</tr>
<tr>
<td>6 hour</td>
<td>1209</td>
</tr>
</tbody>
</table>

**8.2.4 Fire Tests**

No one knows what happens in an actual accidental fire. So, in 1928, Ingeborg conducted certain tests in the National Bureau of Standards, U.S.A. Based on his findings, he put forward the time-temperature curve (Figure 8.2) and suggested that it be followed for testing purposes. The British standard 476 and the American ASTM (E-219) generally follow it, but other relationships (curves) are also used for special tests. For instance, in tests for oil platforms, the temperature is assumed to rise to 1800°F in the first 10 minutes instead of 1300°F specified in the standard curve. The fire tests furnaces quite big and can accommodate large test specimens. In the wall-test furnace, the specimen is heated on one side only and arrangements are there for loading or restricting the specimen within a frame. Columns are heated on all sides and for this purpose a column-test furnace can be split into two sections. Likewise, in the floor/slab and beam-test furnace, arrangements are there for loading from above.

All the specimens are loaded/restrained before the test in the same manner as they are in actual use so as to develop stresses similar or nearly similar to those produced in a real fire. During the test the furnace maintains a time-temperature relationship as in the standard curve or any other pre-determined relationship. It should be admitted that all the variables that come into play in an actual fire are not replicated in a laboratory test, but we can regard the fire test as close to the real thing. At the Fire Research Institute, Rookie, there are furnaces for wall and floor testing along with a 30-ton overhead crane for loading purposes.

Another test which is important for fire safety is the flame Spread Test determining how quickly flames spread across the surfaces of materials which are used in paneling, linings, etc. The specimen is fixed to a non-combustible backing and its face is held at the edge of a vertical radiant panel furnace at right angles to the panel. The rate of fire spread is regarded as very low or (classes I) when no more than 19 CMS. Effective spread of flame occurs. In low category (class II), the flame does not spread above 30 CMS in the first 1.5 minutes and does not exceed more than 60 CMS in total. The flame spread is medium when it is above 30 cms in the first 1.5 minutes but is limited to 85 cms in the first 10 minutes (class III). When the flame spread is more than the medium values, it is called rapid or class IV. The National Building Code recommends:
In addition, there are tests for non-combustibility, ignitibility, fire propagation and so on.

### 8.2.5 Fire Effects

The effects of fire on people is death by burns, asphyxiation, smoke inhalation and panic behaviour as also various injuries which we will review in the next unit. Here we will limit our discussion to the deterioration of properties of constructional materials like concrete, bricks and steel during a fire.

**Concrete:** The effect of fire on concrete depends on the moisture content, on the nature of the aggregate used, on the cement aggregate ratio and on the load applied. By load, we mean here the compressive load, because it is for the excellent compressive strength cement is so widely used. The tensile strength of concrete is ordinarily not high; to increase which steel reinforcement is used.

Any way, generally concrete (both stressed and unstressed) does not suffer any appreciable loss of compressive strength up to 200°C. At 400°C, there is a loss of 20-30% strength depending on the aggregate; at 600°C, excepting limestone aggregate, it is below 50% which goes down further as the temperature goes up. It should, however, be noted that concrete rarely attains temperatures above 600°C through its whole mass in a fire, which is why concrete generally retains its integrity, and strength even it is exposed to a fire.

Actually, in an hour-long test, a temperature of 550°C was depth of 25 mm from the heated cement surface; while 35 mm and 57 mm were the distances in 2 hours and 4 hours respectively. Provided there is sufficient cement cover on the steel reinforcement and the cement remains in its place without spalling, then the cement generally retains its tensile strength at such temperatures.

Spalling is the damage due to excessive heat and is in the form of breaking off of pieces or layers of cement, sometimes with explosive force. Spalling is due to

- i) excessive compression or restraint,
- ii) generation of high pressure steam in the matter, and
- iii) disintegration of the aggregate.

The harmful effect of spalling is slight when there is only mild surface damage. If, however, large chunks fall off exposing the steel reinforcement or the steel structural members, then there could be a sudden loss of fire resistance, because structural steel generally loses half its tensile strength at temperature around 550°C. To prevent spalling, sometimes a secondary reinforcement covering the main one is used. It is usually in the form of a wire mesh holding in place the cement cover of the primary reinforcement.

Yet another indication of the severity of fire can be guessed from the change of colour of the cement, which is believed to be due to the presence of ferric oxides in the aggregate, that lose water on heating or react with the lime already there. At 650°C, it becomes grey again and is friable. At 1000°C, the cement turns into a buff colour. As these changes are irreversible, we get an idea of the temperatures reached after the fire was over.

**Brick:** Like concrete, they do not lose much of their compressive strength up to 400°C; at 500°C they start losing and at 600°C above the deterioration become rapid. Generally, brick works behave well in fire; the high temperatures and gradual cooling at the time of manufacture of bricks as also the numerous joints therein prevent thermal stress build up. However, load-bearing walls during fire conditions deflect towards the fire due to greater expansion of the surface layers near the fire. The failures that may occur are due to this
and not for any loss of compressive strength. Anyway, brick walls and floors are effective fire separations and depending on the methods of construction withstand even severe fires.

**Steel:** An important constructional material, steel when used alone is not dependable in a fire situation, because it loses half of its tensile strength at 550°C. Steel generally is used in two ways: as beams and columns holding the structure and as reinforcement for cement providing tensile strength. Many varieties are there, but generally beams and columns are of mild steel and are of alloy steels at times. So also are the rods used for reinforcement? It is, however, in pre-stressed members, strong, high-tensile steel rods used for reinforcement. It is, however, in pre-stressed members, strong, high-tensile steel rods and cables of any of the following types of steel are used:

- a) self-hardening,
- b) cold-drawn, and
- c) heat-treated.

With rise in temperature, cold-drawn and heat-treated steels lose their strength more rapidly than mild steel and self-hardening types. Again, on cooling, mild steel and self-hardening types get back nearly their original strength while cold-drawn and heat-treated types lose permanently a part of their original strength on being heated above 300-400°C. This return to original strength of mild steel and self-hardening types are of significance, especially in fire situations. Nonetheless, for our purposes in fire situations, mild steel is 10% stronger at 200°C, is of the same strength as that at ambient temperature of 350°C and is only half as strong at 550°C. Having regard to the fact that only 50% of ultimate tensile strength are taken into consideration for structural purposes, we will regard 550°C as critical for steel structures.

### 8.2.6 Fire Severity

Anyone with a personal experience in a fire situation will possibly find the description 'a severe fire' little too obvious, because to him all fires are a terrifying experience. However, the tip of a laboratory burner flame is 1500°C, just half that of an oxy-acetylene (3000°C) flame used for welding. So, severity depends on 1) the maximum temperature reached, and 2) how long it persists. Naturally, these two factors depends on a) fuel, b) oxygen, and c) loss of heat and proceeding further we can say that in a room in a building the arrangement of the fuel and the size of the windows (supplying air, doors are presumed to be closed) are important. If the room is insulated, the loss of heat through the walls will be low thus leading to heat build up inside. As regards arrangement of fuel, consider a can of fuel burning at the open end. If the can is kicked and the oil spilled, then it will burn over a surface many times large in area than the open top end of the can. As stated earlier, it is not just the fire load but the fuel surface area (arrangement) along with the size of the windows now control the fire.

![Figure 8.2: Time-Temperature Curves with Different Fire Load Densities and (window/wall) Area Ratios](image-url)
Tests have indicated that fuel-surface controlled fires in compartments are independent of fire loads and burn out quickly; and that air supply depends on room size and the number of windows there. Shallow rooms of small size with a number of windows, which are not too high, assure effective air supply.

Figure 8.2 shows the various time-temperature curves obtained in tests with different fire load densities (fld) and different window openings. It would be seen that the curve 60 (1/4) meaning fld of 60 kg/m² with window openings equal to 25% of wall area represents a more severe fire (high temperature, longer duration) than that represented by the curve 60 (1/2) where the fld is the same but the area of the window openings is just double.

8.2.7 Hazard and Risk

These two terms are wrongly regarded as synonymous and interchangeable. However, in scientific literature hazard means anything that can cause harm, like chemical hazard. Risk is the chance or probability of getting affected by the hazard. Thus, if welding is carried out in a flammable liquid store without stringent precautions, the risk of a fire is almost certain.

8.2.8 Ignition

Ignition is the beginning of a self-sustained process of combustion. If the ignition is brought about by external means, like a flame or an electrical spark or a glowing piece of material (ember), it is called assisted or piloted ignition. If it starts without the help of an external source, it is auto-ignition. We may therefore define ignition temperature of a substance as the temperature to which it must be heated for ignition to occur. Consequently, the ignition which is piloted or assisted is at a lower temperature than that necessary for its auto-ignition. The auto-ignition temperature of a substance, however, changes considerably with changing conditions of the tests carried out for its determination. We thus have different auto-ignition temperatures for the same substance. The factors influencing it, in addition to composition and pressure, are the shape and size of the space (container) where the ignition occurs, rate and duration of heating as also the type and temperature of the ignition source, and catalytic or inhibiting effect of other materials which may be present. Ignition temperatures of some of the common materials are: Coal (130°C), Hay (175), Newspaper (185), Sawdust (220), Jute (195), Cotton (230), and Wood (200-220).

