

Building Surveying

BCGSV5009A

**Assess the Impact of Fire
on Building Materials**

Learning Manual



Acknowledgements

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Enquiries should be addressed to:

Institute of TAFE Tasmania
GPO Box 2015
Hobart TAS 7001
Tel : (03) 6233 7900
Fax : (03) 6233 7997
Email : lms@tafe.tas.edu.au

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CHAPTER 1

Combustion

Element

Research combustion process as it relates to different materials

Performance criteria

1. Processes and flame characteristics of combustion of solids, liquids and gases are identified and recorded
2. Factors contributing to combustion are identified and recorded
3. Endothermic and exothermic processes are researched and recorded
4. Heat of combustion fuels are calculated without error
5. Factors contributing to propagating of flame front are analysed and recorded

Introduction

This module is designed to introduce the building surveyor to the concepts involved in the relationship between building structures and fire.

To properly understand the dangers associated with fire in materials and structures, it is essential that building surveyors can relate the need for regulations and precautions to the mechanisms of fire itself. This allows the building surveyor to assess the merits of structures not only with regard to the composition and fire characteristics of the materials, but also with regard to the end use of the building itself.

Chapter overview

This chapter will give you a detailed look at the processes and flame characteristics of the combustion of solids, liquids and gases. You may have wondered why some materials burn more quickly and with a different coloured flame than others and why some materials produce more smoke than others. Much of the explanation can be linked to the chemical reactions that are taking place when materials burn. So this chapter examines the chemistry of combustion and how different compounds can radically change the nature of fire.

How does combustion relate to the state of fuel material?

Material may be in one of three states, solids, liquids or gases. Most materials will eventually burn but only in their gaseous state.

Solids, liquids and gases differ in the way that their molecules are arranged, the amount of movement that these molecules are allowed within the structure and the speed with which they travel.

The important thing to remember is that of the three states of matter, it is vapours or gases that burn; solids and liquids must change to the gaseous state before they will burn. There are a few exceptions such as carbon which can oxidise in the solid state. Generally it is easier to turn liquids into the gaseous state than it is solids.

Endothermic and exothermic processes

Before we go on to investigate the nature of combustion of the different states of matter, we need to look at the processes of adding heat or taking heat from the surroundings.

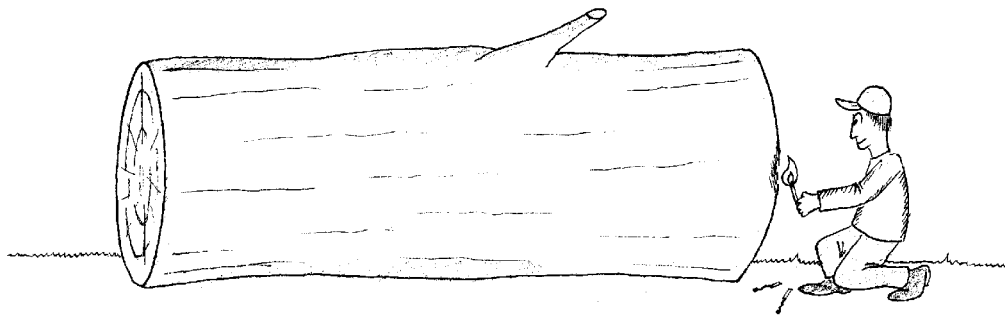
Initially heat needs to be added to the material to induce it to release gaseous vapour. Adding heat to induce a reaction to occur is an endothermic process.

An example of an exothermic process is combustion. As the combustion reaction is occurring, a by-product is heat, which is transferred to the surrounding medium. When heat is given off as a result of a reaction, this is called an exothermic process.

Most combustion reactions involve a heat input to initiate them and then they become an exothermic process.

How combustible are solids?

You may recall that solids have a very rigid molecular structure. The molecules are packed tightly together, allowing no movement of individual molecules, other than vibration. If heat is applied, the molecules vibrate more quickly and so transfer the heat along the material. If enough heat is applied, the molecules may gain enough energy to break the bonds that hold them together and so the material may melt.



The term pyrolysis is used to describe heat-induced chemical decomposition, resulting in the solid being turned into a gaseous vapour. Some materials melt before pyrolysis occurs.

With some materials, the bonds between molecules are so strong that it would take a very large amount of heat to break them. Before this occurs, some of the surface molecules break free and form a vapour close to the outside layer of molecules. Remember before a solid can burn, heat results in a gas being formed and it is this that burns. The heat allows a chemical reaction to take place between these molecules on the outside of the material and oxygen in the air. Combustion may be in the form of burning, if the vapour has formed, or charring, if it has not.

This is illustrated in Figure 1.1, which shows how solids can either go directly to the vapour state or more usually, via the liquid state.

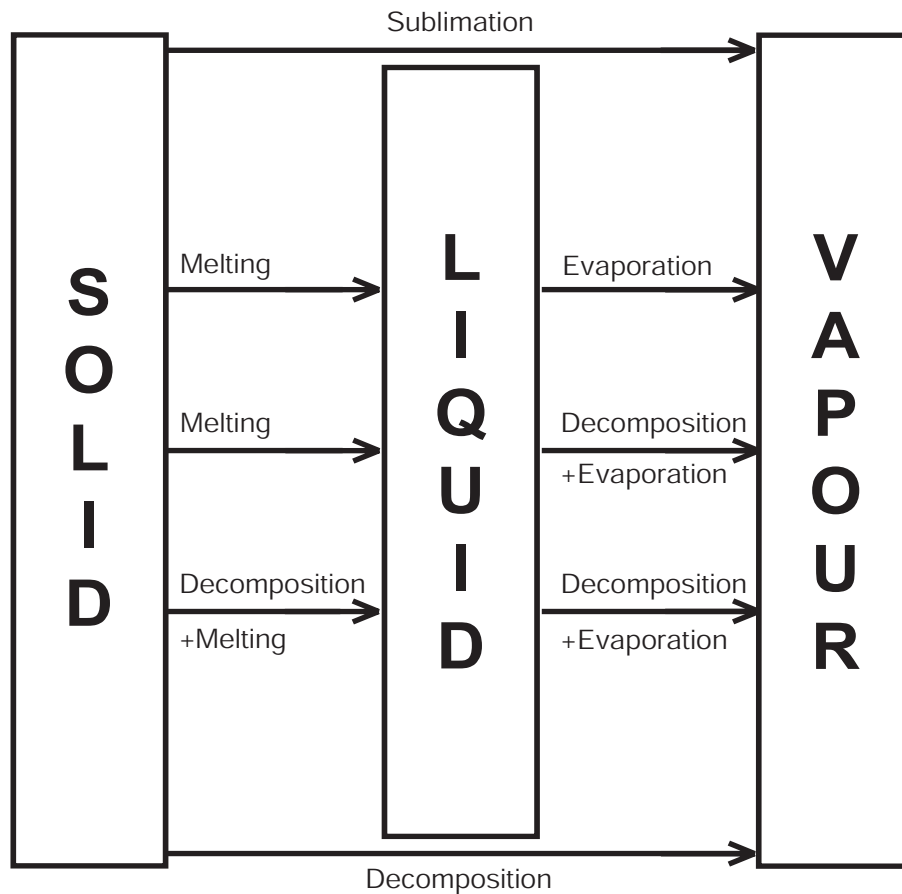


Figure 1.1: Changes of state for solids.

Lower flammability limits

The lower flammability limit for a gas is the amount of gas required to mix with the air to just allow it to burn. This condition usually requires solids to produce gaseous vapour at the rate of a few grams per square metre per second.

The minimum condition for igniting a solid is the heating of its surface to a high enough temperature so that the pyrolysis gases are being produced rapidly enough to exceed the lower flammability limits at the surface.

Ignition of solids

How well a solid will ignite depends upon the ignition source and the pre-ignition heating rate.

Ignition source

A flame or a spark is usually required to ignite material. Spontaneous ignition can possibly occur when material is heated to a very high temperature such as when clothes are placed too close to a radiant heater.

Pre-ignition heating rate

Sometimes the material loses heat to the outside environment almost as quickly as it gains it. With thick solids, the slower the rate of heating, the less quickly the heat drains off. This is because the heat travels through the solid at much the same rate as it is being supplied and the material around the solid also heats up, acting as an insulating barrier. With very rapid heating, the heat differential between the outside of the solid and the inside is so great, that the heat flows away to the interior and the surrounding medium very quickly. This is why trying to light thick solids with a match often proves impossible.

The burning behaviour of solids

After a solid has been ignited, it may exhibit different burning characteristics. Materials can be divided into two classes according to their burning behaviour.

One class burns with the formation of a growing char layer. This includes wood and a very few plastics, as well as charcoal and coking coal. The char layer forms as a thermal decomposition product and slows down the rate of pyrolysis of the underlying material. It is not a good conductor of heat. Ultimately it develops cracks and fissures.

Another class burns with either no char or a small amount of char. This class includes most of the plastics (polyethylene, polystyrene and polymethyl methacrylate), and the absence of char allows the material to combust more freely. This high rate of burning makes these more dangerous than the charring combustibles.

How fast does flame spread in solids?

How fast a flame will spread in solids depends upon three main factors.

Direction of spread

Flame spread in an upward direction is much more rapid than in a downward one. This is related to the upward movement of hot air as it rises, allowing the flame to propagate in the direction of the air movement. This builds upon itself, the air becoming hotter as the flames become longer and larger, so creating more updraught.

Radiative preheating

Preheating of a solid increases the rate of flame spread considerably.

The thickness of the solid

The rate of flame spread is generally inversely proportional to the thickness. That is, the thinner the material, the faster the flame spread. This is related to the

amount of heat required to preheat the material. The thinner it is, the faster the preheating.

How combustible are liquids?

Liquids are different from solids in that their molecules are free to move around within the containers that hold them. As we all know, liquids will run freely when spilled, the molecules still being attached to each other, but in an elastic fashion. This means that the number of molecules that are exposed on the surface of a liquid are limited by the container. The larger the surface area of the container, the more molecules are exposed to form a vapour and these are then available to mix with oxygen.

Again, how flammable a liquid is depends upon how readily individual molecules will turn into a gas and react with oxygen, and how many molecules are available. If molecules do not react with oxygen at all, then the liquid has no flammability. This is the case with water. If the molecules react readily with oxygen then the liquid will be very flammable, as is the case with petrol. Only a small amount of heat energy is needed to start the reaction off with petrol. Understandably, in a spill situation there are going to be vastly more molecules available for combustion than in a container, due to greatly increased surface area.

The other important factor that often makes liquids more flammable than solids, is the fact that the bonds that hold the molecules together are weaker. It takes much less energy to separate the molecules from each other to form vapour than it does in solids.

Flash point and fire point

There are two very important measurements that characterise the fire behaviour of liquids. Flash point is the temperature at which enough vapour is formed to allow a flame to be formed by an ignition source, but the flame will not continue after the vapour has been consumed. Fire point is the temperature at which the flame will continue after the first lot of vapour has been consumed. That is, more vapour is formed as the first lot is consumed. We shall discuss this in more detail in the next chapter.

Flame spread on liquids

Liquids differ from solids in that the rate of flame spread is dependent mostly on temperature. The rate of evaporation of a liquid is highly dependent on temperature, so the amount of vapour available for flame spread is temperature dependent. It is possible to ignite a liquid by localised heating even if the overall temperature is below flash point. This would mean that fire spread at temperatures below a liquid's flash point is much slower than at temperatures above flash point, because the adjacent areas need to be heated first. If the

temperature is above the liquid's flash point, then the flame spread is almost instantaneous. Wind and air convection currents also may affect spread rates considerably as the vapour layer above the liquid is vulnerable to air flow.

How combustible are gases?

Gases, as you would expect now that you have looked at solids and liquids, are generally more combustible than the others. The reason is that, under normal conditions, the molecules of a gas are not bonded to other molecules, but are free to roam inside the boundaries of their container. As such they mix readily with air molecules and are therefore available for combustion, if they are flammable.

Some gases are not flammable, for example helium, neon and argon. Other gases such as carbon dioxide, nitrogen and water vapour are generally not flammable, unless they are heated to a very high temperature such as in a metal fire.

Flame spread in gases

Any mixture of gas and air within the flammability limits is capable of propagating a flame. The speed at which a flame is capable of moving through the gas mixture depends upon the composition of the gas, the temperature and the pressure. This is known as the burning velocity.

However, there are three reasons why a flame can move considerably faster than the burning velocity.

- **The temperature of the gas.** If this is raised to abnormal levels the gas expands (gas law). This causes motion of the gas so that the flame is carried toward unburnt gas.
- **The angle at which the gas is moving into the flame surface.** The burning velocity of the flame will change according to the angle of the flame.
- **The type of flame that is being propagated.** Burning velocity is based on laminar flame propagation (taking place along straight lines with little fluctuation in behaviour). A turbulent flame will propagate several times as fast as a laminar one.

How do free radicals contribute to flame propagation?

All living and non-living things are made up of tiny particles called atoms, which consist of a nucleus in the centre and electrons, which are negatively charged particles that move around the nucleus. Positively charged particles called protons and uncharged particles called neutrons make up the nucleus.

If atoms join together, they form larger particles called molecules. Molecules may be made up of the same type of atoms or of different types of atoms. The charged electrons usually are shared or given up by one atom to another. In either case a

bond is formed which holds the atoms together. When this happens the positive and negative charges that make up atoms all balance out to make them neutral.

In free radicals, although the atoms have a neutral charge, they are chemically unstable in that they actively seek out other atoms to react with. This is because one or more of the electrons that are attached to them are no longer in pairs. In symbol form this is indicated by placing a dot after the symbol or formula. For example a chlorine molecule is written as Cl_2 , while a free radical chlorine atom may be written as $\text{Cl}\cdot$. Because they now have one unpaired electron, this makes them chemically very active, ready to react with other elements or compounds that come along. For example the most common free radical is the hydrogen ion. This results from the breakdown of the hydrogen molecule into two hydrogen atoms.

Free radicals are important in the series of chemical reactions we call combustion. A chemical reaction occurs when atoms join up, bond or are separated.

A flame front is set up when an ignition source is established in a flammable medium. This enables a chemical reaction to take place in the layer of gas adjacent to the ignition source. As the temperature adjacent to the flame rises, the production of free radicals accelerates and leads to oxidation reactions between the free radicals, the gaseous vapours and any available oxygen. The higher the temperature in the vicinity of the front, the faster the production of free radicals and gaseous vapour and the greater is the availability of individual atoms or molecules for a reaction with an available oxygen atom. This means that the progress of an advancing flame front is very much dependent on the temperature, as we observe in a real situation. For solids and liquids, the temperature of the flame front heats up the material until it liberates combustible vapours and then proceeds as for gases.

Self-help exercise 1.1

1. Pyrolysis means.
 2. Of the three states of matter, only. burn.
 3. Adding heat to a reaction is an process.
 4. The lower flammability limit is.
 5. Fire point is
-

Understanding chemical reactions

The following pages go quickly through a revision of basic chemistry to refresh your memory. If you find some of the material is still not crystal clear, then you should refer to a basic chemistry text before proceeding to the next section.

All the chemicals that make up this world are examples of matter, whether they make up books, food, people or anything else you care to name. Matter is anything that occupies space and has mass.

Matter combines in an incredible variety of ways to form different materials. It generally falls into three different classes, elements, compounds and mixtures.

Elements

These are pure substances and there are a limited number of known elements. Elements are made up of atoms of one type. So far there are 108 known elements, but we only need to deal with a much smaller number. Many of these elements occur only in very small amounts and are not often encountered.

Elements serve as the building blocks for all the more complex compounds that we may come across. The 108 elements that have been identified can be viewed in an arrangement called the Periodic Table of Elements. We will examine the organisation of the Periodic Table later in this section.

Compounds

Elements combine in chemical reactions to form compounds. A compound is a substance that is made up of two or more elements. For each compound the elements that make it up are always present in the same proportions by mass. This means that in any sample of a particular compound the ratio of the mass of the atoms of the different elements is always the same. When hydrogen and oxygen combine to form water they always do so in exactly the same proportions by weight, that is one gram of hydrogen to eight grams of oxygen.

One of the important things to remember about this process is that when elements form a compound, they lose their identity completely and the new compound formed has totally different characteristics. Referring to water again, under normal conditions, water is a liquid made up of two gases.

Mixtures

Mixtures are composed of elements, compounds or both, that are mixed together, but do not bond with each other. In other words they can always be separated from each other, although this is difficult at times. When mixtures are made, the chemical properties of the constituents do not change. This is quite different

from compounds. Examples of mixtures are salt water, brass, and a sand/salt mixture. All of these can be separated back into their original components.

Symbols, formulas and equations

Symbols

Chemical symbols are used for elements as a form of shorthand. We use these symbols to write formulas, much as we use letters of the alphabet to make up words. Formulas are used to construct chemical equations much like we make sentences from words.

Each element has a chemical symbol assigned to it that consists of one or two letters. This symbol is often related to the English name of the element. The first letter of the symbol is a capital letter, the second is lower case. Some examples are oxygen, O, magnesium, Mg and silicon, Si. All of the names and symbols for the elements are included in the Periodic Table of Elements. A copy of a simplified version of the Periodic Table is included in Figure 1.2.

Elements may occur as atoms or as molecules. Atoms are the small building blocks that make up elements. An atom of a particular element is unique in its structure. Elements are only made up of atoms of that particular type. Sometimes atoms of the same type join together in an element. When two or more atoms join together tightly into a single package, they form a molecule. This means that you may have a molecule of an element (two or more atoms of the same type, eg oxygen, O_2), or you may have a molecule of a compound (two or more atoms of a different type, eg water H_2O). Some elements occur naturally as molecules, eg nitrogen, N_2 , chlorine, Cl_2 , while others occur as single atoms, eg zinc, Zn.

Self-help exercise 1.2

Use the Periodic Table to determine what elements these symbols represent.

1. Mn.
 2. Fe.
 3. Br.
 4. N.
 5. C.
-

Formulas

Chemical formulas tell us immediately what atoms are present in a compound and how many atoms of each element there are. Using the same example as above, water is made up of two atoms of hydrogen (H) and one of oxygen (O). The small number below the symbol tells us how many atoms of that particular element there are in the compound. For example, the compound sulphuric acid, H_2SO_4 , has two atoms of hydrogen, one atom of sulphur and four atoms of oxygen in it.

Some chemical formulas are more complex and may have brackets included with them. The brackets indicate that everything inside the brackets is considered as one unit and the small number after the brackets tells us how many of these units there are. An example of this is aluminium sulphate, $\text{Al}_2(\text{SO}_4)_3$. In this compound there are two atoms of aluminium and three units of sulphate (SO_4). This means in total, three sulphur atoms and twelve oxygen atoms as well as the two atoms of aluminium.

| | | | | | | | |
|---|----|---------------|-----|-----------|--|-------------|--|
| | | Atomic Number | | Name | | Atomic Mass | |
| 1 | IA | 1 | H | 1.00794 | | | |
| 2 | | 3 | Li | 6.941 | | | |
| 3 | | 4 | Be | 9.01218 | | | |
| 4 | | 11 | Na | 22.98977 | | | |
| 5 | | 12 | Mg | 24.31 | | | |
| 6 | | 19 | K | 39.098 | | | |
| 7 | | 37 | Rb | 85.4678 | | | |
| | | 55 | Cs | 132.905 | | | |
| | | 87 | Fr | 223.0197 | | | |
| | | 20 | Ca | 40.078 | | | |
| | | 38 | Sr | 87.62 | | | |
| | | 56 | Ba | 137.327 | | | |
| | | 88 | Ra | 226.0254 | | | |
| | | 21 | Sc | 44.9559 | | | |
| | | 39 | Y | 88.90585 | | | |
| | | 57 - 71 | | | | | |
| | | 72 | Hf | 178.49 | | | |
| | | 74 | Ta | 180.9479 | | | |
| | | 76 | Os | 190.2 | | | |
| | | 78 | Pt | 195.08 | | | |
| | | 80 | Hg | 200.59 | | | |
| | | 82 | Pb | 207.2 | | | |
| | | 84 | Po | 208.98037 | | | |
| | | 86 | Rn | 222.0176 | | | |
| | | 104 | Unq | 261.11 | | | |
| | | 105 | Unp | 262.11 | | | |
| | | 106 | Unh | 263.12 | | | |
| | | 107 | Uns | 262.12 | | | |
| | | 108 | Unk | 263.12 | | | |
| | | 109 | Unl | 263.12 | | | |
| | | 110 | Uun | 263.12 | | | |
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| | | 119 | Uue | 263.12 | | | |
| | | 120 | Uub | 263.12 | | | |
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| | | 122 | Uuq | 263.12 | | | |
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| | | 128 | Uub | 263.12 | | | |
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| | | 130 | Uuq | 263.12 | | | |
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| | | 133 | Uus | 263.12 | | | |
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Self-help exercise 1.3

Write down the number of atoms of each element in the following compounds.

1. Fe_3O_4
 2. NH_4Cl
 3. H_3PO_4
 4. $\text{C}_2\text{H}_6\text{S}$
-

Equations

Chemical equations are written to show the chemical changes that occur when compounds react with each other. It tells us which compounds have been put together to react and what happens after the reaction has occurred.

For example, a simple reaction is copper being heated with sulphur to produce copper sulphide.

This may be written as $\text{Cu} + \text{S} \rightarrow \text{CuS}$

This is very easy to follow as there are no numbers involved in the equation. This is not usually the case as the equations can often be very complex.

Many of the equations that you will encounter contain numbers called coefficients. These numbers are written in front of the compounds and tell us how many molecules of that compound are involved in the reaction.

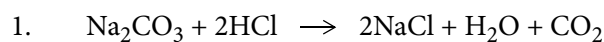
An example of a more complex equation involves the reaction between butane and oxygen. Butane is the liquid used in disposable cigarette lighters. The equation shows us what happens when butane burns.

This is written as $2\text{C}_4\text{H}_{10} + 13\text{O}_2 \rightarrow 8\text{CO}_2 + 10\text{H}_2\text{O}$

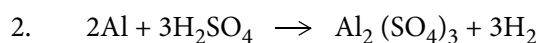
The coefficients tell us that two molecules of butane and 13 molecules of oxygen react to give eight molecules of carbon dioxide and 10 molecules of water. This equation is said to be balanced, because there are the same number of atoms on both sides of the equation. For example, there are eight atoms of carbon on the left and eight atoms of carbon on the right. This applies to all the other elements in the equation.

Self-help exercise 1.4

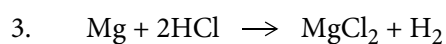
Examine the following equations and write down the number of molecules for each compound.



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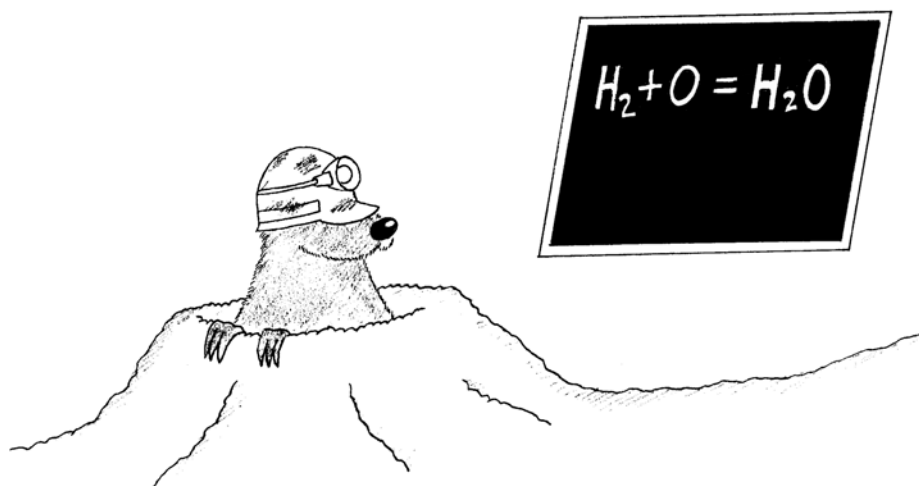


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The mole concept

As we have discussed, elements are made up of atoms. These atoms have a specific structure that can be identified as belonging to that element.

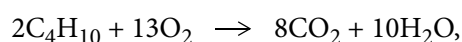
When atoms combine to form compounds, they do so in whole number ratios, that relate to their structure. The subscript numbers that we mentioned earlier, tell us the ratio in terms of the numbers of atoms that are combining. Magnesium chloride for example (MgCl_2) has one atom of magnesium combining with two atoms of chlorine. This is always the case for magnesium chloride and other compounds have their own ratios that always apply.



Atoms, however, are very, very tiny particles and not a useful measure for making up compounds in the real world. Fortunately we can translate the ratios that we have mentioned into measurable weights by looking up the atomic mass for that element. For this purpose, mass is the same as weight, although this is not strictly true in the scientific sense. The atomic mass tells us the weight of a specific number of atoms for that element. Hydrogen has an atomic mass of one, while oxygen has an atomic mass of 16. We can look these up in tables provided in all chemistry texts. In other words, equal numbers of atoms of oxygen and hydrogen weigh different amounts, that is 16 grams and 1 gram respectively.

The question that I hope you have asked yourself at this point is, how many is a specific number of atoms. **Obviously it has to be the same number for all elements and it is labelled as one mole of atoms. This is one of the most important concepts in chemistry.** The exact number is 6.022×10^{23} atoms and this is equal to one mole of atoms of a particular element. Because the mole relates to that number specifically, we can use it to describe molecules as well. That is one mole of water, tells us that we have 6.022×10^{23} molecules of water. Two moles would be twice that amount.

