NEW ZEALAND FIRE SERVICE
Whakaratonga Iwi

Qualified Firefighter Programme

Study Guide Seven

Fire Science and Ventilation

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Essentials of Firefighting (4th Ed.). IFSTA.

Introduction

Module aim

This module will equip you with the knowledge you will need to explain how fire starts, develops, spreads and can be extinguished.

What this module contains

Theory

The theory component contains this Study Guide, a Workbook, and an assignment.

There are three sections in this Study Guide:

1. Principles of Fire Science
2. Practical Fire Science
3. Ventilation.

QF Stage 1 practical training

During the practical training you will:

- Observe fire growth
- Observe flashover
- Observe backdraught
- Use postive pressure ventialtion fans.

Consolidation period

During the consolidation stage you must use various methods of ventilation.

Delivery

The theory component is delivered by distance education (this Study Guide). Read through the Study Guide and complete the activities and assignments when prompted.

Section 1: Principles of Fire Science

What this section contains

This section contains the information you need to explain the underlying principles of fire science. It includes:

1. The recipe for fire
2. Putting out a fire
3. Extinguishing principles
4. Burning
5. Chemistry for combustion
6. Effects of heat on matter
7. Specific heat and latent heat
8. Temperature
9. Gases and vapours.

By the end of this section you will be able to:

1. Demonstrate understanding of the components and principles of the fire triangle, fire tetrahedron and fire terms
2. Demonstrate understanding of the common methods of extinguishing fire
3. Demonstrate understanding of the principles of extinguishing fire
4. Demonstrate understanding of the combustion process and the products of combustion
5. Demonstrate understanding of the chemistry for combustion
6. Describe the upper and lower limits of flammability
7. Demonstrate understanding of the effect of heat on solids, liquids and gases
8. Demonstrate understanding of specific heat and latent heat
9. Demonstrate understanding of temperature
10. Demonstrate understanding of gases and vapours.

Why you need to know this

To effectively fight fires, you need to understand:

- What ingredients are necessary for fire
- How these ingredients interact
- How to fight a fire by removing one or more of the ingredients of a fire.

The recipe for fire

What is fire?

Fire is a chemical reaction needing three ingredients: oxygen, heat and fuel.

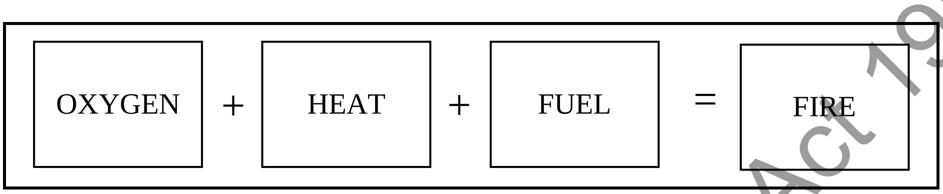


Figure 1.1: The ingredients for fire

Fire is scientifically considered an *exothermic* chemical reaction heat is given off between fuel and oxygen.

To stop a fire, you must remove one or more of these ingredients.

You must understand these ingredients – how they interact, and how you can interrupt this 'recipe'.

Fire is not always destructive. It can be thought of in two ways:

- *Controlled burning* is beneficial (e.g. for cooking, light, heat, motor vehicles and aircraft engines)
- *Uncontrolled burning* is (most often) unintentionally started, and can grow into raging infernos if conditions are suitable (e.g. scrub fires, forest fires, house fires, explosions, other large destructive fires).

The fire triangle

The fire triangle

The ingredients for fire are often represented using the 'fire triangle' (see Figure 1.2). This shows the relationship between the elements.

The burning process is a continuous chemical reaction between fuel particles and oxygen. The heat released by this chemical reaction can cause fire to spread – and grow, as it transfers its energy into nearby fuels (combustibles).

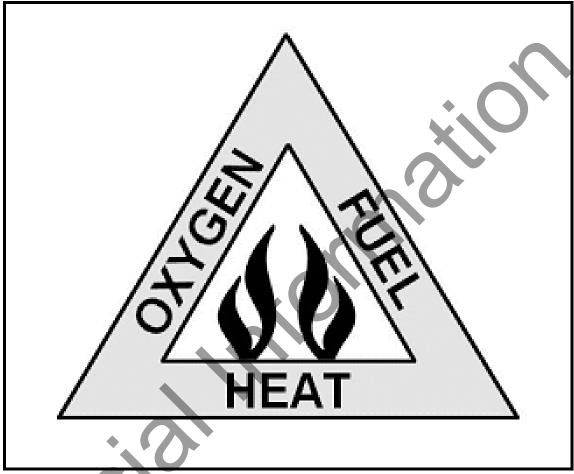


Figure 1.2: The fire triangle

The fire triangle and fire tetrahedron

Fire triangle

While the fire triangle illustrates the three main components of fire, there is a fourth combustible component – the chemical chain reaction.

Fire tetrahedron

The ‘fire tetrahedron’ is a three-dimensional triangular figure (a triangle with four surfaces – see Figure 1.3). This demonstrates fire’s need for the following four components:

- Oxygen (or other combustion supporter – an ‘oxidising agent’)
- Fuel
- Heat
- A self-sustaining chemical chain reaction

Remove any one of the four components and combustion will not occur.

If ignition has already occurred, then fire is extinguished when one of the components is removed from the reaction.

Note: A fire triangle represents one ignition – an actual fire is millions of ignitions or chemical reactions. That’s millions of fire triangles every second!

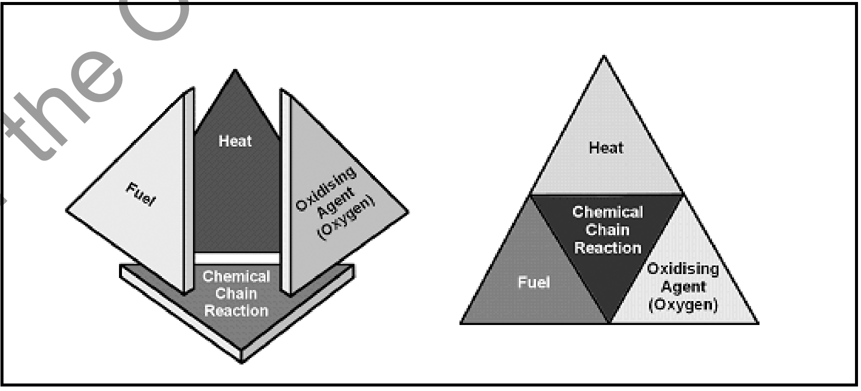


Figure 1.3: The four components of the fire tetrahedron

Oxygen

Introduction

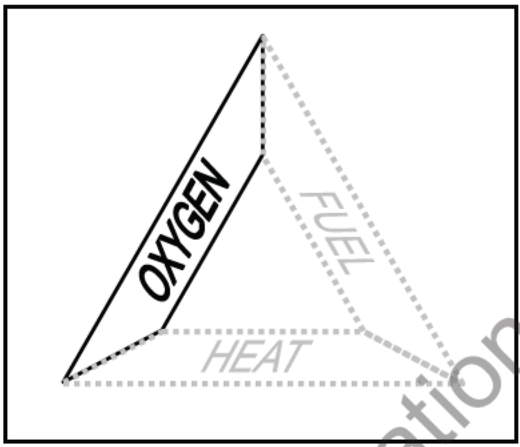


Figure 1.4: Oxygen and the fire triangle

The oxygen required for a fire usually originates from the surrounding air. The earth's atmosphere is about 21% oxygen. Fire's intensity is dependent on the amount of available oxygen – if the oxygen concentration is raised, the fire becomes more vigorous. Reducing the oxygen concentration hinders the fire – and once the oxygen level drops below about 12%, the fire will stop.

Note: Oxygen is also essential for human life. If the oxygen level falls below 12%, humans will faint, become unconscious, and eventually die.

Oxidising agents

Oxygen is the most common oxidising agent (combustion supporter). But there are other oxidising agents – and compounds containing oxygen – that readily release oxygen when heated. These include:

- Nitric acid
- Hydrogen peroxide
- Ammonium nitrate.

Other combustion supporters

Halogens (e.g. chlorine, fluorine and bromine) contain no oxygen atoms. Yet they react the same as other oxidising agents.

The most common halogens are:

- Chlorine and hypochlorites (e.g. bleach, and granulated chlorine used in swimming pools)
- Peroxides (e.g. components of hair dyes, antiseptics, and industrial bleaching of fabrics like cotton)
- Chlorates (e.g. a component of weed killers)
- Concentrated sulphuric acid (e.g. components of lead car batteries, and used in manufacturing paints, explosives, plastics, and fertiliser).

Fuel

Introduction

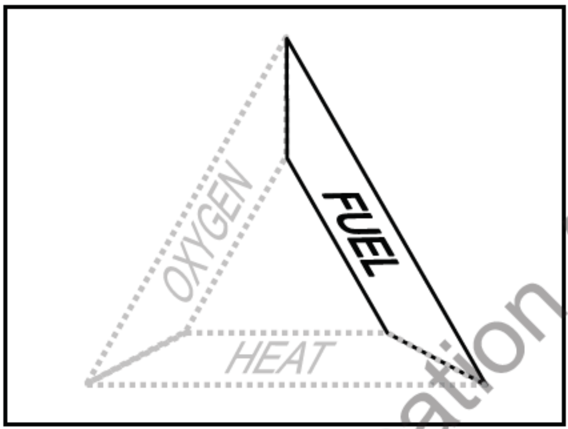


Figure 1.5: Fuel and the fire triangle

Fuel can exist in any of matter’s three states (solid, liquid, or gas / vapour) – but only fuel *vapour* actually burns.

For combustion to occur, the fuel must be converted to a vapour first. In scientific terms, the fuel in a combustion reaction is the *reducing agent*.

Fuel sources

Fuel sources are wide ranging, and can include:

- Liquids (e.g. petroleum, alcohol, lacquer, paint and oil)
- Gases (e.g. butane, natural gas, carbon monoxide and hydrogen)
- Solids (e.g. coal, cloth, grain, straw, plastic, wood, grease and sugar).

Solid fuel

The molecules in solid materials are packed closely together. This gives the material its density, and to some extent defines its physical state.

Combustion
Applying heat to solid material agitates the molecules, and they begin to collide with one another. Some molecules break apart and combine with oxygen, becoming *oxidised*. Oxidised molecules then release even more heat, causing more reactions. This is *combustion* – a chemical chain reaction.

With solid material, the applied heat is absorbed into the mass and dissipates to some degree. However, when the amount of applied heat exceeds the ability of the mass to dissipate that heat, chemical breakdown occurs and the self sustaining burning reaction results and continues (unless it is interrupted or runs out of fuel). *(Delmar Thomson Learning, 2001, p. 97–98.)*

The physical nature of the solid determines how it will burn (i.e. large surface-area-to mass versus small surface-area-to-mass).

Example: Compare a stack of timber to sanding dust. The dust can produce violent, explosive fires in extraction ducting units (called *dust explosions*).

A solid fuel's physical position also affects the way it burns – a vertical or horizontal position determines burn characteristics (see Figure 1.6).

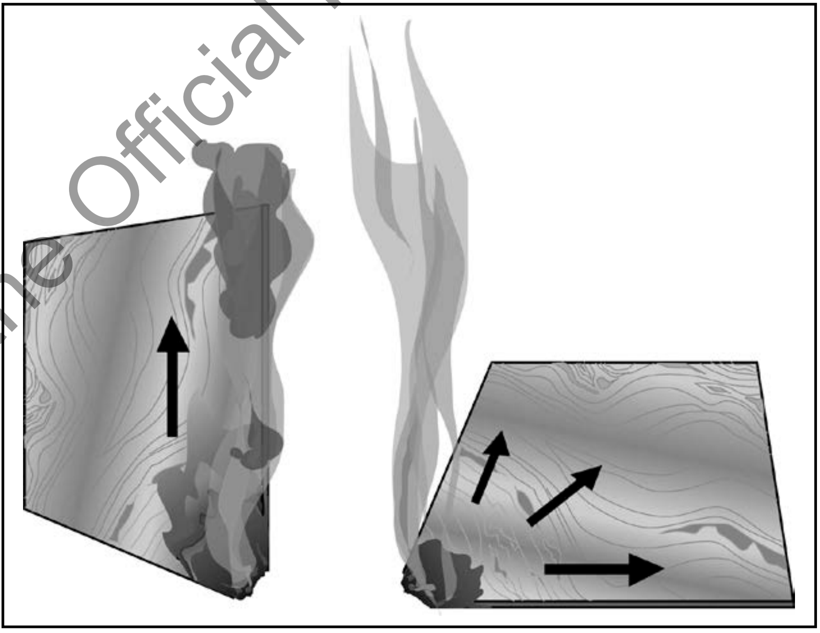


Figure 1.6: The physical position of a solid fuel affects the way it burns

Pyrolysis of solid fuel

Most solids, when heated, become liquid and then gas (e.g. ice becomes water, then steam).

Pyrolysis
Heating some solid fuels chemically breaks them down, bypassing the 'liquid' stage. They emit toxic, flammable gases (e.g. burning wood has no liquid stage). This change of state is *pyrolysis.*

When a substance undergoes pyrolysis, it emits flammable vapours and leaves behind decomposition by-products. Figure 1.7 shows a heated piece of wood. Gases are generated and create a toxic, flammable atmosphere. Charring is the carbon residue left when the wood undergoes pyrolysis.

Figure 1.7: Pyrolysis

Liquid fuel

As with solids, liquids must change state into a gas (vapour) before combustion can happen. For a combustible liquid to ignite, it must first evaporate. The liquid's temperature determines the evaporation rate.

For combustible liquids (as with solids), the heat absorbed will dissipate into cooler areas of the liquid. But when the entire liquid is heated (or the ability to dissipate is overcome by the applied heat), the temperature rises, resulting in boiling (vaporisation). Vaporisation continues until *flash point ignition* is reached.

However, not all liquids burn. Some will boil and evaporate, but will not combust (e.g. water).

What causes the typical "chip-pan" fire?

- You cannot ignite a liquid fuel below its *flash point*. To ignite a liquid at its flash point, you still need to introduce an ignition source to the vapour / air mixture.
- If you continually heat a combustible liquid significantly above its flash point, the fuel may reach its *auto-ignition temperature* – the vapour / air mixture can ignite without an external ignition source. This causes the typical 'chip-pan' fire.

Flammable liquids

Most flammable liquids used in industry are organic (i.e. they contain carbon). These are commonly fuels or solvent compounds, such as:

- Alcohols (e.g. methanol and ethanol)
- Ketones (e.g. acetone in nail polish remover)
- Meth-ethyl ketones (e.g. 'thinners')
- LPG (which is only in liquid form when pressurised in a cylinder)
- Petrol
- Diesel
- Kerosene.

