INTERNATIONAL FIRE TRAINING CENTRE

FIREFIGHTER INITIAL

PHYSICS AND CHEMISTRY FOR FIREFIGHTERS

Throughout this note he means he/she and his means his/hers.

INTRODUCTION

In order to understand how fires behave and how they can be extinguished, it is necessary to understand some physics and chemistry. This training note will introduce firefighters to the relevant physical and chemical processes and then show how these work together in the phenomenon that we call fire.

Extinguishing fires is a matter of interrupting one or more of these processes so that burning cannot continue. Firefighters will appreciate that it is, therefore, important to acquire a good understanding of what happens in a fire in order to be able to choose the best method available to extinguish it and to avoid making it worse.

AIM

The aim of this training note is to introduce students to some basic theory that will enable them to understand how fires behave, how they develop and how they can be extinguished.

OBJECTIVES

After the technical lesson covering this subject and studying this training note you will be able to:

• State the physical properties of matter
• Define heat and temperature
• Explain heat transmission
• State the basis of chemistry and combustion
• State how a fire can be extinguished
• Define Pyrolysis
• Define Flammable Range
• Define Flashover
• Define Backdraught

THE PHYSICAL PROPERTIES OF MATTER

Matter is the name given to all material things – anything that has mass and occupies space. Solids, liquids, gases and vapours are all matter. The amount of matter is known as the mass, and is measured in kilograms. In everyday life, the mass of a solid is measured in kilograms, although for liquids, gases and vapours, we are more accustomed to using volume, the amount of space occupied by a given substance, simply because it is easier to measure. Thus, we talk about litres of petrol and cubic metres of gas.
DENSITY

Understanding density is extremely important for a firefighter. For example, the density of a gas or vapour determines whether it will tend to rise or sink in air, and be found in the greatest concentrations at the upper or lower levels in a building. The density of a burning liquid partly decides whether it is possible to cover it with water to extinguish the fire, or whether the firefighter will need to use foam or other extinguishing medium.

CALCULATING DENSITY

Imagine two solid rods, both the same length and width, one made of wood and one from iron. Though they are the same size, the iron rod weighs much more than the wooden rod. The iron rod is said to have a greater density than the wooden one.

The density of a material is defined as the mass of one cubic metre of material. One cubic metre is the standard “unit volume”. A unit volume of iron has a greater mass than a unit volume of wood and is thus denser.

Calculating values for the densities of different substances enables meaningful comparisons to be made. The density of a substance is calculated by dividing the mass of a body by its volume.

\[
\text{Density} = \frac{\text{mass}}{\text{volume}}
\]

In symbols \( D = \frac{M}{V} \)

So \( M = D \times V \) and \( V = \frac{M}{D} \)

If mass is measured in kilograms (kg) and the volume in cubic metres (m\(^3\)), the “units” of density will be kilograms per cubic metre (kg/m\(^3\)).

COMPARATIVE DENSITIES

If the density of a substance is lower than the density of water and does not mix with water, then that substance will float on water. To use our previous example, the density of wood is lower than that of water and the density of iron is higher, so wood floats and iron sinks.

SPECIFIC GRAVITY

When comparing the densities of liquids, the term specific gravity is used. There are no units to express specific gravity. Water, the substance that is the benchmark against which all other liquids are measured has a specific gravity of 1. We can therefore say that any liquid that will not dissolve (not miscible) in water, with a specific gravity higher than 1, will sink, whilst those with a specific gravity lower than 1 will float on top. For example:

1m\(^3\) of water (1000 ltrs) weighs 1000 kg
1m\(^3\) of aviation gasoline (1000 ltrs) weighs 720 kg

Aviation gasoline has a specific gravity of 0.72 and will, therefore, float on the surface of water.
VAPOUR DENSITY

A similar process can be used to compare the densities of gases and vapours. In this case the term ‘vapour density’ is used and, for fire service purposes, the comparisons are made against air which has a vapour density of 1 (once again no units). If a gas has a vapour density of less than 1 it is lighter than air and will therefore rise whilst those with a vapour density higher than 1 will sink to lower levels.