When we deal with chemical equations, the coefficients tell us how many moles of that compound are involved. For example, if we take the same reaction as earlier,



then two moles of butane react with 13 moles of oxygen to give eight moles of carbon dioxide and 10 moles of water.

Now remember that one mole can be translated into grams by taking the atomic mass in grams. In the case of a molecule, this means the molecular mass in grams. **The molecular mass is calculated by adding up all the atomic masses in that compound.**

For example, considering the two moles of butane, C_4H_{10} , it has two times four atoms of carbon and two times 10 atoms of hydrogen. In the tables, we find that the atomic mass for carbon is 12. Four carbon atoms gives us $4 \times 12 = 48$ grams. The atomic mass of hydrogen is 1, so 10 atoms gives us $10 \times 1 = 10$ grams. When we add the two together we get 58. The molecular mass of butane is therefore 58 grams. This is for one mole, so two moles weighs 116 grams. We can do this for all compounds in the equation and this allows us to take the theoretical and convert it into the practical. We can do this for any equation. Remember atomic masses are provided in tables in any chemistry text.

Self-help exercise 1.5

Find the molecular weights for the following compounds:

1. Na_2SO_4
 2. CaCO_3
 3. CHCl_3
-

The Periodic Table of Elements

One table that is used extensively by chemists is the Periodic Table. This is usually included in chemistry texts, often on the inside back or front cover. It can provide us with most of the values that we require when dealing with elements and compounds, as well as giving us an indication of the characteristics of particular elements.

The Periodic Table lists all the known elements in order of increasing atomic number, as shown in Figure 1.2. This starts at hydrogen, with an atomic number of one and works upward. We can use the table to identify the symbol and to find its atomic mass.

Each atom is made up of protons, neutrons and electrons. These are arranged as shown in the diagram in Figure 1.3. Protons are positively charged particles located in the nucleus, together with neutrons which are neutral. Protons and neutrons make up nearly all of the atomic mass of the atom. Electrons are negatively charged particles orbiting the nucleus of the atom. Electrons determine how an element will react with other elements. The number of protons tells us how many electrons are required to make the atom electrically neutral, that is by balancing out the positive and negative charges. The atomic number indicates how many protons there are in the nucleus of each atom.

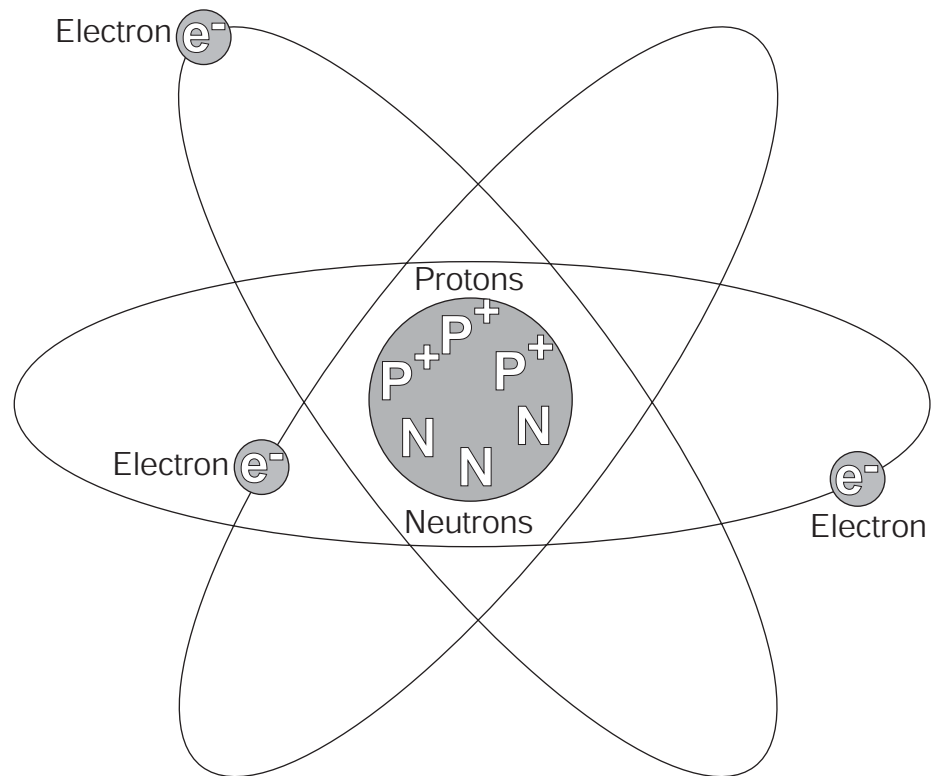


Figure 1.3: Diagram of an atom.

The arrangement of elements in the Periodic Table also indicates whether an element is a metal or a nonmetal in nature. Generally metals are located on the left hand side of the table and nonmetals are on the right hand side. Many compounds are formed through the reactions of metals with nonmetals, so this organisation can be important.

Combustion and chemical equations

What is combustion?

The term combustion usually refers to an exothermic (heat producing) chemical reaction between some substance and oxygen. If we were to look at the products of combustion, we would typically find the presence of molecules made up of oxygen atoms and other types of atoms. For example CO_2 , H_2O , SO_2 , NO_2 .

There are examples of combustion where oxygen is not required. Hydrogen and chlorine will burn, acetylene will decompose and combust, as will hydrazine. Generally the fire protection industry is concerned with the combustion reactions between various materials and oxygen in the air.

Nearly all fuels involved in fires are hydrocarbons. These contain the elements carbon and hydrogen only or at least have a significant proportion of carbon and hydrogen in their structure, with small amounts of oxygen, nitrogen, chlorine or sulphur making up the balance.

For fuels of this type to burn properly, the amount of available oxygen is critical.

If we have exactly the right amount of oxygen available to combust a given amount of fuel, we have what is known as a stoichiometric fuel/oxygen (or fuel/air, because this is the most common source of oxygen for a fire) mixture. This means that at the end of the reaction, all the fuel will have been used up, after reacting with the oxygen molecules. In other words, the oxygen molecules must match up with the fuel molecules in the ratios that are required for the reaction. For example, some fuels may require two oxygen molecules for each fuel molecule in a reaction, while others may require only one oxygen molecule for each fuel molecule.

Remember we are talking about oxygen molecules not air. We can use the knowledge of percentage of oxygen in air to work out air ratios. We will deal with this in more detail later, when we use the reaction equations to help us find the exact ratios for combining fuel with oxygen.

Values for the ideal ratios for combustion of fuels are shown in Table 1.1.

| Fuel | Mix | |
|-------------|-------------|------------|
| | Fuel | Air |
| Petrol | 4.5% | 95.5% |
| Methane | 9.5% | 90.5% |
| LPG | 5.5% | 94.5% |
| Ethylene | 19.5% | 80.5% |
| Acetone | 7.5% | 92.5% |
| Ethanol | 11.5% | 88.5% |
| Benzene | 4.0% | 96.5% |

Table 1.1: A table showing stoichiometric values for fuels and air.

At stoichiometric mix, combustion will be at its most efficient; flame temperatures and heat generated at a maximum and products of incomplete combustion such as soot and carbon monoxide at a minimum.

In Table 1.1 the air/fuel mixes correspond to the mid-point of the flammable ranges of the above fuels. That is, the fuel may burn when there are lower or higher air/fuel mixes but this table deals with the middle of the range.

What happens in combustion

For fuels containing carbon, hydrogen and oxygen (eg. ethanol, methanol and acetone), again at stoichiometric mix, in theory the only products of combustion are carbon dioxide (CO_2) and water vapour (H_2O). However in practice small amounts of carbon monoxide, soot and some oxides of nitrogen (caused by atmospheric oxygen and nitrogen combining chemically in the flame) will also be produced.

Once we introduce nitrogen, chlorine and sulphur into fuels, the chemistry of combustion becomes more complex and gives combustion products such as cyanide, sulphur dioxide, hydrochloric acid and so on.

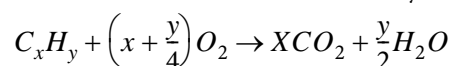
Because of this complexity, we will restrict our chemical calculations, in this manual, to fuels involving carbon and hydrogen or carbon, hydrogen and oxygen.

Equations

As mentioned earlier, at stoichiometric mix a hydrocarbon fuel will produce CO_2 (gas) and H_2O (gas).

Fuel, oxygen and combustion products can be linked in a chemical equation.

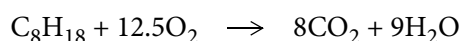
For any general hydrocarbon C_xH_y the following holds true.



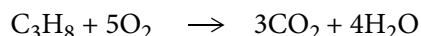
This means that for any of a variety of hydrocarbon fuels, we look at the number of carbon atoms, which equals x , then at the number of hydrogen atoms, which equals y and use these numbers to work out the values for the other molecules in the reaction.

Let's take an example. If we consider octane which has the formula C_8H_{18} , then

$x + \frac{y}{4}$ becomes $\left(8 + \frac{18}{4}\right) = 12.5$. The combustion equation then becomes:



As another example, take propane, C_3H_8 . $x = 3$, $y = 8$. The equation for the reaction is therefore:



Not all hydrocarbon compounds are made up of only carbon and hydrogen. Many contain other elements as well, such as oxygen and nitrogen. These compounds can also be analysed by working out their equation of combustion. They do not follow the rule as laid out above, but have to be balanced on each side of the equation by standard chemistry procedures. This is how most chemical equations are balanced. At this point in your studies it is not yet necessary to do calculations involving other elements.

Now try some examples on general hydrocarbons for yourself.

Self-help exercise 1.6

Work out the equations of complete combustion for:

1. Butane C_4H_{10}
 2. Pentane C_5H_{12}
 3. Methane CH_4
 4. Hexane C_6H_{14}
-

Heat of combustion

Heat reactions

Soon we are going to start determining the heat of combustion of various fuels. Firstly though we need to know about heats of formation because we use that information to determine heats of combustion.

We are delving further into thermochemistry here. That is the branch of chemistry dealing with the quantities of heat evolved or absorbed during chemical reactions. As students of fire behaviour you need to do this because fire is essentially a chemical reaction producing a large amount of heat.

Chemical reactions are either:

- exothermic and produce heat as they proceed (that is, the surroundings get hotter) or
- endothermic and absorb heat as they proceed (the surroundings get colder).

The majority of chemical reactions, including combustion, fall into the first category.

The heat of combustion is defined as the amount of heat energy evolved when one mole of a substance is burned in excess oxygen. The amount of heat change that occurs during the course of a chemical reaction is measured in terms of kilojoules (kJ).

The symbol for heat change in a chemical reaction is ΔH . The symbol for Greek letter delta Δ is often used to denote a change in quantity.

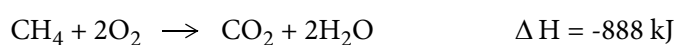
For exothermic reactions ΔH has a negative sign. This is because the heat that is contained in the products of the reaction is less than the heat that was contained in the two reactants that reacted with each other. The negative sign tells us how much less heat there is and therefore how much heat has been given off as a consequence.

This is shown in detail in the example.

Example

If one mole (16 g) of methane (natural gas, CH_4) is burned in air, 888 kJ of heat energy is given off.

Chemically this would be represented in the following manner:



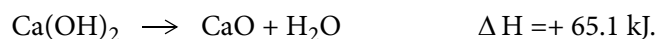
This shows that there was 888 more kJ of energy tied up in the compounds on the left hand side of the equation than in the products on the right hand side. This heat was liberated as the reaction took place.

For endothermic reactions ΔH has a positive sign. This is because the heat that is contained in the products of the reaction is more than the heat that was contained in the two reactants that reacted with each other. The positive sign tells us how much more heat there is and therefore how much heat has been required to initiate the reaction.

Example

If calcium hydroxide is heated, it will form calcium oxide and water. The change in heat required is + 65.1 kJ.

Again, chemically this would be represented in the following manner



This shows that there are 65.1 less kJ of energy tied up in the compounds on the left hand side of the equation than in the products on the right hand side. This means that the calcium hydroxide had to be heated before the reaction took place.

Standard heats of formation

Before we examine the measurement of heat of combustion, we need to look at the way in which heat is used to help produce compounds. Most compounds require heat to get a reaction started. The exact amount of heat required to produce a certain amount of a compound can be measured accurately and there are tables available containing heats of formation values, for a wide range of compounds. We have included a table of standard heats of formation in Table 1.2 for your use.

The standard heat of formation is defined as the amount of heat released or absorbed when one mole of a compound is formed from its constituent elements.

The symbol for standard heat of formation is ΔH_f° .

By definition, the standard heat of formation for a pure element is zero. This means that when we come across elements, such as oxygen or hydrogen that are by themselves in a chemical equation, then their heat of formation is zero.

Example

The heat of formation of liquid water (H_2O) is -286 kJ. Thus when one mole of water is formed from hydrogen and oxygen, 286 kJ of heat energy is released.

Chemically, this would be represented in the following manner:



Now given our statement above, that elements have zero heats of formation, and the fact that the amount of heat on both sides of the equation must be the same, you can see that 286 kJ of heat must be given off to balance the -286 kJ of the heat of formation.

Example

The heat of formation of methane (CH_4) is -75 kJ. When one mole of methane is formed from carbon and hydrogen, 75 kJ of heat energy is released. A mole is the gram molecular weight of the compound. Mathematically we can calculate it by calculating the molecular weight of the compound and putting it into grams. In this case, methane has a molecular weight of approximately 16, so one mole weighs 16 grams.

The heat of formation of octane (C_8H_{18}), one of the main components of petrol, is -269 kJ. When carbon and hydrogen react together to form octane, there is an energy input of 269 kJ, which is stored in the octane as the heat of formation. This energy is released when octane undergoes combustion.

Standard Heats of Formation

| Species | kJ/mol | Species | kJ/mol | Species | kJ/mol | Species | kJ/mol |
|--|---------|------------------------------------|---------|---|---------|-------------------------------------|--------|
| ALUMINIUM | | COPPER | | NITROGEN | | SODIUM | |
| Al (s) | 0 | Cu (s) | 0 | N ₂ (g) | 0 | Na (s) | 0 |
| AlCl ₃ (s) | -704.2 | CuO (s) | -157 | N (g) | 472.704 | Na (g) | 108.7 |
| Al ₂ O ₃ (s) | -1676 | FLUORINE | | NH ₃ (g) | -46.11 | Na ⁺ (g) | 601 |
| BARIUM | | F ⁻ (g) | -322 | N ₂ H ₄ (l) | 50.63 | NaBr (s) | -359.9 |
| BaCl ₂ (s) | -860.1 | F ⁻ (aq) | -329.1 | (NH ₄) ₃ AsO ₄ (aq) | -1268 | NaCl (s) | -411.0 |
| BaSO ₄ (s) | -1465 | F ₂ (g) | 0 | NH ₄ Cl (s) | -314.4 | NaCl (aq) | -407.1 |
| BERYLLIUM | | HF (g) | -271 | NH ₄ Cl (aq) | -300.2 | Na ₂ CO ₃ (s) | -1131 |
| Be (s) | 0 | HF (aq) | -329.1 | NH ₄ I (s) | -201.4 | NaOH (s) | -426.7 |
| Be(OH) ₂ (s) | -907.1 | HYDROGEN | | NH ₄ NO ₃ (s) | -365.6 | NaOH (aq) | -469.6 |
| BROMINE | | H (g) | 218.0 | NO (g) | 90.25 | SULPHUR | |
| Br (g) | 111.8 | H ₂ (g) | 0 | NO ₂ (g) | 33.2 | S (s, rhombic) | 0 |
| Br ₂ (l) | 0 | H ₂ O (l) | -285.8 | N ₂ O (g) | 82.05 | S (g) | 278.8 |
| Br ₂ (g) | 30.91 | H ₂ O (g) | -241.8 | N ₂ O ₄ (g) | 9.16 | S ₂ Cl ₂ (g) | -18 |
| BrF ₃ (g) | -255.6 | H ₂ O ₂ (l) | 187.8 | N ₂ O ₅ (s) | 11 | SF ₆ (g) | -1209 |
| HBr (g) | -36.4 | IODINE | | NOCl (g) | 52.59 | H ₂ S (g) | -20.6 |
| CALCIUM | | I (g) | 106.6 | HNO ₃ (l) | -174.1 | SO ₂ (g) | -296.8 |
| Ca (s) | 0 | I ₂ (s) | 0 | HNO ₃ (g) | -135.1 | SO ₃ (g) | -395.6 |
| Ca (g) | 192.6 | ICl (g) | 17.78 | HNO ₃ (aq) | -206.6 | SOCl ₂ (l) | -206 |
| Ca ²⁺ (g) | 1920 | IRON | | OXYGEN | | SO ₂ Cl ₂ (l) | -389 |
| CaC ₂ (s) | -62.8 | Fe (s) | 0 | O (g) | 249.2 | H ₂ SO ₄ (l) | -814.0 |
| CaCO ₃ (s) | -1207 | FeO (s) | -272 | O ₂ (g) | 0 | H ₂ SO ₄ (aq) | -907.5 |
| CaCl ₂ (s) | -795.0 | Fe ₂ O ₃ (s) | -824.2 | O ₃ (g) | 143 | TIN | |
| CaF ₂ (s) | -1215 | Fe ₃ O ₄ (s) | -1118 | OF ₂ (g) | 23 | Sn (s) | 0 |
| CaH ₂ (s) | -189 | FeS ₂ (s) | -177.5 | PHOSPHORUS | | SnCl ₂ (s) | -350 |
| CaO (s) | -635.5 | Fe(CO) ₅ (l) | -774.0 | P (g) | 58.91 | SnCl ₄ (l) | -511.3 |
| CaS (s) | -482.4 | Fe(CO) ₅ (g) | -733.8 | P ₄ (s, white) | 0 | SnCl ₄ (g) | -471.5 |
| Ca(OH) ₂ (s) | -986.6 | LEAD | | P ₄ (s, red) | -73.6 | SnO ₂ (s) | -580.7 |
| Ca(OH) ₂ (aq) | -1002.8 | Pb (s) | 0 | PCl ₃ (g) | -306.4 | TITANIUM | |
| CaSO ₄ (s) | -1433 | PbCl ₂ (s) | -359.4 | PCl ₅ (g) | -398.9 | TiCl ₄ (l) | -804.2 |
| CARBON | | Pb(OH) ₂ (s) | -515.9 | PH ₃ (g) | 5.4 | TiCl ₄ (g) | -763.2 |
| C (s, graphite) | 0 | PbS (s) | -100.4 | P ₄ O ₁₀ (s) | -2984 | TUNGSTEN | |
| C (s, diamond) | 1.897 | LITHIUM | | H ₃ PO ₄ (s) | -1281 | W (s) | 0 |
| C (g) | 716.7 | Li (s) | 0 | POTASSIUM | | WO ₃ (s) | -842.9 |
| CCl ₄ (l) | -135.4 | LiOH (s) | -487.23 | K (s) | 0 | ZINC | |
| CCl ₄ (g) | -103 | LiOH (aq) | -508.4 | KCl (s) | -436.5 | ZnO (s) | -348.3 |
| CHCl ₃ (l) | -134.5 | MAGNESIUM | | KClO ₃ (s) | -391.2 | ZnS (s) | -205.6 |
| CHCl ₃ (g) | -103.1 | Mg (s) | 0 | KI (s) | -327.9 | | |
| CH ₄ (g) | -74.81 | MgCl ₂ (s) | -641.8 | KOH (s) | -424.7 | | |
| C ₂ H ₂ (g) | 226.7 | MgO (s) | -601.8 | KOH (aq) | -481.2 | | |
| C ₂ H ₄ (g) | 52.26 | Mg(OH) ₂ (s) | -924.7 | SILICON | | | |
| C ₂ H ₆ (g) | -84.86 | MgS (s) | -347 | Si (s) | 0 | | |
| C ₃ H ₈ (g) | -103.8 | MERCURY | | SiBr ₄ (l) | -398 | | |
| C ₆ H ₆ (l) | 49.03 | Hg (l) | 0 | SiC (s) | -65.3 | | |
| C ₈ H ₁₈ (l) | -268.8 | HgCl ₂ (s) | -224 | SiCl ₄ (g) | -657.0 | | |
| C ₂ H ₅ OH (l) | -277.7 | HgO (s, red) | -90.83 | SiH ₄ (g) | 34 | | |
| C ₂ H ₅ OH (g) | -235.1 | HgS (s, red) | -58.2 | SiF ₄ (g) | -1615 | | |
| CO (g) | -110.5 | NICKEL | | Si ₄ (g) | -132 | | |
| CO ₂ (g) | -393.5 | Ni (s) | 0 | SiO ₂ (s) | -910.9 | | |
| CS ₂ (g) | 117.4 | Ni(CO) ₄ (g) | -602.9 | H ₂ SiO ₃ (s) | 1189 | | |
| COCl ₂ (g) | -223.0 | NiO (s) | -244 | Na ₂ SiO ₃ (s) | 1079 | | |
| CEASIUM | | | | H ₄ SiF ₆ (aq) | 2331 | | |
| Cs ⁺ (aq) | -248 | | | SILVER | | | |
| CsF (aq) | -568.6 | | | Ag (s) | 0 | | |
| CHLORINE | | | | | | | |
| Cl (g) | -121.7 | | | | | | |
| Cl ⁻ (g) | -226 | | | | | | |
| Cl ₂ (g) | 0 | | | | | | |
| HCl (g) | -92.31 | | | | | | |
| HCl (2q) | -167.4 | | | | | | |
| CHROMIUM | | | | | | | |
| Cr (s) | 0 | | | | | | |
| (NH ₄) ₂ Cr ₂ O ₇ (s) | -1807 | | | | | | |

Figure 1.4: The standard heats of formation values for a variety of compounds

The main use of heats of formation is in the calculation of the DH values of a wide variety of chemical processes. This can save the need of having to actually run the reaction and measure the heat change.

note

The most important point to remember in any chemical reaction is that what goes in must come out, although it might be in a different form.

As far as heat goes, the sum of the heat change values on one side of the equation must equal those on the other side. This means that if we find out the heats of formation for the different compounds then we can work out what heat value is missing to make both sides equal. This heat value must be the change in heat in the reaction.

Let's look at a worked example

Calculate the ΔH for the reaction $\text{CO} + \text{Cl}_2 \rightarrow \text{COCl}_2$

COCl_2 is the chemical formula for phosgene - a rather nasty poisonous gas.

Heat of Formation $\Delta H^\circ \quad \text{COCl}_2 = -223 \text{ kJ}$

$\Delta H^\circ \text{CO} = -111 \text{ kJ}$

$\Delta H^\circ \text{Cl}_2 = 0$

Remember, by definition the heat of formation of an element is zero.

Now let's examine the summation of the heat on each side of the equation.

On the left side or reactants side of the equation, we have

$$-111 + 0 = -111 \text{ kJ}$$

On the right hand side or products side of the equation

$$-223 \text{ kJ}$$

The difference between the right hand side and the left hand side is -112 kJ .

Therefore 1 mole of CO (28 g) when combined with 1 mole of Cl_2 (71 g) to form 1 mole of COCl_2 (99 g) would release 112 kJ of heat energy.

Heats of formation can be used to calculate heats of combustion for various compounds.

It is useful to be able to compile lists of the heat of combustion of various compounds. This way we can tell how much heat is liberated when a certain amount of material is burned.

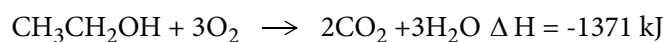
The heat of combustion is defined as the amount of heat energy evolved when one mole of a substance is burned in excess oxygen. Calculating heat of combustion

One of the main uses of heats of combustion is to give an approximate idea of a fuel's heat content and to rank potential fuels in some sort of order. To make our calculations less complicated we can approximate by making two assumptions:

- that combustion is complete (this is not always so) and
- that the only products of combustion are carbon dioxide and water vapour (there are often other by-products such as carbon monoxide).

The heat of combustion of ethanol, the main component of methylated spirit, is 1371 kJ/mol.

This means that burning one mole of ethanol ($\text{CH}_3\text{CH}_2\text{OH}$) would produce 1371 kJ of heat.



Let's have a look at an example

Methane (CH_4). If we burn methane, then we get



Note that the equation is properly balanced. Remember, balancing an equation means that the number of atoms of any element should be the same on the left hand side of the equation as on the right hand side. This is most important as the heat of combustion cannot be calculated without it being so.

On the left hand side of the equation, we have

CH_4 , which has a heat of formation of -74 kJ, plus 2O_2 , which is an element and has 0 kJ.

The total is -74 kJ.

On the right hand side of the equation we have

CO_2 , which has a heat of formation of -393 kJ, and $2\text{H}_2\text{O}$, which has 2 x -242 kJ.

The total is $-393 + -484 = -877 \text{ kJ}$.

This means that to go from -74 kJ on one side to -877 kJ on the other, then 803 kJ of heat must be liberated.

Thus, burning one mole of methane (16 g) would release 803 kJ of heat energy.

Another example

Octane (C_8H_{18}), if we burn octane, we get $C_8H_{18} + 12.5O_2 \rightarrow 8CO_2 + 9H_2O$ (gas).

We are calculating the heat energy to be released when one mole of octane is burnt. Therefore we take one mole of C_8H_{18} and then adjust the amount of oxygen, in this case 12.5 moles. This is the amount necessary to completely convert the octane to carbon dioxide and water.