When these flammable liquids are stored in bulk (e.g. on docks, in warehouses, laboratories, or fuel outlets), they can become dangerous fire hazards.

Gaseous fuel

Gaseous fuel is in a ready-made state for a chemical reaction (i.e. combustion).

You can prevent vaporisation – thereby preventing or minimising combustion, by:

- Keeping combustible liquids or solids cool
- Excluding oxygen.

This is important when dealing with a tank truck fire or a liquid fuel spill. *(Delmar Thomson Learning, 2001, p. 96–97).*

Density of matter

The density of matter (the mass over a given area of a solid, liquid or gas) affects how it will behave. For example:

- A pile of dust or wood splinters burns more easily than solid wood, because oxygen can surround each dust particle, helping to sustain the fire.
- Vapours of most flammable liquids are heavier than air. When released into the atmosphere, they sink close to the floor or ground.
- Some liquids are heavier than water and will sink, while others are lighter and will float.
- Many flammable gases are lighter than air and will rise and collect at the ceiling of a building, or escape vertically if in the open air. *(AFAC, 1996, p. 15.)*

What happens to fuel within the fire triangle

- *Gaseous fuel*
  Gases burn easily because gas and oxygen mix easily. The heat generated encourages further burning.
- *Liquid fuel*
  Liquid fuels burn when the heat from a fire boils some of it, producing a vapour. The vapour then mixes with the oxygen in the air.
- *Solid fuel*
  Solid fuels burn when the heat from a fire decomposes the fuel into a vapour. This vapour then mixes with oxygen in the air. The process happens either by liquidisation (melting) and then vaporisation; or by directly changing the solid fuel to vapour (pyrolysis).

Smouldering

Smouldering combustion happens when a fuel and an oxidising agent combine and react. (This happens for two reasons: either the oxidising agent supply is limited or the generated heat is quickly dissipated.) This is a complex process, common to solid fuels that char when heated.

What is flame?

The flaming region *(flame)* is an area where a sustained heat-releasing reaction takes place between a fuel in its vapour state, and oxygen in the air. The flame emits light (e.g. yellow / orange or blue), depending on:

- The substances burning
- The efficiency of the oxygen and fuel vapour mixing.

Classes of fire by fuels

Class A fire	*Combustible solids* – Carbon-type solid fuels (e.g. wood, paper, plastics, and clothing).
Class B fire	*Flammable liquids* – Alcohol, paint, wax, tar, and petroleum-based liquids (e.g. petrol, oil, thinners, and kerosene).
Class C fire	*Flammable gases* – Either vapour or liquefied gas (e.g. LPG, propane, butane, methane, and acetylene).
Class D fire	*Combustible metals* – Including magnesium, sodium, potassium, and aluminium.
Class E fire	*Electrical* – Including energised or ‘live’ electrical equipment or services (e.g. household appliances, computers, transformers, and overhead transmission lines). **Note:** Electricity is *not* a fuel. Once you remove the electrical energy, the fire class becomes specific to the burning fuel (usually Class A).
Class F fires	*Fat and grease* – Including cooking fats and oils.

Heat

Introduction

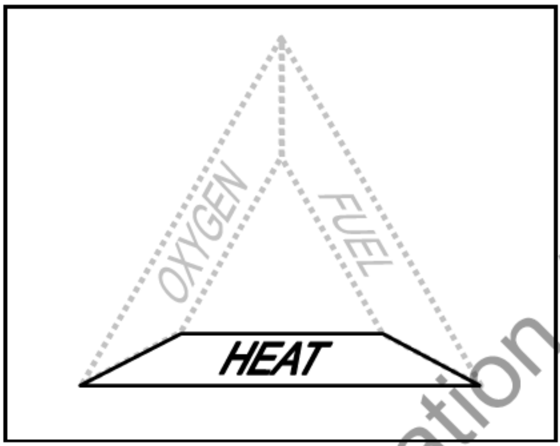


Figure 1.8: Heat and the fire triangle

Heat drives the burning process of fire, and causes the most destructive effects. If fresh fuel is not heated, then a fire cannot spread. Fire growth results from heat moving away from the flame into a nearby area with fresh fuel. Removing the heat extinguishes the fire.

What heat does

When heat contacts a fuel, the heat energy supports the combustion reaction in the following ways:

- Heat causes pyrolysis / decomposition (vaporisation of solid and liquid fuels), resulting in the production of ignition vapours or gases, as shown in Figure 1.9
- Heat provides the energy necessary for ignition
- Heat causes the continuous production and ignition of fuel vapours or gases, so the combustion reaction can continue. (*IFSTA, 2001, p. 45.*)

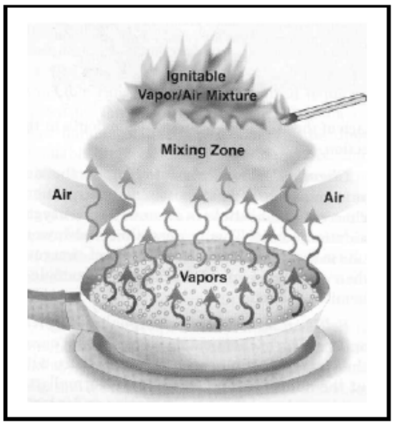


Figure 1.9: Fuel gases generated from heat mix with air, producing an ignitable mixture
(Source: Reprinted from *Essentials of Fire Fighting*, 4th Ed., IFSTA)

Spontaneous heating

Spontaneous heating and combustion is also known as *self-heating.* This is a *chemical reaction* between the two materials – when a material's temperature increases with no external heat source.

Heat from a chemical reaction is usually produced by slow oxidation. It also tends to dissipate to the surrounding area almost as fast as it is generated. For spontaneous heating to progress to spontaneous ignition, the material must be heated to its ignition temperature (the minimum temperature for that substance to ignite).

Examples:

- Mixing paint and resin
- Oil-soaked rags rolled into a ball left in a corner
- Mould in damp hay or compost
- Bacteria in damp charcoal.

For spontaneous heating to occur:

- The rate of heat production must be great enough to raise the material's temperature to its ignition temperature
- The air supply surrounding the material must be adequate to support combustion
- The insulation properties of materials surrounding the fuel must prevent heat dissipation as ignition temperature is reached.

Materials subject to spontaneous heating

These examples show the tendencies of certain materials for spontaneous heating:

- *High:*
  Charcoal, fish meal / fish oil, linseed oil rags, brewers' grains, feed
- *Moderate:*
  Foam rubber, hay, manure, iron metal powder, waste paper
- *Low to moderate:*
  Rags (bales).

Heat energy

Heat energy is categorised the following five ways (detailed later in this section):

- Chemical
- Electrical
- Mechanical
- Solar
- Nuclear.

Chemical energy

Chemical energy is the most common source of heat in combustion reactions. When any combustible material is in contact with oxygen, oxidation can occur, and heat results.

When this reaction generates heat, the resulting fire will be self-sustaining. The generated heat will heat the surrounding combustible materials to their ignition temperature.

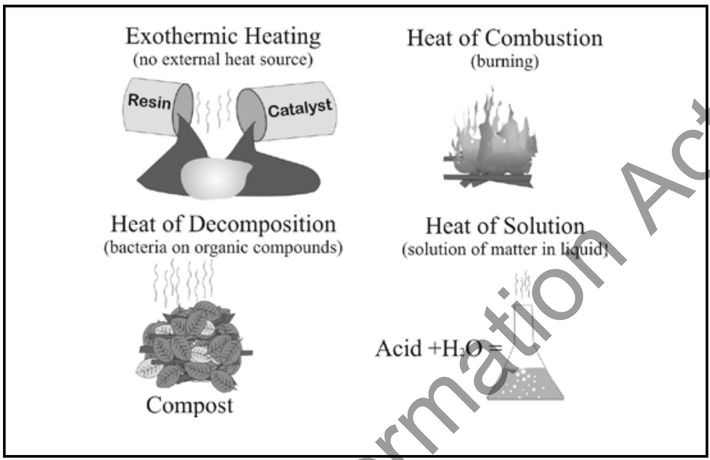


Figure 1.10: Chemical potential energy converted to heat energy

Electrical heat energy

Electrical energy can generate temperatures high enough to ignite any combustible materials near the heated areas.

Electrical heating can happen by:

- Resistance heating – poor electrical connection through corroded terminals
- Leakage
- Arcing
- Static – current flow through resistance
- Overload or over-current
- Microwave.

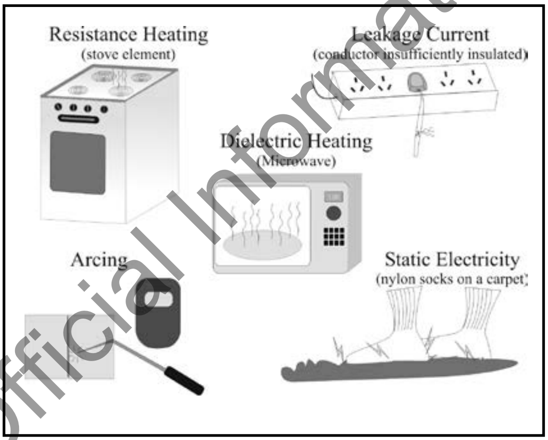


Figure 1.11: Electrical energy converted to heat energy

Mechanical energy

Friction and compression can generate energy.

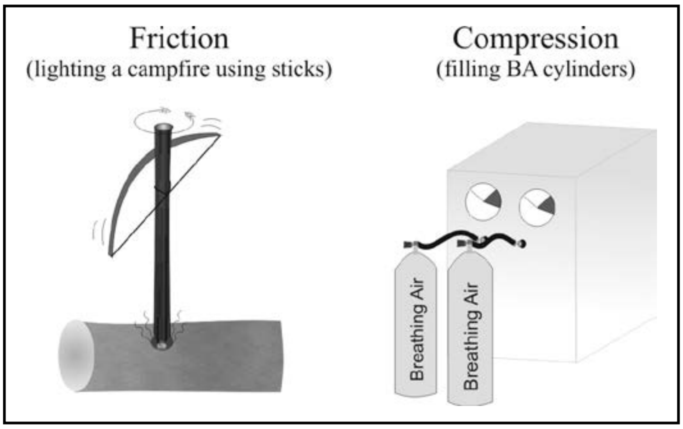


Figure 1.12: Mechanical energy converted to heat energy

- *Heat of friction*

Heat is created when two surfaces move against each other. This generates heat and / or sparks, especially in machinery. Because heat is generated, a cooling agent must be present to carry the heat away from the source (e.g.

water or a chemical solution / coolant). Any breakdown of a cooling agent will cause the two materials rubbing against each other to heat up to a point where the surrounding materials may ignite. *(Delmar Thomson Learning, 1999, p. 81.)*

Note: Understanding how friction causes fires becomes important when inspecting for fire hazards. You must also ensure the heat source has been stopped when extinguishing fires.

- *Heat of compression*

Heat occurs when a gas is compressed. Diesel engines use this principle to ignite fuel vapour without a spark plug. This why a BA cylinder feels warm to the touch after being filled.

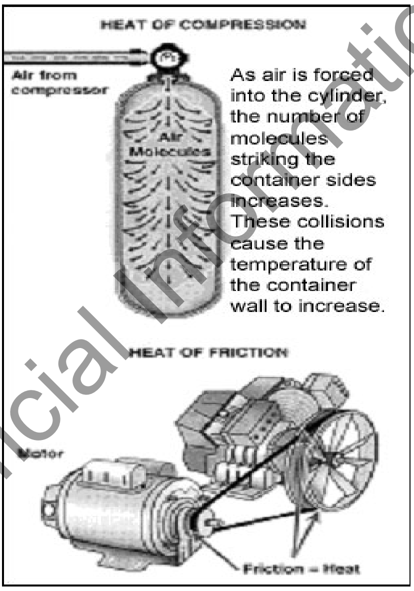


Figure 1.13: Examples of mechanical heat energy
(Source: Reprinted from *Essentials of Fire Fighting*, 4th Ed., IFSTA)

Nuclear and solar energy

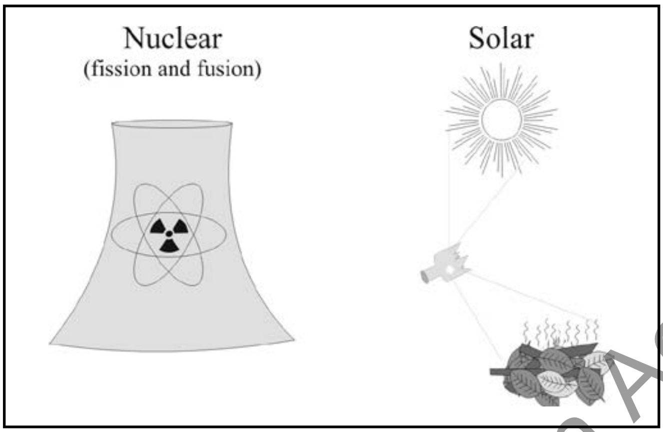


Figure 1.14: Nuclear and solar energy converted to heat energy

- *Nuclear energy*

  Energy is released when atoms either split (*fission*) or combine (*fusion*). In a controlled setting, fission heats water to drive steam turbines and produce electricity. In an uncontrolled setting, the reaction is so fast that – if the fuel is pure (e.g. refined uranium) – it is violently explosive (e.g. a nuclear bomb).

- *Solar energy*

  Solar energy radiates from the sun as light and heat: a magnifying glass can focus solar energy to ignite combustibles, and solar energy panels generate electricity.

Note: Solar energy is a product of a *fusion* reaction, and is a form of nuclear energy. *(IFSTA, 2001, p. 47.)*

Self-sustaining chemical chain reactions

Introduction

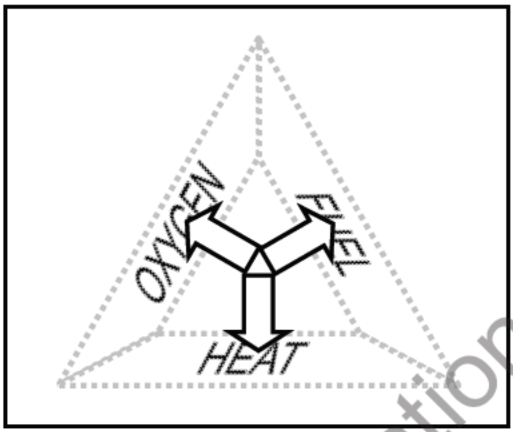


Figure 1.15: Self-sustaining chemical reaction

For a fire to be self-sustaining, all three factors of the fire triangle must exist simultaneously.