In fact, the exact value of ignition is somewhat difficult to explain. For example, when coal gets heated it starts decomposing chemically; the more the heat, the more the decomposition reaction. In this way, a stage is reached when the decomposition reaction is giving off more heat than is necessary to maintain a steady temperature. The state of ignition has now been reached and we need an ignitor to start the ignition process. If the ignitor is not there, the temperature continues to rise when it ignites spontaneously. All these reactions take place in the vapour phase.

Explained in the light of thermochemistry, the necessary condition for ignition is that both the fuel and the oxygen molecules are to be excited or activated to some extent so as to enable them to react chemically to produce heat. This activation is started by a flame, or a spark, or by raising the temperature of the body of the fuel, when after reacting with oxygen the fuel produces other excited molecules along with heat. With sufficient fuel and oxygen present, ignition proceeds evolving an adequate number of other excited species of molecules which in turn excite (heat-up) more of fuel and oxygen. A chain-reaction thus sets in when the rate of evolution of excited species of other molecules is more than the rate of their natural decay. This process continues until the fuel is consumed, or the oxygen is cut off, or the flame is put out or the excited species of other molecules are reduced in number. Usually, self-sustained ignition proceeds when the conditions are suitable for self-sustained combustion. Thus, if the air pressure (consequently, oxygen) is not adequate for ignition to continue, it will also be not adequate for sustained combustion.

Flaming reaction for most of the combustible liquids or solids generally takes place in the gas or vapour phase. The exceptions are pure carbon and certain metals where direct
oxidation of solid surfaces take place. It is necessary therefore to provide sufficient thermal energy to convert a part of the fuel to vapour, so that a combustible vapour-air phase is there. In conditions such as this, there is a minimum temperature for solid or liquid fuel which fuel which supplies a combustible mixture to the surface. This is the piloted or assisted ignition temperature since some external assistance is needed to start the combustion process. When the fuel is a liquid, the temperature is its flash point.

The flash point of a flammable liquid is thus defined as the temperature when its vapour pressure is quite adequate to form an ignitable mixture with the air near the surface of the liquid. Plainly speaking, it is the temperature at which a liquid starts to burn in air when a small flame is brought near its surface. (In fact, it is the fire point of the liquid, which is a little higher than the flash point by a few degrees.) A liquid which has a lower flash point than the ordinary room temperature (Benzen 11°C) is thus more hazardous than the one which has a higher flash point (Turpentine, 33°C). It is for this reason flash point is regarded as one of the main parameters in hazards classification. An important point to note in this regard is that a big flame/fire near the surface of a liquid will set it on fire even when its temperature is below its flash point. The heat radiated by the flame/fire in such an instance would turn the liquid on the surface to vapour at the necessary minimum rate for combustion, which is 4 gms. per sq. metre per second for common fuels.

8.2.9 Limits of Flammability

Combustion of a flammable gas in air is possible only when the composition of the gas-air mixture is within certain limits. The gas-air mixture will not burn when the gas concentration is below a certain value, the Lower Flammability Limit or the Lower Explosive Limit; at that concentration, the mixture is too 'lean' to burn. Likewise, there is a higher value above which the mixture is too 'rich' to support combustion (Upper Flammability/Explosive Limit) and the concentrations between these two values form the Flammable/Explosive range. It is the range which makes a substance more hazardous, e.g., hydrogen (L.E.L. 4%, U.E.L. 75%, in air, by volume) with its wide range between 4% and 75% is one of the most hazardous.

Usually, but not always, mixtures are flammable when they correspond to the stoichiometric mixture (that follows the laws of proportions and of conservation of energy) necessary for combustion. It has been found that the lower and upper limit ratios are closer to one-half and twice of the stoichiometric ratios respectively. The flammability limits are affected by pressure and temperature. The ordinary variations of atmospheric pressure have no effect, but the range becomes narrow (the LFL goes up, the UFL comes down) under reduced pressure and wide under increased pressure. Similar results are obtained under lower and higher temperatures. Flammability limits are not restricted to air or oxygen only; there are flammability limits for substances which burn in chlorine (e.g. Hydrogen). Flammability of substances in air can be suppressed by addition of inert gases like nitrogen and carbon dioxide. Thus flammability of methane (LFL-5%, UFL-15%) is suppressed by adding 38% of nitrogen or 24% of carbon dioxide by volume to the methane-air mixture. The graph in Figure 8.3 shows how concentration

![Figure 8.3: Temperature Effect on Flammability Limits](image-url)
of the saturated vapour-air mixture of a flammable liquid fuel increases with the
temperature. The LFL is reached at the lower temperature $T_L$ and a self-sustaining
reaction commences with ignition. Mists are formed in the region left of the saturation
line obtained from the vapour pressure of the liquid which can also burn if ignited. As the
temperature increases, there is a corresponding increase in vapour pressure until the UFL
is reached at $T_u$. As we have noted earlier, further increase in temperature widens the
range (LFL) goes down, UFL goes up) and this brings the vapour to the Auto-ignition
Temperature when the thermal motion of the reactant gases is sufficient to initiate a self-
sustaining reaction. We can see that AIT is a curve, which explains why we get so many
values of AIT for the same substance.

8.2.10 Vapour-Air Specific Gravity

It is the ratio of the weight of a vapour-air mixture obtained by the vapourization of a
liquid under ambient temperature and pressure and an equal volume of air under the same
conditions. This vapour-air specific gravity or density depends on the ambient
temperature and the pure vapour pressure of the liquid at the ambient temperature. For
liquids with a high boiling point, the pure vapour pressure at ordinary temperatures may
be so low that the vapour-air mixture, containing mostly air, would have a density nearly
equal to that of pure air, that is 1. When the temperature of the liquid is raised to its
boiling point, the vapour displaces the surrounding air and the density of the mixture
tends to become equal to the pure vapour pressure density. Such a mixture, because of its
heaviness, will sink to lower levels and can travel quite a distance from its point of origin
without getting diluted by diffusion and mixing by convection like lighter vapour-air
mixtures.

This property of heavy flammable vapour-air mixtures is the cause of many fires and
explosions. Occupying lower levels at the places of origin, they flow into cavities,
hollows and basements of buildings, when chance or inadvertent flames or sparks set
them alight or cause them to explode.

8.3 CHEMISTRY OF FIRE

Fires are quite complex chemical reactions and though there is a considerable body of
knowledge about it, not all its features are understood. Having said this and considering
that we have already defined, as the chemical reaction of a substance with air (oxygen),
fires we will begin our study of the chemistry of fire with oxidation reactions. However,
before so doing, we will endothermic and exothermic reactions.

Endothermic and Exothermic Reactions: Heat given out or absorbed during a reaction
is called heat of reaction. In endothermic reactions, the new substances formed contain
more energy than the reactants thereby taking in energy. The products of exothermic
reactions contain less energy than the substances out of which they are formed and hence
given out energy. Energy as we know, appears in many forms and is usually in the form
of heat absorbed (endothermic) or released (exothermic) in chemical reactions.

Oxidation Reactions: Heat is evolved in the oxidation reactions in fires, that is, they are
exothermic. A combustible material (fuel) and oxygen therefore must be present for an
oxidation reaction to proceed. Materials not generally in their highly oxidized states are
the constituents of most of the fuels. Whether or not a material can be oxidized depends
on its chemical structures. Usually, materials containing carbon and hydrogen can be
oxidized. Solid organic materials and flammable gases and liquids belong to this group,
containing as they do high percentages of carbon and hydrogen. Common among the
oxidizing materials is the oxygen in air, made up of roughly 20% oxygen and 80%
nitrogen. There are chemicals, like sodium nitrate ($\text{NaNO}_3$) and potassium chloride
($\text{KClO}_3$) which readily produce oxygen, but they are not generally found in fires. There
are also others, like cellulose nitrate which contain a lot of oxygen in their molecules and
can burn partially without taking oxygen from air. The point to note here is that if a fuel
which is not recognized as a fuel and an oxidizer which is also not recognized are kept
together in a building, the risk of a fire is indeed great.

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So, this brings in the problem of what we should have or not within a building and the answer (or a part of it) would be the list of hazardous materials prepared by the insurance companies or by government departments. The list is quite long and it may not be always possible to exclude them in a building. However, we should at least know the hazards and make a general survey of the materials of which we should be careful. In addition to fuels and oxidizers, our list would include broadly catalysts, inhibitors, contaminants along with stable and unstable materials. A catalyst affects the rate of a reaction by its presence but does not take part in it. Platinum in a car’s catalytic converter helps to burn off the excess fuel in the exhaust gases, but does not take part in it. Inhibitors are the opposites of catalysts and slow down the rate or altogether stop violent reactions. Fire retardants, like bromine or chlorine related compounds are generally inhibitors, but they are not effective in large fires. Besides, they are against environmental regulations concerning the ozone hole in the atmosphere. Contaminants are things that should not be there in a substance and from a fire hazard point of view harmless. However, there could be contaminants which act as catalysts thereby accelerating reactions. Materials are stable when they resist the changes in their chemical composition when exposed to air, heat, water, shock and pressure. Most of the solid materials belong to this category, but, nonetheless, they burn. Unstable materials degenerate, decompose, become more unstable by coalescing together (polymerise) and turn self-reactive on exposure to air, water, heat, shock or pressure. Pure gaseous acetylene, normally kept dissolved in acetone under pressure in cylinders (for welding purpose) decompose into graphite and hydrogen giving out 54 kilo calories of heat per Mole, which instantaneously heats up the decomposition products to about 2600°C causing them to explode violently.