The heats of formation for octane is -267 kJ, carbon dioxide is -393 kJ and water is -242 kJ.

On the left hand side of the equation the heat of formation of octane is -267 kJ.

On the right hand side we have 8 x -393 plus 9 x -242 kJ. For this side the total is -5322 kJ.

To go from -267 kJ on the left hand side to -5322 kJ on the right hand side, 5055 kJ of heat would have to be liberated.

Thus burning one mole of octane (114 g) would release 5055 kJ of heat energy.

Now try calculating some heats of combustion for yourself.

Self-help exercise 1.7

Calculate the heat of combustion of the following fuels.

1. Acetylene C_2H_2

.....

2. Ethylene C_2H_4

.....

3. Ethane C_2H_6

.....

4. Propane C_3H_8

.....

5. Benzene C_6H_6

.....

Hint

Go back to examine the way to work out the equation for combustion first.
Then look up the standard heats of formation in Table 1.2 for all of the
compounds involved and follow the examples.

Some common heats of combustion

Examples of some values for heats of combustion for some common fuels are shown in Table 1.2. You may note that the value for acetylene is slightly different to the value that you may have arrived at in the calculation. This is because you have not been able to use values to quite the same degree of accuracy as those in the table.

| Some common heats of combustion | | | |
|---------------------------------|----------------------|------------------|--------------------------|
| Name | Formula | Molecular weight | Heat of combustion kJ |
| Cane sugar | $C_{12}H_{22}O_{11}$ | 342 | 5643 |
| Styrene | C_8H_8 | 104 | 4376 |
| Toluene | C_7H_8 | 92 | 3904 |
| Benzene | C_6H_6 | 78 | 3269 |
| Ether | $C_4H_{10}O$ | 74 | 2721 |
| Acetone | C_3H_6O | 58 | 1785 |
| Ethanol | C_2H_6O | 46 | 1371 |
| Acetylene | C_2H_2 | 26 | 1237 |

Table 1.2: Common heats of combustion for a range of fuels.

On a kJ per mole basis, sugar has the highest heat content of the fuels shown in the table.

We can also examine how much heat energy is available in a fuel by looking up its calorific value. The calorific value of a fuel is the amount of heat energy contained in the fuel on a kJ/gm basis. If we compare the calorific values of the fuels in Table 1.3 some interesting results emerge.

| Fuel | Heat energy (kJ) per gram of fuel |
|-----------|-----------------------------------|
| Acetylene | 47.6 |
| Toluene | 42.4 |
| Styrene | 42.1 |
| Benzene | 41.9 |
| Ether | 36.8 |
| Acetone | 30.7 |
| Ethanol | 29.8 |
| Sugar | 6.5 |

Table 1.3: The calorific values (heat energy) for a range of fuels.

As fuels are often measured by weight rather than number of moles, these figures are probably more useful to you than heats of combustion may be. Each measurement though tells us different things about the fuel. We know that acetylene generates considerable heat when burnt and this is supported by the figures in Table 1.3.

We can also make some other observations from the data.

Some hydrocarbons give off more heat than others during combustion. If we were able to have a closer look at the structure of these materials, then we would find that they fall into two classes, unsaturated and saturated hydrocarbons. Unsaturated hydrocarbons generally give off more heat and are more reactive being able to more easily take on other atoms. They are able to do this because the carbon and hydrogen atoms within the structure have double or triple bonds rather than the standard single ones. This allows them to use one of the bonds to take up other atoms. Acetylene and ethylene are examples of unsaturated hydrocarbons. Saturated hydrocarbons have single bonds and cannot easily do this without replacing what is already bonded with something else. Methane and propane are examples of saturated hydrocarbons.

An increase in the number of carbon atoms in a fuel usually means an increase in flash point and a higher heat of combustion value. That is, high molecular weight fuels are more difficult to ignite, but once burning they release more heat.

CHAPTER 2 Flammability and Fuels

Element

Analyse the flammability on the different states of matter

Performance criteria

1. Flammability in terms of the fire triangle and fire tetrahedron theories is analysed and recorded
2. Flammability of matter in physical states is examined and recorded
3. Flammability in terms of upper and lower flammability limits is identified and recorded
4. Factors contributing to the explosiveness of dusts are identified and recorded

Chapter overview

This chapter is concerned with a detailed look at how things burn and how fires are extinguished. We all know that different materials burn with different intensities and rates. When things burn incredibly quickly we may be faced with an explosion. Determining how things burn also enables us to work out how they may be extinguished. Different materials and conditions call for different methods of extinguishment and sometimes different pieces of equipment.

What is flammability?

Combustion is a chemical process that produces a considerable amount of heat and is usually accompanied by a flame. Flame may be defined as a reaction having the ability to propagate or spread through an atmosphere with the emission of heat and light. The flame region is thought to be the region separating burnt and unburnt gases. The flame is the zone in which the chemical combustion processes are occurring.

The flame boundary occurs due to the reaction running out of fuel, or the temperature being too low to allow combustion to continue. Flammability may be defined as being a measure of the fuel/oxidant mixture that will support combustion and allow a flame to spread through an unignited region.

Flames have varying structures depending on the gas or vapour being burned. The differing zones in a flame are often characterised by the type of reaction going on in each zone. If for example, the flame is starved of oxygen, the volatile material may go far in search of oxygen and so produce a long flame. All fires involve chemical decomposition of the fuel. Soot is the formation of carbon rings in the cooler part of the flame from smaller radicals. Carbon monoxide is also given off as a result of incomplete combustion.

How does the fire triangle explain flammability?

Although fire is often seen as an entity in itself, you should always try to remember that it is nothing but a series of chemical reactions.

We can:

- take away any of the compounds that contribute to the chemical reaction
- alter the conditions that govern the chemical reaction.

If we do, we stop or change the reaction and so affect combustion.

Combustion can be described in terms of the fire triangle shown in Figure 2.1 - a concept that you may already be familiar with.

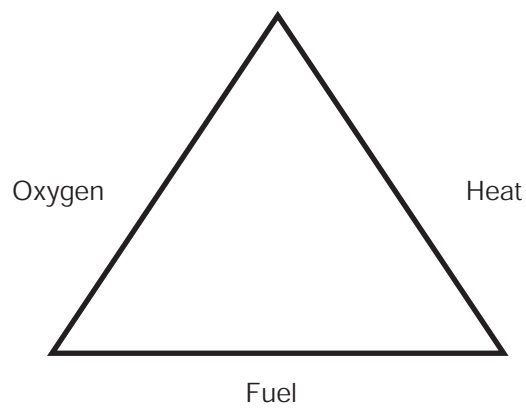


Figure 2.1: The fire triangle.

If we remove one of the components of the fire triangle then combustion will not occur and the triangle collapses.

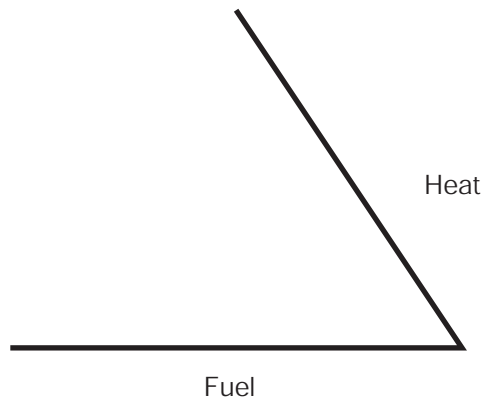


Figure 2.2: The fire triangle with oxygen removed.

Oxygen may be removed by smothering.

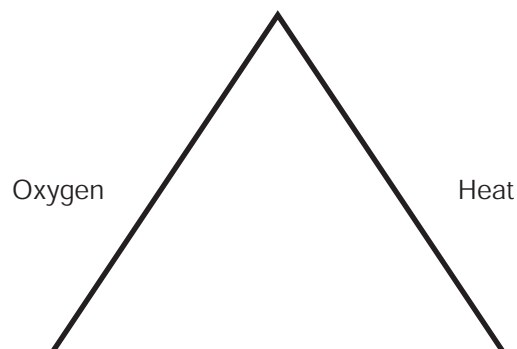


Figure 2.3: The fire triangle with fuel removed.

If fuel is removed the fire starves.

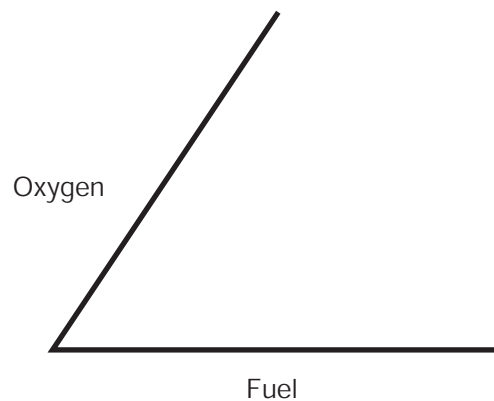


Figure 2.4: The fire triangle with heat removed.

Heat may be removed through cooling.

In all of the cases above, the fire will eventually be extinguished.

However, in the 1950's and 1960's a new type of extinguishing agent, namely the halon gas type (now banned from everyday use) was introduced. When these were used, they did not neutralise or remove any of the three components and yet they put out the fire. This meant that the concept of the fire triangle had to be reviewed. The new concept that evolved was the fire tetrahedron.

The fire tetrahedron

How does the fire tetrahedron differ from the fire triangle?

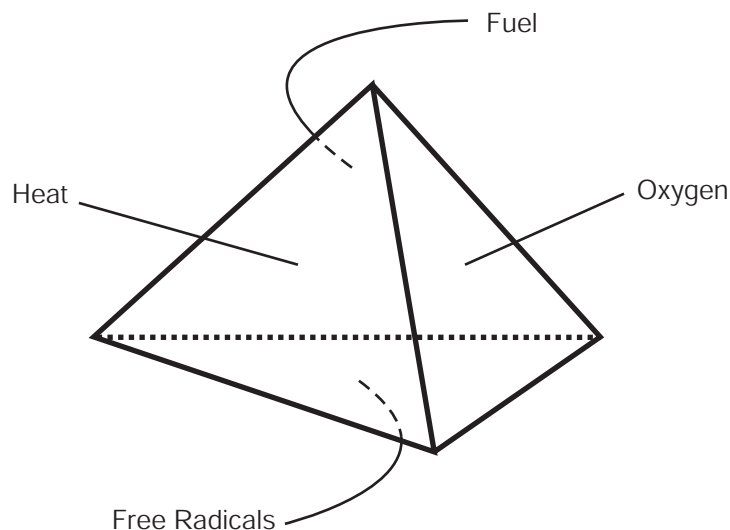


Figure 2.5: The fire tetrahedron.

A tetrahedron is a triangular pyramid. It has four faces as compared with the three sides of the triangle. Each of these represents a requirement for a fire.

The four basic requirements of a burning fire are:

- heat - this supplies activation energy
- fuel - combustible material
- oxidant - usually oxygen from the atmosphere, or from another chemical
- free radicals - formed by heat and involved in chemical chain reactions occurring during the course of a fire.

Self-help exercise 2.1

1. Flammability may be defined as
.....
2. Sketch a diagram of the fire tetrahedron and label all sides.

3. Free radicals are
.....
-

How does flammability relate to the type of fuel material?

Fuel material exists in one of three states, solids, liquids and gases. Most things are combustible given the right temperature and conditions. The rate and intensity of combustion depends on the nature of the material. Of the three states of matter, only vapours (gases) burn. Solids, liquids and gases differ in their structure, by the way that their molecules are arranged, the amount of movement that these molecules are allowed within the structure and the speed with which they travel. The important thing to remember is that solids and liquids must change to the gaseous state before they will burn. Usually it is easier to turn liquids into the gaseous state than it is solids.

How flammable are solids?

You may recall that solids have a very rigid molecular structure. The molecules are packed tightly together, allowing no movement of individual molecules, other than vibration. If heat is applied, the molecules vibrate more quickly and so transfer the heat along the material. If enough heat is applied, the molecules may gain enough energy to break the bonds that hold them together and so the material may produce volatile gases.

Pyrolysis is the thermal degradation of solids. In solids that will burn, pyrolysis involves the molecular breakdown, or decomposition of the solid, to produce smaller volatile substances. These volatile substances can be released into the vapour phase, producing the potential for combustion. With some materials the bonds are so strong that it would take a very large amount of heat to break them. Before this occurs some of the molecules break free and form a vapour close to the outside layer of molecules.

Remember, before a solid can burn, heat results in volatiles being formed and it is these that burn. The heat initiates a chemical reaction between the molecules on the outside and oxygen in the air. This is combustion and may be in the form of burning if the vapour has formed, or charring if it has not. As solids are so rigidly held together, it is only the molecules on the very outside of the material that have access to the oxygen and it is only when combustion has removed these, that the next layer can form a vapour and react with the oxygen and so on.

The flammability of solids then depends on the nature of the molecules that make it up. If these are very flammable, then they will quickly burn away and allow access to the layers below. If they are not so flammable, they may char and so protect the layers below. During the combustion of solids, as with other types of materials, free radicals are extremely important factors in the process. Most solids have the capacity to provide large numbers of free radicals when they are subjected to heat. These free radicals, such as oxygen atoms, hydroxide molecules and hydrogen atoms, react rapidly with other gases entering the combustion zone

and set up chain reactions that rapidly change into branch reactions. In other words, what might begin as one reaction can rapidly turn into a large number of reactions, which explains how the combustion process can escalate so quickly, once it has taken hold.

What are some common examples of flammable solids?

Many of the solids that are reasonably flammable are organic. This does not mean that they are formed from living material, it simply means that they are made up of long chains of carbon to which may be attached a variety of other elements and compounds. As far as flammability goes these long carbon chains provide ample opportunity to form free radicals and often oxidising agents which help combustion. Oxidising agents are compounds or elements that help other compounds to oxidise. Often they supply the oxygen for the reaction. The common combustible solids include wood, plastic, fibres and textiles. Other solids that do combust include metals, but their behaviour is more difficult to classify.

How flammable are woods and wood based products?

Wood is organic in nature being made up primarily of long chains of carbon, hydrogen and oxygen. As explained earlier, this makes it highly combustible. It produces a long-flaming fuel, which burns readily and spreads fire quickly. How well a particular wood or product will burn depends upon its moisture content. If this is high, then a considerable amount of heat is required to turn the water to steam and so the wood may smoulder or char before it ignites. The temperature at which decomposition of wood first occurs is 170°C, where carbon dioxide, carbon monoxide and water are given off. Then, at 302°C, a further decomposition occurs which liberates considerable heat. Reactions that give off heat are called exothermic reactions.

How flammable is plastic?

Plastics are made by synthetically producing long organic chains of carbon, hydrogen and oxygen. By altering the arrangement of these atoms, it has been possible to produce a very large number of types of plastics, all with different properties and different degrees of flammability. The flammability and dangers associated with plastics are further complicated by the addition of a variety of chemicals to alter the properties of plastics. For example, they may contain stabilisers, fillers, plasticisers or colouring materials all of which alter the fire characteristics and the toxic nature of the combustion products.

How flammable are liquids?

Liquids differ from solids in that their molecules are free to move around within the container that holds it. As we all know, liquids will run freely when spilled, the molecules still being attached to each other, but in an elastic fashion. This means that the number of molecules that are exposed on the surface of a liquid are limited by the container shape and size. The larger the container, the more molecules are exposed to form a vapour and mix with the available oxygen. Again, how flammable a liquid is depends upon how readily individual molecules will turn into a gas and react with oxygen, and how many molecules are available. If molecules do not react with oxygen at all, then the liquid has no flammability. This is the case with water.

If the liquid evaporates and the molecules react readily with oxygen, then the liquid will be very flammable, as is the case with petrol. It only requires a small amount of heat energy to start the reaction off. Understandably, in a spill situation there are going to be vastly more molecules available for combustion than in a container. The other important factor that often makes liquids more flammable than solids, is the fact that the bonds that hold the molecules together are weaker. It takes much less energy to separate the molecules from each other to form vapour than it does in solids.

Flash point and fire point of liquids

For flammable liquids, there are two different temperature points that you should be aware of. These are flash point and fire point. The temperature at which enough vapour has been generated to momentarily 'flash' but not to continue burning if ignited, is called the flash point.

warning!

The lower the flash point the more dangerous the liquid.

The temperature at which burning would continue is called the fire point. This is usually 3 - 4°C above the flash point. According to the United Kingdom classification of flammable liquids, a flammable liquid is defined as one whose flash point is below 60°C. These can further be divided into highly flammable and flammable. Highly flammable liquids have flash points below 32°C. Flammable liquids have flash points above 32°C but below 60°C. Combustible liquids have flash points above 60°C. This classification is very similar to the one in the United States, differing by only a degree or two (see figure 2.6).

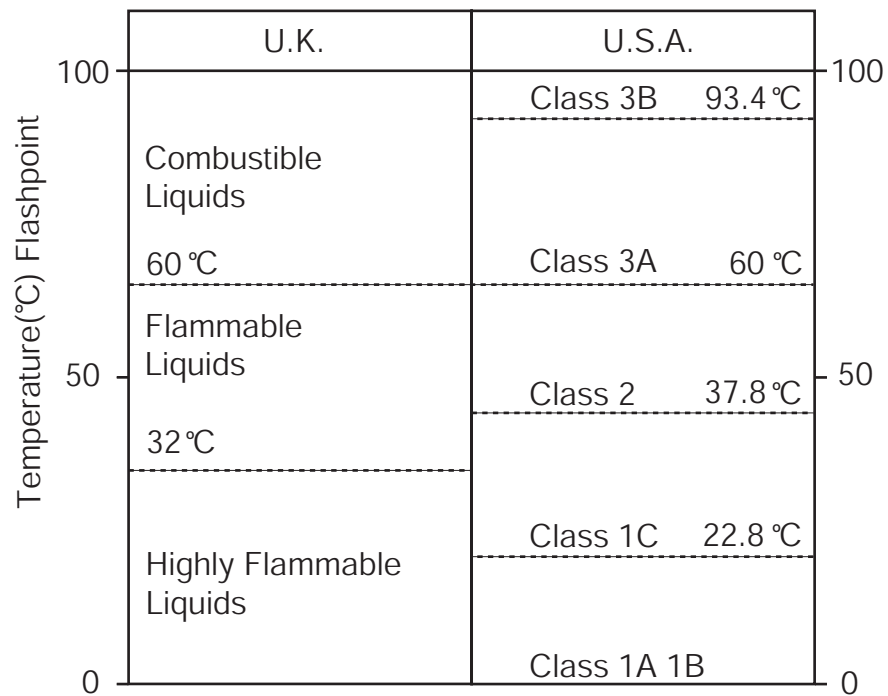


Figure 2.6: A diagram of flammability points against temperature, showing the classifications for the UK and the USA.

Which liquids are flammable?

There are many examples of flammable liquids. Some of the common ones are petrol, acetone, benzene, ethanol, toluene, kerosene and diethyl ether. Less volatile liquids such as diesel, need to be warmed up above their flash points before they can be ignited.

warning!

It is the vapour of the flammable liquid rather than the liquid itself which ignites when mixed with air. It is extremely important to store flammable liquids in proper containers to prevent this.

How flammable are gases?

Fuel gases, as you would expect now that you have looked at solids and liquids, are generally more flammable than the other states of matter. The reason is, that under normal conditions, the molecules of a gas are not bonded to other molecules, but are free to roam inside the boundaries of their container. As such they mix readily with oxygen molecules in the air and are therefore available for combustion.

Which gases are flammable?

Some gases are not flammable, for example helium, neon, argon, nitrogen. Oxygen is not actually a flammable gas, but it is a powerful oxidising agent that can make other materials highly flammable.

There are many gases that are flammable. A few common ones are hydrogen, acetylene, ethylene, propane, butane and methane. LPG (Liquefied Petroleum Gas) is a gas, liquefied by pressure, which is mainly composed of propane.

What are upper and lower flammability limits?

The flammable range of a fuel is the concentration range of vapour, expressed as a percent volume in air, which will burn or explode if an ignition source is present. In other words, it tells us the minimum and maximum amounts of vapour needed to be present for the fuel to ignite.

The flammability range is usually given as:

- the lower flammability limit or lower explosive limit (LEL), or lower limit (LL)
- the upper flammability limit or, upper explosive limit (UEL), or upper limit (UL).

These are expressed as percentage by volume in air. Measurements have been made of limits of flammability for hundreds of gases and vapours. Let's look at Table 2.1. Methane has a lower limit of 5% and an upper flammability limit of 14%. This means that if the methane vapour concentration is below 5% by volume in air, then there is not enough concentration of methane molecules to combust. The mixture is too lean. If the concentration is above 14% by volume in air, then there are too many methane molecules relative to oxygen molecules available for combustion to occur. The mixture is too rich. It is only between these limits that the vapour can be ignited.

| Material | Lower limit | Upper limit |
|-----------|-------------|-------------|
| Methane | 5% | 14% |
| LPG | 1.5% | 9.5% |
| Ethylene | 2.7% | 36% |
| Acetylene | 2% | 80% |
| Hydrogen | 1% | 75% |
| Acetone | 2.5% | 13% |
| Ethanol | 4% | 19% |
| Benzene | 1% | 7% |
| Ether | 2% | 48% |

Table 2.1: A table showing the flammability limits of some materials.

warning!

The wider the flammability range the more dangerous the material.

Self-help exercise 2.2

1. Sketch diagrams of the different molecular structures of solids, liquids and gases in the boxes below. Use dots or small circles to indicate molecules.



Solids



Liquids



Gases

2. Name four common combustible solids

.....
.....

3. Distinguish between flash point and fire point

.....

Dusts explosions

Dust explosions have occurred in industries utilising fine, particulate, combustible materials. Typical industries at risk include those involving the manufacture or handling of agricultural products (grains especially), foodstuffs, polymeric materials, rubbers, metals, coal and wood. Dust explosions pose serious hazards to both life and property.

The reaction

Dust explosions occur when fine, combustible materials are suspended in air (or any other suitable supporting atmosphere) and are subjected to an ignition source of sufficient energy. For the purposes of fire/explosion, dust may be considered as consisting of particle of less than 500 micrometres (μm) in size. One μm equals one millionth of a metre. Ignition sources for dust explosions include flames, sparks, hot surfaces, and electrostatic discharge. Minimum ignition energies range from 1 mJ (megajoule) to 500 mJ (very hazardous to least hazardous).

A dust explosion produces a flame front that will rapidly propagate through the dust suspension, releasing heat at a rate that is likely to vastly exceed the ability of the surrounds to take up that heat. The reaction will also produce gaseous products of combustion that, in most cases, will require larger volumes than the solid particulate matter from which they are derived. Consequently, a dust explosion will be accompanied by significant expansion and pressurisation effects. In unconfined dust explosions, the pressurisation effects will be local and far less destructive than explosions occurring in confined or restricted areas where the pressure cannot be readily dissipated.

Explosive limits

Dust explosions have similarities to gas explosions, especially with regard to the chemical processes involved, particularly when involving particles of less than 5mm. Dust clouds exhibit upper and lower explosive limits. The lower explosive limits (LEL) of many dusts have been determined and exist in the range 10 g m^{-3} (grams per cubic metre) to 600 g m^{-3} (approx), but for practical purposes it is assumed that most dusts have a lower explosive limit of 20 g m^{-3} . It should be realised, however, that suspensions of dust are unlikely to be homogenous, normally containing a range of concentrations of particles and that some particles will settle out of suspension due to gravity.

Some early literature will express explosive limits of dust in ounces per cubic foot. Fortunately, the conversion is relatively easy as $1\text{ oz /ft} = 1\text{ kg/m}$ (approx).

Factors affecting a dust explosion

The severity of a dust explosion is influenced by:

- the chemical nature of the material
- the particle size - severity increasing as particle size decreases
- the amount of dispersal
- concentration, homogeneity and turbulence
- the degree of confinement - severity increases with greater confinement
- moisture content of the dust cloud
- the amount of non-combustible matter in the dust cloud. (This material has the ability to act as an inerting agent, free-radical terminator, or to take up heat). A free radical terminator is a material that reacts with free radicals and stops them from forming any more free radicals.

Self-help exercise 2.3

1. What is combustion?

.....

2. Why are dusts considered to be potentially explosive?

.....
.....

3. List four factors that affect a dust explosion.

.....
.....
.....
.....

CHAPTER 3

Conditions at the Fire Point

Element

Identify conditions of burning at the fire point

Performance criteria

1. Limiting Adiabatic Flame Temperature (LAFT) values are interpreted accurately
2. Process of extinguishment related to the combustion process is analysed and recorded

Chapter overview

This chapter is concerned with what is happening within the flame and how different conditions may affect this. We can use this knowledge to help us work out the most efficient method for extinguishment. The four different methods for achieving extinguishment are discussed.

What is fire point?

We have already touched upon fire point and flash point in the previous chapter. Just to remind you, let's go through the definition again.

Fire point is the temperature at which the flame will continue once ignition of the vapour has been consumed. The heat of the of the flame and the temperature of the fuel is sufficient for continued production of vapour and combustion.

Within this process the vapour then mixes with air to allow combustion to take place. If the vapour mixes with the oxygen before combustion, it is referred to as a premixed flame. If it mixes with the oxygen during combustion, it is referred to as a diffusion flame. Premixed flames are blue in colour and are hotter than yellow diffusion flames.

What is Limiting Adiabatic Flame Temperature (LAFT)?