Once fire or flaming combustion occurs, it can only continue when the resulting heat energy causes the continued production of fuel vapours or gases. This is a *chemical chain reaction*.

The initial heat (ignition energy) reduces fuel to a simple vapour element (a *free radical*). It then combines with an oxidising agent to form the new combustion product.

In a fire, this reaction is highly *exothermic* (generates heat). The released heat drives further vaporising and decomposing of the fuel, which then reacts with oxygen. This is a chemical chain reaction: a continuing, self-sustaining (or 'uninhibited') process.

Summary

The following summary checklist sums up the main points of the section.

In order for **combustion** to occur, all the **ingredients** of the **fire tetrahedron** must exist:

- Oxygen or other combustion supporter of combustion (an ‘oxidising agent’)
- Fuel
- Heat
- Self-sustaining chemical chain reaction

Supporters of combustion:

- Oxygen is needed to support combustion (some chemicals will produce oxygen when heated)
- Halogens such as chlorine, peroxides, chlorates and acids will also support combustion.

Fuel:

- Fuel must be converted to a vapour before combustion can occur. Keeping fuel in solid or liquid form by cooling it reduces combustion risk.
- When heated, some materials undergo *pyrolysis* and are converted from solid to gas without becoming liquid first (e.g. wood).

Heat:

- Drives the combustion process
- Vaporises solid and liquid fuels
- Provides the energy for ignition
- Causes the continued production of vapour to sustain the burning process.

Self-sustaining chemical chain reaction
The released heat from combustion drives further decomposition of the fuel, which can react with the oxygen to sustain the chemical reaction.

If you are unsure about part of this section, go back and review it. If you still want to know more, or want to make your own notes, write them in the space marked **Notes and questions** below, and discuss with your officer.

Notes and questions

Workbook Activity

You are now required to complete any appropriate questions in your Workbook.

Putting out a fire

Introduction to extinguishing principles

The following extinguishing principles (principles of putting out a fire) are outlined in this section:

- Smothering
- Starving
- Cooling
- Interrupting the chemical chain reaction.

For combustion to occur, the four elements of the fire tetrahedron must be present:

- Heat
- Fuel
- Oxygen (or other combustion supporter)
- A self-sustaining chemical reaction.

The extinguishing principles can remove any of these essential components to collapse a fire. Try:

- Eliminating oxygen
- Eliminating fuel
- Decreasing temperature
- Interrupting the chemical chain reaction.

These extinguishing principles – and the respective techniques – are expanded in later sections of this Study Guide.

Smothering

Smothering: removing oxygen

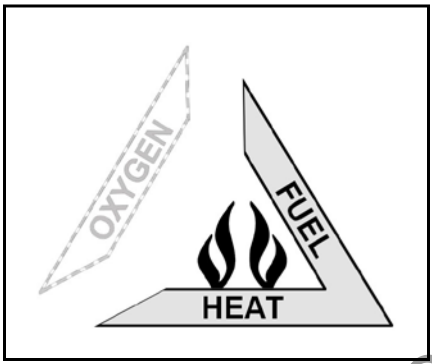


Figure 1.16: Smothering – removing of oxygen

Smothering a fire means cutting off the oxygen supply. Reduce the oxygen content of the atmosphere in the immediate area of the burning material. If oxygen is sufficiently reduced, combustion will stop.

Examples of smothering include:

- Putting a cover over a pan of burning food
- Snuffing a candle
- Capping a burning oil well
- Sealing a ship's hold
- Throwing sand or soil over a camp fire
- Flooding an area with inert gas (e.g. carbon dioxide or nitrogen), displacing the oxygen, disrupting the combustion process
- Blanketing the fuel with foam
- Steam or fine water mists.

Note: When a fire is extinguished by smothering, the fuel temperature may remain above its ignition temperature for some time.

If the fuel is still emitting flammable vapours, it will easily re-ignite with any re-supply of oxygen. This is *flashback*, and is common when extinguishing flammable liquid fires with a smothering medium, such as a fire extinguishment powder.

Starving

Starving: removing the fuel

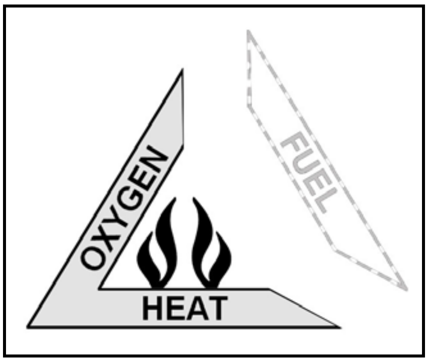


Figure 1.17: Starving – removing the fuel

Removing the fuel starves a fire and interrupts the combustion process. A fire starves when:

- All fuel is consumed
- You remove unburnt fuel (e.g. turning off / stopping liquid or gas fuels, spreading out, or draining out fuels)
- Fire is removed from the unburnt fuel.

Examples of starving include:

- Creating fire breaks, back-burning, or cutting trenches in vegetation fires
- Draining fuel from burning oil tanks
- Demolishing structures to create a fire stop
- Removing the fuel (e.g. removing cargo from a ship fire)
- Spreading out the fuel (e.g. hay bales).

Cooling

Cooling: reducing the temperature

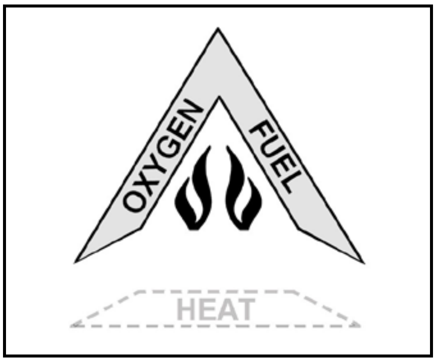


Figure 1.18: Cooling – removing the heat

Cooling involves limiting or reducing the temperature.

When the rate of heat loss from a fire *exceeds* the rate of heat production, a fire will go out. Remove heat from a fire by cooling its fuel, and eventually the fire will cease. This is one of the most effective ways of stopping many kinds of fires.

Water is the most common and effective cooling medium – especially when converted to steam, as it causes a smothering effect (e.g. placing water on a fire can reduce the temperature of the fuel, preventing further emission of flammable vapours).

In a good coolant, the following properties should be as high as possible:

- Specific heat capacity
- Latent heat of vaporisation
- Heat of decomposition. *(AFAC Fire Suppression 1, 1996, p. 32.)*

These water-cooling properties will be detailed later.

Interrupting the chemical chain reaction

Interrupting: breaking the chain reaction

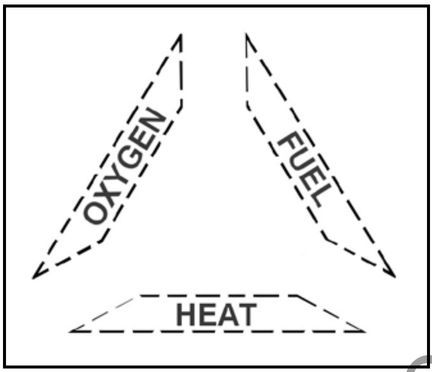


Figure 1.19: Interrupting the chemical chain reaction

By interrupting the chemical chain reaction, combustion is stopped.

Examples of interrupting the chemical chain reaction include:

- Fire retardants added chemically to a material, or applied to its surface. Retardants contain active elements that bind with the vaporised fuel to stop it reacting with oxygen.
- Dry powder extinguishers and salt which bind the vaporised fuel.
- Halon gas extinguishers, such as BCF, which work by interrupting the chemical chain reaction. (These gases are harmful to the ozone layer and are no longer used.)

Note: The term ‘fire retardant’ is often confused with ‘fire resistant’, but they are quite different.

- A fire retardant *material* is able to resist ignition or slow flame spread.
- A fire resistant *structure or barrier* is able to stay intact under prolonged fire.

Summary

The following summary checklist sums up the main points of the section.

In order to stop **combustion**, remove at least one of the **ingredients** of the **fire tetrahedron**.

Smothering: Cutting off the oxygen (or other combustion supporter). For example:

- Covering a pan of burning food
- Snuffing a candle
- Capping an oil well
- Sealing a ship's hold
- Throwing sand or soil on a camp fire
- Flooding a fire with an inert gas
- Blanketing a fire with foam
- Steaming or water misting.

Starving: Removing the fire's fuel by:

- Creating fire breaks, back burning or cutting trenches in vegetation fires
- Draining fuel from burning oil tanks
- Demolishing structures to create a fire stop
- Spreading out hay bales
- Removing cargo from a ship's hold.

Cooling: Remove heat from a fire by cooling the fuel (e.g. use water to absorb heat from a fire).

Interrupting the chemical chain reaction: Chemically bind the fuel or the oxygen to prevent the chemical chain reaction. Use:

- Fire retardants
- Dry powder extinguishers or salt
- BCF extinguishers (these are no longer to be used).

If you are unsure about part of this section, go back and review it. If you still want to know more, or want to make your own notes, write them in the space marked **Notes and questions** below, and discuss with your officer.

Notes and questions

Workbook Activity

You are now required to complete any appropriate questions in your Workbook.

Extinguishing principles

Introduction

This section includes extinguishing principles and media:

- *Water (cooling)*
- *Carbon dioxide (smothering)*
- *Dry powder (interrupting)*
- *Wet chemical (smothering)*
- *Vaporising liquid (interrupting)*
- *Dry sand and earth (smothering)*
- *Foam (smothering / cooling).*

It also includes:

- *Miscibility* (the ability of a liquid to mix, either completely or partially, with another liquid) and density
- When water is unsuitable

All extinguishing techniques work by removing one or more of the elements from the fire tetrahedron.

Solid, liquid, or gaseous extinguishing media

The state of the extinguishing medium (solid, liquid, or gas) determines how successfully it can attack and affect the fire:

- *Gas extinguishing media* (e.g. CO_2 or halons)
  Gases freely move about materials and fill compartments. However, as gases move three-dimensionally and are light, they can be easily swept away from the hot flaming region (e.g. by winds).
- *Liquid extinguishing media* (e.g. water, foam, or wet chemicals)
  Liquids only have a two-dimensional attack ability – they can only drop down or move across a material. But they are denser, and can soak into or fall onto a fire.
- *Solid extinguishing media* (e.g. salts and earth)
  Solids only have a one-dimensional attack ability, so take great care applying solids. But due to their high density, solids are not easily dislodged or vaporised (like liquid or gas).

Water (cooling)

Water as an extinguishing medium

Water is the most efficient, cheapest, and most readily available fire extinguishing medium – and the most effective, due to its *cooling* action.

Water has high specific heat and latent heat of vaporisation (the heat absorbed when liquid changes into gas). Using water absorbs a large amount of heat from the fire, as the water's temperature rises and changes into steam.

Most heat is absorbed during water's change of state from liquid to steam. To be most effective, use as much water as possible.

Water converted to steam at 100°C occupies 1,700 times its original volume.

Steam also has a blanketing effect – expanding steam displaces oxygen in the atmosphere.

Water may also be used to smother a fire where the burning material has a greater density than water, as the water will float.

Methods of using water:

- Jet stream
- Spray pattern
- Fog pattern

Safety Note

Water conducts electricity – do not use water on electrical Class E type fires.

Water may also be dangerous on other types of materials, especially in Class D, B, and F fires.

Carbon dioxide (smothering)

Carbon dioxide as an extinguishing medium

Carbon dioxide (CO_2) for extinguishing fires is stored at high pressure in a liquid state.

CO_2 reduces oxygen content in the air so combustion can no longer occur. It therefore extinguishes a fire by smothering it.

CO_2 is heavier than air (1.5 times as dense). When used, it disperses in a cold, white cloud at ground level (which can reduce breathable oxygen). CO_2 will only work in a confined space – it is easily dispersed by wind in open spaces.

Although CO_2 is generally applied using a fire extinguisher, it may be available – on request – in bulk (e.g. for fires in silos, ship's holds or down drains).

Note: Materials which supply their own oxygen will continue to burn, as will any reactive material that removes the oxygen from CO_2 (e.g. burning magnesium or phosphorous).

Uses:

- Class A, B, E, and F fires.

Features:

- Non-corrosive and non-conductive
- Leaves no residue.

Safety Note

Carbon dioxide (CO_2) does not conduct electricity, so its major use is on electrical Type E fires.

However, before extinguishing a fire involving live electrical wiring or equipment, you must always attempt to disconnect the electrical supply. Otherwise, the fire could re-ignite. (*AFAC Fire Suppression 1, 1996, p. 35.*)

Dry powder (interrupting)

Dry powder as an extinguishing medium

Dry chemical powder is usually pressurised *sodium bicarbonate*.

- Applying dry powder produces a cloud of finely divided particles, achieving a smothering effect. Sodium bicarbonate also releases carbon dioxide (CO_2) when heated.
- Carbonates also have a high specific heat in powder form, and will absorb heat – giving a cooling effect. Sodium bicarbonate is also thought to interrupt the chemical chain reaction in combustion.
- Dry powder is effective at extinguishing flame (‘rapid knock-down’).

Uses:

- Class D (metal) fires (only use dry powder specifically designed for metal fires)
- Class B (flammable liquid) fires
- Class E (electrical) fires
- Sometimes on Class A (combustible solids) and Class C (flammable gas) fires
- Non-conductive, but corrosive (surfaces need to be washed down after applying dry powder).

Application:

- Dry chemical powder is expelled from containers (with specially designed nozzles) by gas pressure. Aim dry chemical powder at the fire in a concentrated cloud. This cloud also screens the operators from the flames and enables a close attack (to guard against flashback).
- You must also take care to leave the liquid surface intact: do not walk over the surface after extinguishing a spillage fire. (*AFAC Fire Suppression 1, 1996, p. 48.*)

Note:
There may be a ‘flashback’ risk due to dry chemical powder’s lack of cooling ability. The fire could re-ignite if enough heat is present (especially with liquid fuel).

Wet chemical (smothering)

Wet chemical as an extinguishing medium

A wet chemical is a water-based solution – typically *alkali metal salts*. It's designed to extinguish fires in cooking oils and fats. It reacts with the surface of the oil or fat and smothers the fire.

The liquid extinguishing agent rapidly converts burning fuel (e.g. fats or cooking oils) to a combustion-resistant soap (*saponification*). It then smothers and suppresses flammable vapours and steam, helping to prevent re-ignition.

Uses:

- Class F (fat and oil) fires
- Class A (combustible solids) fires.

Features:

It is alkaline in nature:

- Avoid contact with eyes and skin
- Prompt clean up is advised
- Wear eye protection and chemical-resistant gloves.

It also:

- Conducts electricity
- Can have corrosive properties when applied to fires involving hot cooking surfaces.

Example
Wellington's Westpac Stadium kitchen has a wet chemical system installed over cooking vats of fat for cooking chips.