HEAT AND TEMPERATURE

Some of the most destructive effects of fire are caused by heat, so it is obvious that the firefighter should understand the effect of heat on materials.

Heat is a form of energy. Before we go any further it is important to understand the following about energy:

- It has the ability to do work
- It can neither be created nor destroyed
- It can exist in a number of forms
- It can be changed from one form to another

Heat can be produced by chemical means, e.g., by burning aviation fuel or by mechanical means, by friction. Passing electrical current through a resistor also produces heat as in an electric fire.

Energy can be converted from one form to another, e.g., a car travelling along a road possesses kinetic energy (motion). If we want to slow the car we apply the brakes which, through friction, convert the kinetic energy into heat energy.

TEMPERATURE

The amount of heat energy in a body cannot be easily measured. It is true that, when heat energy is supplied to a body, its temperature will rise, however, temperature is just a measure of how hot a body is not the amount of heat energy it contains. The fact that heat and temperature are not the same thing can be proved by a simple example:

*Imagine a piece of fine aluminium wire being held in the flame of a match. After a couple of seconds the wire will melt which tells us that the temperature of the wire is in excess of 600°C*

*Now imagine the same match being held under a kettle full of water. The temperature of the water would not change noticeably yet the amount of heat supplied to the wire and the water would be roughly the same.*

HEAT TRANSMISSION

Heat always travels from areas of high temperature to areas of lower temperature. If a hot body and a cold body are placed in contact with each other, the hot body will lose heat whilst the cold one would gain heat. This can be referred to as heat transmission.

There are three ways by which heat may be transmitted:

- Conduction
- Convection
- Radiation
CONDUCTION

Conduction may occur in solids, liquids or gases, although it is most clearly present in solids. In conduction, heat energy is passed on from molecule to molecule travelling away from the heat source towards areas that are at a lower temperature. The rate at which this occurs will depend on the thermal conductivity of the materials involved. Metals are generally the best conductors of heat.

In this picture, flames are in contact with a steel girder. The heat conducts along the girder and spreads to other materials causing them to ignite.

CONVECTION

Convection occurs only in liquids and gases. For firefighters, this can be a particular problem when it occurs in gases, i.e., the air. In a fire situation the air above a fire becomes heated. As it is heated it expands and becomes less dense. This causes the air to rise away from the fire to be replaced by a current of cooler air that provides the fire with a fresh supply of oxygen. This means that provided there is sufficient fuel the fire will continue to grow. The rising air will continue to rise until it cools or until it comes across a barrier like a ceiling. In this case the heated air will collect at ceiling level raising the temperature of substances in that area.

In this picture, a fire at ground floor level is causing heated air to rise through stairways to upper floors. The heated air raises the temperature in that area until substances ignite.

RADIATION

In this case, heat energy is passed through a space. It travels in straight lines and can be absorbed by bodies that are at a lower temperature. If you stand near to a coal fire on a cold day, radiated heat from the fire will provide you with a feeling of warmth. This method of heat transfer can be a particular problem to firefighters because substances or structures close to, or in some cases some distance from, a fire may well become affected.
Here we can see clothes that have been placed too close to a heat source. They absorb radiated heat until they are so hot that they ignite.

CHEMISTRY FOR FIREFIGHTERS

Up to now we have considered the physical properties of matter and heat. We will now deal with the chemistry of combustion. Chemistry is the science of the composition of substances, their properties and reactions with each other. Substances may be solids, liquids or gases. They may be living or non-living but all have one common factor - they consist of chemicals.

ATOMS, ELEMENTS AND MOLECULES

Atoms are the foundations or the building blocks of all substances. They cannot be broken down by chemical means. Substances that consist of only one type of atom are known as elements. An example of an element is carbon. Iron is another. If an element consists of more than one of the same type of atom, chemically bound together, it is known as a molecule. Oxygen is an example of this as its chemical make up consists of two oxygen atoms bound together.

The term molecule can also be used to describe a substance that is made up of more than one type of atom. Water is an example. A molecule of water contains two atoms of hydrogen and one atom of oxygen, chemically bound together. A molecule is therefore the smallest particle of a substance that can exist without that substance losing its identity.