The LAFT for a material is equal to the temperature required for a material to undergo combustion at its lower flammability limit. Remember that the lower flammability limit is the minimum amount of gaseous vapour required in air to just allow the fuel to burn. This combustion produces enough energy to balance out the heat losses and maintain the temperature above the LAFT. Thus at the LAFT an energy equilibrium is reached and fire point conditions are achieved.

LAFT values

It is possible to calculate the LAFT for a fuel using balanced equations and thermochemical data.

If we know the LAFT for a fuel, we can assess the fire risk involved. For example, for most hydrocarbons, the LAFT values vary between 1500 and 1700 K (K is the symbol for degrees Kelvin or degrees absolute. 0°C is equal to +273 K). If the temperature can be dropped below these values then the flame will go out, as there is not enough energy to support combustion.

The lower the LAFT value, the less energy is required to support combustion, so it is easier to ignite and requires more cooling to extinguish. Acetylene is a good example of this as its LAFT is around 1200 K.

Self-help exercise 3.1

1. Premixed flames burn than diffusion flames and are in colour.
 2. Diffusion flames are in colour.
 3. The limiting adiabatic flame temperature is
.....
.....
 4. Knowing the LAFT for a fuel helps us to assess its
.....
.....
-

Extinguishing agents as reaction inhibitors

The combustion reaction is of considerable importance to the firefighter.

If the combustion reaction can be slowed or halted then the fire is controlled or extinguished.

The chemical reactions that do occur in a flame happen very quickly, at very high temperatures and in a very small volume. Combustion is a chain reaction, that is it builds upon itself, yielding energy or products that cause further reactions of the same kind.

We have just discussed the relationship between temperature, combustion and how cooling a fuel can be used to extinguish a fire. As you might remember, from a previous module, the other ways to extinguish a fire are to deprive it of fuel or to deprive it of oxygen.

There is another factor that we have mentioned previously and that is the free radical mechanism that fires depend upon. These have been incorporated into the fire tetrahedron, so that there are in fact four factors that can be used as a basis for fire extinguishment.

If we remove one section of the fire tetrahedron, then combustion will cease.

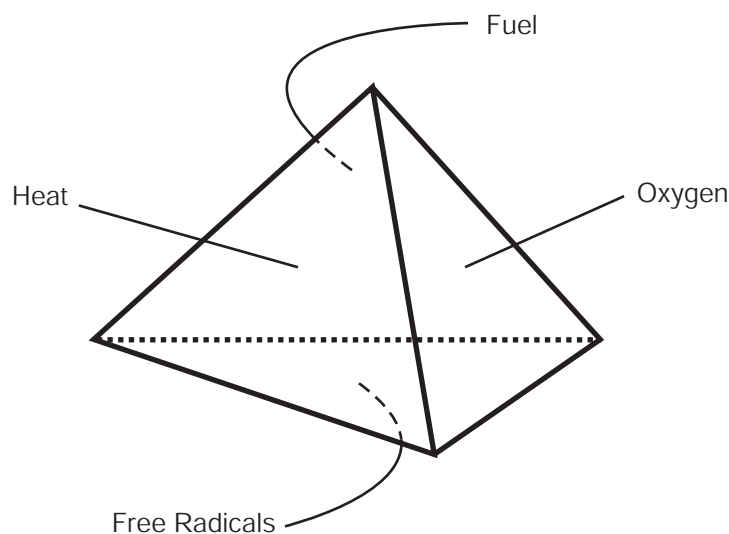


Figure 3.1: The fire tetrahedron.

Temperature

A fire can be extinguished by either cooling the gaseous combustion zone or cooling the solid or liquid combustible. The latter cases involve stopping the formation of gaseous vapours. This is what happens when we cool burning wood with water.

The extinguishing medium absorbs heat from the combustion process at a greater rate than the amount of heat produced by the process and so the reaction can no longer proceed.

The medium may undergo changes of its own when it absorbs the heat, such as having its temperature raised, being converted into a vapour, decomposing or reacting chemically with the burning material.

When selecting extinguishing agents that operate through a reduction in temperature, it is essential that a measurement of its particular characteristic be examined to determine how effective it will be. This might be its thermal capacity (heat absorption), its latent heat of vaporisation (amount of heat needed to turn it to a vapour), its heat of decomposition (heat required to make it decompose) or its heat of reaction (heat required to make it react chemically).

Starvation - depriving fires of fuel

Combustion will cease if we remove combustible material from the neighbourhood of a fire, remove a fire from the neighbourhood of a combustible or subdivide the burning material to allow the smaller fires to burn themselves out.

Chemically, removing the fuel from a fire leaves the oxygen with nothing to react with and hence the reaction ceases eg fire breaks in forests.

Smothering - limiting the oxygen supply

Similar to fuel reduction, limiting the oxygen supply leaves nothing for fuels, such as hydrocarbons, to react with. So the combustion reaction ceases.

Reducing the oxygen content of the atmosphere around the burning material can be most effectively done by smothering the fire. This can range from snuffing a candle to capping a burning oil well. The principle remains the same.

There are many different methods of smothering fires. These range from the use of foams to inert gases.

Foams form a viscous coating over the burning material and limit the supply of air. It also prevents the formation of flammable vapour.

Sodium bicarbonate is commonly used as a dry powder to extinguish fires. As well as smothering, these powders absorb heat and provide a cooling effect.

Specialised powders have been developed for use on metal fires. These powders fuse at a high temperature and form a crust over the burning metal, excluding the air.

Inert gases displace air around a fire and so reduce the amount of oxygen available. This is short lived however and may be vulnerable to convection currents and wind. Carbon dioxide and nitrogen are often used in this way.

Some chemicals containing 'halons' and 'halogenated hydrocarbons', for example BCF, have also been used to extinguish fires. These reduce the concentration of free radicals that participate in the chain reactions and slow down the combustion reaction. Unfortunately these chemicals have been found to be toxic and environmentally unsound.

Quenching free radicals

We have briefly touched upon free radicals and what they are in the first chapter. If we are able to halt the production of free radicals, then we remove one side of the fire tetrahedron and this can halt the fire.

Free radical reactions tend to require high initial activation energies because chemical bonds must be broken to form the radicals. This can be accomplished by light or heat. Once the free radicals are formed the chemical reactions in which they are involved tend to be very rapid. In many cases, a free radical reacts with a reactant molecule to give a product molecule plus another free radical. Reactions that involve this step are called chain reactions. Many explosive reactions are chain reactions involving the free radical mechanisms.

The heat of a fire is sufficient to cause this type of chemical breakdown. It can also cause the formation of more complex free radicals, involving carbon and hydrogen. The types and quantity formed depends on the fuel being burnt. In a fire, these free radicals combine with oxygen in a rapidly propagating chain reaction process. If free radicals are removed, or their formation is prevented, then the complex chemical reactions that they promote can be limited and the fire extinguished. Extinguishing agents such as the dry chemical powders and the halons (regulated use), use the free radical quenching mechanisms to extinguish fires.

Self-help exercise 3.2

1. If the combustion process can be then the fire is controlled or extinguished.
 2. Fires may be extinguished by, or
 3. Starvation of a fire involves
 4. Reducing the oxygen content around a fire can be most effectively done by:
.....
 5. We can use quenching mechanisms to extinguish fires.
-

CHAPTER 4 Heat Transfer

Element

Record mechanisms of heat transfer during fire growth, development and spread

Performance criteria

1. Heat transfer factors in fire situations are identified and recorded
2. Processes of self-induced heating are analysed and recorded
3. Behaviour of fires in partially and fully enclosed compartments are observed and recorded
4. Amount of smoke produced from a fire is calculated

Chapter overview

This chapter is concerned with the mechanisms of heat transfer through conduction, convection and radiation. It also deals with ways of measuring heat transfer by the three mechanisms and how this relates to real situations.

Self-induced heating is examined and the variety of situations in which this may occur are discussed as are the preventative measures that may be taken.

Fire in enclosures and explosions are also covered in this chapter. Preventative and safety measures are reviewed in a comprehensive fashion.

Heat transfer in fire situations

The way that heat is transferred is crucial to the direction and speed of fire spread. In a fire situation, heat can be transferred in three ways. These are conduction, convection and radiation.

Heat transfer by conduction

This method of transmission of heat may be defined as the flow of heat through a body from places of higher temperature to places of lower temperature.

If one end of an iron bar is held in a fire, the other end soon becomes hot. According to the kinetic theory of matter, the fire causes the molecules at the heated end of the bar to vibrate about their fixed sites more rapidly. These molecules collide with their neighbours, causing them to move faster and this process continues until the increased motion has been transmitted to all the molecules and the entire body has become hot. In a fire situation, heat may be transmitted through buildings as steel beams heat up and the heat is conducted along to the other end.

If we examine this idea in terms of solids, liquids or gases, then we need to look at the mechanism in terms of the way that molecular composition affects the process. This molecular composition is illustrated in Figure 4.1.

In solids, the molecules are closely packed together in well-ordered arrangements.

In liquids, the molecules tend to be less closely packed and less ordered.

In gases, the molecules are spaced randomly and at relatively great distances.

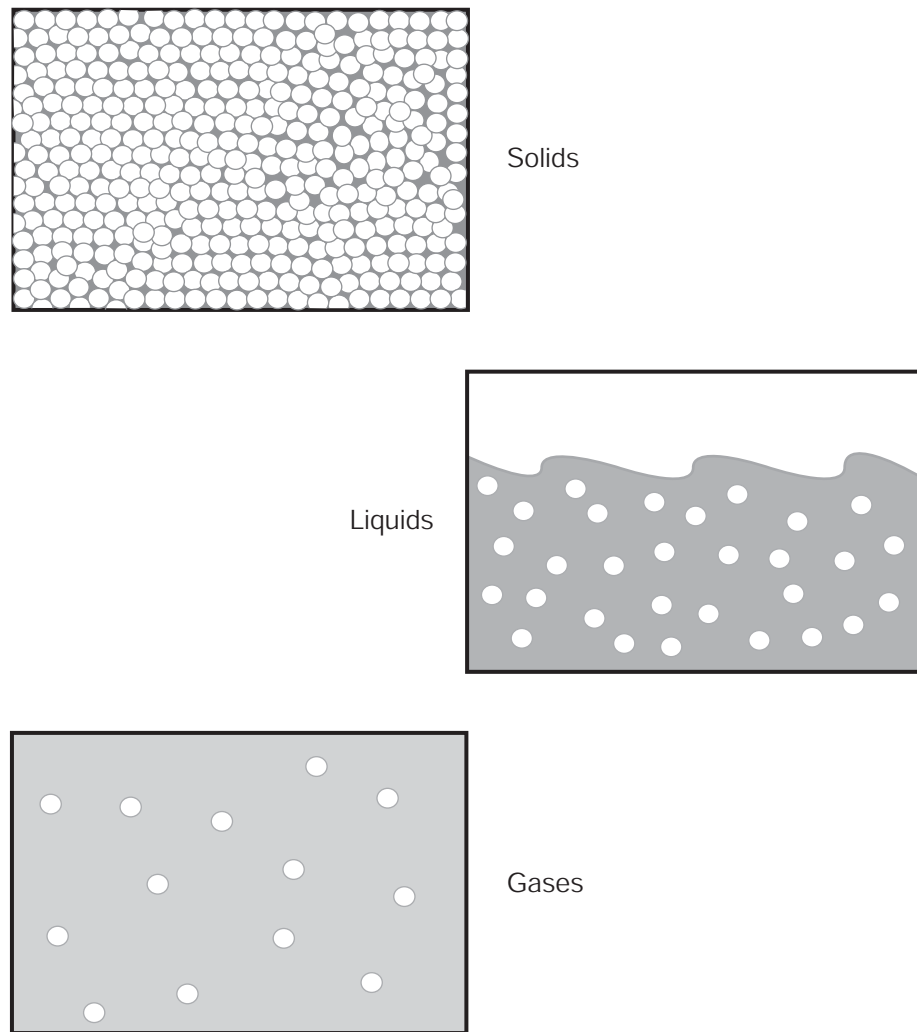


Figure 4.1: A schematic diagram showing the arrangement of molecules in solids, liquids and gases.

When matter is heated, molecules become 'excited', thereby making them more energetic. In the case of solids, the closely-packed, well-ordered molecules, which can usually manage to vibrate only in their own individual space, tend to become a little more active and may begin to knock into each other. By doing so, energy is transferred gradually from one to another - from the more energetic to the less energetic.

This transfer of energy from molecule to molecule is called conduction.

Since molecules are closer together in solids, it is more likely that conduction will be more efficient in this state than in liquids or in gases. For this reason, conduction is the heat transfer method most usually associated with solids though not strictly confined to them.

Some solids are more efficient than others at conducting heat. Most metals are very good conductors of heat.

Those most efficient are known as conductors, while those least efficient are known as insulators.

Heat transfer by convection

This is the transfer of heat from one part of a fluid (liquid or gas) to another by the movement of hotter portions of the fluid away from the source of heat.

Convection currents are due to the fact that when a liquid is heated it expands and becomes less dense. This allows it to rise and there is a continual circulation of liquid as the cooler material drops. The whole liquid therefore becomes warm because the heat is carried throughout its bulk by moving streams.

In a fire situation in a building, convection currents can convey hot gases produced by combustion upwards through stairwells and open lift shafts, thereby spreading fire to the upper parts of the building. Cool air comes in to replace the rising hot air and so accelerates the burning. This is also the case in bushfires, where convection currents will assist the fire to spread up hills and gullies.

Heat transfer by radiation

Heat reaches us from the sun and yet there is no solid to conduct heat, nor is there air to form convection currents. It follows that there is another way that heat can be transferred. This is called radiation.

Heat contained by a body, say the sun, is in the form of kinetic energy, that is the energy of movement within atoms. Because this energy is transmitted through space which is a vacuum, it cannot be in the form of heat energy. A new term, radiant energy, is used to describe it. When radiant energy falls on another body, it sets the molecules of that body into more rapid vibration and is therefore reconverted into heat.

When a body is heated, the quality of the radiation it emits depends upon its temperature. Below 500°C it emits a form of radiation which can be detected only by its heating effect. This radiation, unlike light, does not excite the retina of the eye and is therefore invisible. It is called infra-red radiation.

At 500°C a body becomes red-hot and begins to radiate red light in addition to infra-red radiation. At 1000°C it becomes white-hot like the sun or like the filament of an electric light bulb, and radiates both white light and infra-red radiation.

All forms of radiant energy are transmitted at the same speed, the speed of light, 300 million metres per second. If infra-red radiation travelled more slowly than light, we would see the sun before we felt the warmth of its rays. But we experience both simultaneously. The rays take about eight minutes to travel the

150 million kilometres of space. Both light and infra-red radiation from the sun may be concentrated on a very small area by means of a glass lens.

Radiant energy travels in straight lines and the intensity falls off inversely as the square of the distance from the source of radiation. This means that at twice the distance, the intensity is one quarter; at three times the distance, the intensity is one ninth and so on. Radiant energy follows the inverse square law, similar to light. This is important when considering the effects of radiation from fires.

When radiation falls on a body there are three possible effects. Firstly the energy may pass straight through, if it is transparent; secondly it may be absorbed, so raising the temperature; thirdly it may be reflected.

Some substances selectively absorb radiation, for example glass allows light to pass through but it absorbs infra-red rays. Sometimes glass may then act as a screen to stop radiation and is used to screen fires in some cases. Carbon dioxide and water vapour also act in this way.

How well a body absorbs or reflects radiation may also depend upon its degree of shininess and its colour. White shiny surfaces are the best reflectors, while matt black surfaces are the best absorbers. Interestingly enough good absorbers of radiation are also good emitters, hence most wood stoves are painted matt black, as are solar collecting panels.

Many fires have been caused by radiation and some cases of 'so called' spontaneous combustion of human beings have been traced to this. The colour of a burning object may give us an indication of how hot it is due to the fact that different wavelengths of radiation are emitted at different temperatures. Lower temperature objects emit radiation in the longer wavelengths, while very hot objects emit them in the shorter blue range.

In a fire situation, radiant heat is probably the most dangerous as far as heat transfer goes. The amount of heat absorbed depends upon the qualities of the material absorbing it, and also the closer an object is to the fire, the greater the amount of radiant energy available. If you think about it, this is not necessarily the case with the other types of heat transfer.

How does heat transfer affect real fire situations?

Heat transfer factors affect different types of fires in different ways.

In a typical fire, heat transfer and loss will occur in the following ways.

- **Conduction**
This accounts for about 20% of the heat loss from a fire. The heat is conducted away through walls, ceilings and floors.
- **Convection**
This accounts for about 40% of the heat loss from a fire. Heat is lost to the atmosphere via hot gases and smoke.
- **Radiation**
This accounts for about 40% of the heat loss from a fire. Heat is transferred to the surroundings.

For the fire to continue, energy from the combustion reactions must compensate for these losses.

Structural fires

Conduction, convection and radiation are all important factors in structural fires.

Conduction is important because the nature of the building materials determines whether heat may be transferred from one part of a building to another by steel girders or pipes for example. Poor heat conducting material will act as insulators, limiting the heat spread.

Convection currents are set up in places where there are stairwells or other openings between floors of buildings, allowing heat to spread quickly from the lower to the upper storeys.

Heat transfer through radiation is often believed to be the cause of many domestic dwelling fires. Radiation hampers firefighting strategies considerably as the temperature of the fire increases. It can also be a major contributing factor in helping fire spread between buildings in high density construction areas.

Self-help exercise 4.1

1. Heat transfer by conduction is from to
 2. Heat transfer by radiation is usually through
 3. Heat transfer by radiation does not require to travel through.
 4. Free convection is not as effective as convection.
 5. In a real fire situation, most of the heat transfer occurs through and
.....
-

Self-induced heating

If ignition is caused by some external source such as a spark or a flame, it is referred to as piloted ignition.

If it is caused by a chemical reaction taking place spontaneously due to certain conditions, then it is referred to as spontaneous ignition.

Self-induced heating and spontaneous ignition

Whenever the following four conditions exist, self-induced heating or self-heating, can occur.

- The material can undergo, however slowly, a heat generating (exothermic) reaction at its normal temperature with the oxygen of the air.
- The rate of this reaction increases rapidly with increasing temperature.
- The physical arrangement of the material is such that heat cannot escape readily from its interior.
- The material, if ignited, is capable of smouldering (must be porous and must form rigid char).

Most common solid materials react so slowly with oxygen at normal temperatures that the self-heating, if measurable at all, usually amounts to no more than one or two degrees. However, there are special cases where self-heating raises the temperature to an extent where spontaneous ignition can occur.

The self-induced heating process

Once the conditions are met, there are two major processes which can lead to self-induced heating. These are oxidative reactions and biological reactions.

Oxidative reactions

Oxidative reactions occur where the material reacts with atmospheric oxygen.

This can happen if:

- there is enough surface area for the oxidative process
- the oxygen is able to reach the sites where the reaction will take place within the material
- the site of the reaction is insulated to prevent heat loss and allow the heat to build up.

Consider a large pile of coal or dust. Neither of these materials conduct heat well because of the air gaps between the individual particles. Accordingly, even a very slow rate of heat generation in the interior can eventually cause a substantial temperature rise, even though weeks or months could pass before the temperature rose enough to initiate smouldering combustion in the interior. Then, if the pile

is disturbed, bringing fresh air in contact with the glowing region in the interior, a sudden transition to flaming combustion often occurs. Or, the transition to flaming could occur when the glowing zone progressed from the interior to the surface.

Numerous examples of such fires have been observed. They are especially dangerous in the holds of ships. Among the most dangerous are rags or other fibrous materials in contact with unsaturated oils such as corn oil, fish oils, linseed oil and pine oil.

Such oils are reactive with oxygen at room temperature. The presence of the rags or fibres is necessary to provide more surface area for the material to initiate the oil-oxygen reaction, and also to confine the heat and permit the temperature to build up. Saturated oils, on the other hand, do not cause spontaneous combustion. Some examples of saturated oils are mineral oil, common hand oil, petroleum-derived oils, lubricating oil, or heating oil. Remember that we touched on the reasons for this in the previous chapter. Saturated oils have their bonds all fully occupied, whereas unsaturated oils have double bonds to their carbon atoms and hence one of these can be used to join with other elements.

Other materials in which self-induced heating occurs are combustible solids which are porous, such as dusts.

Furniture, beds, and newspapers do not burst into flame spontaneously. This is because most common solid materials react so slowly with oxygen at normal temperatures that the self-heating, if measurable at all, usually amounts to no more than one or two degrees.

In general, then, the ability of a material to ignite spontaneously depends on the basic nature of the material, its porosity, its size, its moisture content, and the temperature of its surroundings. The time required could be as long as one month. The theory of spontaneous ignition is understood well; however, the biological or chemical rate of heat generation at normal temperatures is unknown for most materials.

Once self-heating is established, then it becomes self-perpetuating, as the increase in temperature allows the reaction rate to increase and encourages further reactions to take place at other sites. This can eventually lead to ignition.

Biological self-heating

Biological reactions occur where there is microbial heating from the growth and respiration associated with microbes.

This process usually involves animal or vegetable products stored in bulk over long periods of time. Examples are hay, grains, animal or vegetable fibres.

An essential component of the process is a high humidity value (around 75%), which is usually associated with a high moisture content (greater than 8%). This is why wet hay is so vulnerable to self-combustion when it is put into a stack.

There are two types of organisms that are active in the lead-up to biological oxidation. The first are mostly fungi, which are active up to 50°C, the others are bacteria, active up to about 75°C. After this temperature is reached, the organisms die. The decomposition byproducts of the material continue to oxidise until ignition occurs.

Let's have a look at the processes that occur when hay decomposes until it spontaneously ignites.

Spontaneous ignition in hay

If we consider a pile of hay stacked tightly, we have a unique situation with regard to fire. The material cannot conduct heat well because of the gap between individual particles. Accordingly, even a very slow rate of heat generation in the interior can cause a substantial rise in temperature over a period of one or two weeks. If the pile is disturbed, bringing in fresh oxygen, a transition to flaming combustion can occur.

If the hay stack is a few metres across, then the temperature will rise to about 75°C in several days or weeks. Above this temperature, the organisms, referred to above in biological self-heating, are no longer active. However, a slower chemical oxidation then takes over. It is believed that the oxygen is not reacting with the hay itself at this stage, but with the decomposition products of the hay, which were formed during the biological heating. After several more weeks, the temperature could rise to the point where flaming ignition occurs spontaneously.

Spontaneous Ignition Temperature (SIT)

Spontaneous Ignition Temperatures of solids can be measured by slowly heating a sample of the material, and checking the temperatures of both the heat source and the sample. The SIT that will be determined will depend to some extent on the conditions of the test and the size of the sample. These results indicate the variation in SIT according to the conditions at the time. Remember that these values are only indicators rather than exact.

Table 4.1 shows SIT values for a selection of materials. These values are smouldering rather than ignition temperatures. This is because the actual ignition temperature varies tremendously depending on the ignition source, availability of air and so on

| Material | Ignition temperature °C |
|----------|-------------------------|
| Coal | 125-130 |
| Hay | 172 |
| Sawdust | 192-220 |
| Cotton | 228 |
| Rayon | 234 |

Table 4.1: Ignition temperatures for materials subject to self-heating.

Prevention of self-induced heating

- Measures used to prevent self-induced heating could include:
- the use of anti-oxidants on some materials
- the application of microbial growth inhibitors on organic material
- allowing organic material to age before stacking
- making stacks of material smaller
- monitoring the temperature rise
- increasing ventilation
- inerting the atmosphere surrounding the stored material by using non-reactive gases.

Self-help exercise 4.2

1. The two major processes that lead to self-induced heating are
..... and reactions.
 2. Some of the most dangerous material to help induce self heating is the presence of
.....
 3. The two types of organisms that help self heating in organic products are
..... and
 4. Making hay stacks is one way of reducing the chance of self-induced heating.
 5. Spontaneous ignition temperatures are only. of the potential ignition temperature.
-

Fire in enclosures

Fires in enclosures operate under quite different conditions to those in the open. We have briefly touched upon the differences in heat transfer factors earlier. Now we will have a more detailed look at the way fires behave in enclosures.

Enclosures may be defined as a room or other compartment, bounded by a ceiling and up to four walls. If there are four walls and openings that can be sealed off then it is a fully enclosed compartment. If there are less than four walls and the enclosure cannot be sealed off then it is a partially enclosed compartment.

Fires in enclosures are limited by the amount of oxygen available and the heat balance situation.

Effects of enclosures on fire spread

The following features of fires in enclosures make them distinct from fires in the open.

- Heat from the fire will not be easily nor immediately lost from the environs of the fire.
- Hot gases and combustion products in the buoyant plume will rise from the fire and be trapped under the ceiling where they will be forced to move laterally, spreading out and heating the enclosing surfaces.
- Heat will be radiated down from these heated upper surfaces and hot gases to the fuel bed below.
- The fuel's rate of burning will increase, leading to the fire's accelerated growth.
- The greater the feedback of heat to the fuel bed, the more rapid will be the growth of the fire.

The effects of walls and ceilings on fire development

Simply placing a ceiling over a flame in the open has been shown to increase the burning rate of a fire considerably, because the flames are deflected and radiant heat is reflected back to the firebed. When walls are included, the development of the fire within the enclosure has been shown to follow three well-defined stages. Assuming there is adequate ventilation the three stages of fire in walled spaces are:

- the growth period
- the fully developed fire and
- the decay period.

We will now examine these stages more closely.

The growth period (including flashover)

The growth period may be thought of as the time from ignition until the moment when all combustibles within the enclosure are burning, if indeed such occurs.