Theories of Fire: Generally, the researches on fire carried out in laboratories involve simple configurations, which bear very little or no relation to large, unintended fires. However, those simple situations are important, as they provide useful information on principles thus helping us to gain some insight into the conditions prevailing in large fires. The simplest situation is the burning of fuel droplets or small samples of simple plastics where burning occurs in gas-phase laminar diffusion flames, flames where the rate of burning is dependent on fuel and air supply. The basic difference between fire and explosion (which we will study in a subsequent section) is that in fire the fuel and the oxidant is initially separate and unmixed. Due to this, burning rates in fires are controlled by the availability of fuel and air to the flames and not on the reaction rates of the processes taking place within the flames. This burning within usually occurs along thin flame sheets, known as diffusion flames, which act as a separation between regions rich in fuel vapour and regions rich in oxygen. From opposite sides of the flame sheet, fuel vapour and oxygen diffuse towards each other, intermingle and produce combustion products and heat, which in turn diffuse away from the flame sheet. In burning a candle or a match, the diffusion flames are small and thus appear smooth and steady. Known as laminar diffusion flames, they dance around in large fires in search of more fuel or oxygen. In still large fires, they turn chaotic when they are called turbulent diffusion flames.

Quite a lot is known about small fires involving laminar diffusion flames. There, the burning rates depend on the convective heat transfer from the flames to the solid (or liquid) fuel which helps it to convert into gas or vapour that feed the flames. The oxygen is provided by the air rushing upwards induced by the buoyant flow of the hot products of combustion. The convective heat transfer from the flames to the fuel is also helped by this buoyant flow. Where the fire is spreading, the rate of its spread will depend on the heat transfer forward to the yet uninvolved fuel, which should be preheated sufficiently so as to give off flammable vapours for the burning to continue.

In really large fires involving turbulent diffusion flames, there are difficulties in understanding turbulent gas motions as also the large amount of radiation from the flames which is the principal form of heat transfer (from the fire to the fuel) there. It has been observed that this radiated heat in large fires alter the flammability gratings of fuels to higher grading than their erstwhile grades under small scale tests. In other words, combustible things become more combustible, that is, catch fire easily when they are located near large fires.
Flammability: The previous paragraph introduced flammability applicable to solid and high flash point liquid combustibles as opposed to flammability limits applicable to gases and low flash point liquids studied earlier. (Incidentally, we should rather use term fire point at which the burning is sustained. In flash point, as the term implies, there is just a ‘flash’). It is quite important, contributing as it does to fire hazards in real fire situations. We have discussed, however, one of the flammability properties, heat of combustion, earlier.

Stoichiometric Oxidant: It is the mass of oxidant required to burn completely a unit mass of combustible. Combustibles requiring more of stoichiometric oxidant produce flames of large height and thus have greater fire spread hazards. The stoichiometric oxidant is usually proportional to the heat of combustion of the combustible and organic combustibles normally release the same amount of heat per unit mass of oxidant consumed. (Combustibles requiring more oxygen to burn completely produce flames of large height which cause fires to spread. Heat released in such fires is constant per unit mass of oxygen consumed.)

Melting: Combustibles that melt in a fire are hazardous in the sense that the molten mass spreads, the increased surface gets heated by the flames and ultimately catches fire.

Toxicants: A product of incomplete oxidation, carbon monoxide is the main toxicant produced in a fire. Combustibles containing elements other than carbon, hydrogen and oxygen produce additional toxicants, e.g. polyvinyl chloride.

Soot Formation: A product of incomplete combustion, soot increases the flame radiation thereby helping the fire to spread besides contributing to smoke damage.

Ignitibility (Assisted): It is inversely proportional to the time taken by a material in getting heated on the surface to its assisted ignition temperature and is significant both for ignition and fire spread.

Char Formation: This is a carbonaceous residue developed on materials like wood subjected to heating when the volatile constituents evaporate leaving the carbon behind. It often forms an insulating layer which prevents the material below from getting heated further.

Now that we know about the flammability properties we can create the scenario of a fire in, say a wood-burning chula. Let us imagine a stick of wood that is getting heated by flame radiation. As the temperature rises to the boiling point of water, hot gases (mainly steam) rise which have no combustible content or very little of it. As the temperature rises further, the drying process migrates deep into the surface of the wood. Presently, we reach a temperature of 300°C, decomposition by heat (pyrolysis) has started discolouring the wood; combustible gases now evolve and burn; charring appears, the pyrolysis also migrates inside.

A break: If there is no source of ignition present, then the combustible gases evolving with the onset of pyrolysis will not burn. The burning would be delayed till such time the wood surface gets heated further and auto ignition temperature is reached. That, however, is not the situation in our chula. When burning started a diffusion flame covered the pyrolyzing surface from coming into contact with oxygen. However, the flame itself heated the surface increasing the rate of pyrolysis. Suppose, now we take out the burning wood. It is quite likely that the diffusion flame would go out, because there is too much loss of heat from the surface by radiation and conduction to the interior. So, we place, the log back, next to another. Much of the radiated heat is now intercepted and returned and the wood is burning again. (This explains why it is difficult to keep a single log fire going and several ones placed together are necessary to recapture the radiation losses.)

As the burning continues, the char layer builds up preventing pyrolysis of the interior of the wood. It could also be that all the wood beneath the charred surface has been pyrolysed and converted into char. Anyway, there would be presently a decrease in the rate of pyrolysis (as also in the rate of evolution of combustible gases), the diffusion flames will die out allowing the oxygen from air to come into direct contact with the char, glowing combustion on the char surface would start provided there is not too much radiation loss.
We have assumed that the chula opening near the base is ample to accommodate the logs leaving sufficient space for air to go in. Supposing that is not so, all the combustible gases will not burn now due to the insufficiency of air, the excess will come out of the gap between the top of the chula and the pot placed on top and burn. Incidentally, from the beginning, smoke is produced, because the combustion would never be complete totally.

Or, suppose we leave the door open and wind from outside blows hard on the pyrolyzing surface, literally flooding it with more oxidant than is necessary for combustion. The excess air will drive away the diffusion flames cooling the surface much below the temperature for pyrolysis to continue; the fire goes out. That is how we blow out a match; its reverse is when we fan the dying embers of a glowing fire, increase the rate of pyrolysis (combustible gases evolve) and start a flaming combustion. In larger fires, unfortunately, the similarity is with the second instance. The rate of burning increases due to more flame to fuel surface heat transfer which, in turn, increases the fuel supply. The fire grows.

Anyway, after a while of uninterrupted burning, the flames will spread over the entire surface. We may regard this as a series of piloted ignitions. The flames pyrolyze the surfaces near, ignition occurs, diffusion flames appear which in turn pyrolyze... and so on. It would be seen that the horizontal flame spread is slower than the vertical one where the hot gases generally travel upward and supply heat to a greater area in that direction.

Materials which ignite quickly also spread flames rapidly. Resistance to heating (also known as thermal inertia) and the rise in temperature necessary to start pyrolysis are the factors that influence the ignitibility of a substance. Materials with low thermal inertia, like wood used in packing boxes have low thermal inertia, are easy to ignite and spread flames quickly. Teakwood has a relatively high thermal inertia and is rather difficult to ignite.

The big and hazardous fires have their burning rates controlled mainly by the radiation from the flames to the pyrolyzing fuel surface. Before they cool down by radiation, the soot and unburned fuel vapour in a well-ventilated fire come into contact with the surrounding air leading to a reduction in smoke and amount of un-burnt fuel. In a poorly-ventilated fire, a great amount of smoke and incomplete combustion products, like carbon monoxide is released. There fuel vapours do not have sufficient air to burn completely before cooling down and dispersing from the fire area. Poorly ventilated fires are dirty generating a copious quantity of smoke and hot incomplete products of combustion.

8.4 PHYSICS OF FIRE

Energy in the form of heat has quantity as also intensity or potential (temperature). Thus two bodies may hold different quantities of heat measured in Joules (or B.T.U.), but there would not be any transfer of heat between them unless there is a difference in temperature measured in degrees centigrade (or OF). Temperature is the condition that decides whether heat would flow from one body to the other. Once there is a temperature difference heat will flow from the hot body to the cold (or less hot) one. Thus, ignition is increasing temperature by adding heat; while fire extinguishment is lowering the temperature (cooling) by pouring water.