Vaporising liquid (interrupting)

Vaporising liquid as an extinguishing medium

Vaporising liquids for firefighting are *freons* and *halons*.

- Vaporising liquids include BCF (*bromochlorodifluoromethane*) and BTM (*bromotrifluoromethane*).
- These substances are stored under pressure as a liquid (usually pressurised with nitrogen) – they vaporise when released. The substances vaporise rapidly when heated, forming a dense cloud of non-flammable vapour. This smothers and blankets the fire by displacing the air.
- As the vaporising liquids decompose on heating, they interfere with the chemical reaction of flame development by removing the 'chain carries', and thus extinguish by chemical flame inhibition.

Uses:

- Class A, B, C, and E fires
- Specialist applications (e.g. aircraft fires).

Features:

- Non-conductor of electricity.

Note:
Halons were used in earlier extinguishers, but are no longer used because they destroy the ozone layer. (*AFAC Fire Suppression 1, 1996, p. 48.*)

Safety Note

For Class C (flammable gas) fires, remove the fuel source first – turn *off* the gas supply before extinguishing the fire.

Dry sand and earth

Dry sand and earth as an extinguishing medium

Dry sand and earth can be used to smother a fire when other media may react with the burning material.

Uses:

- Dry sand can prevent burning liquids (e.g. paints and oils) from flowing down drains or into basements
- Sand is useful for containing shallow liquids (Class B fires) – foam or water spray can then be applied without spreading the fire
- Sand should not be used on machinery or electrical motors, as it may cause permanent damage
- If using on a Class A (combustible materials) fire, ensure you apply sufficient amounts to completely cover the burning material.

Other types of smothering agents:

- Powdered talc
- Soda ash
- Limestone
- Powdered graphite

Foam (smothering and starving)

Foam as an extinguishing medium

Foam floats on the surface of a burning liquid, forming a ‘blanket’ and smothering the fire.

Foam also prevents flammable vapour from forming, so it has a starving effect. The water content in foam also reduces the fuel’s temperature.

Uses:

- Class B (flammable liquid) fires (e.g. petrol or oil)
- Some foam is designed for Class A fires where access is difficult (e.g. vegetation fires, or confined spaces like a basement or ship’s hold), and is referred to as Class A foam.

What is foam?

Foam is formed by mixing three components. The percentage of each component in a mix varies:

- Foam concentrate
- Water
- Air.

Foams are grouped into two types of concentrate:

Protein based – Made from natural products such as hoof, horn, and animal blood, for example:

- Fluoroprotein (the most common type)
- Film-Forming Fluoroprotein (FFFP).

Synthetic based – Man-made products containing hydrogen and carbon, for example:

- Film-forming foams include Aqueous Film Forming Foam (AFFF), and Alcohol Resistant Foam (ARF), which is also known as ATC (Alcohol Type Concentrate)
- High expansion foam. (*AFAC Fire Suppression 1, 1996, pp. 39-48.*)

Note:
This information on foam is just a brief overview. More detail is given in the *QF Foam Study Guide*.

Miscibility and density

Understanding *density* and *miscibility* is key to using foam. The density of a gas or vapour determines whether it tends to rise or sink in air, and where it will be found in greatest concentrations (at upper or lower levels of a compartment or building).

A material s density is defined as its mass (kg) over a given volume (one cubic metre of material). Examples of how density behaves in heat include:

- Vapours of most flammable liquids are heavier than air – you will find them close to the floor or ground
- Some liquids are heavier than water and will sink. Others are lighter and will float on water
- Many flammable gases are lighter than air and will rise to collect at the ceiling of a building, or escape vertically in open air.

Miscibility **–** a substance’s ability to be mixed with other substances.

Although gases and vapours can be lighter or heavier than air, it is important to note that, once mixed with air, they will not settle back into layers.

Density of liquids

If the density of a substance is lower than the density of water, and does not mix with (dissolve in) water, then that substance will float. The example in Figure 3.1 shows petrol as much lighter (i.e. less dense) than water.

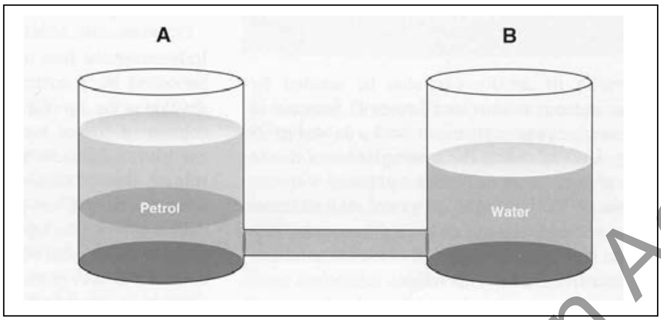


Figure 1.20: Diagram showing the difference in density in liquids

The density of most flammable liquids is less than that of water. The specific density of water is 1.0 (i.e. a one-metre cube of water weighs one tonne).

The density (specific gravity) of a burning liquid partly determines whether it is possible to cover it with water, or whether you need to use foam or another extinguishing media. For example: foam must be used on a petrol fire, as petrol has a lower density than water and will float on the water.

Examples of the different specific density of materials:

- Mercury has a high density of 13.6 (i.e. it is 13.6 times more dense / heavier than water), so it sinks in water. A one-metre cube of mercury will weigh 13.6 tonnes
- Petrol has a low density of 0.7 (i.e. it is lighter than water), so it floats on water. A one-metre cube of petrol will weigh 0.7 tonnes.

Miscibility and immiscibility

Miscibility is the ability of a liquid to mix, either completely or partially, with another liquid.

If a liquid does not mix with another, then it is *immiscible*.

The Fire Service is primarily interested in whether a flammable liquid is miscible or immiscible with water.

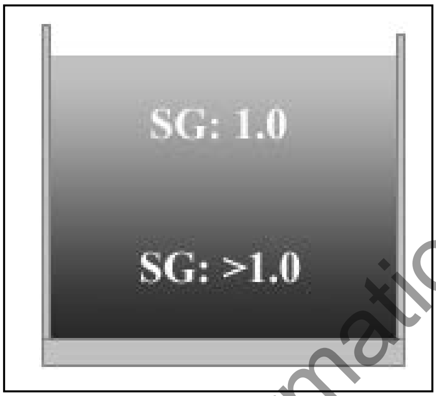


Figure 1.21: Liquids with different specific gravities (SG) are immiscible

The specific gravity (SG) of water is 1.0 (i.e. a one-metre cube of liquid will weigh 1 tonne).

- If a liquid is *immiscible* with water and is *less dense* than water, it will float on water.
- If a liquid is *immiscible* with water and is *denser* than water, it will sink.

Most flammable liquids (e.g. petrol, diesel, oil, and paint) are immiscible, and are also less dense than water, and so will float.

Flammable liquids immiscible / miscible with water

All hydrocarbons are immiscible with water, and are also less dense than water. For example:

- Pentane
- Octane
- Kerosene
- Light fuel oil
- Lubricating oil
- Greases and waxes.

Some flammable liquids *are* miscible with water, such as alcohols and polar solvents. For example:

- Alcohols (e.g. methanol, ethanol and 2-propanol)
- Polar solvents (e.g. acetone, methyl ethyl ketone)

Flammable liquids that are miscible with water tend to mix with conventional foams (FFFP, AFFF, and protein foams). They reduce foam's effectiveness.

However, alcohol-resistant foams have an insoluble barrier in the bubble structure that resists breakdown at the interface with the fuel. These are effective on alcohols and polar solvents.

Density of gases and vapours; vapour density (VD)

Unlike many liquids, all gases and vapours are completely miscible with each other. However, differences in density will affect the way they mix.

Example:
Methane (the main component of natural gas) is a light gas with a vapour density (VD) of about 0.5. (Air is 1.0.) If methane is leaking into a room from a faulty gas appliance, it will rise to the ceiling, mixing with air as it rises, and forming a layer. This layer (the methane and air mixture) will eventually descend to the level of the leak.

All heavier-than-air gases, like carbon dioxide (e.g. VD 2.5), will accumulate in low places such as wells and cellars. This increases the risk of *asphyxia* (suffocation), and fire – especially with flammable vapours.

Density differences can also be caused by changes in temperature. Temperature increases cause expansion, and a lowering of density (e.g. hot air is less dense than cold air, so it rises).

When water is unsuitable

Water's suitability as an extinguisher

Extinguishing methods depend on *density* and *miscibility* of all liquids involved.

Water is a suitable extinguisher when:

- It is applied to burning liquids that are *miscible* with water, because water tends to mix with miscible liquids, diluting them and making them non-flammable
- It is applied to burning liquids that are *immiscible* with water, but *denser* than water. Water will float on these types of liquids, smothering them.

Water is *not* a suitable extinguisher when it is applied to burning liquids that are *immiscible* with water, but *less dense* than water – the liquid will float on the water ***and may spread*** (e.g. petrol). In this case, you should use foam.

The following table outlines the relationships between water and some flammable liquids, and how you should deal with them:

Density	Miscibility	Example	Method of extinguishing
Lighter than water	Immiscible	Petrol	Foam (to blanket)
	Miscible	Methylated spirits	Flood or spray (to dilute) or use alcohol resistant foam
Heavier than water	Miscible or immiscible	Carbon disulphide	Swamp / flood (to cover with water)

Note: Sand is recommended for confining the flow of thicker types of burning liquids (e.g. paints and varnishes).

Metals that react with water

Metals that react with water to produce hydrogen gas include:

Potassium
Sodium
Calcium
React with cold water → **Hydrogen gas**

The *more* reactive metals will react with cold water to form highly flammable hydrogen gas, for example:

Magnesium
Aluminium
Zinc
Iron
Burning metal + water → **Hydrogen gas**
Hot metal + steam → **Hydrogen gas**

Potassium and sodium metals will float on water. The resulting *hydroxide* is a *caustic alkali*.

All metals react more vigorously when they are in dust or powder form (e.g. fireworks). You should extinguish fires involving reactive metals by smothering them with dry sand – or use dry powder designed for metal fires.

Chemical reactions making water unsuitable

Do *not* use water with fires involving:

- *Calcium carbide*
  Reacts with cold water to produce highly flammable acetylene gas (e.g. in miners’ carbide lamps).
- *Sodium peroxide*
  Reacts violently with water to produce oxygen (a combustion supporter), sodium hydroxide (caustic soda) and heat.
- *Quicklime*
  Reaction with water may generate enough heat to ignite nearby flammable materials, or cause a steam explosion.
- *Concentrated sulphuric acid*
  Reaction with water will generate sufficient heat to cause a steam explosion. This may cause the corrosive acid to spatter in all directions – or rupture its container.

You can combine water with acids in some situations: always add an acid to water so it quickly becomes diluted, and add sufficient quantities of water to acid to dilute and cool it, preventing a steam-explosion scenario.

- *Sodium nitrate*
  Combining sodium nitrate with water creates *molten* sodium nitrate. The resulting nitrate bath has a temperature of about 300°C. The resulting steam explosion could cause nitrate to spatter in all directions.

Note: Sodium nitrate is also an oxidising agent. At this temperature (300°C), it would cause immediate ignition of *any* combustible materials it came in contact with.

Summary

The following summary checklist sums up the main points of the section.

Solid, liquid and gas extinguishing media

Correct selection can determine firefighting success.

- Gases will freely fill a compartment, but are easily dispersed by wind
- Liquids will soak or fall into a fire
- Solids are not easily vaporised by a fire or dispersed by winds.

Water acts by cooling the fire. Water:

- Absorbs large amounts of heat as the temperature rises and water is converted to steam
- Is cheap and readily available
- Needs special care when used with some classes of fire – run-off may occur.

Carbon dioxide (CO_2) smothers fires by displacing oxygen. CO_2:

- Is effective against electrical fires
- Leaves no residue
- Will settle and can cause breathing difficulties
- Is easily dispersed by winds.

Dry powder smothers and cools fires, interrupting the chemical chain reaction. Dry powder:

- Consists of pressurised sodium bicarbonate
- Is effective on most fires
- Is corrosive – surfaces need washing down to prevent damage
- Needs special care so liquid surfaces aren't broken after fighting a spillage fire.

Wet chemicals smother fires by reacting with fat or oil. Wet chemicals:

- Are water-based solutions for extinguishing cooking oil or fat fires
- Conduct electricity
- Can be corrosive.

Vaporising liquid smothers by displacing air and interferes with the chemical chain reaction. Vaporising liquid:

- Is stored as a pressurised gas
- Vaporises once deployed
- Does not conduct electricity.

Dry sand and earth is used to smother fires. Dry sand and earth:

- Can be used to control burning spills
- Can create retaining dams so other agents (e.g. foam) can be used.

Foam smothers and starves a fire. Foam:

- Is a mixture of foam concentrate, water and air.

If you are unsure about part of this section, go back and review it. If you still want to know more, or want to make your own notes, write them in the space marked **Notes and questions** over the page, and discuss with your officer.

Notes and questions

Workbook Activity

You are now required to complete any appropriate questions in your Workbook.

Burning

Combustion process

Introduction

The combustion process is a self-sustaining chemical reaction involving rapid oxidation, usually accompanied by the production of heat and light.

This is in contrast to slow oxidation, which does not produce heat fast enough to reach ignition, e.g. rusting iron or yellowing paper.

This process is discussed in the following topics:

- The combustion process
- Range of flammability
- Products of combustion
- Composition of smoke
- Toxicity of smoke and gases in combustion.

Fuel configuration and combustion (solid surface-to-mass ratio)

The shape and make-up of the fuel (called the fuel configuration) plays an important part in the combustion process.

When a fuel is mixed with an oxidiser in the right proportions and heated, ignition occurs. The fire then grows to a size where the heat given off is sufficient to release more flammable vapour, and the process is then self-sustaining:

- The greater the surface-area-to-mass ratio, the quicker the fuel will reach ignition temperature
- The greater the surface area, the more radiant heat the fuel will receive
- The smaller the mass, the less heat energy is needed to raise it to ignition temperature.

This is why we chop a log into kindling to start a fire. The fuel configuration of kindling means it has a much greater surface-area-to-mass ratio than a single solid log of equivalent mass. As the surface area increases, more material is exposed to heat and oxygen, and this generates more burnable gases due to pyrolysis.

A large surface-area-to-mass ratio also means more oxygen is available for the combustion process.

Liquid surface-to-volume ratio

Like the surface-area-to-mass ratio for solid fuels, the surface-area-to-volume ratio of liquids is an important factor in their ignitability. When a liquid is contained, it usually has a low surface-to-volume ratio. But when spilt or released onto the ground, it causes this surface-to-volume ratio to increase, which increases the vaporisation and likely ignition.