COMPOUNDS AND MIXTURES

Where a substance is made up of identical molecules it is referred to as a compound. Compounds can only be changed or broken down by chemical reaction. Water, as well as being a molecule, is a compound.

A mixture is a term used to describe a substance that is made up of more than one type of molecule. It can be separated into its constituent parts by physical or mechanical means. Salt water is an example. If salt water were boiled, the water and the salt would be separated so we would be left with water molecules and salt molecules.

COMBUSTION

Combustion is a chemical process. For it to occur, oxygen, usually from the air, must combine with a fuel. A fuel is any substance that will burn and may be in any one of the three states, solid, liquid or gas.

The term ‘combustion’ can be used to describe two processes;

- Smouldering Combustion
- Flaming Combustion
Smouldering Combustion involves a reaction between oxygen from the air and the surface of the fuel. This is a complex process and in general only occurs with solid fuels that char when heated. For the purpose of gaining a good basic understanding of this subject we can concentrate on Flaming Combustion.

For Flaming Combustion to occur, a solid or liquid fuel must first be converted to a vapour. This then mixes with air and reacts with oxygen. If the resulting mixture of oxygen and fuel vapour is sufficiently heated or finds an ignition source, a flame zone will develop. This process can also be referred to as Burning.

THE TRIANGLE OF COMBUSTION

One way of explaining ‘burning’ is in terms of the Triangle of Combustion. For combustion to occur three things are necessary:

- HEAT
- OXYGEN
- FUEL

Combustion will continue as long as these three factors are present. Remove one of them and the triangle will collapse so combustion will stop.

THE TRIANGLE OF COMBUSTION

OXYGEN

For combustion to occur approximately 16% of the air surrounding a fuel must be oxygen. In normal circumstances air contains around 21% oxygen. There are however some substances that contain sufficient oxygen in their make-up to support combustion.

HEAT

Heat is required to raise the temperature of the fuel so that it turns to vapour and reaches its ignition temperature. The heat can be generated by:

- Compression of gases
- Electrical energy
- Friction
- Chemical action
- Hot surfaces
- Open flame
FUEL

Fuel can be in either solid, liquid or gas form but solids and liquids must first be converted into vapours for combustion to occur.

There are some other terms that a firefighter must be able to identify with, in order to fully understand the combustion process. They are:

- Flash point
- Fire point
- Spontaneous ignition temperature

FLASH POINT

Imagine a small container of a flammable liquid such as diesel. A region will exist above the liquid surface in which the evaporating fuel vapour is well mixed with air. If the diesel is heated above 40°C the region will become flammable. The lowest temperature at which this occurs is called the Flash Point, it is the temperature of the liquid at a point whereby the application of an ignition source will cause a flame to flash momentarily across the surface of the liquid.

FIRE POINT

If we use the same example as before and we continue to increase the temperature of the fuel in the container, we will reach a point at which the flash will be followed by a sustained flame. This temperature is known as the firepoint, the lowest temperature at which the rate of supply of fuel vapour will sustain flame.

SPONTANEOUS IGNITION TEMPERATURE

If fuel escaping from a ruptured aircraft fuel tank came into contact with a hot wheel assembly it may well ignite leading to a large fire. This is because the fuel has been heated, turned into a vapour and mixed with air. On this occasion, because of the amount of heat involved, the fuel may ignite automatically, that is, without the need to apply a flame or other ignition source. The lowest temperature at which this happens is referred to as the spontaneous ignition temperature (sometimes known as auto ignition temperature).

CLASSIFICATION OF FIRE

In order to safely extinguish a fire we must first identify what materials are involved and assess the size and intensity of the fire. To assist we can classify a fire according to the materials involved, as follows:

Class A
These are fires on solid materials, usually organic, leaving glowing embers. Class ‘A’ fires are the most common and the most effective extinguishing agent is generally water in the form of a jet or spray.

Class B
These are fires involving liquids or liquefiable solids. For the purpose of choosing effective extinguishing agents, flammable liquids must first be identified. Agents which may be used include foam, halon, carbon dioxide and dry powder.