Heat retention capacity of a substance is determined by its specific heat, the amount of heat it hold as its temperature goes up. Described accurately, it is the thermal energy required to raise the temperature of a unit mass of the substance by 1 degree centigrade. The specific heat of water is 1 calorie per gram, which is higher than that of nearly all other substances. In fire protection, specific heat plays an important role by indicating the amount of heat needed to raise a substance to a level of danger or be removed in another to render it safe. Water with its high specific heat is very effective in extinguishing fires by its cooling action.
Latent heat is the heat absorbed by a solid when it turns into a liquid as also when a liquid turn into a gas. The first is called the latent heat of fusion; the second, the latent heat of vapourisation. The latent heat of fusion of ice into water atmospheric pressure is $333.4$ Joules per gram or $80$ calories per gram, while the latent heat of vapourisation of water into steam at $100^\circ C$ is $2257$ J/g or $539.5$ cal/g. This high latent heat of vapourisation makes water perhaps the perfect agent for extinguishment of fire by cooling. One kg of ice at $0^\circ C$ is converted to steam at $100^\circ C$ when $3$ million Joules of heat is added to the mass. All other substances have latent heats much lower than that of water. On application of water, the burning fire loses quite a lot of heat, heat that goes into vapourising the fuel or into pyrolysis thereby restricting/cooling or killing the fire.

**Heat Transfer:** We have earlier referred to heat transfer, emphasising the role it plays in ignition, burning and extinguishment of generally all fires. Conduction, Convection and Radiation are the three ways by which heat is transferred.

Conduction is the process of heat transfer by direct contact as it happens when a pipe carrying steam inadvertently comes to rest on a block of wood; the pipe is the conductor in this instance. The amount of heat carried by conduction through a body or at a specified time is dependent on the temperature difference and the conductance of the medium in question. Conductance is a function of thermal conductivity, the cross-sectional area through which the heat flows at right angles and the length of the path of flow. Thus, heat transfer rate is the amount of heat flowing per unit time and heat 'fuse' is the amount of heat flowing per unit cross-sectional area per unit time:

\[
\text{Rate of heat transfer} = \text{Heat flux} \times \text{cross-sectional area}
\]

Heat transfer through air or gases is generally independent of pressures. It approaches zero at very low pressure and becomes zero in a perfect vacuum. This relative resistance of gases to conduction is utilised in the better class of insulators where fibres or particles of matter in its body are separated by tiny spaces filled with air. The insulation, however, does not completely stop condition; it just has a low thermal conductivity. Like a tap that slowly leaks, it restricts the quantity of heat conducted; unlike a value that completely shuts off. For this reason, it is necessary to keep combustibles some distance away from the walls (especially, in storage areas) so as to enable the air in between the gap to carry away the heat by convection and not to depend entirely on the insulation properties of the wall. It has been observed that fires have occurred by heat conduction over long periods of time through concrete as thick as $0.6$ m ($2$ ft.)

Physical properties which are important for conduction of heat are thermal conductivity, $(k)$, specific heat $(c)$ and density $(\rho)$. In fact, the product of specific heat and density $(c\rho)$ is the measure of heat conduction which may be defined as the amount of heat necessary to raise a unit volume of the body by unit temperature. It's unit can be Joules per cubic centimeter per degree centigrade and it can be called thermal capacity per unit volume. In thermal conductivity we have to introduce the concept of unit temperature gradient, which means that the temperature is falling off on going down by one degree celsius for every cm of distance in the direction of the heat flow. With that explained, thermal conductivity may be defined as the quantity of heat flowing through a unit area of the material with unit temperature and is expressed as $J/(cm \cdot sec \cdot ^{\circ}C)$.

Heat conduction problems are quite complex, but an interesting feature derived from the solutions thereof is the time constant of a thickness $(x)$ of the material. It has been found that when there is a sudden rise in temperature on the surface of a material, than the temperature at depth $x$ of the material (thickness) will start rising after a certain time interval.

\[
t = \frac{x^2 \rho c}{k} = \frac{cm^3 \cdot (J/cm^3 \cdot ^{\circ}C)}{J/(cm \cdot sec \cdot ^{\circ}C)} = \text{sec.}
\]

The Joules, centimetres and degrees celsius in the expression cancels out, leaving only time in seconds. The time expressed in seconds here is a constant. As it goes up, the rate of heat transfer falls down. Also, the time required for the heat to go deep inside the body of a material increases with the square of its thickness.
Convection: A circulating medium is necessary for heat transfer by convection. A room heater in this way heats up a room. First, the air in contact with the heater is heated by conduction, this heated air then circulate around the room and/or reach the distant objects in the room by convection. Finally, the heated air heats up the objects in the room by conduction, that is, getting into contact with them. Heated air expands and rises as it becomes light which is why convective heat transfer is generally in an upward direction. However, such air currents can be made to travel in any direction by a blower as is done in a hair drier.

Radiation: Like radio waves and x-rays, radiation energy travels through space or materials an electromagnetic wave. Radiant energy waves travel through vacuum at the speed of light and if a body is placed on their path, they are absorbed or reflected or transmitted. What we see (wave length $0.4 \times 10^{-6}$ m to $0.7 \times 10^{-6}$ m, violet to red) is only a tiny fraction of the solar emission, radiant waves belong to this scale and are in the non-visible infra-red (beyond red) region.

The flame of a diya is an excellent example of radiant energy. The flame draws air from the surroundings which supplies the oxygen necessary for combustion. Heat rises above with the hot air and the products of combustion, yet there is a sense of warmth if we hold our hand by the side if the flame. If, however, the hand is hold on top the heat felt would be more and would be scorched if held very near the tip due to the convective heat, while in the first instance it is radiant heat. In a small fire, like the one in a diya, a high proportion of the heat leaves by vertical convection while a large fire release nearly equal amounts of convective and radiative energy. Convective heat is, in a sense, less dangerous, because with the rising hot gases it moves past the surface that is exposed. Radiative heat, in contrast, will be absorbed by the surface on which it falls and cause the temperature to rise. As radiant energy travels in straight lines, its quantity would be less if the emitting surface is small. It would be correspondingly high when the emitting surface is high, even when the two surfaces are radiating the same amount of energy per unit area. Figure 8.4 gives an idea of the difference in radiant energy received by the same surface when the source is: A) Small and B) when it is large.

![Figure 8.4: Radiant Energy from Sources A (Small) B (Big)](image)

The earth receives heat from the sun mostly in the form of radiant energy which passes freely through symmetrical diatomic molecules like, hydrogen, oxygen and nitrogen. Accordingly, not much radiant energy is absorbed by the air unless it is burdened with heavier, unsymmetric molecules, like water vapour, carbon monoxide, carbon dioxide, sulfur dioxide and hydrocarbons, as also solid particulates such as smoke. Normally, the concentration of such substances in the air is very low and the quantity of radiation absorbed by them is quite small. As, however, water drops capture almost all the infra-red radiation, it is in the form of mists or sprays very good in attenuating (reducing the damaging effects of ) radiant energy. This property of mist and water spray is utilised in fire fighting operations by applying water through fog/spray nozzles.

Two bodies, one hot and the other cold, facing each other will have a radiant heat flow...
the same temperature). This heat flow will depend on the kind of surface of the cooler body and the radiating surface area of the hotter one. If the receptor surface is smooth and shiny, most of the radiant heat will be reflected away; if it is black or dark in colour, most of the radiant heat will be absorbed. In this sense, generally all non-metallic are "black" to infra-red radiations, although they may appear lightly coloured to visible radiation. Water and glass are transparent to visible radiation, but they are opaque to infra-red radiations in general. It is for this reason green houses are made of glass allowing the suns visible rays to get in but preventing the heat from escaping outside.

According to the Stefan-Boltzmann law the radiant heat given out per unit area by a black body is proportional to the fourth power of its absolute temperature and is given as

\[ q = \sigma \epsilon T^4 \]

where, \( q \) is the heat emitted per unit area, \( \epsilon \) is the surface emissivity correction factor (generally equal to unity for most of the non-metallic materials and hence ignored), is the Stefan-Boltzmann constant (given as \( 5.67 \times 10^{-12} \text{ W/(cm}^2\text{k}^4) \)) and \( T \) is the absolute temperature given in Kelvin (degree celsius + 273). Due to this fourth power of the absolute temperature, a rise of 100°C of an emitter surface (initially at 260°C) would double the quantity of the heat emitted, while an increase of 240°C would raise the emission by 4.3 times.

At 260°C, \( q = 0.46 \text{ Watts/cm}^2 \); at 360°C, \( q = 0.91 \text{ W/cm}^2 \) and at 500°C, \( q = 2.0 \text{ watt/cm}^2 \)

Although scientists can find out the amount of heat radiated by solids and gases on fire with reasonable accuracy, they face difficulties in estimating the radiative heat output of large flames. The difficulty is due to the reason that in flames most of the radiant heat is emitted by soot particles, the data on which is rare. Nonetheless, a rule of thumb says that in flames of heights not less than 200 mm (8") the radioactive heat output is 30-40%, the convective heat output is about the same and the remaining fraction of the total heat developed is accounted for the heat carried away by the products of incomplete combustion.