Heat loss during combustion

Heat is lost from the combustion process by:

- Heating up the unburnt fuel
- Chemically breaking down the fuel (pyrolysis)
- Radiation into the environment
- Convection in the rising smoke (about 70% in a typical fire).

The combustion process is therefore a balancing act:

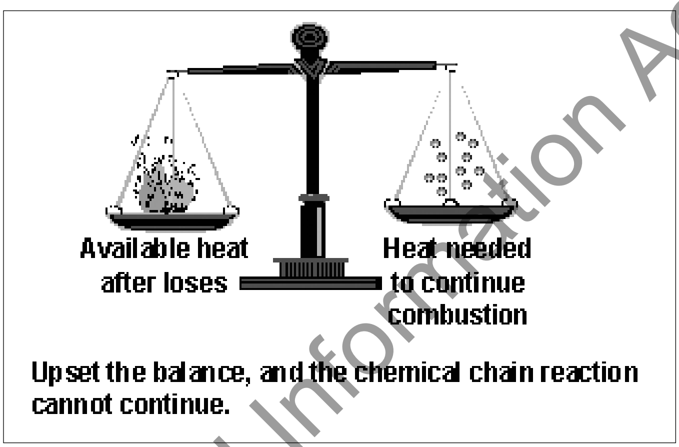


Figure 1.22: Heat balance in the combustion process

To extinguish a fire, we do not need to overcome *all* the heat being produced, because much of it is already lost. It only needs to be cooled enough so that the heat being given off is insufficient to vaporise more fuel.

Range of flammability

Introduction

For combustion to occur, a fuel must be converted into a gaseous state, and must be mixed with air (oxidiser) in the proper ratio. The range of concentrations of the fuel vapour and air (oxidiser) is called the *flammable* (*explosive*) *range.*

Lower and upper flammable limits

The flammable range has limits:

- *The lower flammable limit* (or *lower explosive level*) for a fuel is the **minimum** concentration of fuel vapour and air that supports combustion. If the concentration is below the LFL, there is too much air and not enough fuel to burn (i.e. it is *fuel-lean*).
- The *upper flammable limit* (or *upper explosive level*) for a fuel is the **maximum** concentration above which combustion cannot take place. If the concentration is above the UFL, there is too much fuel and not enough air to burn (i.e. it is *fuel-rich*).

Variations in temperature and pressure can cause the flammable range to vary considerably. Generally an increase in temperature or pressure broadens the range, and a decrease narrows the range.

Flammability limits also change depending on surrounding conditions, for example a concentration of carbon monoxide at 37% is very significant if the reading was taken in a warehouse building. An explosion could lift the roof off its supports, and blow out the concrete walls.

Compare this, however, to a reading of 37% taken in a shoebox-sized container. This is much less dangerous; it might only emit a slight 'pop' if ignited.

Comparing the flammable or explosive limits of one substance with another is important for Firefighters when evaluating different situations and substances.

Ratio of fuel to air

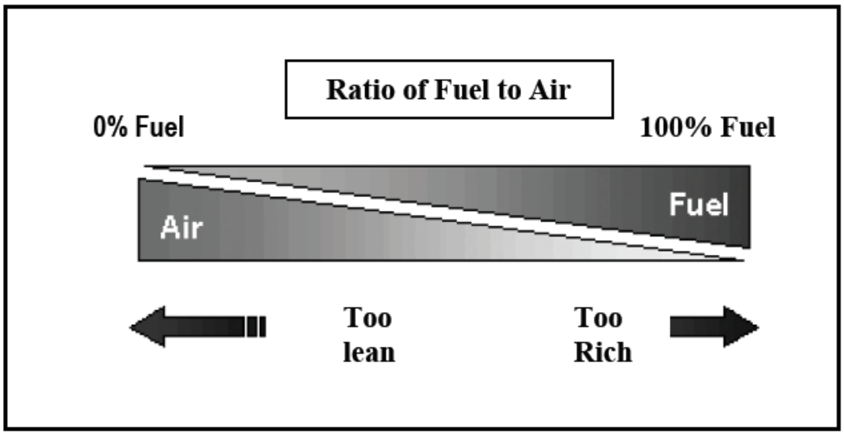


Figure 1.23:Range of flammability – ratio of fuel to air

Range of flammability for a common range of fuels

The range of flammability for a selected example of fuels is shown below**.**

Note: These flammability ranges shown are at 25°C. If the temperature is increased, the range of flammability will widen.

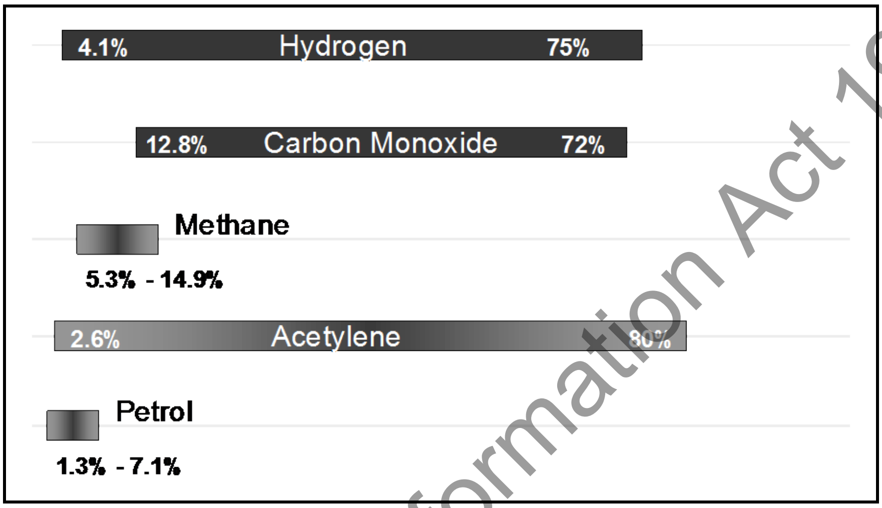


Figure 1.24: Range of flammability for a range of fuels

Ideal mixture

The *ideal mixture* (IM) is the concentration of fuel and air that will burn with the most intensity and with the hottest flame. This is because the fuel and air are in ideal proportions. A mixture burning at the IM will produce near-complete combustion (i.e. if there is no excess fuel leaving the flame as smoke, all fuel is consumed [oxidised]).

Products of combustion

Introduction

When a fuel burns, there are four products of combustion released: heat, light, smoke, and flammable vapours.

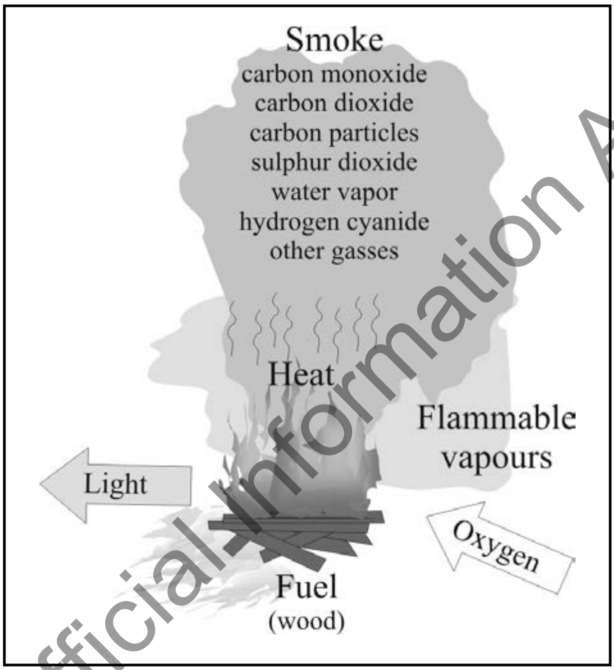


Figure 1.25: Products of combustion

Chemical changes

When material (fuel) burns, it undergoes a chemical change. None of the elements making up the fuel are destroyed in the process; however all of the materials are transformed into another form or state.

For example, burning a piece of paper releases the gases and moisture contained within the paper. The remaining solids take on the appearance of carbonised, charred flakes. Incomplete combustion leaves behind some unburned and charred fuel as well.

Burning also results in the generation of airborne fire gases, particles, and liquids – referred to as *products of combustion.* The energy released is in the form of light and heat.

The heat energy from a fire is responsible for the spread of the fire, and can also cause burns, dehydration, heat exhaustion and injury to a person's respiratory tract.

Flame

Flame is the visible, luminous body of burning gas.

When a burning gas is mixed with the proper amounts of oxygen, the flame becomes hotter and less luminous. Thus flame is considered one of the products of combustion, even though it is not present in smouldering fires.

Note: With some fuels, such as alcohol, the flame is not visible.

States of combustion

There are two main states of combustion:

Flaming combustion
For example, burning logs in a fireplace.

Surface or smouldering combustion:

- Burning with no visible flame
- Normally results in slow fire development, which can continue for hours or days
- May die out without progressing to full, flaming combustion
- Can be dangerous – it may not produce sufficient heat to activate some types of fire protection systems such as sprinklers or heat detectors, but the smoke produced can be toxic enough to cause injury or death.

Composition of smoke

What is smoke?

Smoke is a hot buoyant gas – made up of hot air plus contaminants. It therefore obeys the fundamental laws of fluid mechanics.

The amount of smoke produced by a fire will vary depending on the:

- Size and heat output of the fire
- Characteristics of the fuel burnt
- Path along which the smoke flows.

Constituents of smoke

The plume of hot gases above a fire has three parts:

- Hot vapours and gases given off by the burning material
- Unburnt decomposition and condensation matter (which varies in colour from light-coloured to black and sooty)
- A quantity of air heated by the fire and entrained into the rising plume.

Smoke consists of a well-mixed combination of these three components, containing gases, vapours, and dispersed solid particles.

Density and toxicity of smoke

The density and toxicity of the smoke produced will depend on the fuel burning, but the total volume of smoke produced will depend on the size of the fire and the building in which it occurs.

As solid materials in a fire heat up, hot volatile combustible vapours are given off which, if energetic enough and capable of mixing with sufficient oxygen, will ignite:

1. Above the fire, a column of flames and hot smoky gases rises with a definite upward movement, as it is lighter than the cold surrounding air
2. The surrounding air is ‘entrained’ into the rising stream and mixes with it
3. Much of the vaporised fuel escapes the flaming region without successfully igniting, yet it is still flammable, so all smoke is hazardous.

See Figures 1.26 and 1.27.

Smoke production diagram

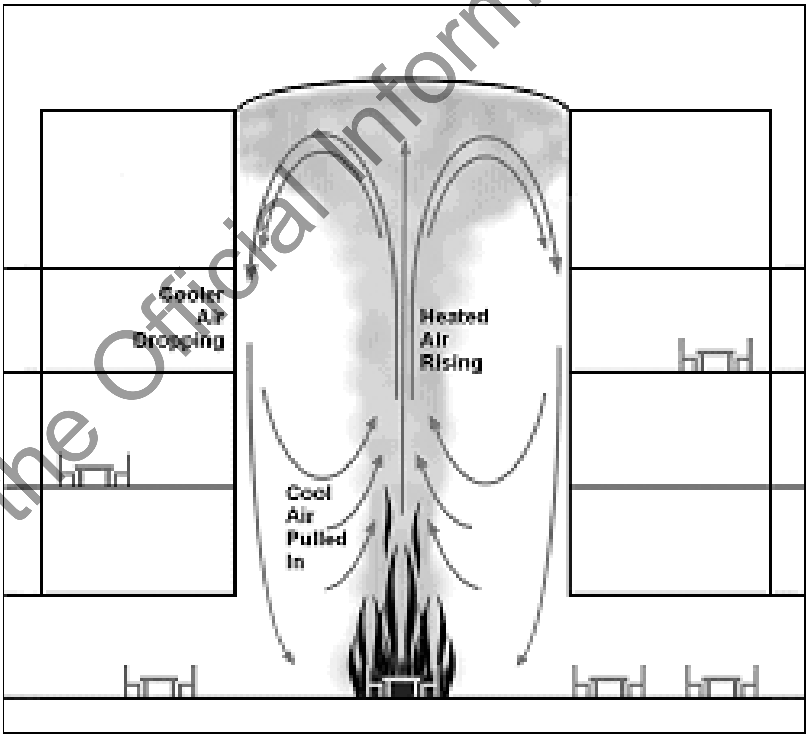


Figure 1.26: Smoke production

Fire plume diagram

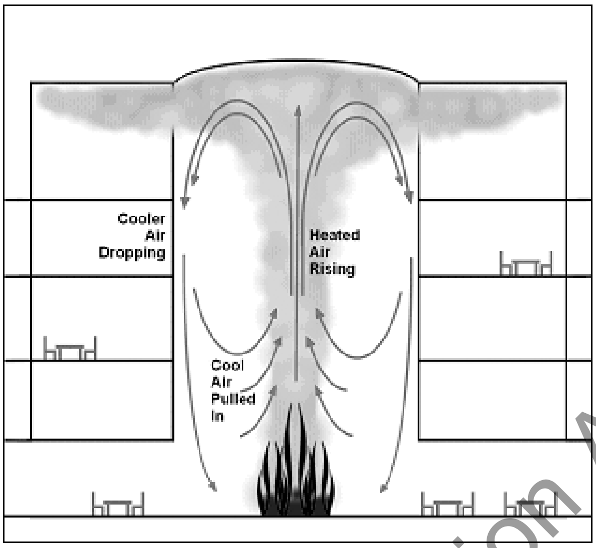


Figure 1.27: Fire plume

Smoke formation

Part of the entrained air will supply the oxygen needed for the combustion of the gases from the decomposing fuel, and produce flames.

However, because the temperature in the plume is not high enough, and the mixing of the oxygen into it is incomplete, the combustion of the gases will also be incomplete. Incompletely decomposed and dispersed solid fuel particles form the sooty component of the smoke, which typically makes smoke visible.

The entrained air is pulled into the plume as it rises. It serves to dilute and cool the hot smoke as it rises.

Smoke particles

Smoke particles typically measure approximately one micron (1 / 1000 of a millimetre) across. However, there is a big difference between the shapes of smoke particles from smouldering and flaming fires:

- Smouldering fires tend to make tarry droplets, which are large and spherically shaped
- Soot particles from flaming fires are small and stringy in character.

These different shapes are caused when small particles formed in the flame collide and stick. The shape that results depends on how randomly the particles stick together.

Toxicity of smoke and gases in combustion

Smoke and toxic components

Ordinary air (oxygen and nitrogen) is the primary constituent of smoke. But it also includes combustion gases and unburnt, partially decomposed fuel particles (soot) that give smoke its colour.

The main combustion gases (especially from hydrocarbons) are water vapour and carbon dioxide.