Class C
These are fires involving gases or liquified gases in the form of a liquid spillage, or a liquid or gas leak and these include methane, propane, butane, etc. Although dry powder or foam can be used to extinguish flames, the safest way is to use water spray to cool containers whilst isolating the supply.

**Class D**
These are fires involving metals. Extinguishing agents containing water are ineffective, and even dangerous. Carbon dioxide or dry chemical powders containing bicarbonate will also be hazardous if applied to most metal fires. Powdered graphite, powdered talc, soda ash, limestone and dry sand are normally suitable for Class D fires. Special fusible powders have been developed for fires involving metals but may be difficult to apply.

**Class F**
These are fires involving cooking oils and fats. Special extinguishers are available for use on fires involving cooking fats and oils, e.g., chip pans and deep fat fryers, but these should only be used by specially trained people. This area is of limited interest to the Airport Fire Service.

**EXTINGUISHING FIRE**

As previously stated, for a fire to exist, all three sides of the triangle of combustion have to be present in the correct proportions. It follows then, that to remove one side or to make the proportions incorrect, would cause the combustion process to cease and the fire to go out. This can be achieved as follows:

**Starvation – Limiting Fuel**
This involves starving the fire of fuel and can be done in three ways;

- Removing potential fuel from the neighbourhood of the fire
- Removing fire from the mass of combustible material
- Isolating a supply of fuel to a fire by turning off a valve

Starvation is recognised as the safest way to deal with a Class C fire.

**Smothering – Limiting Oxygen**
If we could place a physical barrier between the fuel source and the oxygen supply or dilute the oxygen to the point that there is not enough for the combustion process to continue, the fire would be smothered. Examples of smothering a fire include the use of;

- Fire blankets
- Foam
- Carbon Dioxide

This method is regarded as the best way of dealing with a Class B fire.

**Cooling – Limiting temperature**
Cooling involves reducing the temperature of the burning mass by taking away some of the heat energy. Because the rate of vapour production is increased as temperature increases, it follows that to reduce temperature would reduce this rate and therefore eventually lead to insufficient vapour being produced for combustion to continue.

One way to achieve this is the application of water. If water is applied in spray form the droplets will absorb heat. The water will then turn to steam and move away from the fire taking the absorbed heat with it. If the rate of application is sufficient for the circumstances the temperature of the fuel will be reduced to the point that insufficient vapour is produced so the fire will be extinguished.

This is recognised as the most efficient method of dealing with a Class A fire.

**FIRE BEHAVIOUR**
PYROLYSIS

Pyrolysis is the chemical decomposition of a substance by heat. When heat is applied to a substance, a chemical reaction takes place and breaks down into new substances.

The original substance breaks down into molecules (smallest substance capable of existing independently), which recombine and form new substances. For example:

Wood is made up of hydrogen (H), carbon (C), and oxygen (O2), the chemical formula being C6H10O5.

When pyrolysis occurs in wood the following substances are produced:

- Carbon Dioxide (CO2)
- Water vapour (H2O)
- Carbon particles (C)
- Carbon Monoxide (CO)

These substances form the substance we USED to call smoke; they are now called ‘FIRE GASES’

FIRE GASES

Certain flammable fire gases have to be present in various quantities (percentages) to form an explosive mixture. This percentage mixture is commonly known as its ‘Flammable Range’ or ‘Explosive range’

FLAMMABLE RANGE

A flammable gas will only burn in air if its composition lies between certain limits. If too little or too much fuel is present burning will not take place; the mixture is either too lean or too rich.

These limits are referred to as the lower explosive limit (LEL) and the upper explosive limit (UEL).

The lower limit is defined as the lowest concentration of fuel that will just support a self propagating flame. The upper limit is defined as the highest concentration of fuel that will just support a self propagating flame.

Between these limits, which are given as percentages, is the flammable range of the gas.

For every gas there is a particular concentration where the amount of gas is exactly right in relation to the amount of oxygen in the air for combustion to occur. This is known as the ideal mixture (IM) and is found between the lower and upper limits. Combustion occurs with maximum force at the ideal mixture.

On a scale from 0 – 100% the flammable range for any gas can be marked, eg.