The quantity of heat absorbed by a receptor at a certain distance has been calculated by scientists by using what is known as the view factor method. In one such instance, the heat is from a natural gas flame 6 m diameter and 18 m high at an angle of 60°C to the vertical. Assuming that the temperature of the flame is 900°C (1173 k), the quantity of radiant heat absorbed by the receptor at a distance of 24 m is:

\[ Q = 0.38 \text{ watt/cm}^2 \]

### 8.5 COMBUSTION

**Combustion:** A self-sustained exothermic reaction, combustion involves a solid, liquid or gaseous fuel. Generally, but not always, the reaction is between a fuel and atmospheric oxygen with the evolution of heat, light and the products of combustion. When a solid or a liquid is burning, it is not the solid or the liquid that is on fire, but the combustible gases or vapours produced from them by the heat of reaction. Solids, however, do burn sometimes with a glowing combustion or just smoulder.

The gas-phase reaction in combustion is swift generating heat, emitting light and releasing products of the burning accompanied with a flame. In flames emitting no light (non-luminous) the reactants and the products are all in gas phase, while flames emitting light (luminous) release some solid products (carbon, soot) which actually produce light due to their incandescence inside the flames. Although energy is radiated from both the non-luminous and luminous flames, the energy from the first lies mostly outside the visible spectrum. Most of the energy radiated by the two, however, lies in the infra-red region of the spectrum.

Although oxygen is the common element in oxidation reactions, such reactions can also occur with other elements, like chlorine and bromine with the characteristic evolution of heat as in an oxidation reaction. Thus, hydrogen "burns" in chlorine producing...
hydrochloric acid gas, likewise, zirconium dust can be ignited in carbon dioxide and 
under certain condition magnesium, aluminium and calcium can "burn" in nitrogen.

Anyway, combustion for our purposes is reaction with oxygen evolving heat and thus we 
have the fire triangle (Figure 8.5) with fuel, oxygen and heat forming the three sides. In 
fire fighting, we try to demolish the triangle by removing one side. We remove fuel from 
the fire site and deprive it of the very substance which burns. An example of this is a 
firebreak in forests where a strip of land sufficiently wide is cleared of trees and 
under-growths so that fire will stop at its edge. The width is to be large enough so that 
radiation of heat from its one side would have no effect on the other. Removal of oxygen 
is called "starving" which we can do in a manner by diluting the oxygen. (Most of the 
liquid fuels do not burn when the percentage of oxygen in the air goes below 15 per cent. 
Wood, however continues to burn with glowing combustion even at an oxygen 
concentration of 5 per cent). In a confined space, we can starve the fire by flooding it 
with carbon dioxide. Removal of heat is essentially cooling for which purpose water is 
the most efficient, readily available and cheap medium. We can apply water as a solid 
stream or a mist or a spray or in a combination of all the three (the solid stream be 
directed at the core while the fog and the spray will smother the fire.

In 1974, an American fire protection consultant, Walter Haessler put forward the theory 
of uninhibited chain reaction of combustion process. According to him, glowing 
combustion (the combustion that takes place on pyrolysed wood surfaces) is represented 
by the fire triangle. Flaming combustion in which combustible gases evolve from fuels 
due to pyrolysis/heat is best represented by a tetrahedron, in which the fourth surface is 
the uninhibited chain reaction; the other three surfaces being fuel, heat and oxygen 
(Figure 8.6).
Uninhibited chain reaction can be illustrated by the burning of hydrogen in air. On being supplied with the necessary ignition energy \((0.019 \text{ mJ})\), molecular hydrogen splits into two active species: \(\text{H}_2 + e \rightarrow 2\text{H}^*\) which react with oxygen to produce active species of hydroxyl and oxygen: \(\text{H}^* + \text{O}_2 \rightarrow \text{OH}^* + \text{O}^*\) and the reaction proceeds:

\[
\text{OH}^* + \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{H}, \quad \text{O}^* + \text{H}_2\text{O} \rightarrow \text{H}_2\text{O} + \text{H}^* \quad \text{and so on}
\]

It would be seen that the active species \(\text{H}^*, \text{O}^*\) and \(\text{OH}^*\) are both reactants and products and with this dual role, they provide the “chain” in the reaction along which it proceeds “uninhibitedly” until such time the hydrogen (or oxygen) supply runs out.

According to Mr. Haessler, in extinguishment by flame inhibition, these active species are not allowed to fulfill their functions. This is achieved by throwing into the fire fine powered alkaline compounds (dry powder) most prominent among which is sodium bicarbonate. On being thrown into the flames, these compounds dissociate into their cationic and anionic components, which catalyze the active species of hydrogen and oxygen to combine again thus breaking the “chain”. It is not exactly clear how the cationic and anionic components do this, but applied by proper amounts, they (also called free radicals) extinguish fires very quickly. Extinguishment by flame inhibition through dry powder (as the description implies) is possible only for flaming combustion. They are not effective for glowing combustion.

Several factors come into play when a flammable gas mixture starts to burn. Neighbouring gases carry away the heat from combustion by conduction. Heat is lost by radiation in all directions. ‘Cold’ reactant gases diffuse into the flames, while ‘hot’ products diffuse out. (Cold and hot here is relative; the cold gases are either vapours evolving from heated liquid fuel or gases coming out of pyrolysed solid fuels, while the hot products of combustion are quite hot, hotter than the reactants). All these factors tend to quench or cool the flames. When the rate of heat production is more than the rate at which heat is given out the flames (or the fire) will grow. When the heat generation and heat loss are equal or nearly equal, the flames will be steady or will flicker. The flames diminish (also the fire) when the heat loss is more than the gain.

A combustion wave is propagated at a constant rate when a flammable gas mixture is ignited, the gas mixture being of fixed composition and under constant pressure and temperature. This propagation mechanism is quite complex, because it involves mass and thermal diffusion along with flow mixing and the chemical kinetics of the reactions. However, the feature burning velocity, which is observable, gives us an idea of the energetic state of the reactants. Hydrogen, the most active fuel, has a burning velocity of \(320 \text{ cm/sec. in air (7.17 miles/hour)}\) which is faster than walking. We extinguish a match stick by an air puff from our mouth that exceeds the burning velocity of the flame. Likewise, in an oil well on fire, the flame is put out by the blast of air from a triggered explosive change.

Another important aspect of combustion is the flame temperature. Now, flames can be premixed and they can be diffusion. In a premixed flame the fuel and the air mixed before they burn while in a diffusion flame they mix (diffuse) as they burn. Obviously, in an unintended fire, a premixed flame would be rare, but in a bunsen burner in the laboratory we can have both. The flame with the primary air-hole open is premixed, it is diffusion when the air hole is closed. It is also possible to classify the flames as laminar and turbulent as we have noted earlier.

An interesting feature observed in laboratory experiments is that the flame temperatures of a variety of fuels (with no excess air) having different heats of combustion are not very different. Thus, hydrogen has a flame temperature of \(2045 \text{ °C}\); carbon monoxide, \(2100\); methane, \(1875\); ethane, \(1895\); propane, \(1925\); butane, \(1895\) and acetylene, \(2325\). The high temperature of an oxy-acetylene welding torch \(3000 \text{ °C}\) is due to the high pressure of oxygen and acetylene.

A laminar flame has a temperature around \(1600 \text{ °C}\), while a turbulent diffusion flame with its greater heat release is of a temperature of nearly \(2000 \text{ °C}\). Considering that a lot of heat release from such flames is by radiation and taking into account the fourth power of absolute temperature the emission is proportional to, turbulent diffusion flames are
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much hotter than the laminar types. Emissivity, which directly affects the heat radiated, is quite high in luminous flames due to the presence of solid carbon particles and to some extent carbon dioxide and water vapour. Typical values of emissivity of luminous flames are 0.8-0.9 and for non-luminous flames, 0.1-0.3.

So, combustion, which can be of either flowing mode or flaming mode or a combination of both depends on the fuel, its arrangement and air supply, and can be controlled by the removal of heat, oxygen and fuel for glowing mode. These options are also available for controlling a flaming mode fire and in addition there is the method of flame inhibition which, however, is not suitable for large fires. Combustion in closed spaces deplete the oxygen available, but this need not lead to fire extinguishment all the time. There is every likelihood of accumulation of flammable gaseous products of incomplete combustion and the temperature of other combustible substances being raised to their ignition temperatures. Accidental entry into such a space by opening a closed door (even for fire fighting) when air (and oxygen) rushes in may result in an explosion or a 'flash-over'; that is, all the combustibles burst into flames all together.

8.6 EXPLOSION

A sudden and violent release of energy is the characteristic of an explosion, the violence depending on the rate at which energy is released. An overinflated car tyre is capable of bursting which can be prevented by slowly releasing the tyre pressure. Energy releases from explosions are generally physical and/or chemical. There is, of course, nuclear explosion, which we will leave out of our discourse.

Physical energy could be in the form of pressure energy in the gases, strain energy in metals, etc. Explosion of a cylinder due to high gas pressure or its rupture due to metal fatigue/brittle fracture are examples of physical energy. Burning velocity of flames which we have already discussed is of critical importance in explosions. It is a burning (or deflagration) front when the velocity is subsonic (or lower than the speed of round in air). If, however, the propagation is at a supersonic speed, the reaction wave is called a detonation. The peak or highest pressure developed by a gas which burns or deflagrates may increase up to 8 or 10 times the initial pressure as against the 40 or more times the initial pressure a detonating gas develops gives an idea of the destructive potential of these two types of explosions.