There can also be trace combustion product gases including narcotic or asphyxiant gases, and irritants (which are almost always invisible to the naked eye), such as:

- Carbon monoxide
- Hydrogen cyanide
- Hydrogen chloride
- Ammonia
- Nitrogen dioxide
- Sulphur dioxide.

Narcotic or asphyxiant gases affect the central nervous system, which can:

- Result in reduced awareness and intoxication
- Lead to a loss of consciousness and death.

Reduced oxygen levels will also cause a narcotic effect.

Irritants in smoke are substances that cause:

- Breathing discomfort (pulmonary irritants)
- Inflammation of the eyes, respiratory tract, and skin (sensory irritants).

Some materials give off more smoke than others, for example:

- Liquid hydrocarbon fuels generally give off dense, black smoke
- Oil, tar, paint, varnish, rubber, sulphur, and many plastics also give off dense smoke.

Note: Because of smoke and its toxic components, Operational Instruction *E3-2* requires breathing apparatus (BA) to be worn at all fires, including during the overhaul stage.

Gas exchange in the body

The tissues of the body require oxygen (O_2) for normal metabolic processes (i.e. the oxidation of food to produce energy). They must also eliminate carbon dioxide – the waste product of respiration.

Gas exchange takes place in the lungs. Inhaled air enters an extensive system of sac-like structures called *alveoli*. Within each *alveolus* lies a vast network of *capillaries* (minute blood vessels). Gases can pass through the alveolar membrane into the capillaries.

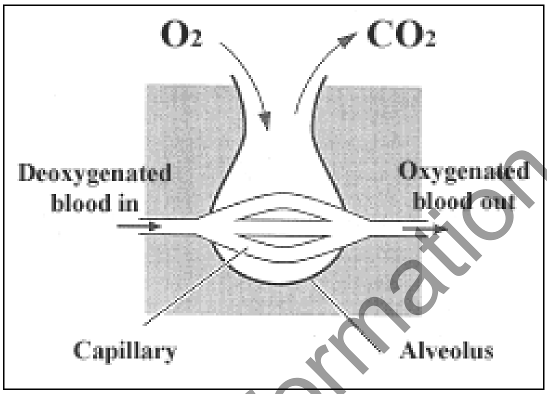


Figure 1.28: Gas exchange in the lungs

What happens to the oxygen in the lungs

Oxygen is carried from the lungs to the body's tissues by *haemoglobin* in the blood. Once it gets to the body's tissues, oxygen is released by the haemoglobin. The waste CO_2 is picked up and carried to the lungs, where it is exhaled.

Noxious fumes and gases may prevent respiration from taking place by: damaging the alveolar membrane, which prevents gas exchange, combining with the haemoglobin, preventing oxygen from combining with the haemoglobin to be carried around the body.

Summary

The following summary checklist sums up the main points of the section.

Combustion process

The combustion process is a self-sustaining chemical reaction involving rapid oxidisation, usually accompanied by the production of heat and light.

- The physical shape and make up of the fuel affects the combustion process
- Greater surface to mass ratio increases combustion (wood kindling versus wood logs)
- Greater surface to volume ratio in liquids increases combustion (spilt petrol versus a bucket of petrol).

Range of flammability

In order to be flammable, fuel vapour and air need to be mixed in the correct ratio. Fuel smothers a fire by displacing oxygen:

- The Lower Flammable Limit (LFL) and the Upper Flammable Limit (UFL) are the extremes of the proper ratio
- The Ideal Mixture (IM) is the ratio where the fire will burn most intensely, and with hottest flame.

Products of combustion

The chemical reaction of combustion produces:

- Heat
- Light
- Smoke
- Flammable vapours.

Smoke

Smoke is a hot buoyant gas made up of three parts:

- Hot vapours and gases from the burning material
- Unburnt decomposition and condensation matter
- Air heated by the fire.

Toxicity of smoke and gases

Some of the gases given off can be narcotic, asphyxiant, or irritant:

- Narcotic or asphyxiant gases can cause reduced awareness, intoxication, loss of consciousness or death
- Reduced oxygen can have a narcotic effect
- Irritants can cause breathing difficulties, sore eyes, and skin irritation.

If you are unsure about part of this section, go back and review it. Then if you still want to know more or want to make your own notes, write them in the space marked **Notes and questions** below, and discuss with your officer.

Notes and questions

Workbook Activity

You are now required to complete any appropriate questions in your Workbook.

Chemistry for combustion

Overview

Temperature of material and ignition

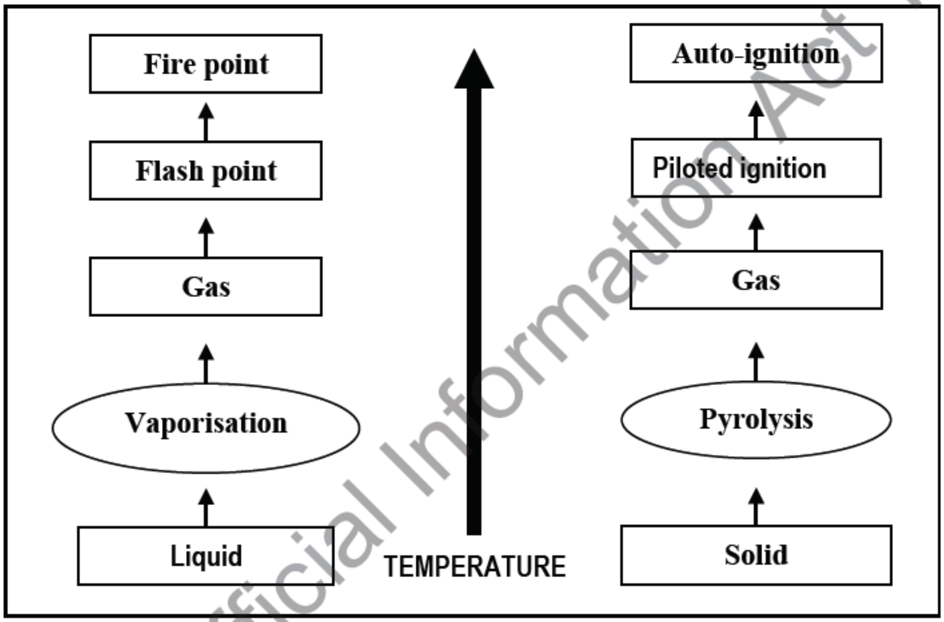


Figure 1.29: Temperature and ignition

Flash point and fire point

Flash point

Flash point is the lowest temperature at which sufficient vapour is emitted by a liquid to flash momentarily if ignited – but not continue to burn. It burns out or self-extinguishes when it has consumed all the vapour.

Examples:

- The flash point of methylated spirits is around 2°C
- The flash point of kerosene is between 27 and 50°C
- The flash point of engine oil is around 200°C.

Fire point

If heating rises past the flash point, a temperature is reached where ignition of the vapours leads to a ‘flash’, followed by development of a sustained diffusion flame at the surface. This temperature is known as *fire point.*

Fire point is the lowest temperature at which sufficient vapour is given off by a liquid (evaporation) to enable combustion if ignited, and will continue to burn after the ignition source is removed.

Ignition and auto-ignition temperature

Ignition temperature

The lowest temperature of a substance at which sustained combustion can be initiated.

Piloted ignition temperature is the minimum temperature at which a substance *will* ignite in the presence of a pilot flame (e.g. a match or spark). The pilot flame may be the primary means of heating the substance (e.g. a pot of cooking oil heating on the stove. When the oil reaches its ignition temperature, it will ignite when a match is held over the pot. (The match is the pilot flame.)

Auto-ignition

Auto-ignition temperature is the minimum temperature at which a substance will ignite *without* a pilot flame. Auto-ignition temperature is typically much higher than ignition temperature. For example, if the above pot of oil is left heating on the stove, it will eventually ignite on its own when the oil gets hot enough – even in the absence of a pilot spark or flame.

The heat source is *external* – the substance does not create the heat itself. (The heat source for the pot of oil is from the stove element.)

Spontaneous ignition temperature

With *spontaneous / self-heating ignition*, the source of heat is internal (i.e. it creates its own heat).

As the temperature rises, the reaction rate increases – doubling for roughly every 10°C rise in temperature. So even more heat is given off and the temperature rises faster (if the heat isn't dissipated or able to escape).

The spontaneous ignition temperature is the lowest temperature at which a substance will ignite without the introduction of an ignition source.

The ignition temperature is reached by a chemical reaction within the substance, or between substances that have been mixed together. For example:

- Action of organisms in haystacks, leading to active combustion
- Cloth soaked in linseed oil and left in a heap
- Powdered material, such as powdered coal used in some power stations, or coal piles incorrectly stored
- In the manufacture of some plastics (e.g. polyurethane foams).

Exothermic reaction

This is any chemical reaction that is accompanied by the emission of heat. For example:

- Combustion of fuels
- Water + quicklime
- Water + concentrated sulphuric acid.

Summary

The following summary checklist sums up the main points of the section.

Flash point is the lowest temperature at which sufficient vapour is given off by a liquid to flash momentarily if ignited – but will not continue to burn after the ignition source is removed.

Fire point is the lowest temperature at which sufficient vapour is given off by a liquid to enable combustion if ignited – and will continue to burn after the ignition source is removed.

Ignition temperature is the temperature at which a substance can be ignited by a spark or flame (e.g. a match held over a pot of hot cooking oil).

Auto-ignition temperature is the minimum temperature that a substance will ignite without a match or spark (e.g. an overheating pot of cooking oil will eventually ignite on its own).

Spontaneous ignition temperature is the temperature at which a substance will ignite with no external heat source (the source of heat is an internal chemical reaction).

Toxicity of smoke and gases in combustion

Some gases given off can be narcotic, asphyxiant, or irritant:

- Narcotic or asphyxiant gases can cause reduced awareness, intoxication, loss of consciousness or death
- Reduced oxygen can have a narcotic effect
- Irritants can cause breathing difficulties, sore eyes and skin irritation.

If you are unsure about part of this section, go back and review it. Then if you still want to know more or want to make your own notes, write them in the space marked **Notes and questions** below, and discuss with your officer.

Notes and questions

Workbook Activity

You are now required to complete any appropriate questions in your Workbook.

Effects of heat on matter

Composition of matter

Matter

Matter can be broken down into atoms, elements, compounds and mixtures.

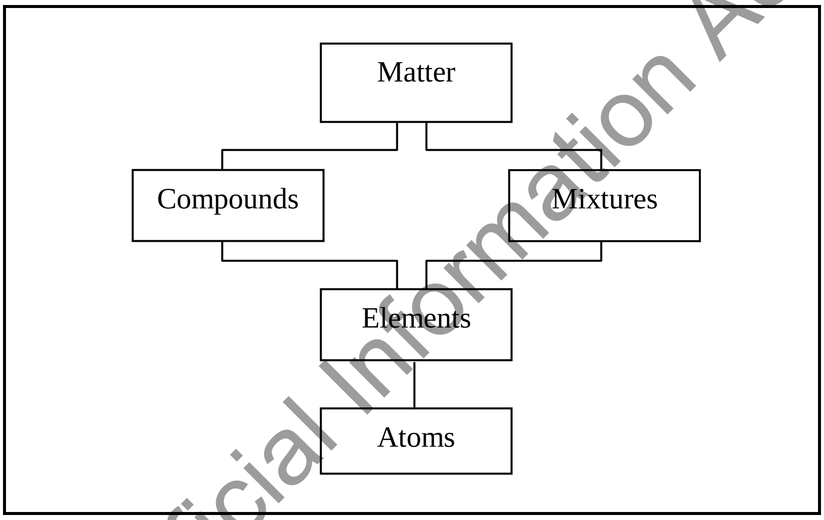


Figure 1.30: Composition of matter

Atoms

All matter is made of atoms. An atom is the smallest part of an element, and has all the properties of the element. If you break down a cylinder of oxygen into its smallest parts, you would end up with atoms of oxygen.

Atoms are extremely small particles – *20 million* atoms could fit on a *one centimetre* long line.

There are about 103 different types of atoms. Each of these types is known as an *element* (e.g. oxygen, carbon, and hydrogen).

Elements

An element contains only *one* type of atom, which means it cannot be broken down into any simpler forms by chemical means. An element is one of the basic chemical ‘building blocks’ (e.g. oxygen or hydrogen). Each element has unique characteristics.

Following is a selection of common elements from the periodic table of common elements – with its chemical symbol notation:

Element	Symbol	Element	Symbol
Aluminium	Al	Magnesium	Mg
Calcium	Ca	Nitrogen	N
Carbon	C	Oxygen	O
Chlorine	Cl	Phosphorus	P
Hydrogen	H	Potassium	K
Iron	Fe	Sodium	Na
Lead	Pb	Sulphur	S

Figure 1.31: Table of common elements

Compounds

A compound is formed when two or more elements (atoms of a different type) are *chemically combined.*

Example:

Water is a compound formed by the elements hydrogen and oxygen. The chemical name for water is H_2O – two hydrogen atoms chemically combined with one oxygen atom.

The properties of compounds are *not the same* as the properties of the elements they are made from (e.g. at room temperature, hydrogen and oxygen are gases, but their compound (water) is a liquid).

Elements and compounds are *pure substances* – they can only be changed by chemical reaction. The melting points and boiling points of elements and compounds are constant (e.g. water).

Compounds and molecules

A *molecule* is the smallest portion of an element or compound that can exist by itself and still retain the properties of that substance. For example:

- A molecule of water is made up of two hydrogen atoms and one oxygen atom
- A compound is a material made from a quantity of only one kind of molecule (e.g. a bucket of water).

Mixtures

A mixture is formed when two or more elements or molecules are combined, but are not *chemically* combined.

Example:
When salt is mixed with water, they combine to form a mixture – but there is no chemical combination between the two. If the water is allowed to evaporate, the salt will reappear.

Melting, boiling and evaporation

Effects of heat and pressure on matter

In nature, all materials are in one of three forms: solid, liquid or gas. However, pressure and temperature will affect the state of matter. For example:

- If pressure stays the same, but temperature increases or decreases, the form of the substance changes (solids melt to form liquids, and liquids freeze to form solids)
- If pressure increases or decreases, but the temperature stays the same, the form of the substance changes
- Gases compressed to liquids under great pressure will generate heat.

Melting point, freezing point and boiling point

Melting point is the temperature at which a solid will change state to a liquid. At *freezing point*, a liquid changes to a solid. The melting point and the freezing point are the same for a given substance, under fixed conditions.

The temperature at which a liquid boils and becomes a vapour is the *boiling point*. The transition between water and ice at normal atmospheric pressure takes place at 0°C. The transition between water and steam at normal atmospheric pressure takes place at 100°C.