Burning is initially localised, the fire spreading from the material first ignited to adjacent combustibles, with burning occurring close to the surfaces producing the volatiles. The period is characterised by ventilation well in excess of that required to supply sufficient air to the fire and, hence, the rate of burning is controlled only by the amount of fuel and its available surface area. Temperatures are relatively low and, initially, non-life-threatening.

The growth period continues until the fire has developed sufficiently from localised burning to involvement throughout the whole enclosure as the combustibles begin to disintegrate. Flashover is said to have occurred.

It should be noted that flashover is a transition period between two stages rather than an instantaneous event in itself. The flashover period involved is short, relative to the times associated with the other various stages of a fire; nonetheless, it is an event in time. You should note that, in very long or extended enclosures (eg corridors), flashover may occur at one end of the enclosure.

Flashover is often associated with flames reaching the ceiling of an enclosure, then spreading out in an effort to entrain more air, thereby increasing the amount of heat transfer to combustibles at lower levels and, often, at some distance away from the material first ignited.

warning

When flashover occurs life-threatening temperatures have probably been reached.

The fully developed fire

During the fully developed stage of a fire, burning is no longer localised. The production of volatiles is at a maximum and all materials are involved through the turbulence created by the mixing of volatiles with air drawn into the enclosure.

If insufficient air is available within the enclosure, flames will project out of any available opening as volatiles achieve a flammable mix with the outside air. The potential for fire spread to adjoining or adjacent enclosures becomes significant, due to both direct flame impingement and increased radiant heat flux.

Temperatures peak during this stage. Actual temperatures will depend upon the quantity of fuel, ventilation and the thermal properties of walls and ceiling.

This period of the fire is most significant in terms of the fire resistance of the structural elements.

The decay period

A diminishing burning rate and a decrease in the temperature profile are associated with the decay period of a fire in an enclosure.

Combustibles have been essentially depleted of their volatiles, and flaming is gradually replaced by surface combustion (smouldering).

Some workers in the field suggest that the decay period has been reached when the enclosure's temperature has decreased to 80% of the maximum temperature achieved.

Fires in fully enclosed compartments

The discussion so far has been around fires that have adequate ventilation. Now we will go on to discuss what happens when the fire is fully enclosed and there is limited ventilation. In this case there are two possibilities - either there is insufficient ventilation for development or there is sufficient ventilation for development. Let's look at both in turn.

Insufficient ventilation

If ventilation is extremely poor, a fire within an enclosure may not develop beyond the small localised stage typical of the early growth period.

Two possibilities for such a fire may be that it:

- dies out completely, due to oxygen starvation or
- decays into a smouldering fire.

The first is desirable, the other is potentially hazardous. During smouldering combustion, both heat and volatile products of incomplete combustion are produced. The enclosure may become filled with these volatiles which given the introduction of air may mix with the oxygen and erupt into flames. This may be accompanied by the development of significant pressure.

This phenomenon is often described as flashback or backdraught, something to be wary of particularly if you are the one who is opening the door.

Sufficient ventilation

If there is sufficient ventilation for the fire to proceed to the fully developed stage, then there are two types of burning regimes that can develop. These are the ventilation controlled regime and the fuel controlled regime.

The ventilation controlled regime

This is where the fire has enough fuel supply and depends upon the movement of gases into and out of the enclosure to determine its burning rate.

Air supply alone is not the thing that controls a ventilation controlled fire. Ventilation is the operative word and ventilation includes the flow of gases both into and out of the enclosure.

For a ventilation controlled fire, for openings of equal area, the greater the height of an opening, the greater the burning rate of the fuel.

This is logical when you consider both the incoming flows (cooler gases) and outgoing flows (hot gases), in that the greater height provides vertical separation for competing gas flows associated with enclosures. That is cooler incoming gases will be moving through an opening at lower levels, whilst hot out-going gases will be escaping at upper levels.

The fuel controlled regime

If you increase a ventilation opening beyond a certain size, a point is reached where the rate of burning becomes independent of the amount of ventilation and depends instead upon the surface area of the fuel available to the fire.

The transition then from the ventilation to the fuel controlled regime is determined by the surface area of the fuel.

Again, considered logically, there is adequate air for the developing fire, thus it is the amount of fuel available to be burned that will determine the speed at which it develops its final size. This is because the amount of exposed surface area will determine the rate of production of volatiles.

Self-help exercise 4.3

1. Fires in enclosures are limited by the amount of
..... and the
 2. The greater the of
to the fuel bed, the more rapid will be the growth of the fire.
 3. The three well defined stages of fire development within an enclosure are the
..... the and the
 4. In a fire with sufficient ventilation, the two types of burning regimes that may develop are the
..... and the
 5. An effective suppression system requires a
a and a
-

Flame characteristics of different materials

As we have already discussed, materials burn differently according to what they are made from. They liberate varying amounts of heat and give off different products. You would expect therefore that the flame characteristics of these chemical reactions are also going to vary considerably. And they do! The only problem is that most fires occur in wood-based materials, so we do not actually see all the variations. When we do, it is usually important.

The colour of smoke and flame associated with a fire can indicate the type of combustible fuel that is burning and the approximate temperature of the fire. The colours of the flame in the early stages of the fire are far more important than in the later stages of the fire when many petroleum based products become involved.

Flame colour and materials

In reality, for most fires the flame colour is not likely to be especially significant, because most structural as well as outdoor fires involve organic material such as wood and paint. The flame is likely to be yellow or orange in colour and the smoke will vary according to the fuel.

Table 4.2 gives an indication of smoke and flame colours produced by certain fuels.

This does not mean that different flame colours will not be observed in routine fires, it might mean that they are the exception rather than the rule and hence are very important indicators. If for example the blue or purple flame of alcohol was observed in the very early stages of a fire, then this might indicate that alcohol was used to start the blaze. This is distinct from the yellow colours of liquid fuels and natural gas. If there is an abundance of air, then natural gas flames will show some blue around the edges.

| Smoke and flame colours for certain fuels | | |
|---|---------------------------|------------------|
| Smoke colour | Flame colour | Fuel |
| Grey to brown | Red to yellow | Wood/paper/cloth |
| Black | Red to white | Gasoline |
| White to grey | Yellow to white | Benzene |
| Black to brown | yellow to white | Turpentine |
| Black | dark red to orange-yellow | Kerosene |
| Black | Blue white to white | Naptha |
| Note: Overall the lighter the colour of the flame, the higher the temperature. The significance of the colour of the smoke and flames in a fire should be considered with the time at which they were observed. | | |

Table 4.2: Smoke and flame colours for some common fuels.

Another gas of special interest is carbon monoxide. This burns with a blue flame also. This is a good indicator of excess fuel in a fire because, in a limited area, excess fuel to air generates large amounts of carbon monoxide. If this escapes to a region that is richer in air, then it may ring the primary fire with blue flames.

Note here that although three different blue flames have been identified, it is where and when the colours are observed that indicates the type of gas involved.

Special flame colours are always of some significance to a firefighter. Elements have specific colours associated with them when they burn. This principle is used to analyse the makeup of materials in the laboratory using very sophisticated equipment. For our purposes some simple identification colours may be useful.

Strontium salts give the bright red colour used in flares and fireworks. Copper halides burn with an intense green colour. Potassium salts burn with a violet colour, while barium salts burn yellowish green. Identifying special colours can be useful in determining the cause and sequencing of fires.

Flames and temperature

Flame colour may be linked to temperature, when not influenced by special elements, such as those mentioned above. The colour is also related to the oxygen mix with the fuel, so that it indicates the stage of the fire as well. This complicates using flames as a direct temperature guide, as the colour should be considered in relation to when it was observed, relative to the life cycle of the fire.

Table 4.3 indicates the colour of flames at certain temperatures. This is under ideal experimental conditions and is therefore useful as a guide and indicator rather than a measuring device.

| Flame colours and temperature ranges (°C) | | | |
|---|-------------|--------------|-------------|
| Flame colour | Temperature | Flame colour | Temperature |
| Light red | 900-1000 | Salmon | 1600-1700 |
| Dark red | 1000-1100 | Orange | 1700-1800 |
| Dark Cherry | 1100-1200 | Lemon | 1800-1900 |
| Medium cherry | 1200-1300 | Light yellow | 1900-2100 |
| Light cherry | 1300-1400 | White | 2150-2250 |
| Bright red | 1400-1500 | Bright white | 2500+ |
| Note: Overall the lighter the colour of the flame, the higher the temperature. The significance of the colour of the smoke and flames in a fire should be considered with the time at which they were observed. | | | |

Table 4.3: Flame colours and their associated temperature ranges.

Smoke production

The amount of smoke produced in a fire varies considerably through the different stages. Even so, observation of the colour and type of smoke can be a helpful indicator of the type of fuel involved. When complete combustion occurs little or no smoke is produced. This rarely happens.

The colour of smoke is almost entirely determined by the character and type of fuel and the availability of oxygen for complete combustion. Most materials must pre-mix with air to burn completely even in the presence of excess air. As hydrocarbon molecules become larger more air is required and this pre-mixing becomes even more difficult. This is why large volumes of dense black smoke are often associated with petroleum distillate substances in fires. However, this has limited value as an identification procedure, due to the fact that dense black smoke is often associated with the stage of burning and with a lack of ventilation in a fire.

Partially oxidised organic materials burning freely often produce little or no coloured smoke. Alcohol, wood and most organic building materials produce a white or a light grey smoke and sometimes, no smoke at all. Even when air supply is restricted, they do not produce heavy black smoke.

Tar paper, some paints, sponge rubber upholstery, adhesives, sealing compounds and some floor coverings will generally produce a black smoke. This generally occurs late in the fire and is not an indicator of what may have started it in the first place.

Smoke colours other than neutral white, grey or black may indicate special fuels being combusted. A smoke that has a special colour, such as red or yellow should lead to an inquiry as to the presence of materials other than standard building materials and furnishings.

Self-help exercise 4.4

1. The Periodic Table can be used to find the symbol of an element and to find its
.....
 2. A stoichiometric fuel/oxygen mixture is one which has exactly the right amount of
..... available to
a given amount of fuel.
 3. The heat of combustion is the amount of
evolved when one mole of a substance is burned in excess oxygen.
 4. Heats of combustion are used to
.....
.....
.....
 5. The colour of smoke is determined by the amount of oxygen and the
.....
-

CHAPTER 5

Building Materials and Fire

Element

Record the behaviour of building materials subjected to extreme levels of heat

Performance criteria

1. Building materials are evaluated for fire safety and recorded
2. Effect of fire on structural and non-structural elements are identified and recorded
3. Effect of fire on plastic and textile materials is identified and recorded

Chapter overview

This chapter looks at how different building materials will react in a fire situation. This is the most important of design principles for fire prevention and restriction.

All materials undergo either physical or chemical change, or both, when exposed to a fire. The individual elements of construction and whole buildings are also subjected to many changes, mostly detrimental. We will firstly look at the properties of the various building materials at elevated temperatures before trying to understand the responses of the building elements and the complete structures to the high temperatures experienced in building fires. There is usually a behavioural pattern during building fires that is common to all building material but there are often changes that are observed only in certain materials.

How do building materials behave in fire?

Practically all building materials change when exposed to building fires. With regard to their general behaviour they are divided into combustible and non-combustible materials. It should be noted that combustible and non-combustible are relative terms. There are specific standard tests that are used to establish whether a material is combustible or non-combustible.

Physical and chemical changes

All materials undergo changes when exposed to elevated temperatures. Non combustible materials, and combustible materials prior to ignition, will undergo:

- dimensional changes, that is, expansion or contraction
- changes of state such as softening, melting or in the case of liquids, evaporation
- changes in mechanical properties, such as strength, elasticity, strain, creep, bond and other engineering properties.

Combustible materials

Once ignited, a combustible material will continue to support the exothermic reaction while there are the three essential requirements for sustaining the combustion process, that is, heat, fuel and oxygen.

In a fully developed fire the most important properties of all combustible building materials are:

- chemical decomposition, support of combustion, spread of flames
- release of heat energy which is transmitted by various ways to the surroundings
- development of smoke and the release of volatile products of combustion.

Timber

Wood is a combustible material which consists mainly of cellulose, hemicellulose and lignin. The material is essentially non-homogeneous and even for a particular timber species the structural properties will depend on the grain direction and on the size and distribution of the various defects such as knots and shakes. Up to temperatures of about 800°C, timber expands, with an expansion coefficient of approximately 3.5×10^{-6} per °C. Thereafter, it shrinks continuously until full decomposition has occurred at about 400°C.

On heating in air, timber will ignite, depending on the conditions of exposure and on the amount of free moisture contained in the particular specimen. It is generally assumed that, with the presence of a pilot flame, timber will ignite at temperatures between 230°C and 250°C. If no pilot flame is present, the combustible volatiles will ignite at temperatures around and beyond 350°C – self-induced ignition. The ignition would depend also on the density (porosity) of the timber.

When timber burns, it forms a layer of charcoal on the burnt surface which helps to insulate the unburnt layers below from the fire. The average rate of charring for soft wood appears to be approximately 0.6 mm/min of exposure, under the time-temperature conditions of the standards fire-resistance test.

Timber is not a good conductor of heat. As it is slowly heated beyond the 100°C limit, it commences to lose some of its free moisture. This loss of water changes the cellular structure of the timber, thus reducing its structural strength in the sections heated beyond 100°C but below the range 230°C - 250°C. This area, in a cross-section of a timber member, is relatively small and consequently it is considered that a loss of about 10 per cent in strength for the unburnt cross-section of the timber member, for any selected period of fire exposure, is adequate for the purpose of design calculation.

Cellulose or wood particle boards

A wide range of building boards contains cellulose fibres and/or wood particles. All of these boards are combustible, but the general surfaces depend not only on the timber content. They are also influenced by the type and nature of the other material components of such boards, mainly the binding materials. If the binder burns with greater ease than the timber, the new man-made board would represent a greater fire hazard than a layer of timber of the same thickness. If the binder is portland cement or any other inorganic cement the fire hazard would be appreciably lower.

All combustible boards could be subjected to fire-retarding processes.

Non-combustible materials

Steel

Steel is a non-combustible material which loses its strength when exposed to the high temperatures experienced in building fires. There are two main grades of steel commonly used in building construction, the normal structural grade or mild steel and the cold-worked, high-tensile grade.

There are also two distinct ways in which steel is used in building construction. It can be used as separate structural members rolled into various shapes or as reinforcement in concrete members in the shape of bars, wires or tendons.

Let's look firstly at the performance of the normal structural grade steel in fire. On heating, there is an increase in its ultimate strength at temperatures up to about 250°C, after which the strength is progressively reduced. At approximately 550°C it retains only about 50 per cent of its ultimate strength at normal temperatures. That strength level is accepted by most design codes as being the design or working strength of the structural grade of steel. This means that when this steel is heated to about 550°C, the design stress is sufficient to cause plastic flow in the steel followed by a quick structural collapse of the particular steel member. At approximately 650°C the steel retains only 20 per cent of its cold strength. There is no permanent loss of strength for this type of steel on cooling if it has been heated

only to about 550°C. If the steel member has been exposed to a higher temperature, there could be a permanent reduction of up to a maximum 20 per cent of its ultimate strength.

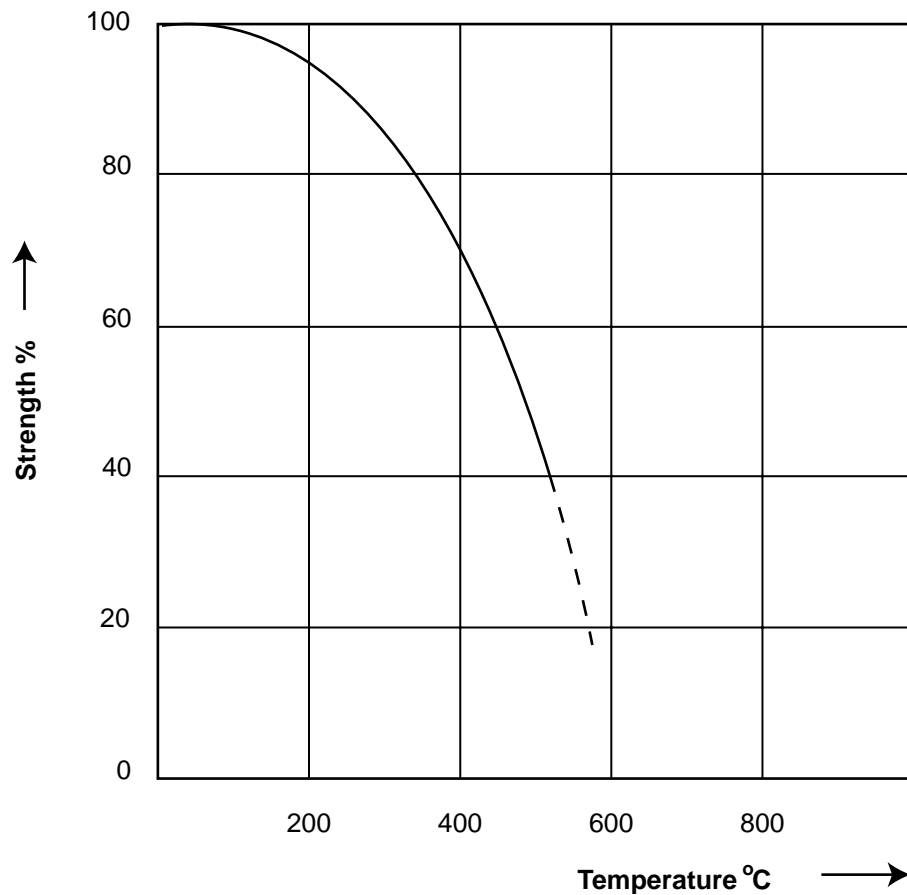


Figure 5.1: Approximate strength of structural grade steel (mild steel) at elevated temperatures.

Now let's look at cold-worked, high tensile grades of steel. When they are subjected to high temperatures they undergo much greater reduction in strength. At about 400°C these grades of steel revert to the grade of mild steel and lose permanently their high-tensile strength properties. Therefore the critical temperature at which failure of this grade of steel will occur is about 400°C, compared with a level of 500°C for the normal grade of structural steel.

The thermal conductivity of all grades of steel is high in comparison with that of concrete, timber, bricks and other building materials. Steel has also a high coefficient of thermal expansion which can lead to an integrity failure of the building structure where it is used as structural framing or cladding as shown in Figure 5.2.

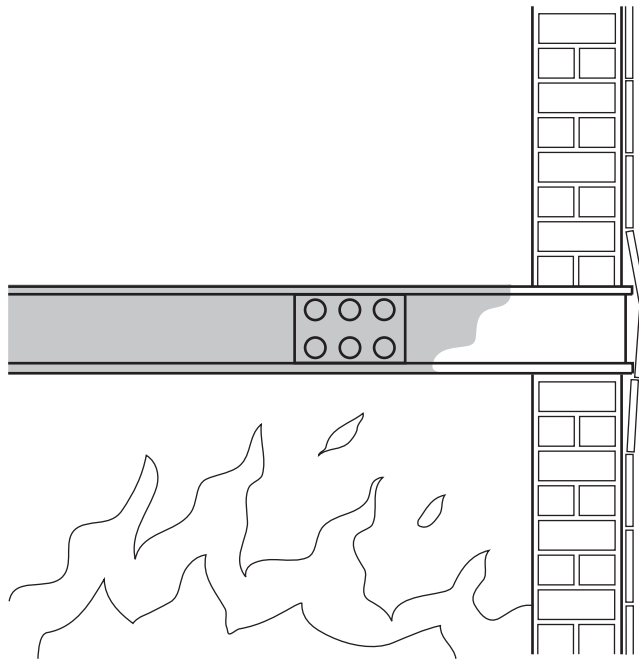


Figure 5.2: Steel beam elongates and pushes out external wall.

The high temperatures influence not only the strength of steel, but also other engineering properties of the material such as its modulus of elasticity, creep, stress/strain relationships and strain deformations. The detailed study of these properties and relationships is considered to be outside the scope of this subject.

Stainless steel is seldom used as a structural material, but is often used as the material for door jambs, architectural frames of lift-landing doors, frames of doorsets and for other decorative purposes. The loss of tensile strength at high temperatures is relatively low, but the coefficient of thermal expansion is about 50 per cent higher than that of mild steel. Consequently the dimensional changes are correspondingly greater.

Concrete

Concrete is a composite material whose behaviour during fire is controlled by the aggregates, the cement matrix, the amount of free water, some other ingredients and additives in the concrete mix and, in the case of structural concrete members, the steel reinforcement.

Concrete is a non-combustible material that is usually subjected to numerous changes when exposed to high temperatures. A certain amount of thermal expansion is characteristic during the early stages of the exposure, followed by shrinkage due to the evaporation of the free moisture at temperatures exceeding 100°C. The two most important variables that determine the behaviour of concrete exposed to a fire are its aggregates and the quantity of free water in its composition. The aggregates influence not only the thermal conductivity at

elevated temperatures, but also its integrity and, in some circumstances, its stability. The best performances are obtained from concrete containing lightweight aggregates, such as expanded shales and clays, cindered fly ash, foamed slag, exfoliated vermiculite and perlite, as well as naturally occurring scoria and pumice. The feature of these aggregates is that they are made from a heat-producing process, which bloats the basic material and produces an aggregate of much lower density than naturally excavated dense aggregates. The lightweight aggregates could be man-made, or could come from natural deposits like scoria and pumice.

Concretes made of lightweight aggregates can still achieve high strengths, but they have better insulation qualities than concretes made of dense aggregates. As the lightweight aggregates have already been subjected to high temperatures and have undergone the expected changes in their structures, the concretes made from them are considerably more stable when exposed to high temperatures. Their thermal deformation is less.

Concretes made from calcareous dense aggregates do not perform as well at high temperatures as concretes made of lightweight aggregates. Their thermal conductivity is better but their thermal insulation properties are worse.

The siliceous aggregates are the usual type of dense aggregates used in the manufacture of normal concrete. The natural rocks in this category are river gravel, crushed granite, dolerite, basalt and various other igneous rocks. Concrete made of this type of aggregate expands considerably at high temperatures and its thermal insulation properties are the worst, when compared with those of concretes made of calcareous dense aggregates, or of lightweight aggregates. Quartz, quartzite and flint aggregates are particularly unstable at high temperatures. They expand violently and, due to physical changes in their crystalline structures, shatter at temperatures around 75°C. This behaviour causes widespread damage to the concrete containing these coarse aggregates. River gravel usually contains a large proportion of these minerals and consequently may also exhibit similar behaviour.

Often, but not necessarily always, the surfaces of concrete members may crack and shatter when exposed to a fire with rapidly rising temperature. This fairly complex phenomenon is referred to as spalling. It depends on the following factors:

- excess amount of free moisture in the concrete
- porosity of the concrete
- type of aggregates
- stress level to which the concrete is subjected.

Three types of concrete spalling are usually observed.

- **local spalling** – mainly pitting, blistering and local removal from the surface materials.
- **general destructive spalling** – large or small pieces of concrete are violently pushed from the concrete surface, accompanied by loud noises. This spalling occurs at an early stage of the fire exposure. It causes extensive damage to the concrete, or complete destruction to several layers of the concrete.
- **sloughing off** – a gradual progressive form of breakdown involving partial separation of surface materials. This may continue slowly throughout the fire exposure.

Not only concrete, but cement-lime-sand render is also subjected to excessive spalling.

The thermal conductivity of concrete depends on the nature of the aggregates, porosity and moisture content. As already noted, concretes made of lightweight aggregates provide much better thermal insulation at high temperatures experienced during fires in buildings.

All types of concrete lose strength on heating, but up to temperatures of about 200°C only a slight reduction occurs. At approximately 500°C the strength of concrete made of dense aggregates is reduced to half that at ambient temperature. Concrete that has been heated above 600°C has little residual strength. This is illustrated in the graph in Figure 5.3. Such temperature, however, is seldom reached throughout the complete thickness of a concrete member. Concretes made of lightweight aggregates also lose strength when heated, but the reduction of strength is less.

All concretes undergo chemical changes at high temperatures, and change colour, depending on the temperatures of exposure. Their colour changes to pink when exposed for longer periods to about 300°C. At around 500°C to 600°C the pink colouring reverts back to grey, and at 950°C the concrete develops a buff colour indicating a complete change of chemical composition.

The bond between concrete and reinforcement in the structural members of reinforced and prestressed concrete also deteriorates at high temperatures. The modulus of elasticity shows a steady reduction and the short-term creep appears to increase.