In an explosion, the fuel and the oxidant is already mixed and the whole mass burns almost instantaneously. We use the word 'almost', because there is a flame front which is moving at subsonic/supersonic speed and in a limited space (whether confined or not) the reaction time is thus almost instantaneous. As an illustration, let us consider the burning of a block of wood weighting, say, 1kg. A solid cube, we would have difficulty in igniting it if the source of ignition (a candle, not just a match stick) is removed after a short time. It would take quite sometime for the block to burn completely. If the wood is in the form of thin strips or shavings, a match stick would suffice to set it on fire (increased fuel surface area) which would be over within a relatively short time. If, however, we pulverise the block to a fine dust, disperse it entirely in air and ignite, there would be an explosion when it would be consumed almost instantaneously.

Explosions are classified as confined or unconfined. Confined explosions occur within some kind of containment, like a pipe or a vessel or a building, while unconfined ones take place in the open air. A confined explosion could be a deflagration or a detonation, both of which are destructive, but detonation particularly so. The conditions for a deflagration are that the gas mixture is within the flammability range and a source of ignition is present or that the mixture is heated to its auto ignition temperature. Similar conditions are necessary for detonation to occur with the exception that the mixture should be within the detonation range, which (some experts say) is narrower than the flammability range. Alternatively, a deflagration may convert itself to a detonation in a pipe where $1/2d$ is greater than 3. This is, however, very unlikely in a building.

The sources of ignition are generally:
1) flames and hot surfaces;
2) sparks;
3) chemicals (unstable compounds, reactive compounds and catalysts); and
4) static electricity.
5) compression.

Compression, an unlikely source, has proved to be otherwise in an instance when compressed air at 60 psi striking a peculiarly shaped depression in the end of a block of wood set it on fire.

Generation of a blast or a shock wave is one of the main effects of an explosion, which in turn gives rise to overpressures destroying buildings and properties and killing people. The shock wave is due to the rapid rise of pressure in an explosion (8 to 10 times the initial pressure in deflations and 40 times or more in detonations) which moves outward from the center of explosion with the higher pressure parts moving at higher velocities. After travelling some distance, the shock wave reaches a constant limiting velocity which is higher than the speed of sound. Meanwhile, the peak pressure at the front of the shock wave also falls as it travels.

A sort of scaling is done to characterise the effects of a blast wave from an explosion which dates back to 1915. Hopkinson of the U.K. Ordnance Department postulated that two charges of different weights of the same explosive would generate similar blast waves at distances R which are proportional to the diameters d of the charges. Considering that the energy E of a charge is proportional to its weight and since the diameter of a spherical charge is proportional to its weight, Hopkin on formulated:

\[
\frac{R}{W} = \frac{R}{W} = Z
\]

Where, Z is a proportionality constant or scaled distance from the exploding source of the blast wave. Hopkinson has been proved correct by many research workers who measured overpressures at various distances from different sized charges of diverse explosives. Those difficult investigations had their usual uncertainties, but it was found that most of the explosives can be related to TNT equivalent and represented by a single curve on a log-log plot. The Figure 8.7 shows the log-log graph of overpressure-scaled distance of TNT explosives or the equivalent of some other explosive.

Now that we have made the TNT as our point (or rather the explosive) of reference, let us consider what happens when we set off 1 lb (453.4 gms) of it. Its volume is around 300 ml, the size of an orange and it can release 500 kcal of heat, for which it needs no air. 0.1 lb of petrol also releases that amount of heat, but needs a lot of air, while doing so. On detonation, which takes 12.5 micro seconds or 1/30,000 th of second this 300 millilitre volume will hold 330 litres of heated gases at 3600°C and at a pressure of 1,09,000 atmospheres or 1.6 million psi. This extremely high-pressure gas expands in all directions generating a spherical high wind or the blast wave. If it is close to the ground a shockwave similar to that created due to the fall of a very heavy weight is produced. If it is within some form of containment, the reaction rate is greater producing more extreme pressure and still higher temperature. The energy released by the source interacts with the inert surroundings in a number of ways:

a) Energy is radiated by the hot source gas to the surrounding air as it cools. This process is over quickly and occurs early in the distribution process.

b) The extremely high pressure gas pushes on the surrounding air generating a blast wave that has kinetic and potential energies. The kinetic energy dissipates as the blast wave expands, falling to zero at a further distance. The spreading blast wave passes on its potential energy to the surrounding air and since the atmosphere is very much agitated and churned up, the potential energy is given up and ultimately it returns to its ambient level.
c) Both kinetic energy and potential energy is imparted to the fragments of materials ejected from the source centre which follows random and parabolic flight paths. They lose the kinetic energy when they come to rest after which their potential energy is constant.

With regard to effects, let us begin at the ground level where explosions on the surface, especially those of condensed phase (gelatins, slurries, cartridges, etc.) explosives, often form a crater. The size of the crater formed depends on the type of soil and the magnitude of the explosion but generally the diameter is given by

\[ D = 1.5 \sqrt[3]{W} \]

Where, \( W \) is the weight of the charge in lbs and \( D \) is in feet. Likewise, the depth is also dependent on the soil characteristics and is about a quarter of the diameter. The crater is formed due to the scouring action of the blast and the scooped out earth, pebbles and debris are ejected like missiles and damage things coming into their paths.

Tests were carried out on living animals, like mice, rat, pig, dog and goat to find out what constitutes 50% of a lethal dose (\( L_{50} \)) of blast overpressure. Extrapolating the information, it has been found that \( L_{50} \) for a 70 kg animal (man) is exposure to 55 psi for 400 milliseconds; other tests to find out physiological effects indicate that an overpressure of 1 psi knocks a man down and 5 psi cause the eardrum to burst; at 15 psi lung damage commences for some people and 40-80 psi is the range for severe damages to occur; and 100-120 psi is the threshold for lethality while death is certain at 180-230 psi.

As per structural elements and structures, window glass shatters at 1 psi; corrugated asbestos sheet shatters, aluminium/steel panel buckles and wooden structure fails at 1-2 psi, and concrete/cinder block wall collapses at 2-3 psi. At 5 psi Steel-framed, steel panel structure collapses and steel storage tank ruptures at 3-4 psi wooden poles snapped into
2-3 pieces. At 7-8 psi, shear and flexure failures occurred and brick (8”×12”) walls collapsed.

The discourse we had so far related mostly to condensed-phase explosions. Another type of explosion which could occur within or near a building is the gas-phase or flammable gas explosion or explosion of a cloud of flammable vapour. The differences between a TNT (condensed-phase) and vapour cloud explosion are 1) a large volume of cloud; 2) relatively low overpressure at centre of source; 3) different initial shape of the blast wave, and 4) longer duration of the blast wave. (1) is quite obvious when we compare (from our earlier study) 1 lb of TNT in the shape of an orange to the many times large volume of 0.1 lb of petrol vapour along with the necessary air for complete combustion. (2), (3) and (4) are not so obvious, but become so considering the initial volumes of the two charges. For instance, the TNT developed a pressure of 109000 bars on detonation, while petrol vapour-air mixture, which deflagrated, would develop around 10 bars of pressure. After the Flixborough (U.K.) disaster of 1974 in which 30 tons of cyclohexane exploded, the vapour cloud was estimated at half a million cubic metre and the overpressure at 0.7-1.0 bar.

Unconfined vapour cloud explosions (UVCE) may occur at a point some distance from the vapour release and thereby endanger a considerable area. The Flixborough disaster in U.K. (1974) involving 30 tons of cyclohexane was an UVCE, which gave an explosion equivalent of some 16 tons of TNT. Another type of explosion which can occur affecting a building is the Boiling Liquid Expanding Vapour Explosion. They are so called because the liquid stored under-pressure in a container converts itself to a gas or vapour on rupture/release, which may then from a vapour-air mixture and explode finding a source of ignition. In Feyzin, France (1966) a sphere containing propane (which is a gas ordinarily, but stored as a liquid under pressure of around 200 psi) developed a leak and caught fire. The fire continued to burn for 1.5 hours, the pressure inside the sphere increased and (although the relief value opened) the sphere burst. Admittedly, such gases under bulk storage are kept in special installations with necessary safety measures; but, there could be (and were) accidents involving tankers carrying such liquified gases near building sites.

8.7 HAZARDS

We have already defined hazard as something that harms and naturally our concern here will be the hazards that cause fires in buildings. There are broadly four, like lighting, heating processes carried out and human negligence. A hand lamp left on among old newspapers, a dish cloth hanging over a burning oven, an overturned can of paint removing spirits etc., illustrate hazards leading to accidental fires in buildings. Using insurance terminology, we will call them direct hazards. Then, there are contributory hazards, which help the fire to grow and spread. These would be wood paneling in rooms, wood interior partitions, unprotected doors and openings in floors and walls through which fire may pass, concealed spaces where a fire may start and grow unseen and the like. Also there are hazards bringing in further losses. An exposed steel column buckling in fire and bringing down the roof, smoke billowing in through air-conditioning ducts fouling computers and electronic circuitry and water for fighting dousing everything in sight and making them unfit for use. Thus, hazard need not be limited to fire, electricity, chemicals and such. Even the agent of deliverance from fire (water) could be a hazard. It is certainly so in the basement of a building, near a nullah that occasionally overflows, specially when it contains valuable goods.