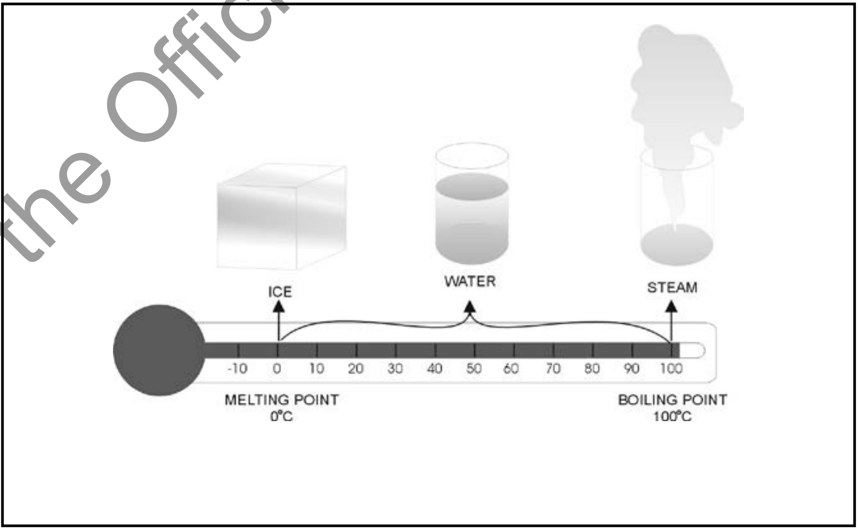


Figure 1.32: Temperature and pressure alter the state of matter

Evaporation

Evaporation is the process of gas molecules escaping from the surface of a liquid (i.e. the conversion from a liquid to a gas under normal atmospheric conditions).

The liquid’s temperature controls the rate of evaporation.

Example:
Water evaporates relatively slowly under normal room temperature. But as the liquid’s temperatures increase, more molecules escape (evaporation) until 100°C (212°F) is reached.

Evaporation at temperatures below boiling point happens when some molecules at the surface of the liquid gain enough energy from colliding with other molecules for them to escape into the surrounding space as vapour.

Sublimation

Sublimation is the conversion of a solid material into a vapour, without changing to a liquid first (e.g. a snowflake is formed when water vapour changes to solid ice; iodine crystals (a solid) change to iodine gas).

Note: This differs from *pyrolysis*, which only happens with fire present.

Boiling point

Boiling point is the **temperature** at which a liquid boils, forms a vapour, and can evaporate under normal atmospheric conditions.

Boiling occurs when vapour is formed throughout the liquid. This takes place when the vapour pressure of the liquid equals atmospheric pressure.

The boiling point will vary according to the pressure the liquid is subjected to. Boiling points are usually given at normal air pressure. The boiling point will:

- Increase at higher pressures (e.g. pressure cookers, autoclaves, and car radiators)
- Decrease at lower pressures.

Vaporisation temperature

Vaporisation is the **process** by which liquids are converted to a gas or vapour. The rate of vaporisation increases with temperature.

Summary

The following summary checklist sums up the main points of the section.

All **matter** is made of atoms, elements, compounds and mixtures.

An **atom** is the smallest part of an element with all the properties of the element.

An **element** is a basic chemical ‘building block’, such as oxygen or hydrogen. Each element has unique characteristics.

A **compound** is formed when two or more elements (atoms of a different sort) are chemically combined (e.g. water, sodium chloride, and carbon dioxide).

A **mixture** is a substance composed of two or more elements that are not chemically bonded together, each of which retains its own characteristics and properties.

Pressure and **temperature** affect whether a substance is solid, liquid or gas.

Melting is the process by which a substance changes state from solid to liquid.

Freezing is the process by which a substance changes state from liquid to solid

Evaporation is the process by which a substance changes state from liquid to gas.

Sublimation is the process by which a substance changes state from a solid to a gas (without becoming a liquid).

If you are unsure about part of this section, go back and review it. Then if you still want to know more or want to make your own notes, write them in the space marked **Notes and questions** below, and discuss with your officer.

Notes and questions

Workbook Activity

You are now required to complete any appropriate questions in this Workbook.

Specific heat and latent heat

Specific heat

Temperature increase

When heat energy is added to a substance, the particle movement (kinetic energy) is accelerated. Since temperature is a measure of the average kinetic energy in a substance, the temperature *increases.*

The amount of temperature increase for a given body will depend on:

- The amount of heat added
- The mass of the body
- What the substance is made of.

Specific heat

The *specific heat* of a material is the amount of heat required to raise the temperature of one kilogram of that substance by one degree, Celsius (°C) or Kelvin (°K). (Celsius and Kelvin are explained in the next section.)

Specific heat is represented by the symbol ‘c’, and is usually measured in kiloJoules per kilogram per degree Celsius, i.e.:

C = (kJ / kg) / °C

The larger the specific heat capacity of a substance, the more energy it takes to raise the temperature by a given amount:

- Water is an efficient cooling agent because it has a high specific heat (i.e. it takes a lot of energy to heat water)
- In comparison, other materials with a low specific heat capacity (e.g. petrol or alcohol) will heat more rapidly in a fire situation.

Latent heat of vaporisation

Change of state

While a solid is changing to a liquid or a liquid is changing to a gas, the temperature does not change.

The heat absorbed is being used to separate the particles, so there is no rise in temperature. When the change is reversed, exactly the same amount of heat is released.

The heat energy involved in a change of state is called *latent heat*

Latent heat of vaporisation, and specific heat capacity

As heat is added to a substance, an increase in temperature may be observed. A change of state follows:

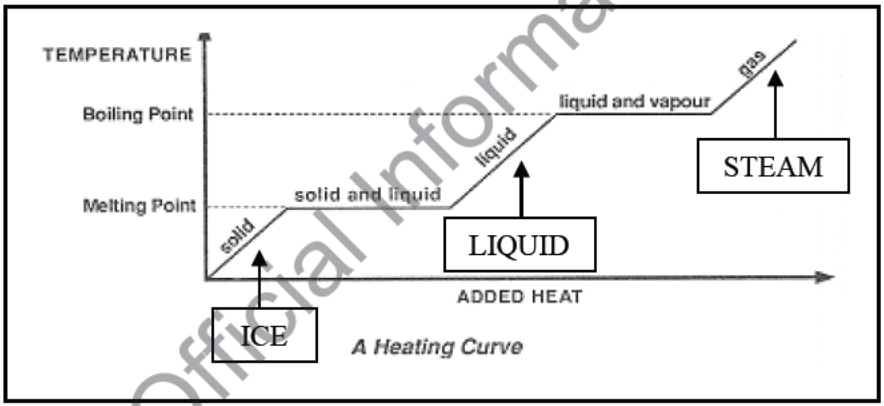


Figure 1.33: Added heat either causes a temperature rise, or a change of state

Latent heat of vaporisation

Latent heat of vaporisation is the amount of energy absorbed when one kilogram of liquid is converted into a gas at its boiling point.

Example:
Water has a latent heat of vaporisation of 2260 kJ / kg (i.e. it takes 2260 kJ of energy to evaporate 1 kg of water). By comparison, alcohol has a much lower latent heat of vaporisation. It takes only 860 kJ / kg to evaporate 1kg of alcohol.

A fire contains a lot of energy. When fire is exposed to water, the energy heats the water and eventually vaporises it to steam. Due to the high latent heat of water vaporisation, water absorbs a large amount of energy from the fire. This is what produces the cooling effect of water.

Latent heat of vaporisation equation

The amount of heat absorbed (or released) as a substance changes state can be calculated as follows:

$$\boxed{\begin{array}{c}\text{Heat Absorbed}\\\text{(or released)}\end{array}} = \boxed{\begin{array}{c}\text{Latent Heat}\\\text{(kJ / kg)}\end{array}} \times \boxed{\text{Mass}}$$

Figure 1.34: Latent heat of vaporisation equation

Examples:
To change 1000 kg of water at 100°C to steam, the following calculation shows how much heat this removes from the fire (energy absorbed), based on water’s latent heat of vaporisation:

Heat absorbed = *2260 kJ / kg x 1000 kg*
= *2,260,000 kJ*

To change 1000 kg of water from a temperature of 10 C to boiling point (100°C), the following calculation shows how much energy this absorbs, based on water’s specific heat capacity:

Heat absorbed = *1000 kg x 4.2 kJ / kg x 90°C*
= *378,000 kJ (Specific heat capacity)*

This shows that approximately six times more energy is absorbed in converting water to steam, compared to raising its temperature. For maximum cooling effect, water should be in the form of a spray or fog. This results in a greater amount of water being converted to steam (due to the larger surface-area-to-mass ratio).

Latent heat of vaporisation ratios

At 100°C, the *expansion ratio* of steam is 1: 1700. This means one litre of water will produce 1700 litres of steam.

However, this ratio is not fixed, but increases with temperature. At around 500°C, the expansion ratio doubles to 1:3400 (i.e. one litre of water will produce 3400 litres of steam).

Expansion of water to steam

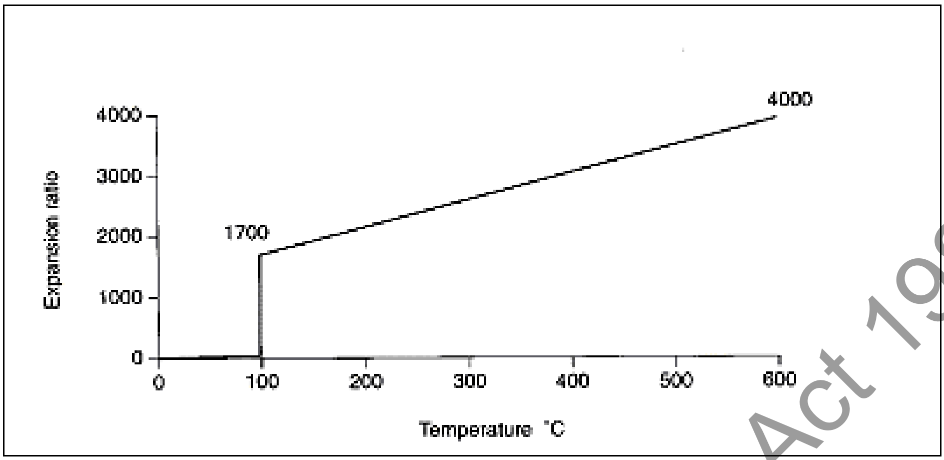


Figure 1.35: Expansion of steam
(Source: Fire Engineering Design Guide – Buchanan)

Effects of latent heat of vaporisation

The effects of latent heat of vaporisation can be seen in the following examples:

- *Steam burns*
  These burns are worse than burns from boiling water, as steam’s temperature is higher than 100°C. Steam contains more latent heat energy, which is given out as the steam changes back to water.
- *Cooling*
  Vaporisation of a liquid removes heat from its surroundings. This can be observed in the release of LPG causing icing-up of valves, or cooling skin by sweating or wearing wet clothing. (Evaporation of moisture in wet clothes cools the body like sweat evaporation.)
- *Volatile liquids*
  Evaporation of volatile liquids (e.g. meths or ether) that have been put on the skin leaves it feeling cold. Some local anaesthetics work in this way to ‘freeze’ the pain.
- *Refrigeration systems*
  These make use of the evaporation of volatile liquids to remove heat from the contents of the refrigerator. The latent heat is later released from the cooling fins on the back, as the vapour is condensed back to a liquid by the compressor.
- *Wind*
  Vaporisation is even more noticeable if there is a wind blowing. This increases the evaporation rate, and causes convective heat loss.

Water as an extinguishing agent

Why water is so effective

Water is an effective extinguishing agent due to its cooling effect. It has this effect because of its high latent heat of vaporisation, and high specific heat.

It can be shown that most of water’s cooling effects occur when water turns to steam. Using fine droplets (e.g. fog or spray) provides the greatest surface area of water, allowing more water to be converted to steam.

Summary

The following summary checklist sums up the main points of the section.

Specific heat

> The amount of heat required to raise the temperature of a 1 kg of a substance by one degree Celsius (°C) or Kelvin (°K).

Latent heat

> The heat energy required to change a substance between solid, liquid and gas. Latent heat energy does not involve a rise in the substance temperature – only a change in state.

Water's **latent heat of vaporisation** is used in firefighting when heat energy is absorbed from the fire by water, as it changes state from liquid to steam. To act as a cooling agent, you need to spray water – providing the best surface area for efficient conversion to steam.

If you are unsure about part of this section, go back and review it. Then if you still want to know more or want to make your own notes, write them in the space marked **Notes and questions** below, and discuss with your officer.

Notes and questions

Temperature

What is temperature?

Temperature versus heat

Temperature is *not* the same as heat. Heat is a form of energy that causes a rise in temperature, or changes an object's state, from solid to liquid, or liquid to gas.

Temperature measures the *degree of hotness* of a body ('how hot'). It doesn't depend on the mass or material of an object. It is a measure of the average kinetic energy of the atoms or molecules within a body.

There are many different types of thermometer used for measuring temperature (e.g. mercury, alcohol, bi-metallic strip, thermocouple, electrical or resistance).

Example:
Putting the same amount of heat energy into one *kilogram* of a substance will not raise the temperature as much as putting the same amount of heat energy into one *gram* of a substance.

As temperature decreases, the kinetic energy of the particles decreases. At some point the kinetic energy of all the particles will reach zero. The temperature at which this occurs is known as *absolute zero.*

Scales of measuring temperature

Temperature is measured using a variety of temperature scales – the most common are Celsius (°C), Kelvin (°K), and Fahrenheit (°F).

0	25	50	75	100	Celsius
273	298	323	348	373	Kelvin
32	77	122	167	212	Fahrenheit

Figure 1.36: Comparison of temperature scales

Celsius (°C)

On the *Celsius scale* (°C), water’s freezing point is 0°C, and its boiling point is 100°C. The range of temperature between is divided into 100 equal units (degrees).

Disadvantages:

- There are temperatures below 0°C
- The pressures and volumes of gases do not change in proportion to Celsius temperature.

Note: Room temperature is considered to be 20°C.

Kelvin (°K)

On the *Kelvin scale* (°K), absolute zero is 0°. The size of the degree unit is the same as for the Celsius scale.

Advantages:

- There are no negative temperatures – nothing can get colder than 0°K
- Pressures and volumes of gases will change in proportion to Kelvin temperature.

The zero point of the Kelvin scale (absolute zero) is 273 degrees below the zero point of the Celsius scale, the freezing / melting point of water (i.e. 0°K equals –273°C).

- To convert from Celsius to Kelvin scales, add 273 degrees
- To convert from Kelvin to Celsius scales, subtract 273 degrees.