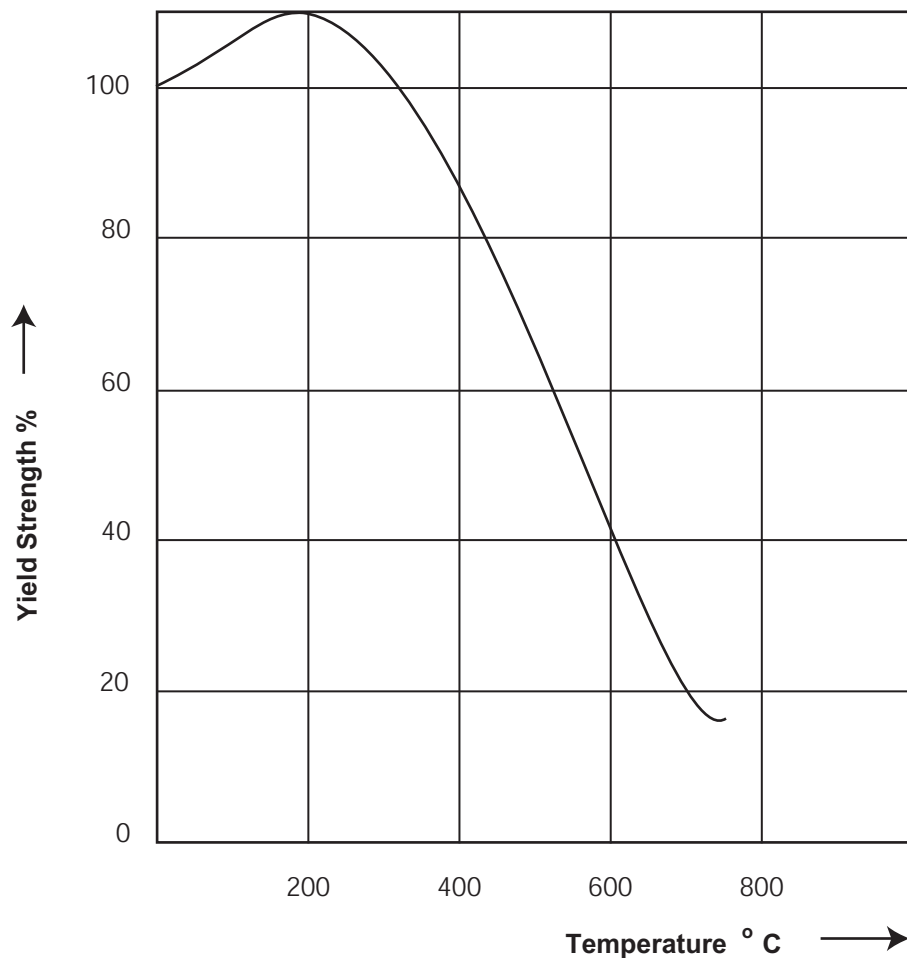


Figure 5.3: Approximate strength of dense aggregate concrete at elevated temperatures.

Masonry units

Burnt clay bricks are chemically stable as they are produced at temperatures comparable with those experienced in building fires. The engineering properties of the burnt clay bricks change at elevated temperatures, but the changes are relatively minor. Concrete bricks and concrete blocks undergo the changes and exhibit the properties that are characteristic for concrete.

The material from which they are made also determines the thermal insulation and thermal conductivity of clay and concrete masonry.

Gypsum plaster and plasterboard

Gypsum plaster, as used in the building industry, is calcium sulphate dihydrate. It contains approximately 20% water of crystallisation by weight. This water has to be removed by a considerable amount of heat input before failure of the gypsum plaster will occur. After the chemically combined water has been driven off as steam, the gypsum plaster shrinks, undergoes chemical changes and loses its

strength. Shrinkage could be further reduced by the introduction of fine lightweight aggregates such as exfoliated vermiculite, perlite or natural pumice.

Boards and blocks made of gypsum plaster have the same inherent characteristics as the basic plaster compound.

Materials containing mineral fibres

Ceramic and other mineral fibres, and to a lesser extent glass fibre, are often mixed with cements and other suitable binders to make boards or mixes used as spray applications. These fibres are fairly stable at high temperatures and, depending on their type and nature, may not melt or soften at temperatures in excess of 1000°C. Glass fibre, however, will soften and melt at about 600°C. The ceramic and mineral fibres now replace the asbestos fibre used extensively in the past as fire-protective material.

Alumina silicate materials which remain stable and maintain their insulating properties at elevated temperatures are also used in the manufacture of special types of building boards.

Trimming, fittings and surface finishes

Aluminium

Aluminium is not at present used structurally to the same extent as steel. Its main use is in the manufacture of window and door frames and various fittings and trimmings. Aluminium has twice the rate of thermal expansion of steel. It has a higher thermal conductivity and less heat capacity than any type of steel. Its load-carrying capacity and structural strength are lost at approximately 250°C.

Aluminium's high ignition temperature is high enough to prevent burning from being a factor in most fires. In powder or other finely divided forms it can present special fire problems.

Where aluminium is substituted for iron or steel, the lower melting temperatures is an important factor whenever resistance to fire temperatures is essential.

Aluminium melts at about 660°C. At this relatively low melting point, aluminium building sides may melt so rapidly during a fire that they give the impression of burning.

Aluminium roofing laid directly on structural supports without a roof deck will melt through and vent a fire beneath it, thus allowing firemen to enter the building with hoses or to direct water on the fire through the melted roof. There may be a greater danger to firemen working on such a roof than on one of steel because of its strength loss in a fire.

Glass

This material is non-combustible, but ordinary glass will melt at temperatures in the range of about 600°C to 700°C. If ordinary sheet glass is subjected to a rapid build-up of heat from one side, as is the case during a fire exposure, it will crack and shatter. The same type of sheet glass with embedded wire mesh as reinforcement will perform considerably better during a fire exposure. This wired glass, called Georgian Wired Glass, cracks just as readily as the unreinforced sheet glass, but the individual glass fragments are kept in position by the wire mesh. The sheet of wired glass will continue to provide separation until it melts at high temperatures.

Toughened glass such as 'Vycor' and 'Pyran' melt at very high temperatures in excess of about 1200°C and 1300°C. They will not crack or shatter when heated rapidly but they fail to provide insulation. Laminated glass which has a layer formation tends to become opaque when exposed to excessive heat thus providing good insulating qualities.

The performance of any glass is totally dependent on its housing. In this regard timber is often a better framing material as it tends not to buckle or twist and provided it is designed to last for a specific time against fire it will provide good support for glass.

warning!

Non-combustible materials are not always fire resistant. Glass and steel are good examples of this. The fire rating of a building may well depend on the way glass and steel are incorporated into a design which supports fire-rating systems.

Plastics

Plastics comprise a group of building materials consisting of man-made organic substances of high molecular weight and complex chemical composition. Plastics are combustible and their combustibility characteristics vary widely. There are about thirty major groups of plastics and the number of the individual plastic materials runs into the thousands. All plastics are divided into two major classes: thermoplastics and thermosetting plastics.

Thermoplastics can be repeatedly softened by heating, and stiffened by cooling. They soften at relatively low temperatures and do not undergo chemical changes at that stage. When cooled they will retain their original forms and shapes. Typical representatives of thermoplastics are acrylics, polyethylene, polystyrene, polyvinylchloride (PVC) and nylons.

Most plastics decompose at around 200°C, although some types remain intact up to temperatures of 400°C to 500°C and even higher. Their ignition temperatures

are again relatively low. The calorific value of plastics is generally high. This means there is a relatively large amount of heat produced by a given weight of fuel on complete combustion. Consequently, the heat radiated from burning plastics is very substantial although not necessarily of long duration. During combustion, plastics produce large amounts of smoke, volatile combustible hydrocarbons and other combustible gases. Highly toxic substances and gases may also be produced, depending on the particular plastic material. The burning sequence may be simultaneous or interactive and may follow this pattern: Thermosetting plastics are also softened when heated, but on continued heating undergo chemical reaction which causes hardening of the softened material. The original forms and shapes are lost on cooling. Typical representatives of thermosetting plastics are epoxies, phenolics, polyesters and urea formaldehyde.

- Plastic softens, melts, even boils.
- The thermal and chemical breakdown commences.
- The exothermic oxidation (combustion) commences.
- High temperatures, dense smoke and combustible gases develop.
- There is extensive heat radiation.
- There is fire spread by ignition of combustible gases at some distance from the seat of the fire.

Lining materials and surface finishes

Many of this large group of materials ignite readily, burn fiercely and develop large quantities of smoke and other volatile products of combustion. The importance of combustible materials in this category are characterised by:

- the ease of ignition and the tendency to spread flame
- the heat developed once ignition has occurred
- the tendency to produce smoke and the density of that smoke
- the toxicity and the corrosive effects of the products of combustion.

Behaviour of structures and elements in fire

An element of construction is a part of a building or structure having its own functional identity such as foundations, walls, floors, roofs, stairs or the structural framework.

The structural behaviour of any building structure is influenced by:

- the properties of the materials used in its construction
- its layout and the arrangement of its structural components
- the specific engineering design of that structure
- the fixing and restraint at the joints and junctions between the individual structural members or elements.

There are two distinct stages which can be recognised in the behaviour of building structures subjected to loading. The first stage covers the behaviour under normal service conditions and is structurally within the elastic ranges of the materials used. The second stage represents the overload condition when the structure is approaching collapse.

A fire exposure from purely a structural engineering point of view, represents the introduction of additional strains and stresses in the balance of the structure and the pronounced deterioration of the structural properties of the materials. All of these factors usually bring the structure affected by fire to the stage of collapse.

Failure of structures

Building structures have three levels of structural failure, the serviceability limit, the ultimate limit and structural collapse.

Serviceability limit

The serviceability limit is reached when the strains are such that the beams, columns, walls and floor slabs camber and deflect excessively, crack, and generally impair the functions of the building elements. Most building design codes give the limits of the permissible permanent deflections and also limit the extent of acceptable local damage.

Ultimate limit

The ultimate limit is reached at the commencement of the state of structural collapse. A building structure involved in a major fire might collapse due to:

- deterioration of the structural materials and reduction of their strength
- increase of strains due to inability to follow freely thermal expansion or shrinkage
- development of thermal stresses and moments

- re-distribution of moments, thus changing the structural stability.

Fire endurance ratio of surface area to mass

The fire endurance of an individual structural member depends not only on the material in that member, plus the applied loads and developed stresses, but also on the ratio of its surface area exposed to the fire to the mass of material per unit length of the member. When all other factors are equal, the best fire endurance will be exhibited by the structural member that has the smallest ratio of surface area exposed to a fire to the mass of material per unit length. Theoretically, a member with a circular cross-section will provide the best solution, followed closely by a member with a square cross-section. The worst performance could be expected from thin and slender structural members. This relationship of surface area to mass is equally valid for structural elements of combustible and non-combustible materials.

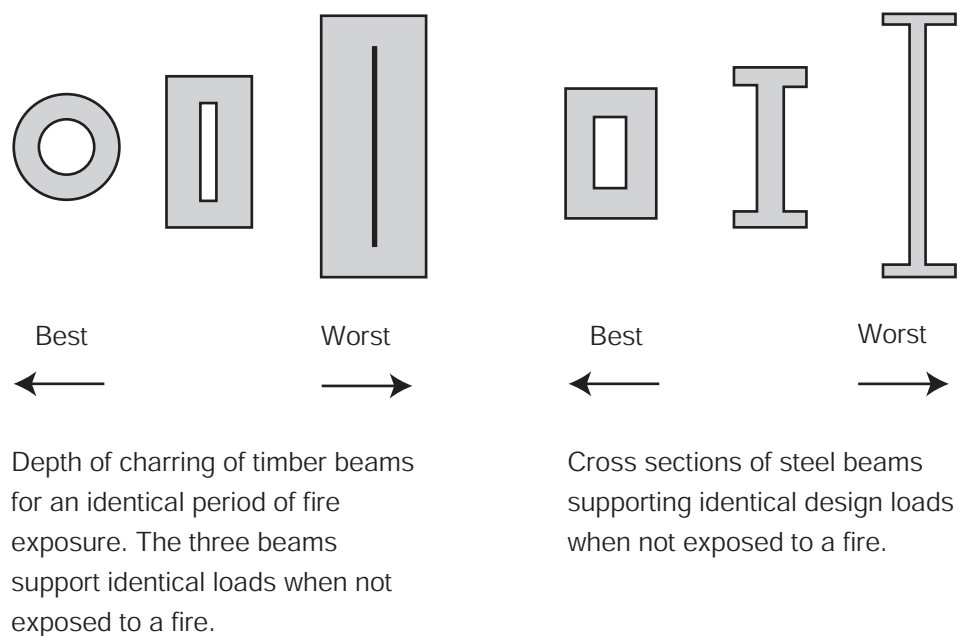


Figure 5.4: Cross sections of steel beams to show relationship of surface area to mass.

Figure 5.4 shows cross sections of beams designed to support the same design loads. Under normal conditions of service, the slender beams will be chosen by the designer because they will be more economical with respect to the material used while providing support capability.

In the case of the timber member, the depth of charring is fairly uniform and depends mainly on the duration of fire exposure. It has been established in standard fire-resistance tests that the depth of such charring is about 30 mm per hour. As the diagram shows, the most unburnt timber is left in the beam with a circular cross-section having the smallest ratio of exposed surface area to mass.

The timber in the slender beam has already disappeared. As the use of structural steel members with circular or square solid cross-sections is seldom practical or economical, the next best solution for the designer is to select from commercially available rolled steel, a section that has the smallest ratio of exposed surface area to mass.

Interaction of components

The behaviour of an individual structural member exposed to a building fire is greatly influenced by the manner in which it interacts with the other components of the complete building structure. Its behaviour is usually examined under the following assumptions:

- The Building Code of Australia (BCA) stipulates that any large building must consist of fire-isolated compartments intended to confine the fire. The floors and roofs provide the horizontal separation and the fire-resisting walls and partitions define the vertical divisions of the compartments. Any separate fire-resisting member represents a structural component of a fire-isolated compartment.
- A structural member will support its design load during the fire exposure and shall not collapse during that period of time.
- The elements of construction separating fire-isolated compartments shall provide considerable thermal insulation during the fire exposure, thus preventing the spread of fire to that adjacent compartment.
- An element of horizontal construction is exposed to more severe fire when the fire is located below such a member.

The statically determined structural members, such as simply supported beams and slabs, fail structurally when the heating reduces their load-carrying capacity below the limits allowed by the design. As the greatest bending stresses are in the middle of the span of the simply supported member, this is the location where yield will first occur and a plastic hinge will be formed. The member then becomes unstable and collapse follows.

If the simply supported beam or slab is restrained at its ends, subjected to uniaxial restraint, it cannot expand during the heating process. A restraining force is developed which in turn develops a moment opposite to that developed by the design loads. The net result is that the magnitude of the new resulting moment is reduced and the structural member can survive the fire exposure for a longer period of time.

A similar situation develops when a continuous beam or a continuous slab is exposed to a fire. Such members are supported over several supports and are described as statically indeterminate members.

note

Although an understanding of the mechanism of these developments is considered beyond the scope of this subject, it is important for you to remember that statically indeterminate members normally exhibit a greater fire endurance than statically determinate or simply supported members.

The magnitude and character of the thermal forces, stresses and moments developed during a fire exposure in a major building will depend on:

- the general structural design arrangement
- the degree of continuity and flexibility
- the types of materials used
- the composite action between the individual structural members of that building.

Their exact distribution will not only differ for each particular building but also will vary throughout the period of fire exposure.

Self-help exercise 5.1

1. In which three ways do materials change at elevated temperatures?
.....
.....
.....
 2. Timber will
up to a temperature of 800°C and as the temperature rises further it shrinks until full
decomposition has occurred.
 3. The materials used to bond man-made boards containing cellulose and wood particles is
important to the material's
 4. At 550°C, normal structural grade steel retains only.
per cent of its strength.
 5. The two most important variables that determine the behaviour of concrete exposed to fire are
.....and.....
 6. Concretes made of lightweight aggregates do not perform as well at high temperatures as
concretes made of calcereous dense aggregates. TRUE or FALSE
 7. Glass fibre will melt at about 600°C while other materials containing mineral fibres are usually
stable up to a temperature of°C.
 8. Aluminium has twice the rate of thermal expansion as
 9. The performance of any glass is dependent on its
 10. The two major classes of plastics are
..... and
 11. The structural member which has the largest ratio of surface area exposed to a fire will have
the most endurance to fire. TRUE or FALSE.
-

CHAPTER 6 Fire Loads

Element

Record the behaviour of building materials subjected to extreme levels of heat

Performance criteria

1. Building materials are evaluated for fire safety and recorded
2. Effect of fire on structural and non-structural elements are identified and recorded
3. Effect of fire on plastic and textile materials is identified and recorded

Chapter overview

This chapter looks at fire loads and how they affect Fire Resistance Levels (FRLs) in buildings. Building controllers need to understand how fire loads are calculated. Fire severity depends on a variety of factors and these must be appreciated and accepted by designers and building surveyors so that appropriate design elements can be incorporated into buildings. The BCA offers a variety of fire control options for all classes of buildings and these are directly related to fire load levels. It is important as building controllers to consider these aspects when surveying building materials, construction techniques and uses of buildings at the design stages and when changes take place over the life of the building.

Fire load

The concept of fire load is very important in building design. The concept is the basis for many of the BCA requirements for fire design in building and this is mirrored in the regulations of many western countries such as the USA and England. Originally, the analysis of fire loads was used as a means of estimating potential fire hazards but the methods for design were rather limited and made assumptions which are now regarded as inappropriate. These assumptions included ideas such as that combustion in buildings would always be complete, that all the combustibles would be part of any fire and that these combustibles were uniformly distributed in the building. It is the case that these assumptions at times may appear correct but simple differences can have a marked effect on the final outcome of a fire. A good example may be two warehouses that store televisions. In one they are stored to the ceiling and in the other they are stored no higher than chest height due to a different pallet system. In the former a fire may be of such intensity that an active sprinkler system may be unable to control the fire and in the latter the system may be far more efficient in its control capacity. Thus whilst fire load in general relates to fire growth it is only one aspect for consideration in fire protection.

The analysis of fire loads in relation to various occupancy types has been used to predict the potential severity of fires. This method still provides a good estimate of probable outcomes in a fire, for a variety of building uses.

Fire load can be defined as being the index of the potential heat which can be liberated during the fire of the combustible contents of a given enclosure. The fire load can be determined for a whole building or only a part of it. It is expressed as a numerical value calculated from the weights and calorific values of the combustible contents. This value is expressed as kJ/kg (kilojoule per kilogram).

The heat content of a combustible material is expressed in terms of the amount of wood required to produce the equivalent amount of heat by burning. In a typical

building, the fire load includes combustible contents, interior finishes, floor finishes and structural elements.

In building fires, the fuel is provided by the contents of the building and by combustible components of the building structure. Therefore, if the fire load is calculated only in terms of the combustible contents of the enclosed space, it is called 'Occupancy Fire Load'. If the combustible components of the surrounding building structure are also taken into account, the fire load is described as 'Cross Fire Load'. The fire load in any form is only incidentally related to the 'live' or 'dead' structural loads.

Fire load density is the fire load of a given enclosure or a building, divided by the corresponding floor area. It is expressed as fire load per unit area of floor space.

It should be noted that the fire load does not take into consideration the forms in which the combustible substances are present. Comparative studies assume average distribution of the combustible material. If that material in one case is in a very loose form, like tinder or fluff, and in another case in the form of solid bulk, the fire load will be the same in each case. The characteristics of the expected fire, however, will be quite different for each case. In the first case, the heat energy will be released as a short-term severe fire, and in the second case it would probably be released as a slow-burning protracted fire of lower severity.

The greater the fire load, the greater will be the potential fire severity and the consequent fire damage. Because most buildings are built for a specific type of occupancy, it is not difficult to predetermine fairly accurately their maximum fire load when the building is in full use. These considerations allow the elements of structure of a particular building to be designed so as to resist the maximum heat release from an expected fire.

Fire severity

The fire severity of a fire is the total energy of the fire. It involves the temperature developed and the duration of burning. Many factors affect the severity of a fire including ventilation, building design features and structural elements. Fire severity is directly related to fire intensity levels and is linked to the flashover points of a fire.

In 1928 Inberg hypothesised that fire severity and fire loads were interrelated and that once the fire load of a building was determined then a fire resistance component

could be applied to a building. His ideas are well founded although his methods are now out of date. This is due to the use of new materials.

The idea of fire severity was further expanded by Law in 1971. She applied modern techniques to Inberg's hypothesis and used the standard time/temperature curve as shown in Figure 6.1.

Although potential fires from flammable liquids cannot be determined by her methodology, the method still provides a useful technique to calculate fire severity and fire resistance levels.

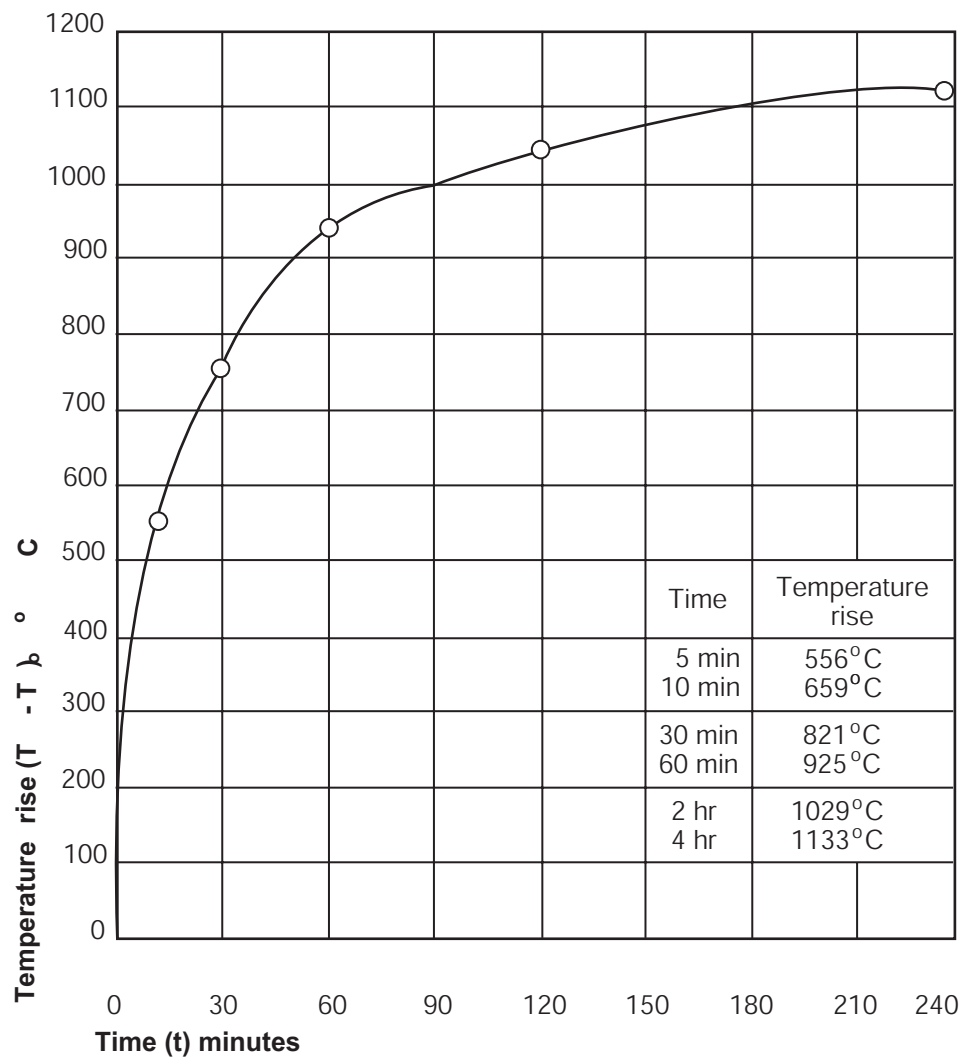


Figure 6.1: The standard time/temperature curve.

Fire severity for buildings depends upon fuel, and its arrangement and placement, ventilation and heat loss. It is determined by a combination of the temperature of the fire and the length of time the fire burns as shown in Figure 6.2.

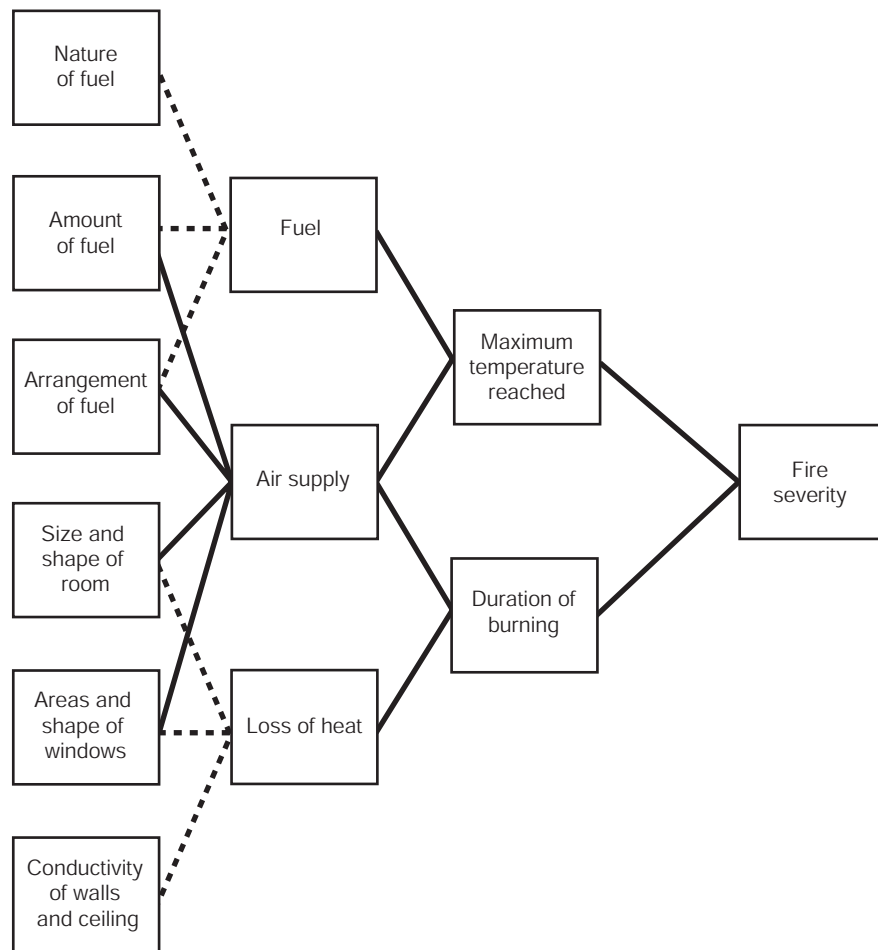


Figure 6.2: Fire severity flowchart.