- Propane – LEL 2%, IM 4%, UEL 10%

This example shows that the range of flammability for propane is very small and most propane/air mixtures are not flammable.

FLAMMABLE RANGE OF GASES AND VAPOURS

The ideal mixture burns quickly and with the most intensity (energy or force). However at the lower and upper limits the gas is only just flammable.
Different gases have different ideal mixtures, different flammable ranges and ignite with different levels of intensity and temperatures, eg.

**LIMITS OF FLAMMABILITY**

Definition of terms;

LEL – lowest explosive limit
The lowest concentration of fuel to air mixture that will just support a flame.

IM – Ideal mixture

The most efficient concentration of fuel to air mixture that produces the highest temperatures, the largest and quickest reaction.

UEL – Upper explosive limit

The highest concentration of fuel to air mixture that will just support a flame.

**FLAMMABLE RANGE SUMMARY**

If a compartment contains flammable gas, air plus an ignition source, it will only ignite providing the gas is within its flammable range (ie between the LEL and the UEL). If the mixture is below its LEL then it is too lean to ignite and if the mixture is above the UEL then it is too rich to ignite. If the mixture is between the IM and the UEL then a rich burn will develop. The nearer the mixture is to the IM then the greater the intensity.

**FLASHOVER**

Stage in a compartment fire when the total thermal radiation from the fire plume, hot gases and hot compartment boundaries causes the generation of flammable products of pyrolysis from all exposed Combustible surfaces within the compartment which, given a source of ignition, this will result in the sudden and sustained transition of a growing fire to a fully developed fire. Flashover has occurred

**FULLY DEVELOPED FIRE**

Once flashover has occurred, providing there is sufficient fuel and air available, the fire will continue to develop until the entire room is involved.

**SIGNS AND SYMPTOMS OF A FLASHOVER**

Flashover is a sudden transitional stage of the development of a fire in a ventilated compartment, just prior to the compartment being fully developed in fire.

Symptom

Ventilated compartment. If there is insufficient ventilation in the compartment, flashover cannot occur due to a lack of oxygen restricting the development of the fire.

**INTERNAL SIGNS**

**Flames visible in the fire gases.** As the fire develops and more flammable gases are produced by incomplete combustion and pyrolysis, the flames will increase in length as more oxygen is required for combustion to occur.

**Combustible materials gassing off due to pyrolysis.** As the fire develops in the compartment and the temperature rises, radiated heat will increase onto the combustible contents causing them to gas off due to pyrolysis.

**High temperatures, speed of combustion.** As the flames increase in size and develop into the ceiling, heat output increases, raising the temperature at ceiling level; the higher the temperatures, the faster the speed of combustion and the more rapid the spread of fire throughout the compartment.

**Neutral plane moving down.** As the development of the fire increases, so does the production of fire gases. If the fire produces fire gases quicker than they can escape from the compartment, the neutral plane will be forced down.
**Sudden increase in development of fire.** As the development of the fire approaches the commencement of flashover, the fire will suddenly increase in speed. This is caused by the large amount of heating being given off by the fire, producing large quantities of gases by pyrolysis. These gases will quickly rise and ignite, increasing the heat output from the fire, increasing the development.

**Pyrolysis at floor level in the compartment.** As the development of the fire approaches the commencement of flashover, the heat output from the fire will be so great that pyrolysis can occur at the floor level. When all exposed flammable surfaces (ie Carpet) are gassing off due pyrolysis, flashover is commencing.

The signs listed above are a progression of events and some may not be visible for various reasons, ie

- Flames visible in the fire gases – if the fire gases are very dense, the flames may not be visible.
- Pyrolysis – If light levels are very low in the room (due to dense fire gases or lack of sunlight), the gases produced by pyrolysis may not be visible.

If firefighters observe the neutral plane descending when they are in a room, they must either:

- Control the development of fire by application of water: or withdraw from the compartment.

**BACKDRAUGHT – Home Office Definition**

Limited ventilation can lead to a fire in a compartment producing fire gases containing significant proportions of partial combustion products and unburt pyrolysis products. If these accumulate then the admission of air when an opening is made to the compartment can lead to sudden deflagration. This deflagration moving through the compartment and out of the opening is Backdraught.