Fahrenheit °F

On the *Fahrenheit scale*:

- The lower fixed point is the freezing point of water, at 32°F
- The upper fixed point is the boiling point of water, at 212°F
- The range of temperature in between is divided into 212 equal units
- There are 180°F between the freezing point and boiling point of water at standard atmospheric pressure (1kPa)
- Room temperature is considered to be 68°F
- To convert from Celsius to Fahrenheit degrees: °F = (°C × 1.8) + 32
- To convert from Fahrenheit to Celsius degrees: °C = (°F – 32) ÷ 1.8.

Gases and vapours

Gas, vapour, and critical temperature

When a liquid evaporates, it becomes a vapour or a gas. Both of these are said to be in a ‘gaseous’ state.

The *critical temperature* of a gas is the temperature above which the gas cannot be liquefied by pressure alone. A gaseous substance is called:

- Vapour, when below its critical temperature
- Gas, when above its critical temperature.

Example: The *critical* temperature for carbon dioxide is 31.1°C.

- At 25°C, carbon dioxide is a vapour, and can be liquefied by pressure
- At 40°, carbon dioxide is a gas, and cannot be liquefied by pressure alone.

Safety Note

It is important that liquefied gases (e.g. LPG) are not heated past their critical temperatures (96.7 °C for propane 150°C for butane). Past that point, all such liquids are converted to gas. The pressure rises enormously, resulting in vessel failure and a Boiling Liquid Expanding Vapour Explosion (BLEVE).

Density of vapours and gases

The density of a gas or vapour, compared with air, is important to Firefighters. This determines whether gases will sink (into basements, wells and sewers) or rise (into attics and upper stories).

Note: All gases, regardless of their density, will diffuse (mix) with air over a period of time to give a uniform mixture of gases.

Vapour pressure

As described earlier in this section, liquids will vaporise to some degree at any temperature. *Vapour pressure* is a measure of the amount of vapour above a liquid. Vapour pressure increases with temperature.

When the vapour pressure of a liquid equals the current atmospheric pressure, boiling occurs (this temperature is called *boiling point*)

The boiling point of a liquid can be raised or lowered by altering the pressure surrounding the liquid.

Workbook Activity

You are now required to complete any appropriate questions in your Workbook.

Section 2: Practical Fire Science

What this section contains

This section contains the information you need to demonstrate the application of fire science principles. It includes:

1. Fire development phases
2. Methods of fire transfer
3. Rollover and flashover
4. Backdraught.

By the end of this section you will be able to observe and describe:

1. Fire development phases
2. Methods of fire transfer
3. Rollover and flashover
4. Conditions that lead to backdraught
5. Ventilation.

Why you need to know this

You will often work in situations where flashover and backdraught potential is high. Therefore you need to have a sound knowledge of these possible conditions:

- How they develop
- The warning signs
- How to carry out your tasks safely and for the protection of you and your crew.

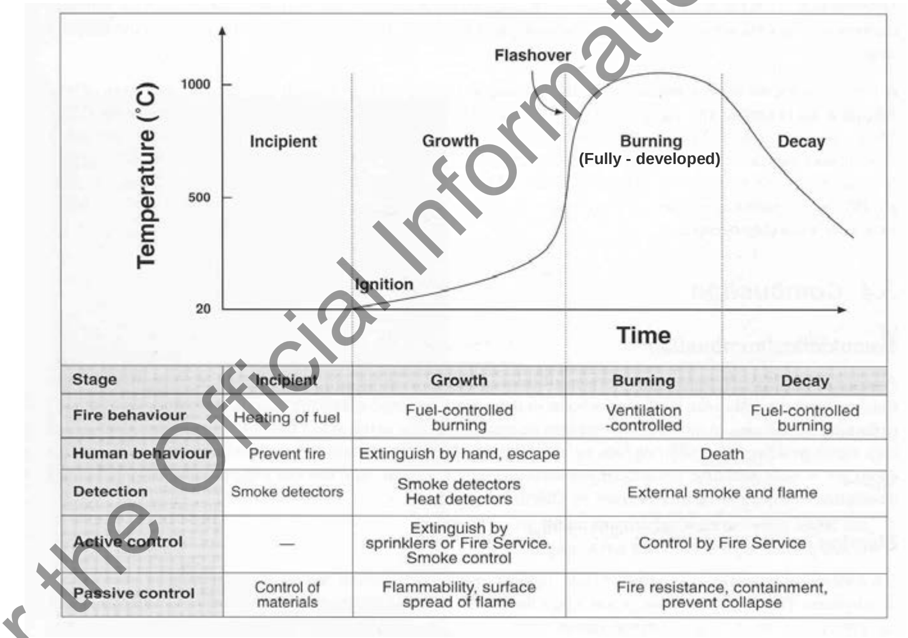
This section covers the theory you will use during the ‘Practical Fire Science’ component of the QF Practical Course.

Fire development phases

Compartment fire development

Overview

Many fires follow a pattern of four development phases, although the time-scales, rates, and magnitude of fires vary widely. Typical fire development phases, where no firefighting intervention takes place, are discussed within this section.



Stage	Incipient	Growth	Burning	Decay
Fire behaviour	Heating of fuel	Fuel-controlled burning	Ventilation -controlled	Fuel-controlled burning
Human behaviour	Prevent fire	Extinguish by hand, escape	Death	
Detection	Smoke detectors	Smoke detectors Heat detectors	External smoke and flame	
Active control	—	Extinguish by sprinklers or Fire Service. Smoke control	Control by Fire Service	
Passive control	Control of materials	Flammability, surface spread of flame	Fire resistance, containment, prevent collapse	

Figure 2.1: Typical fire development curve
(Source: Fire Engineering Design Guide – Buchanan)

Although diagrams (e.g. Figure 2.1) are often used to describe compartment fires, a fire will only develop through the stages shown if sufficient fuel, heat and oxygen are present.

Only a small proportion of fires that start will progress to the fully-developed phase, even when it appears conditions are favourable.

Incipient fire

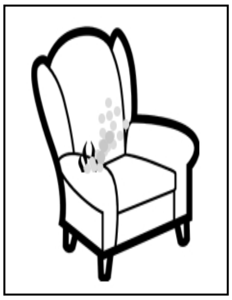
Ignition is always preceded by the heating of potential fuel. This produces decomposed fuel in the form of smoke. In many cases, the smell of smoke or operation of a smoke detector can detect an *incipient* fire before ignition occurs.

The incipient phase can last for a few milliseconds or for several days, depending on circumstances (e.g. the fuel involved, ambient conditions or ignition source). A period of smouldering combustion can also occur following ignition. Flaming combustion can happen without a fire becoming fully developed.

During this phase, the fire may go out if there is no other fuel to enable fire spread. A large number of fires are confined to the item first ignited (e.g. a cigarette left smouldering on a woollen fabric-covered chair). However, there is still a threat to occupants from the smoke.

Ignition

Ignition is the point where the three elements of the fire triangle come together, and combustion begins by heating the potential fuel.



Note: A fire is a series of millions of continuous ignitions / fire triangles.

Ignition can be either deliberate or accidental, and takes place in one of two ways:

- Flame or spark (pilot ignition)
- Spontaneous ignition (auto-ignition without a flame or spark – non-pilot) happens when flaming develops spontaneously due to a sufficiently high temperature within a flammable vapour / air mixture from a gas, a vapour from a flammable liquid, or a vapour from pyrolysis of a solid fuel

Note: Spontaneous combustion in bulk fuels is uncommon – but can result from self-heating in bulk solids due to biological processes or chemical reaction.

Growth phase

The start of the *growth phase* is characterised by self-sustained combustion, where the fire continues to burn even when the ignition source is removed.

The growth phase depends on the growth rate and (ultimately) the size of the fire, which is determined by the following conditions:

- Oxygen: supply (ventilation)
- Fuel: size, shape, amount, properties, and placement
- Insulation: particularly, whether heat is radiated back into unburned areas accelerating growth (insulated), or escapes from the compartment, slowing fire development (uninsulated)
- Container / compartment size: whether heat is radiated back or dissipated.

Note: Knowledge of the growth phase of fire development is important in recognising signs of flashover.

During the growth phase, the fire spreads across the fuel surfaces (by radiation from the flame), increasing the burning area and the corresponding heat release rate (which depends on the flame spread rate).

Initially the air in the *lower* layer is close to ambient temperature. However, temperatures in the *upper* layer rise quickly, due to the heat of the combustion products carried in the plume by convection. When the plume reaches the ceiling, hot gases travel across the ceiling.

This flow of hot gases is known as the *ceiling jet*, and can trigger heat detectors or sprinklers. (*Buchanan, 2001, p. 24*.)

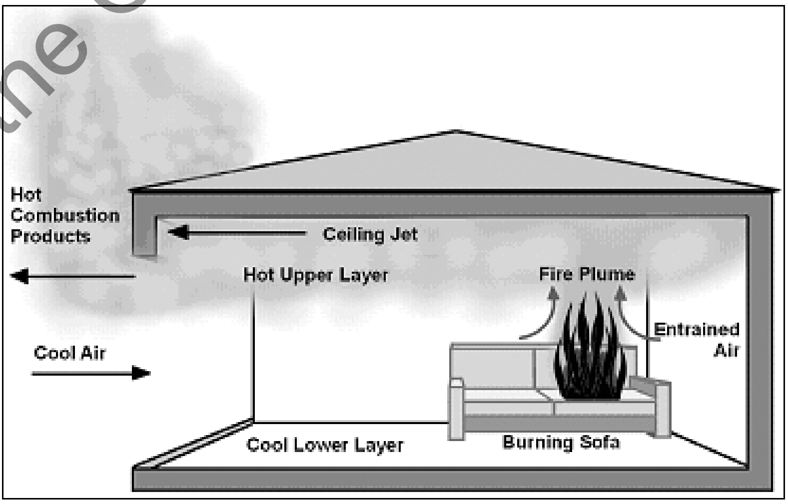
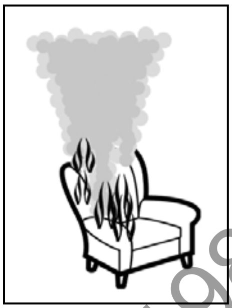


Figure 2.2: Two-zone / layer model with fire plume within the growth phase

Fully-developed fire (‘burning’ or ‘flaming’) phase



The *fully-developed fire phase* is most important when considering property protection, structural stability, and the possibility of fire spread – as the fire is at its hottest.

After flashover has occurred, a fire is fully developed and is characterised by extreme heat release (high temperatures).

Most often in fully developed fires, flames will be seen burning from openings (including exterior flames). This is due to unburnt gases gaining access to the outside air. These unburned fire gases flow into adjacent spaces and ignite where air is more abundant. Thus heat is transferred to the atmosphere and nearby matter by the processes of convection, conduction, radiation, and direct burning.

The duration of the fully-developed fire phase depends on the total amount of fuel and ventilation available.

Decay phase

The *decay phase* begins when the fire passes back from a ventilation-controlled fire to a fuel-controlled fire. This is often defined as the moment when 80% of the fuel has been consumed, and rate of heat release declines.

The fire can only continue if sufficient fuel is available. If not, fire decay will continue until all available fuel is consumed and the fire goes out. However, the remaining mass of glowing embers can result in moderately high temperatures in the compartment for some time.

Note: For fires involving thermal plastics (which melt to form pool fires), the decay phase is quite short. For cellulose fuels (e.g. wood) that form a char, the decay phase will be much longer while the char is consumed.

Factors affecting fire development – heat release rates (HRR)

Factors from ignition to decay

As a fire develops from the incipient phase through to the decay phase, several factors affect its behaviour and development within the compartment:

- Size, number, and location of ventilation openings (i.e. availability of air to support burning)
- Ceiling height of the compartment
- Size, volume, and thermal properties of the fire compartment
- Size, composition, and location of the fuel package that is first ignited
- Additional fuel sources and packages – their location and availability
- Temperatures that develop in the burning compartment.

Heat release rate (HRR)

The temperatures that develop in a burning compartment are the direct result of the energy released – in the form of heat and light – as the fuels burn. This determines how big the fire grows, and how quickly it develops.

This heat energy released over time in a fire is called the *heat release rate* (HRR) or *burning rate*. In other words, HRR describes quantitatively ‘how big the fire is’, which is the single most important variable in fire hazards.

HRR is directly related to the amount of fuel consumed over time, and the heat of combustion (i.e. the amount of heat that a specific mass of a substance gives off when burned).

HRR is measured in kilowatts (kW).

HRR has an effect on:

- Flame height
- Smoke generation
- Transition to flashover
- Fire room temperature
- Other fire safety design considerations.

Material	**maximum HRR (approx)**
Rubbish bin of milk cartons	15 kW
Upholstered chair (cotton padded)	370 kW
Upholstered chair (polyurethane foam)	2,100 kW
Upholstered sofa (polyurethane foam)	3,200 kW
Four stacking chairs (metal frame, polyurethane foam padding)	160 kW
Mattress (box springs, cotton and polyurethane foam)	660 kW
Mattress (polyurethane foam)	2,600 kW
Gasoline / kerosene (1 m^2 pool)	400 kW
Christmas tree (dry)	500 kW

What does HRR mean for you?

You need to be able to recognise potential fire hazards (e.g. fuel packages in a building or compartment), and use this information to estimate the potential fire growth in that space.

Understanding HRR it is also essential to understanding the hazards to occupants, and the effects of fire on a structure.

Materials with high HRR (e.g. polyurethane foam-padded furniture, polyurethane foam mattresses, or stacks of wooden pallets) would be expected to burn rapidly – compared to materials with a lower HRR, which should take longer.

Example: Stackable chairs are common in hotels and conferences centres, which have a metal frame and a small amount of combustible padding or structural material on the seat. A single chair would be a negligible hazard. However, stacked in tall piles and stored close together in a small storeroom, the hazard can be higher.

Generally, low-density materials (e.g. polyurethane foam) burn faster. They have a higher HRR than higher-density materials (e.g. cotton padding).

Fire load, fire load density

Fire load
The total fire load in a compartment of a building is the sum of all the energy available for release if the combustible material were to burn. This is measured in either:

- MegaJoules (MJ, or 1 million joules) available for release
- The equivalent weight of wood in kilograms (kg).

Fire load density
Fire load density is used to compare occupancies to see which has the greater potential fire severity (i.e. to compare different occupancy hazards).

The fire load density is measured as the fire load per unit area.

Example: If 150 kg of wooden furniture is laid out in a room of 15 m^2, the fire load density would be less than if the same amount were stacked in a small store room of only 2 m^2. The heat stored in the fuel is the same in each case, but it is much more concentrated in the latter, giving rise to a greater hazard level.

What does fire load mean to you?

Fire loading to compare occupancies is an important part of the Building Act, so you need to be familiar with this.

Assessing fire loads is a component of building inspections.