Technically accurate methods for relating potential fire severity to fire loads are far more complex than those described in this chapter. Consideration nowadays must also be given to ventilation methods, enclosures, compartmentation, ceiling design and the actual occupancy type and levels and how they vary over the life of a building. They require specific expertise in the design phase.

The BCA and fire safety

The BCA sets minimum standards for construction of all types of buildings. Egress provisions protect life, fire rated walls protect adjoining property and fire rated structural components protect property.

The provision of fire safety in building design in the BCA takes into consideration:

- use of the building
- occupants
- fire load of the building
- height of building
- passive and active fire protection.

The BCA is continually being amended in all areas but building controllers need to be especially conversant with the fire safety aspects of the Code. A good start is becoming aware of the sections of the Code relating to fire. You also need to be conversant with the definitions.

Self-help exercise 6.1

Refer to Building Code of Australia 1996 – Volume 2 and answer the following questions.

1. List three materials, which, although of combustible material or containing combustible fibres, may be used wherever a non-combustible material is required in the Housing Provisions.
.....
.....
.....
 2. Where an external wall does not have a Fire Rating Level (FRL) of 60/60/60 and is not of masonry-veneer construction in which the external masonry veneer is at least 90 mm thick, what thickness must it have and of what type of construction must it be?
.....
.....
 3. The minimum distance between buildings with non-fire rated walls ism.
-

CHAPTER 7

Fire Resistance of Building Materials

Element

Report the requirements of fire resistance of materials, building elements and forms of construction

Performance criteria

1. Fire resistance levels of materials, building elements and forms of construction are researched and recorded
2. Early fire hazard indices are applied to the BCA requirements
3. Australian Standards relating to fire testing of building materials and forms of construction are researched and recorded.

Chapter overview

A building's fire resistance is directly related to the Fire Resistance Levels (FRLs) of its construction materials. Building design should look at the cumulative effect of the inclusion of materials and how the individual FRLs affect the building's overall fire resistance. In Australia FRLs are allocated after materials have been put through a rigorous testing regime. This testing compares a material's performance, under simulated fire conditions, against a recognised standard. A building controller needs to be fully conversant with the testing regime especially when assessing performance-based proposals for a material's use in a building.

Fire testing

Fire testing of building materials has been carried out since the 1950s and many of the original principles of those early tests are still valid today. These early tests ensured that materials tested were representative of construction types, had similar attributes to materials in use and were tested in situ. As with any assessment where human safety is the prime objective, testing methods need to be verifiable over a number of variables and in Australia testing of materials must be done in accordance with AS 1530.4 Fire resistance tests of elements of building construction and carried out in accredited laboratories.

Building materials are tested for three qualities:

- **Structural adequacy** – the ability of a materials and/or elements to function for a known period in a fire.
- **Integrity** – the ability of materials and/or elements to withstand fire and remain intact.
- **Insulation** – this is an essential characteristic of components which have a separating function, such as walls and floors.

All of these three test components are expressed in terms of time in the testing regime, and the FRL attached to the component is directly related to its individual or combined use, for example a timber component in a floor in comparison to a timber door.

The standard time/temperature curve

A major experimental program was undertaken in the 1960s to improve our understanding of the behaviour of the fully developed compartment fire. The object was to provide information which would allow the development of a rational approach to the problems of fire severity and fire resistance. Several research groups have turned their attention to developing ways of predicting the likely temperature–time history of a potential compartment fire. The ultimate objective of such an exercise is to be able to specify for design purposes of the

thermal stress to which elements of structure would be exposed in the event of fire in a particular space, thus providing an alternative to the current building codes and regulations.

The original time/temperature curve was developed by the use of small scale models. Nowadays testing is carried out on full scale models with some cooperative data applied from actual fires.

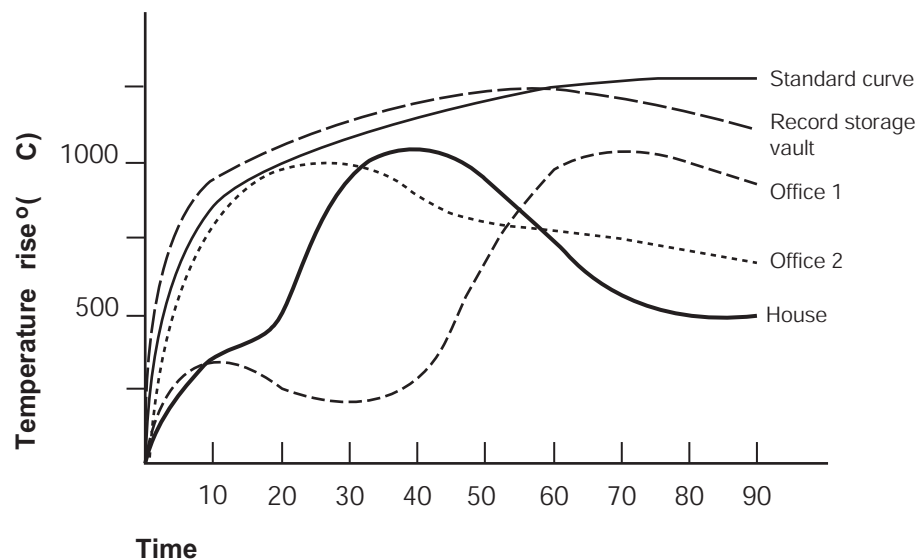


Figure 7.1: The time/temperature curve for a variety of building classifications.

Figure 7.1 shows comparisons with a variety of building classifications. The fires tended to follow the standard curve and variations occurred in duration times and fuel types. However, the 'curve' is regarded as a good measuring stick for most materials and errs on the conservative side which is all the better for occupant safety.

Fire Resistance Levels (FRLs)

Originally fire ratings related directly to the time that a material or element withstood fire. There was a minimum of one hour set for all materials so that if a material could not withstand fire for 60 minutes then it did not achieve a fire rating. Designers felt this to be too prohibitive as materials may not need to last one hour to achieve an overall building fire resistance. Thus FRLs were introduced as they took into account a wider view of materials' adequacy under fire conditions.

A material's FRL is determined with the knowledge of its structural adequacy, its integrity and its insulation capabilities. The standard fire test measures each of these attributes. An element or building material must withstand fire for 30 minutes to achieve a fire rating level for each attribute.

Standard fire test

Tests are tools or aids used to measure some attribute, characteristic or behaviour pattern of a material, a composite product, a structure or a system. The tests provide either a quantitative or a qualitative assessment, and form an essential part of the whole process of selection and appraisal.

Fire tests have been developed as tools for the realistic assessment of specific qualities and behavioural patterns. The development of these fire tests has been influenced by fire research activities, experience and statistical evidence from actual fires. The tests provide important information to building controllers, fire officers, designers, planners, insurance bodies and anybody involved with fire components of buildings and the impact of fires within the community. The fire tests in Australia are described in Australian Standard 1530 Methods for fire tests on building materials, components and structures. There are four separate tests prescribed as follows:

- AS 1530.1 Combustibility test for materials
- AS 1530.2 Test for flammability of materials
- AS 1530.3 Simultaneous determination of ignitability, flame propagation, heat release and smoke release
- AS 1530.4 Fire resistance tests of elements of building construction.

It should be noted that the first three tests apply to materials only and that the fourth test applies to elements of structures, but not to materials.

Let's look at each test in more detail.

Combustibility test for materials

This test applies to the testing of building materials, either coated or uncoated, to determine if they are combustible or non-combustible within a special meaning stipulated by that standard.

AS 1530, Part 1 requires that five test specimens of the same material, of specified dimensions and after being conditioned under prescribed conditions, shall be placed quickly into a special small laboratory furnace. Each test specimen shall remain in that furnace for a period of 30 minutes. The furnace temperatures and the method for measuring temperatures in the furnace and also in the specimen are prescribed. The material is considered as being combustible if any one of the criterion of combustibility occur as defined in Clause 10 of AS 1530 Part 1 can be applied.

All details concerning the combustibility test for materials are contained in AS 1530, Part 1.

Test for flammability of materials

This test method was developed to measure the reaction of thin flexible materials to contact with a match-type ignition source. The test is applied to woven materials, such as curtains and drapes, and to thin pliable sheets of materials, like sarking materials. Six test specimens of prescribed dimensions are required. The six specimens are put under specified conditions for not less than 24 hours before undergoing the test. Each specimen is attached in turn to a near-vertical apparatus frame and subjected along its lower edge to a small alcohol flame. Measurements are made of the distance and rate of flame spread, and of heat released during any subsequent burning. The duration of the test is 160 seconds from the moment at which the alcohol ignites, but temperatures are monitored for 180 seconds. The material under test is graded in accordance with its observed behaviour in terms of three factors, speed factor, heat factor and spread factor. The flammability index is determined from these three gradings. That index is expressed in the range of 0 to 100 with the higher number indicating a higher potential fire hazard.

All details pertaining to the test for flammability of materials are contained in AS 1530, Part 2.

Simultaneous determination of ignitability, flame propagation, heat release and smoke release

This test is used to classify building boards, cladding materials and their surface finishes according to:

- their tendencies to ignite
- their tendencies to spread flame
- the heat they develop once ignition has occurred
- their tendencies to produce smoke.

The test requires that nine representative test specimens, each measuring 600 + 5 mm x 450 + 5 mm and of normal thickness shall be prepared. Of these nine specimens six shall be tested initially. The standard prescribes the details of conditioning the test specimens for a period of seven days, and the construction and operation of the test apparatus.

The test exposes a material to a gradually increasing intensity of radiation until ignition is caused by a small pilot flame. A radiometer measures the intensity of radiation emitted by the burning specimen. Then the rate of surface spread of flame is calculated from the rate of increase of that radiation. The gases emitted from the burning specimen are collected in a canopy above the test apparatus and are diverted up a flue. A collimated light-beam is directed across the flue to a photo-electric cell to determine the optical density of the smoke given off by the

specimen. Each specimen is subjected to that treatment for a period of 20 minutes.

The results are expressed by four indices:

Ignitability Index – range 0-20

The ignitability index is the time taken for combustible gases released from materials to form a gas mixture capable of being ignited by flame. The index number for ignition of a material is 20 minus the mean time of ignition in minutes of the test specimen exposed to the heat radiation. If the test specimen has ignited after an exposure of three minutes, its ignitability index will be 17; if the specimen has not ignited after 20 minutes, the ignitability index will be 0.

Spread of flame index – range 0-10

The spread of flame index relates to the time taken for radiation density to increase by 1.4 kW/m² from the time of ignition. The time is measured in seconds. If the ignitability index is zero, the spread of flame index is also zero. A spread of flame index of 10 for a wall-lining material indicates that the material would cause flames from the floor to reach a ceiling 2700 mm high within 10 seconds of ignition.

Heat evolved index – range 0-10

The heat evolved index relates to the rate at which heat is released by the burning material. It allows distinctions to be drawn between materials on the basis of whether or not the amount of heat evolved from them would be sufficient to cause ignition of nearby combustibles.

Smoke developed index – range 0-10

The smoke developed index relates to the optical density of smoke produced by the burning material. An increase in the index number by one to the next higher number indicates a doubling of the smoke density.

In all four indices a higher number indicates a greater hazard. All details pertaining to the test for early fire hazard properties of materials are contained in AS 1530.3.

Fire resistance tests of elements of building construction

The test used to determine the levels of this resistance is described in AS 1530, Part 4. The test which was developed internationally, principally by research workers in Great Britain and in the USA, became an Australian standard in 1935, was revised in 1959, 1975, 1985 and 1990. The latest revisions make the standard fire resistance test more explicit for each of the structural elements being tested and aligns the previous test more closely with the test described in *International Standard ISO 834*.

The test procedure is as follows. A representative specimen of an element of construction is conditioned and then exposed to heat under controlled conditions in a furnace which is operated to satisfy a specified time/temperature curve. To minimise the effect of a variation in ambient temperature on the outcome of the test, the heating curve is expressed in terms of temperature increments above ambient rather than actual temperature.

Where it is not possible to model the element or system of construction satisfactorily with one specimen, it may be necessary to test more than one specimen. Observations are made on the performance of the specimen while it is subjected to thermal and, where applicable, physical loading. The elapsed times at which various failures occur are recorded.

This test provides information on which the FRL of an element of construction can be assessed. The test report also includes information which may be used by a designer. For example, records of temperature at critical locations at a particular time may be used to assess the fire resistance of a variant of the tested prototype flexural number, where the procedure for such an assessment is defined in the appropriate design code.

Method of test

The test method is to construct a representative prototype of a particular element of construction, to stress and support it as it will be stressed and supported in a building structure, to heat it at prescribed temperatures and rates of heating, to monitor its reaction to the combination of physical and thermal stresses and finally to assess its ability to perform its load-supporting functions, its fire-separating functions, or both, as the case might be.

The test requires that where possible a full-sized prototype element of construction be tested. Where the full dimensions exceed 3 m x 3 m, the testing authority shall test a representative portion of the full-sized element of dimensions not less than 3 m x 3 m. The test specimen is then subjected to its maximum design loading and stresses, if any, and then heated according to a specified time-temperature curve. Points on this curve in AS 1530, Part 4, are:

| | | |
|--------|---|---------------|
| 538°C | – | at 5 minutes |
| 704°C | – | at 10 minutes |
| 843°C | – | at 30 minutes |
| 927°C | – | at 1 hour |
| 1020°C | – | at 2 hours |
| 1131°C | – | at 4 hours |
| 1200°C | – | at 6 hours |

It should be noted that the prescribed time-temperature conditions do not necessarily represent any actual fire condition. They provide, however, the common laboratory denominator under which the elements of construction are examined.

Criteria for failure

The criteria for failure for a fire resistance level are as follows:

- **Structural adequacy** – failure shall be deemed to have occurred when either collapse occurs or, following commencement of the heating, deflection occurs which is in excess of that specified in the Section of AS 1530 Part 4 that is applicable to the element of construction under test.
- **Integrity** – this is in relation to an element that is intended to separate spaces and resist the passage of flame from one space to another. Integrity shall be deemed to have been breached upon collapse or the development or cracks, fissures or other openings through which flames or hot gases can pass.
- **Insulation** – Failure shall be deemed to have occurred when either the average temperature of the relevant thermocouples attached to the unexposed face of the test specimen rises by more than 140 K above the initial temperature, or the temperature of any of the relevant thermocouples attached to the unexposed face of the test specimen rises by more than 180 K above the initial temperature or reaches a temperature higher than 220°C.
- **Radiation** – When the radiant heat flux reaches 10 kW/m² at a distance of 365 mm failure is said to have occurred.
- **Structurally critical temperature** – This is the critical temperature at a selected point.
- **Incipient spread of fire** – This is when the average temperature inside the construction exceeds 180 K above the initial temperature.

Test results

The test results are stated in terms of time in whole minutes from the start of the test until failure has occurred or if no failure has occurred, until the test is terminated.

As an example, the following test results would indicate that a floor/ceiling system failed in respect of resistance to incipient spread of fire, insulation and integrity at the stated times but complied with the requirements for structural adequacy when the test was terminated at 136 minutes.

- Structural adequacy no failure at 136 minutes
- Integrity failed at 118 minutes
- Insulation failed at 106 minutes
- Resistance to failed at 65 minutes

Test report

When assessing designs or new products that include FRL test reports you should ensure that the report contains the:

- name of the accredited testing authority
- name of applicant
- date of test
- manufacturer
- product name
- testing methods
- test results.

Testing requirements and report details are fully laid out in AS 1530 series booklets and building controllers need to be reasonably conversant with these standards to make decisions on a variety of applications they will be presented with. The full list of Australian standards applicable to fire protection is available from Standards Australia in their booklet SL09 free of charge.

warning!

Australian standard codes are continually updated and it is important that you keep an eye on any new standards that may affect the assessment of buildings and materials components. This can be done by becoming a member of Standards Australia or joining the Australian Institute of Building Surveyors who publish a regular journal which keeps members up to date with any changes that may affect them.

Self-help exercise 7.1

Define the following terms and concepts:

1. FRL

.....
.....

2. Adequacy

.....
.....

3. Structural adequacy

.....
.....

4. Standard time/temperature curve

.....
.....

5. Ignitability index

.....
.....

6. Optical density

.....
.....

CHAPTER 8 **Smoke and Smoke Control in Buildings**

Learning outcome

Describe the principles of smoke control in buildings.

Assessment criteria

1. Outline various smoke control systems.
2. Describe the application of computer packages to smoke control systems.

Chapter overview

The main problem that exists for occupants of buildings on fire, especially at the initial stages, is the hazard of smoke. Smoke can affect visibility, obscure exit opportunities and at times cause death. Therefore smoke control should be provided so that rapid egress can be achieved. This chapter will look in more detail at smoke development and smoke control systems.

Smoke in buildings

Most of the people killed by fire in buildings have first failed to find an exit because of the smoke present during the particular fire, and later have been poisoned by toxic gases or suffocated by the lack of oxygen. Usually, the victims of a fire have been dead long before the flames reached their lifeless bodies.

The presence of large quantities of smoke is not only extremely dangerous to the occupants of the building, but also to the members of any firefighting force trying to rescue the occupants and to fight the fire. Consequently, it is imperative to restrict, or at least to try to restrict, the spread of smoke out of the compartment involved in a fire. Its entry into the escape routes should be strenuously resisted.

The time required for the evacuation of the occupants of any larger building is considerably longer than the time required to fill that building with smoke from a building fire. While the fire might be confined in a fire-isolated compartment, thus restricting and, in most cases, preventing its spread throughout the building, the confinement of smoke to one compartment is practically impossible in a building that performs normal functions. This migration of smoke, often mixed with toxic gases, throughout the building represents a much greater hazard to life than the direct heat from the fire. It also represents a considerable impediment to conventional firefighting operations.

Obviously some special measures will be needed to control the smoke movement in a building that might be involved in a building fire. These measures could take the form of natural and mechanical ventilation, pressurisation of specific areas in the building, mechanical smoke extraction, and the provision of specific building components acting as barriers to hinder the spread of smoke.

The objectives of smoke control

The need to control smoke in a fire seems obvious and the BCA requires that occupants of buildings be safeguarded in a variety of ways from the effects of smoke and its potential to hinder their escape.

The objectives of smoke control should encompass:

- the maintenance of escape paths free of smoke
- control of the spread of smoke
- the reduction of smoke that may hinder the firefighter's role
- the reduction of smoke damage to other parts of a building affected by fire.

The mechanism of smoke production

The combustion of solid materials in a fire involves the heating of those materials and the release of hot combustible volatiles. These gaseous products of the combustion also ignite, rising above the fire as a column of flames and hot smoky gases. The density of that column is lower than that of the surrounding colder air and consequently it moves upwards. As a result, the surrounding air is entrained into the rising stream and mixes with it.

Part of the entrained air will supply the oxygen needed for the combustion of the gases produced by the decomposing fuel. Because the temperature in the plume of flames and hot gases is generally not high enough, and because the mixing of the oxygen from the surrounding air into the plume is not complete, there is incomplete combustion, a situation producing the unburnt solid particles that form the sooty component of the smoke. By this time, the excess air has been heated and is already well mixed with the hot smoky products of combustion so that there is a large inseparable cloud of smoke.

Compared with the total volume of air entrained by the fire, the volume of the gaseous and solid products of combustion is relatively small. Therefore, it would be virtually correct to state that the rate of smoke production is approximately equal to the rate at which air is entrained and contaminated by the rising column of hot gases and flames.

The volume of smoke produced

The rate of air entrainment into the column of hot gases and unburnt solid particles above the seat of a fire will depend on:

- the perimeter of the fire
- the heat output of the fire

- the effective height of the column of hot gases above the fire. This is, the distance between the floor of the room or space where the fire is and the bottom of the layer of smoke and hot gases which form under the ceiling of an enclosed space.

Controlled experiments and observations from actual building fires show clearly that the rate of smoke production is directly proportional to the size of the fire and dependent upon the height of the clear space above the fire. Scientists undertaking smoke-control studies express this relationship in scientific formulae.

As the fire grows and its boundaries spread, the rate of smoke production will also increase. On the other hand, the rate of smoke production also depends upon the height of clear space above the fire. As the fire develops, the smoke layer collecting below the ceiling will become thicker, and the clear space above the seat of the fire will be reduced.

As a result of this situation, the rate of smoke production will become less and less. The magnitude of these two opposing effects will depend on the various circumstances prevailing in the building at the particular time. There are also other factors that influence the amount of smoke produced as the fire develops, not least among these being the increase in heat output as the fire increases. It is impossible to quantify all of these variables, but one of the basic principles of smoke control is to make provisions in a building which will either limit the size of fire or restrict its spread.

Smoke density

The smoke produced by fires varies considerably in nature and content. It will vary in appearance from light-coloured to black and sooty, depending on the amount and type of unburnt particles in it and on the presence of coloured gases and condensation products. A relatively small amount of wood (0.5 kg), if burning in a room of approximately 35 m², will produce sufficient smoke to fill that room and to reduce the visibility in it to about 1 m. So that in this case it would be practically impossible to see the hand at the end of an outstretched arm. The same effect will be produced in the same room by the burning of any of the following:

- 0.07 kg of expanded polystyrene
- 0.1 kg of foam rubber
- 0.5 kg of polyurethane foam
- 0.3 litre of kerosene.

The smoke density is an important feature that needs careful consideration because it reduces visibility, thus hindering the progress of a person escaping from a fire. Smoke density can be measured objectively by determining the reduction

in the intensity of a light beam as it passes through a smoky atmosphere. The density may be expressed in terms either of the light obscuration or the optical density of the smoke.

Light obscuration is a measure of the attenuation (reduction or loss of light intensity) of a light beam when it passes through an atmosphere of smoke. It is expressed as a percentage.

Optical density is the logarithmic reduction of the intensity of light passing through a filter, in this case, through smoke. For instance, if in passing through 1 m of smoke the intensity of a parallel beam of light is reduced by 50 per cent, then when the same beam of light passes through the second 1 m of the same smoke its intensity will be reduced again by 50 per cent of 50 per cent, that is to 25 per cent of the original light intensity, and after passing through the third 1 m it will have fallen to 50 per cent of 25 per cent or down to 12.5 per cent of the original light intensity. This proportional reduction of light intensity is known as Lambert's Law of Absorption.

Light obscuration and optical density can also be expressed as mathematical equations. Both are also interrelated so that the percentage of light obscuration can be converted to optical density. However, detailed studies of light and the understanding of the light laws are outside the objectives of this subject.

Visibility

Visibility in smoke depends on many conditions. Some of these conditions are functions of the smoke, others are features of the environment, while others are related to the observer. The colour of the smoke; the size of the smoke particles; the density of the smoke; and the irritant nature of the smoke are all characteristics which influence the degree of visibility.

Features in the environment which have an effect on visibility include size and colour of the object being observed, the intensity of the illumination of the object and whether there is forward or back illumination.

The physical and mental state of the observer and whether the observations are taken in controlled laboratory conditions or in the panic or near-panic state of a real fire will also affect visibility.

To compare the amount of smoke emitted from different common building materials, an overseas test has been developed where boards having the same overall dimensions have been ignited and subjected to efficient combustion, that is burning with a flame. The comparative visibility of smoke produced by common building materials was established. These are shown in Table 8.1.

According to Lambert's Law of Absorption, referred to earlier in this chapter, smoke with an optical density of 1.0 per metre allows a visibility of only 1 m. For smoke with an optical density of 0.1 per metre, the visibility is 10 m.

It is generally accepted that the dense undiluted smoke produced in the average building fire will have an optical density per metre of 10 or even greater. This, according to Lambert's Law will mean a visibility of only 10 cm. As the minimum visibility acceptable on an escape route is considered to be at least 5 m, the optical density of the smoke per metre in that escape route shall not exceed the value of 0.2. Designers must be aware of the levels of fresh air needed to increase optical density in a fire To provide the acceptable level of visibility when smoke at the seat of a fire has an optical density of 10, it will be necessary to mix the original dense smoke with 50 times its own volume of fresh air. This will provide the required optical density of 0.2.

It should be noted however, that many experts and authorities suggest the acceptance of an optical density per metre of 0.1 only. This value represents a smoke concentration of one per cent compared with the original atmosphere in the fire area. The visibility is also increased accordingly.

| Building board | Thickness (mm) | Visibility (m) |
|------------------------------------|----------------|----------------|
| Wood-fibre insulating board | 12.7 | 17.00 |
| Phenolformaldehyde-faced hardboard | 4.0 | 5.20 |
| Polyurethane foam sandwich | 13.0 | 4.80 |
| Sortwood panels | 6.4 | 4.30 |
| Hardboard | 3.7 | 4.10 |
| Melamine-faced hardboard | 3.2 | 4.00 |
| PVC-faced hardboard | 5.7 | 3.00 |
| Rigid PVC panels | 1.6 | 2.80 |
| Chipboard | 12.7 | 2.70 |
| Glass-fibre reinforced polyester | 3.3 | 1.50 |

Table 8.1: Common building materials and comparative smoke visibility.