To put Backdraught in a more simplistic terms, if a too rich mixture has developed inside a compartment and an opening is created (eg firefighters entering, windows breaking, door burning through, etc) the fire gases will dilute back through their flammable range. If the ignition source picks up and the fire gases are in their flammable range then ignition will occur – Backdraught. Depending on where in the flammable range the fire gases are when ignition occurs, this will determine the explosive force of the backdraught.

**SIGNS AND SYMPTOMS OF A BACKDRAUGHT**

A backdraught, is the development of fire in a compartment with no or limited ventilation, which is then ventilated after a period of time. If a fire has been burning for some time with no or limited ventilation, all of the oxygen may have been used up and a too rich mixture is more likely to be present.

**EXTERNAL SIGNS**

**Fire gases being pushed out under pressure from gaps**

If the neutral plane has reached the floor and pyrolysis continues due to heat retained in the compartment, the over pressure inside the compartment increases and forces the fire gases out through any gaps in the structure (ie gaps around doorways, windows, air vents, tiles on roof etc)

**Windows blackened with no visible signs of flame**

With oxygen being used up inside the compartment, incomplete combustion occurs. Carbon particles are a by-product of incomplete combustion, as oxygen levels reduce, production of carbon particles increases, which will be deposited on the surfaces of the compartment. As a too rich mixture starts to develop flames start to die back due to lack of oxygen. Flames can also be obscured due the thick fire gases above the neutral plane.

**Fire gases pulsing out from gaps**
If a too rich mixture has developed inside a compartment, as the fire dies down eventually the temperature will start to drop. As the temperature of the hot fire gases inside the compartment drop, the gases contract, over pressure will decrease and air will be drawn in through any small gaps. This can allow some of the fire gases to dilute into their flammable range and produce localised explosive mixture that may ignite (mini backdraught). If these fire gases ignite, the over pressure increases, forcing the fire gases out through any gaps in the structure (ie gaps around doorways, windows, air vents, tiles on roof etc)

INTERNAL SIGNS

Compartment with no or limited ventilation, then ventilated.

Low neutral plane

If the neutral plane is down to the floor level, then all of the oxygen will have been used up in the compartment and a too rich mixture is quite likely.

Darkening of the fire gases

As a fire develops inside a compartment the neutral plane can eventually reach floor level due to the products of incomplete combustion and pyrolysis. If heat is still retained inside the compartment, pyrolysis will continue producing gases. If the neutral plane has already reached the floor, as more gases are produced they will start to compress. Both effects of incomplete combustion and the compression of gases will darken the appearance of the fire gases.

Inrush of air and fire gases forced out, through the opening

If too rich mixture exists inside a compartment, when an opening is created the hot buoyant fire gases force their way out of the opening and fresh air rushes in. The more forceful this exchange of fresh air/fire gases, the more energy in the compartment, the more potential for backdraught.

Pulsations of fire gases through opening

When an opening to a compartment appears with a too rich mixture inside, fresh air is drawn in through the lower part and hot fire gases escape out of the top part of the opening. Eventually the fire gases will come into their flammable range. If an ignition source is available it will initially ignite the fire gases around the ignition source. The fire gases that initially ignite will rapidly expand and, as they expand, they will successively ignite the gases surrounding them, which will in turn rapidly expand. This process will advance throughout the compartment (providing the gases are in their flammable range). The pressure build-up inside the compartment, due to expansion of igniting gases, can appear at the opening, as pulsation of fire gases (which are not yet alight). It will, however, only be a very short space of time (maybe part of a second in a small room), before more gases ignite internally and force their way out of the opening as flame (BACKDRAUGHT).

SUMMARY

In this training note we have provided relevant information for Recruit Firefighters on the subject of physics and chemistry. It is important that firefighters understand how fires are caused and how they develop. They must also be able to recognise what classification of fire they are dealing with in order to make an informed judgement on the best method of extinguishment to employ. Using the wrong method or wrong type of extinguishing agent could be catastrophic.