So, what should be done in a building to eliminate, reduce, control or mitigate the hazards that could be present. The first thing that is necessary is to have an awareness. We should be aware of the hazards, even when we are doing nothing about it, taking it as an occupational necessity or a trade-off for some benefits or an acceptable risk. The last option raises the question acceptable to whom and is the subject matter of a continuing debate. Elimination of hazards means saying no; for instance, we need not store in bulk explosives or flammable materials or toxic compounds even when those are needed for some purpose or the other in our daily work. The hazards which are unavoidable in such
a context can be mitigated to some extent by structural protection, like a building of good
construction, if not fire resistant.

The utilities there should be dependable, the machinery suited to the purpose for which
they are used and above all a general attitude of care that goes under the omnibus term of
housekeeping. Indeed, it is good housekeeping that reduces, controls and mitigates
hazards. It means keeping things in their proper places like waste in a receptacle and
flammable liquid in a closed container. It means ensuring that neither the machines nor
the electrical wirings are overloaded. It means checking the fire pump daily, even though
it has not been used for once to fight a fire since installation. Good housekeeping consists
of attention to all these small details, which become very important during emergencies,
generally allowing no time for rectification.

So far we have discussed hazards in our work-a-day environment, on what is regarded as
micro-level. On a macro level, that is, in the larger context of the society, things are not
so simple. Good engineering management is not always the answer to societal hazards.
The necessary requirement in such situations is a culture that distinguishes between safe
and unsafe habits. We concern ourselves with such issues because of the complexities of
the time we live in, the interdependence between apparently unrelated entities and our
vulnerability to the consequences of hazards elsewhere. Discussing why warnings of
hazards (disasters) are sometimes ignored, behavioural scientists observe that it is the
sense of personal invulnerability which is essential for most individuals to maintain to
enable them to go about their daily business without constantly worrying about all the
possible hazards that could threaten them. It would appear that the act of living itself is
hazardous, we should learn how not to add any more to it.

8.8 EXPOSURES

Exposure in the context of fire safety in buildings would mean of being subject to
hazards originating elsewhere. The condition for this is to have some sort of
communication with the point of origin to avoid which it is necessary to have some sort
of separation. A wall is such a separation, but there are doors and windows on it which
affect separation even though the wall is fire resistant.

Let us consider a room used for storage on the ground floor of a building. The building is
of r.c.c. construction, its walls and roofs are of 4 hours fire resistance. There are windows
on the outside wall of the room, barred and glass-paned a wooden door opening into a
corridor leading to other parts of the building (Figure 8.8). The room is used for storing
files and papers and over a period of time it has become a repository of broken furniture,
discarded furnishings and the like. Someone in a hurry during a weekend left an open
container of paint and rags used for wiping paints. A fire started in the night from some
defect in the electrical wiring. Although the windows were closed the glasses broke due
to the heat within five minutes. The wooden door withstood the fire for about ten minutes
after which it also burnt down. The fire then came out in the corridor and spread among
the discarded materials kept there (Figure 8.9).
With minor variations here and there, that is how fire spreads from one room to the other. If finds a way to the upper floors through the staircase lobby. It also comes out of the windows and instead of burning away from the walls, cling to it and then get sucked into upper floors through the windows there (Figure 8.10).

This, however, is not considered as exposure by the insurance people; they call it a communicating hazard. Such communication can be stopped by fire doors, which have some degree of fire resistance if built and installed as per specifications. Normally, left open for the movement of people and materials, they close at the time of fire. Usually, the self-closing mechanism is as shown in Figure 8.11. The fire in the area to be separated from the rest burns down a fuse when the weight drops and the door rolls down closing the gap. As the doors are generally of half the fire resistance of the separating walls, it is customary to use double doors. To delay, say, after fifteen minutes. Lift shafts, ducts passing through walls and floors, cable holes for similar purposes also provide fire communication and help fire to spread.
Exposure to insurance people is the hazard which they face, like the burning building shown in Figure 8.10 across a street. It could also be the next adjoining building provided the separating wall is a perfect party wall, failing which it is a communicating hazard. A perfect party wall is of 16" thick brick or 13" R.C.C. and is carried up to the roof and built into it without a gap. On the roof, it is raised at least two feet to prevent flames, which may shoot up through the roof of the next building to curl over and affecting it. (Figure 8.12). We refer to insurance practice, because a lot of information on fire has come from the insurance experience over the past hundred years and more.

![Figure 8.12: Perfect Party Wall](image)

Likewise, an open yard bulk storage of combustible materials, like hay, bamboo, straw, oils, etc. within 15 meters of a building constitutes an exposure hazard. So does a saw mill with its timber yard in the open, but there the distance is double due to the flying brands (glowing embers) that a timber fire is likely to produce. In fact, exposure hazards of this nature are dealt with in municipal zoning schemes where specific areas are set off for hazardous trades, factories, offices, residences and such. For instance, according to National Building Code (Group I, part IV, fire protection) occupancy classes to be accommodated in the zones of a city are:

<table>
<thead>
<tr>
<th>Zone</th>
<th>Occupancy Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A,B,C,D,E&amp;F</td>
</tr>
<tr>
<td>2</td>
<td>E&amp;G</td>
</tr>
<tr>
<td>3</td>
<td>G&amp;H</td>
</tr>
</tbody>
</table>

Where, A is residential, B, educational; C, institutional (hospitals, prisons, etc.); D, assembly (cinema, theatre, etc.); E, business (offices, etc.); F, miscellaneous; G, industrial and H, storage. Incidentally, the code which categorises buildings on their fire resistance (class I-4 hrs., class II-3, class III-2, and class IV-1) states that zone 1 may have any category, zone 2 is open to classes I,II and III, and zone 3 is restricted to either class I or class II. In addition, there are other points for consideration, like the fire fighting facilities available, the floor area ratio (total floor area of all the floors/plot area), the ponting, width of the street and so on.

Conflagration hazard is the extreme form of exposure and is likely to be found in older sectors of the cities with narrow streets having buildings of various types carrying out diverse trades, some of them hazardous, fires in such areas are difficult to control and may go out of hand, especially in the summer season.

8.9 **ELECTRICAL INSTALLATIONS**

Electricity is described as hidden heat in view of the fact that whenever current is passed through an appliance to obtain light (as in a lamp), heat (as in a heater) or work (as in a motor) there is a heating effect. The lamp filament, the heating coil and the motor.
winding are all heated up, the first two giving light and heat respectively while the third is doing some work, like driving a pump. The cables supplying current to the appliances are also heated which is negligible if the cables are of proper thickness. If, however, more appliances are supplied current through these cables, the increased current would heat up the cables and make them hazardous, considering that the heating is proportional to the square of the current flowing, this would lead to a breakdown of the insulation.

Excepting special purposes, like feeding current to overhead travelling cranes, cables are provided with insulated covers. The insulating materials are bad conductors of electricity and offer much more resistance than the current carrying core. When the insulation is damaged mechanically or becomes wet or is weak due to aging it would offer less resistance and the voltage could be sufficient to force some current through the insulation due to the defect. Due to this leakage, more current would now flow than that consumed by the appliance. Such short circuits are quite dangerous. The building fire shown in Figure 10 is stated to have started from a short circuit in the cable of a window-type room air conditioner.

In such a situation a fuse could prevent (but, not always) current overload by cutting off the supply. The fuse in its simplest form is a short length of wire which melts on heating thereby breaking the current path. A part of the circuit, ordinarily it allows current to flow through, melting when there is an increase. It should, however, be noted that there may be sometime lag before the fuse melts and the excess current during that short interval could heat and ignite flammable materials nearby, specially gases, thus starting a fire.

Earthing is connecting to the general mass of earth all metallic parts of the appliance, not meant for carrying current, by a wire. Such metallic parts or work are the frames of motors, the housing of the motor starters, the body of an electric iron, the steel pipes or conduits containing cables (and preventing mechanical damage to them) and so on. Should there be a current leak through the insulation, it would raise the temperature of the body of the appliance thus becoming a source of hazard. The earth connection would avoid this by providing a ready passage, the current would further increase thereby melting the fuse. In this manner, the earth connection (or the earthing) helps in isolating the installation and prevent local heating.

All this should be supported by a conduit system carrying the cables. The conduits are to be electrically continuous and earthed properly so as to provide a ready path to any current leaking to the insulation. In steel conduits, the pipework itself provide the earth connection (subject to it being continuous electrically) while in PVC conduits a separate earth wire of proper grade should be present.