The mechanism of smoke movement

The physical properties of a smoky atmosphere are very similar to those of a normal atmosphere. The concentration of unburnt particles in the smoke cloud, even under conditions of very low visibility, is not sufficient to alter the physical characteristics of that atmosphere enough to affect its movement. The main factors that determine the movement of smoke and hot gases from a fire in a building are:

- the smoke's own mobility, or buoyancy, which is due to the fact that the hot gases and the hot air in the cloud of smoke are less dense than the surrounding air
- the normal air movement inside the building, which may have nothing to do with the fire, but which could carry the smoke around that building.

The importance of these two main factors will depend on various circumstances and will certainly differ from location to location inside the particular building. Close to the seat of the fire the smoke's own mobility or buoyancy will dominate. Away from the fire where the smoke gets cooler, normal air movement inside the building will become the more important factor.

The movement caused by the smoke's mobility, or buoyancy is due to pressure differentials created by:

- the expansion of the gases as they are heated by the fire
- the difference in density between the hot gases and hot air above the flames and the cooler air surrounding the fire.

The normal movement of air in the building is usually caused by the following factors:

- The stack effect, or the pressure differential due to the air inside the building having a different temperature from the air outside. This condition will cause the air inside the building to move upwards or downwards, depending on whether the air inside the building is warmer or colder than the outside air.
- The wind outside; all buildings are to a greater or lesser extent leaky or have openings to the outside. The wind penetrates through these leaks and openings and influences very considerably the internal air movement.
- The presence, or otherwise, of a mechanical air-handling system or mechanical ventilators inside the building.

The air and smoke pressures can be calculated and there are many mathematical equations available for more detailed studies of smoke and hot air movement. There are also various mathematical models and computer programs available to predict the probable smoke patterns in buildings, mostly high-rise buildings. It

should be remembered however, that smoke movement in large and tall buildings is usually extremely complex and that each fire, and the smoke it produces, is different from all other fires. All mathematical models and computer programs are as good as the assumptions made in their development.

Systems of smoke control

There are various methods and design arrangements for smoke control in buildings. These could be one of the following:

- take advantage of the natural forces of air movement to achieve the desired control and subsequent removal of the smoke
- rely on mechanical equipment and installations to guide the air and smoke along predetermined paths leading to a point of discharge outside the building.

Either system, provided it does not interfere with the normal running of a building, should be considered as a means of smoke control. The most efficient smoke control is generally obtained by employing both basic systems, natural and mechanical, as they usually complement each other.

Natural systems of smoke control

The layout and the arrangement of vertical and horizontal divisions can effectively control smoke within a building and also assist in its removal. Smaller and single-storey buildings represent lesser problems, whereas large high-rise buildings and complicated modern shopping complexes pose considerable problems for smoke control.

The movement of smoke within a building will be influenced by many variables. Many of these are unknown or not well defined prior to the fire and therefore it should be realised that it is practically impossible to try to stop the flow of smoke in a building altogether. This is the case in large buildings, particularly high-rise buildings. The more reasonable and realistic approach is to try to prevent the entry of smoke into the defined fire-emergency exit system(s) and to attempt to restrict the spread of smoke into the parts of the building that are not affected by the fire.

Cross ventilation

The simplest method for providing natural ventilation and evacuation of smoke from an enclosed space is the provision of openings in the external walls. These openings should be provided at a high level for the exhaust of the smoke while air inlets at a low level are needed for the entry of fresh air. Normally these openings would be closed, to be opened only during a fire situation. It would be likely that the openings at high levels are protected by windows opened automatically by the

actuation of smoke detectors. Fixed louvres or louvres that open, actuated by smoke detectors, can perform the same function as the windows. The low level air inlets can either be permanently open or they may open only in a case of a fire, again actuated by smoke detectors.

Obviously the cross-ventilation method for smoke disposal is mainly suitable for single-storey situations where the single space is of relatively minor dimensions. The single-storey one space building arrangement is particularly suitable for roof vents. They can be of various types and shapes, and their operation can be power assisted.

The intention for the single-storey single-space building is to keep the smoke in the upper reaches of the building, leaving clear air near the floor to allow people to move freely, and also to allow the unrestricted entry of fresh air. The stratification or layering of the smoke is made possible by the buoyancy of the hot smoky atmosphere produced by the fire. It follows that to be most successful, the high-level smoke layer must remain warm.

In high-rise buildings or in buildings of more complicated layouts, good use can be made of open-ended corridors that are either permanently open to the outside, or have doors or windows that open automatically when actuated by smoke detectors.

Most vertical shafts in a high-rise building, except fire-isolated stair shafts, can also be used as a means of smoke control and smoke extraction. In many cases special smoke shafts or smoke-ventilation ducts and conduits are provided. In all cases the smoke should be discharged into the open and not recirculated within the building.

Air locks

The purpose of air locks or smoke lobbies is to prevent, or at least to reduce considerably, the entry of smoke into the defined fire-emergency exit system. Such a lobby or air lock should preferably be ventilated by natural or mechanical ventilation to the external air. If, because of its location, such ventilation is not possible, smoke control can be achieved by other mechanical means. When air locks protect the entrances to fire-isolated stairs, they may be arranged as:

- lobby-approach stair
- ventilated lobby-approach stair
- balcony-approach stair
- isolated tower stair.

Smoke lobbies are used as both natural and mechanical means for smoke control. One of the virtues of such lobbies is that they form an air lock that preserves the pressure in the defined fire-emergency exit systems, if that system is pressurised.

The other benefit is that in order to reach the exit system, the smoke has to pass through two sets of doors, across each of which a pressure opposing the smoke flow can be developed.

Smoke reservoirs

Smoke reservoirs can be provided by subdividing the underside of the roof of large single-compartment single-storey buildings into separate catchment areas. This can be done by suspending roof curtains from the roof. Such lightweight non-combustible smoke curtains, or other similar physical barriers, form inverted reservoirs at ceiling level that entrain the smoke and hot gases directly over the seat of the fire and for a certain period of time prevent its further spread at ceiling level. Vents are installed in these catchment areas (smoke reservoirs) to exhaust the collected smoke directly to the outside atmosphere.

Smoke doors

Smoke doors automatically seal off the flow of smoke through the particular doorway protected by such a door. The smoke door is not necessarily a fire door and is very often of lightweight construction and may be combustible. Its only function is to prevent, or at least restrict, the passage of smoke whereas a fire door will stop the passage of fire. The important requirement for a smoke door is that such a door must be closed automatically by the action of a smoke detector.

Mechanical systems of smoke control

The mechanical extraction of smoke and the arrangements for providing higher atmospheric pressure in certain parts of a building are used to increase the efficacy of natural smoke control. A mechanical system of smoke control could be:

- power-operated units for smoke extraction or for fresh-air supply
- a particular operation of the air-handling system, or air conditioning, in a building fitted with such a system
- pressurisation of certain parts of a building, principally the defined fire-emergency exit system(s).

Power-operated units

Power-operated units are individual fan units provided to assist the exhaust vents and to increase their efficiency. They can also assist the operation of the fresh-air inlets and are usually activated by smoke detectors during fire situations. They must operate with emergency electrical power as the normal power supply could not be relied upon during a building fire. Such power-operated fans increase the smoke-controlled capacity of any vents and provide a positive control

independent of the uncontrollable climatic conditions affecting any smoke movement.

Air-handling systems

An air-handling or air-conditioning system can be used to efficiently control the movement of smoke in buildings provided certain design requirements are met. Australian Standard 1668, Part 1, Fire precautions in buildings with air-handling systems sets out the requirements for the design, construction, installation and operation of air-handling systems intended to prevent the spread of fire and smoke through a building fitted with an air-conditioning system. When the smoke from a building fire enters the air-handling system, the return-air damper is closed and a smoke-spill damper is opened fully so that all air being carried up the return-air shaft is automatically discharged to the atmosphere without being recirculated within the building during normal service operations. At the same time, the fresh-air intake is opened fully so that 100 per cent fresh air is drawn into the building by the supply-air fan. To ensure that the smoke will be discharged from the building continuously, the return-air fan (smoke-spill fan) is required to handle gases at 200°C for a period at least equal to that of the fire-resistance rating of the return-air shaft. The power needed for the operation of the air-handling system during building fires is provided by emergency electrical power.

Smoke dampers are in certain circumstances required as a component of the air-handling system used for smoke control. Their purpose is to prevent the entry of smoke from one part of the air-handling system into another part.

Pressurised areas of a building

The pressurisation of a building is usually only applied to the fire-isolated exit system. It aims to maintain air at a pressure above the atmospheric pressure. This prevents the flow of smoke into the fire-emergency exit system. Section 6 of AS 1668.1 contains the rules for the design and the performance of a system that will pressurise a fire-isolated passageway. The pressurising system must be independent from all other air-handling systems in the building in question. It should be capable of maintaining an airflow velocity from the pressurised areas of not less than 1 m/s, averaged over the full area of each door opening, when two doors leading from any two successive storeys and the main discharge doors are simultaneously fully open. Also prescribed are the precautions that must be taken with respect to air pressures to ensure that pressures will allow the opening of any door leading into the defined fire-emergency exit system.

A pressurisation system can be used:

- only in the event of a fire with provisions for automatic and manual starting

- at full operation when the building is occupied
- at reduced capacity when the building is normally occupied with an automatic and manual boost to full operation in the event of a fire.

During a fire situation the necessary electrical power is to be supplied from an emergency power source.

Smoke control in large buildings

All systems for natural and mechanical smoke control discussed in this chapter could be used for large buildings. Air-handling systems and pressurisation of the fire-emergency exit are particularly suitable.

Smoke curtains in the roof space and the various types of roof vents are better suited to large single-storey buildings.

As already noted, the roof space is subdivided by lightweight non-combustible curtains into a series of inverted smoke reservoirs which collect the smoke and the hot gases that rise in the fire plume. The smoke curtains hang downwards from the roof sheeting but do not intrude into the work space. No lateral spread of smoke can occur until the smoke cloud forms a layer deeper than the depth of the smoke curtains. The smoke is, however, prevented from accumulating to this depth by the opening of the vents in the roof to discharge the smoke and hot gases. The arrangement of the smoke curtains is dictated by the design of the roof, but in no case should their depth be less than 1.5 m below the bottom of the opening of the vent in the area. Generally the smoke curtains should be located at intervals not exceeding 30 m to form enclosures not exceeding about 900 m² in area measured in a horizontal plane.

The types of roof vents that may be used are:

- permanently open vents usually fitted with fixed louvres
- vents that are set to open automatically when actuated by a detector – usually opened by a gravity or spring action
- combustible roof skylights made of plastics with a low melting temperature, so that when this skylight melts the hole in the roofing acts as a vent opening.

All vents are to be fitted as nearly as possible to the high point of the roof in each of the inverted smoke reservoirs. The recommended square areas of roof vents vary. The aggregate of vent openings in the roof could be as low as 1.5 per cent of the floor area for a low smoke hazard and as high as 3 per cent to 5 per cent for high smoke hazards.

Smoke modelling computer packages

A number of commercial software packages are available in Australia. They use accepted models which can help in the prediction of fire growth and movement, they are:

- Firecalc – developed by the CSIRO
- Yardstick – developed by the University of Adelaide.

These are specialist programs for use by fire engineers. It should be remembered that they only give indications and cannot be regarded as being a true reflection of fire outcomes in every instance.

Self-help exercise 8.1

1. List three objectives of smoke control.
.....
.....
.....
 2. List three factors that influence the volume of smoke.
.....
.....
.....
 3. Which of the following three materials produces the most smoke when burnt: wood foam rubber, expanded polystyrene, kerosene?
.....
 4. List two main factors that determine the movement of hot gases from a building.
.....
.....
.....
.....
-

Bibliography

- Australian Building Codes Board 1996, *Building Code of Australia*, CCH, Nth Ryde.
- Fire Code Reform Centre 1996, *Fire Engineering Guidelines*, Fire Code Reform Centre, Sydney.
- Cote, A. E. (ed) 1991, *Fire Protection Handbook*, 17th edition, NFPA, Massachusetts.
- CSIRO, Notes on the Science of Building (various), CSIRO, Nth Ryde.
- Drysdale, J. W. 1975, *Fire Protection in Buildings*, 2nd edition, CSIRO, Nth Ryde.
- Shields, T. J. and Silcock, G. H. W. 1987, *Buildings and Fire*, Longman, Harlow.
- Standards Association of Australia 1994, *AS 1530.1 Combustibility test for materials*, SAA, Strathfield.
- Standards Association of Australia 1993, *AS 1530.2 Test for flammability of materials*, SAA, Strathfield.
- Standards Association of Australia 1989, *AS 1530.3 Simultaneous determination of ignitibility, flame propagation, heat release and smoke release*, SAA, Strathfield.
- Standards Association of Australia 1990, *AS 1530.4 Fire resistance test of elements of building construction*, SAA, Strathfield.
- Standards Association of Australia 1990, *AS 1682.1 Fire dampers specification*, SAA, Strathfield.
- Standards Association of Australia 1990, *AS 1682.2 Fire dampers installation*, SAA, Strathfield.
- Standards Association of Australia 1990, *AS 1905.1 Fire resistant doorsets*, SAA, Strathfield.
- Standards Association of Australia 1990, *AS 1905.2 Fire resistant roller shutters*, SAA, Strathfield.
- Stollard, P. and Johnston, L. (eds) 1994, *Design Against Fire*, Spon, London.
- Stollard, P. and Abrahams 1991, *Fire from First Principles*, Chapman Hall, London.

Glossary

| | |
|----------------------------|---|
| cellulose | An inert substance, a carbohydrate, the chief constituent of the cell walls of plants, and forming an essential part of wood, cotton, hemp, paper. |
| combustion | A chemical process that produces a considerable amount of heat and is usually accompanied by a flame. |
| compound | A substance composed of two or more elements joined chemically. |
| decomposition | Breaks down to its basic constituents. |
| dissociate | The splitting up of a compound into similar molecules which reunite under different conditions to form the original substance. |
| electrons | Negatively charged particles that orbit the nucleus of an atom. They have very little mass. |
| exfoliation | The scaling of stone caused by weather. |
| extinguishing agent | A substance that stops combustion in some way. |
| flame | A reaction having the ability to propagate or spread through an atmosphere with the emission of heat and light. |
| free radicals | Chemically unstable atoms that have a neutral charge but actively seek out other atoms to react with. |
| halon | A general name for hydrocarbons in which the hydrogen has been partially or wholly replaced by halogens, such as fluorine, chlorine, bromine or iodine. |
| ignition source | A source which provides enough heat energy to initiate combustion. |
| inerting substance | A substance which displaces oxygen from a compartment or enclosed space by replacing it with an inert gas so that combustion cannot take place. |
| lignin | The main part of wood after cellulose, resins which cement the wood fibres together. |

Answers to self-help exercises

Self-help exercise 1.1

1. Pyrolysis means **heat induced chemical decomposition, resulting in the solid being turned into a gaseous vapour.**
2. Of the three stages of matter, only **vapours** burn.
3. Adding heat to a reaction is an **endothermic** process.
4. The lower flammability limit **for a gas is the amount of gas required to mix with the air to just allow it to burn.**
5. Fire point is **the temperature at which the flame will continue after the first lot of vapour has been consumed.**

Self-help exercise 1.2

1. Manganese.
2. Iron.
3. Bromine
4. Nitrogen
5. Carbon

Self-help exercise 1.3

1. Three iron and four oxygen.
2. One nitrogen, four hydrogen, one chlorine.
3. Three hydrogen, one phosphorus, four oxygen.
4. Two carbon, six hydrogen one sulphur.

Self-help exercise 1.4

1. One sodium carbonate, two hydrochloric acid, two sodium chloride, one carbon dioxide.
2. Two aluminium, three sulphuric acid, one aluminium sulphate, three hydrogen.
3. One magnesium, two hydrochloric acid, one magnesium chloride, one hydrogen.

Self-help exercise 1.5

1. $2 \times 23 + 1 \times 16 + 4 \times 12 = 110$
2. $1 \times 40 + 1 \times 12 + 3 \times 16 = 100$
3. $1 \times 12 + 1 \times 1 + 3 \times 35.5 = 119.5$

Self-help exercise 1.6

1. Butane C_4H_{10}
 $C_4H_{10} + 6.5O_2 \rightarrow 4CO_2 + 5H_2O$
2. Pentane C_5H_{12}
 $C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O$
3. Methane CH_4
 $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
4. Hexane C_6H_{14}
 $C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O$

Self-help exercise 1.7

1. Acetylene C_2H_2
 $+226.9 \text{ kJ} + 0 \text{ kJ} \rightarrow -786 \text{ kJ} + -242 \text{ kJ}$
Heat of combustion is 1254.9 kJ
2. Ethylene C_2H_4
 $+52.6 \text{ kJ} + 0 \text{ kJ} \rightarrow -786 \text{ kJ} + -484 \text{ kJ}$
Heat of combustion is 1322.6 kJ
3. Ethane C_2H_6
 $-84.86 \text{ kJ} + 0 \text{ kJ} \rightarrow -786 \text{ kJ} + -726 \text{ kJ}$
Heat of combustion is 1427.14 kJ
4. Propane C_3H_8
 $-103.6 \text{ kJ} + 0 \text{ kJ} \rightarrow -1079 \text{ kJ} + -968 \text{ kJ}$
Heat of combustion is 1943.4 kJ

5. Benzene C_6H_6

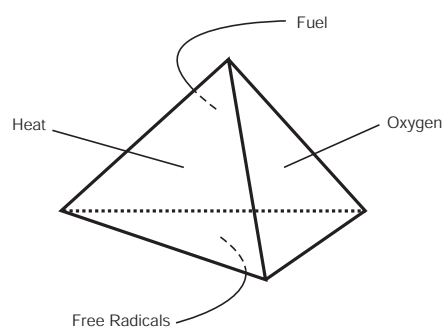
$$40.03 \text{ kJ} + 0 \text{ kJ} \rightarrow -2358 \text{ kJ} + -726 \text{ kJ}$$

Heat of combustion is 3133.03 kJ

Self-help exercise 2.1

1. Flammability may be defined as being a measure of the fuel/oxidant mixture that will support combustion and allow a flame to spread through an unignited region.

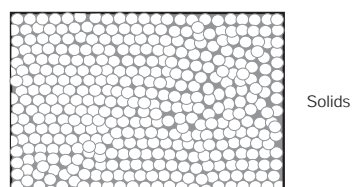
2.



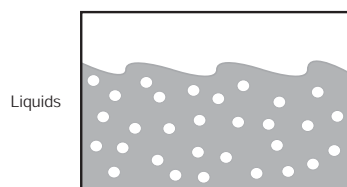
3. Free radicals are chemically unstable in that they actively seek out other atoms to react with.

Self-help exercise 2.2

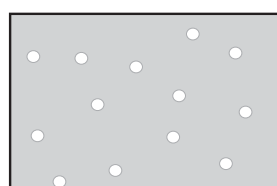
1.



Solids



Liquids



Gases

2. Four common combustible solids are wood, plastic fibres and textiles.
3. The temperature at which enough vapour has been generated to momentarily 'flash' but not to continue burning if ignited, is called the flash point. The temperature at which burning would continue is called the fire point.

Self-help exercise 2.3

1. The term combustion usually refers to a heat producing reaction between a substance and oxygen.
2. Dust explosions occur when fine, combustible materials are suspended in air (or any other suitable supporting atmosphere) and are subjected to an ignition source of sufficient energy. Dust explosions occur because there is an abundance of fine combustible material surrounded by an adequate supply of oxygen that can maintain that combustion.
3. Any four of the following factors can affect a dust explosion. These are the chemical nature of the material, the particle size, the amount of dispersal, concentration, homogeneity and turbulence, the degree of confinement and moisture content of the dust cloud.

Self-help exercise 3.1

1. Premixed flames burn more rapidly than diffusion flames and are BLUE in colour
2. Diffusion flames are yellow in colour.
3. The limiting adiabatic flame temperature is equal to the temperature required for a material to undergo combustion at its lower flammability limit.
4. Knowing the LAFT for a fuel helps us to assess its fire risk.

Self-help exercise 3.2

1. If the combustion process can be slowed or halted then the fire is controlled or extinguished.
2. Fires may be extinguished by cooling, starvation, smothering or quenching free radicals.
3. Starvation of fire involves removing the fuel from the fire.
4. Reducing the oxygen content around a fire can be most effectively done by smothering.
5. We can use free radical quenching mechanisms to extinguish fires.

Self-help exercise 4.1

1. Heat transfer by conduction is from higher temperature to lower temperature.
2. Heat transfer by radiation is usually through radiant energy.
3. Heat transfer by radiation does not require material to travel through.
4. Free convection is not as effective as forced convection.
5. In a real fire situation, most of the heat transfer occurs through convection and radiation.

Self-help exercise 4.2

1. The two major processes that lead to self-induced heating are oxidative and biological reactions.
2. Some of the most dangerous material to help induce self-heating is the presence of unsaturated oils.
3. The two types of organisms that help self-heating in organic products are fungi and bacteria.
4. Making hay stacks smaller is one way of reducing the chance of self-induced heating.
5. Spontaneous ignition temperature are only approximations of the potential ignition temperature.

Self-help exercise 4.3

1. Fires in enclosures are limited by the amount of oxygen available and the heat balance situation.
2. The greater the feedback of heat to the fuel bed, the more rapid will be the growth of the fire.
3. The three well defined stages of fire development within an enclosure are the growth period, the fully developed stage and the decay period.
4. In a fire with sufficient ventilation, the two types of burning regimes that may develop are the ventilation controlled and the fuel controlled.
5. An effective suppression system requires: a means of detection, a mechanism for suppression and a suppressing agent.

Self-help exercise 4.4

1. The Periodic Table can be used to find the symbol of an element and to find its atomic mass.
2. A stoichiometric fuel/oxygen mixture is one which has exactly the right amount of oxygen available to completely combust a given amount of fuel.
3. The heat of combustion is the amount of heat energy evolved when one mole of a substance is burned in excess oxygen.
4. Heats of combustion are used to give an approximate idea of a fuel's heat content and to rank potential fuels in some sort of order.
5. The colour of smoke is determined by the amount of oxygen and the character and type of fuel.

Self-help exercise 5.1

1. Materials at elevated temperatures change in:
 - dimension
 - state
 - mechanical properties.
2. Timber will expand up to a temperature of 800°C and as the temperature rises further it shrinks until full decomposition has occurred.
3. The materials used to bond man-made boards containing cellulose and wood particles is important to the material's flammability.
4. At 550°C, normal structural grade steel retains only 50 per cent of its strength.
5. The two most important variables that determine the behaviour of concrete exposed to fire are its aggregates and the quantity of free water in its composition.
6. Concretes made of lightweight aggregates do not perform as well at high temperatures as concretes made of calcareous dense aggregates. FALSE
7. Glass fibre will melt at about 600°C while other materials containing mineral fibres are usually stable up to a temperature of 1000°C.
8. Aluminium has twice the rate of thermal expansion as steel.
9. The performance of any glass is dependent on its housing.
10. The two major classes of plastics are thermoplastics and thermosetting plastics.

11. The structural member which has the largest ratio of surface area exposed to a fire will have the most endurance to fire. FALSE

Self-help exercise 6.1

1. Any three of the following combustible materials can be used:
 - plasterboard
 - perforated gypsum lath with a normal paper finish
 - fibrous plaster sheet conforming to AS 2185 Specification for fibrous plaster products
 - fibre-reinforced cement sheeting
 - pre-finished metal sheeting as stipulated
 - bonded laminated materials as stipulated.
2. External walls must be at least 90 mm thick and of masonry construction.
3. The minimum distance between buildings with non-fire rated walls is 1.8 m.

Self help exercise 7.1

1. FRLs - the grading period of fire resistance of a material, in minutes, determined in accordance with testing regimes in AS 1530.4 - 1990
2. Integrity - the ability of materials and/or elements to withstand fire and remain intact.
3. Structural adequacy - the ability of a material to withstand deflection and collapse due to heat.
4. Standard time/temperature curve - fires tend to follow a standard curve and variations occur in duration times and fuel types. The 'curve' is a graphical reflection of this process and fire types can be compared to it so that estimates for building fires and fire performance can be made. The 'curve' is regarded as a good measuring stick for most materials and errs on the conservative side which is all the better for occupant safety.
5. Ignitability index - the ignitability index is the time taken for combustible gases from materials to form a gas mixture that will be ignited by flame.
6. Optical density - the reduction of light as it passes through smoke. This can be calculated using logarithmic laws.

Self-help exercise 8.1

1. The objectives of smoke control should encompass:
 - the maintenance of escape paths free of smoke

- control of the spread of smoke
 - the reduction of smoke that may hinder the firefighter's role
 - the reduction of smoke damage to other parts of a building affected by fire.
2. Three factors that influence the volume of smoke are:
 - the perimeter of the fire
 - the heat output of the fire
 - the effective height of the column of hot gases above the fire; that is, the distance between the floor of the room or space where the fire is and the bottom of the layer of smoke and hot gases which form under the ceiling of an enclosed space.
 3. Expanded polystyrene produces more smoke than the other materials.
 4. Two main factors that determine the movement of smoke and hot gases in a building are:
 - the smoke's own mobility, or buoyancy, which is due to the fact that the hot gases and the hot air in the cloud of smoke are less dense than the surrounding air
 - the normal air movement inside the building, which may have nothing to do with the fire, but which could carry the smoke around that building.