Having ensured that the materials used are of required specification and that the workmanship is of a good if not high standard, it is necessary to check that there are no defects in the insulation, the primary requirement for fire safety. Electricity flow through almost all materials, some like copper allowing easy passage. Leakage's thus cannot be entirely stopped, but there is a standardised safe limit which is checked by measuring the resistance in megohms between the current carrying parts of the installation and the earth. This is found out by the megger test, a high reading there (sometimes, even infinity) indicates a very good installation. If, however, the reading is low, then it is not so, due to unnecessary leakage which is perhaps making the installation hazardous. Another benefit of a regular schedule of tests is that it shows the deterioration that is taking place or the damage that has occurred inadvertently. In such an eventuality, there would be time for rectification before the situation becomes dangerous. Although insulation failure is the primary cause of electrical fires, one of the reasons leading to deterioration of insulating properties is overloading. Not only the cables should be of proper thickness, but they should also not be used for carrying currents exceeding the rated capacity. If more and more appliances are connected across, more and more current would flow. Considering that heating is proportional to the square of current, the overloading would heat up the cable more and more leading to cooking of the insulation, its gradual weakening and ultimate failure. A commonly observed method of overloading is to fit adaptors to socket outlets thus burdening the installation with appliances much beyond its capacity to serve. Excess overload may result in a blown fuse, it may also lead to a fire.
A blown fuse indicates that there may be a fault somewhere, on replacement if it blows again, then a thorough check to locate the fault is necessary; replacing it with a bigger fuse would invite bigger trouble. A better alternative to the fuse is the earth leakage trip, which automatically breaks the circuit when leakage current flows from the installation to the earth.

Arcing and sparking observed when a switch is closed or opened could be a source of hazard where flammable gases/vapours are present. The installations there should be flame proof, even the telephones need be so at some locations. The lids, covers and bodies of such equipment are of robust construction, designed to withstand the explosions that may occur inside, but do not allow the flames to come out and ignite the flammable vapours that may be present. A cable that is damaged mechanically would also spark when the current jumps the gap between two broken strands of the wire, igniting the insulation, if not the combustibles nearby.

That is the objection against the use of flexible wiring. They trail on the floor, over things and tend to get hidden from view. Accidental damage in such instances is not too distant a hazard with all its consequences. In view of this, uses of flexible wiring should not be resorted to and wirings should be of a permanent nature. For portable appliances, where flexes cannot be helped, the cable should be heavily insulated if not armoured. Housekeeping is of great importance here, ensuring that the portable appliances are returned to proper storage at the end of the day.

Thus we return to the matter of housekeeping, but deal with it here in respect of appliances that are commonly found in buildings. For instance, fuse boxes should be so located that the motten fuse does not fall over combustible materials. It is also necessary that switch boards and switch gear installations are made of incombustible materials and are placed in dry, well-ventilated areas. Dirt and waste should not be near it and if there is a switch gear room, it should not be used for storage, specially behind the cubicles. Transformers, if they are needed, should be located outside the building. If inside, it should be in a room of 4 hours fire resistance with doors opening on the outside wall. Drains, soakpits and sumps should be provided to catch the oil which may come out (and burn) from a damaged transformers. For large transformers, special from of water spray protection should be provided. Above all, it should be remembered that protection equipment, though they are vital, are not needed every day. Yet, they should be looked after every day, because they cannot look after themselves. Generators used during “load shedding” are of similar hazards as those of the electric motors, but the engines driving them are of comparatively higher hazards. Fuel oils are used to drive them with all its attendant hazards in addition to the hazards of a diesel/fuel oil engine. Such generating plants, should preferably be located away from the building and extra care should be taken to clean the oil that may be spilled during work.

Electric motors are generally well-designed, but the insulation may weaken and a short-circuit may occur. Overload or a foreign body may cause excessive heating and a breakdown, besides there may be arcing and sparking due to dust, neglect and wear and tear. The squirrel-cage motor is more safe, but even there some degree of maintenance is essential. All motors should be earthed by two separate wiring, and drip trays should be placed to catch falling oil and grease. If for some reason, they are required to be placed under a cover, there should be provision for ventilation. Special care should be taken for the cleaning of such enclosures.

8.10 MISCELLANEOUS HAZARDS

Miscellaneous hazards are many; it could be an adjoining, communicating building left unattended. Things could go wrong there, threatening the safety of its neighbours or it could be the employee’s canteen giving rise to a difficult to control. In fact, the list is quite long and we will return to an aspect each of combustion and electricity not dealt with earlier to highlight such hazards.
8.1.0 Spontaneous Combustion

Combustion, as we have seen earlier, is a matter of fuel and oxygen at right proportions (or nearly so) with the necessary addition of heat. Spontaneous combustion results from the presence of the first two without heat being added from an external source. The heat develops from slow oxidation of the fuel materials which finding no ready way of dissipation raises the temperature until the autoignition temperature is reached. It follows therefore that spontaneous combustion can not take place in well-ventilated spaces, where conduction, convection and radiation takes away most of the heat developed. Normally, spontaneous combustion usually commences due to one of the following reasons, singly or in combustion:

1) slow oxidation starting at ambient temperature;
2) porous combustible material absorbing oxygen from air; and
3) bacterial action

The most common example of (1) is oily waste. Usually left in a corner and allowed to accumulate over days, they would be seen smoking, if not flaming one day. The oils that bring about this reaction (susceptible to slow oxidation) are the unsaturated vegetable oil, like linseed oil. As regards (2), a sponge well-soaked in linseed oil illustrates the point. The porosity may be due to the arrangement of stacking. Heaps of small lumps of coal, especially the unfired variety, is very susceptible. Likewise, textile, fabrics with their large fuel surface areas are good combustible materials and in stacks were well insulated (by the bales of textile) by sizable pockets of air (oxygen). The bacterial action usually takes place in freshly cut hay or grass when the vegetable fibres continue to breathe for some time. This produces heat and at the end of the process (taking place in unventilated spaces) there could be charring and ignition. It should be noted that bacterial action is usually limited to the ambient temperature range between 5 and 50°C. They are most active at temperatures above 35 °C.

8.10.2 Static Electricity

The protons and electronic in all matters carry a definite amount of electricity, with protons positively and electrons negatively charged. Thus in a neutral matter, the charges are equal, holding each other in check. It therefore follows that a positive charge could not arise without an equal negative charge surfacing somewhere. Positive charges repel other positive charges attracting negative ones, which is the pattern followed by the negative charges.

Electrons are the carriers of current along a cable; in fact, the current flows in a stream of electrons. In conductors, they move freely; in insulators, they move with difficulty. The property of self-repulsion among like charges causes a surplus charge on a body to appear on its surface.

When two surfaces of materials initially touching are separated suddenly a negative charge is left on one and a positive charge on the other surface. If this is done quickly, the charges appear and accumulate more rapidly than they could dissipate. In this manner they are produced more rapidly in insulators than they are in conductors where they could flow easily.

Thus, for the production of static a solid has to move over a solid or a liquid and vice versa. Gases moving over solids or liquids do not generate static unless they contain dusts. There is normally a potential difference between two surfaces when they are in contact and thus work is done when they are separated which raises the potential difference further. At the beginning of the separation the charges can and do flow across the gap. In conductors, the charges flow together early; but between a conductor and an insulator the separation may be much quicker than the charges to flow leading to a very high potential difference, as much as 1000 volts, between the two.

Arching, which may result in such an instance, could be able to be very hazardous in a flammable atmosphere. Fortunately, a secure earthing connection to all bodies (prone to develop static) would drain away the charge. This is however; not effective for non-conducting surfaces where the charges will drain only at the points of the body with the
earth. Humid air has also the property of stopping the accumulation of charges. When the relative humidity is above eighty per cent charges do not accumulate at all and leak away rapidly. (Water being a conductor of electricity.) The opposite is therefore true in dry climates where one should always be careful to prevent accumulation of static, the problem there being more acute and urgent.

**SAQ**

1) **Define fire resistance. What are the conditions a fire door should satisfy.**

2) **Distinguish between flaming and glowing combustion. Among freshly-mined coal and coal from a coke oven, which one will burn initially with a flame.**

3) **What is the overpressure at a distance of 75 feet when one lb of TNT is detonated and what will be its effect on a building?**

**8.11 SUMMARY**

We devoted this learning unit to the study of fire safety principles with a special emphasis on their application to buildings in general. We learnt how fires start, spread and grow, what is combustion and how exposures affect the safety of nearby building. We concerned ourselves mainly with the theories here and discussed the rudiments of various types of explosions, although they may not be of much relevance in a number of buildings. We also came to know about various fire tests, hazards and the steps to be taken for their mitigation. We tried to know as much as possible about the phenomenon of fire, accidental or otherwise.

**8.12 ANSWERS TO SAQs**

**SAQ**

1) See section 8.2.3. A fire-door should satisfy the conditions of stability and insulation. As it is not meant to carry any load, it need not be restrained or loaded during the fire test.

2) See section 8.5. Coal from coke-oven is like charcoal, all its volatile constituents have been removed by heating, freshly-mined coal, however, has to get rid of the flammable gases that evolve on heating before it can burn with glowing surface combustion. So, the answer is freshly-mined coal.

3) We have, from Section 8.6:

\[ Z = R/W^{1/3} \]

here \( R = 75 \) & \( W = 1 \) lb

\[ Z = 75/1 = 75 \]

From the curve at Figure 8.7, we read, overpressure = 0.5 psi at 75 feet. Therefore, the overpressure will be 0.5 psi and all glass panes will be broken in the building.