

## ELEMENT 2: PRINCIPLES OF FIRE AND EXPLOSION

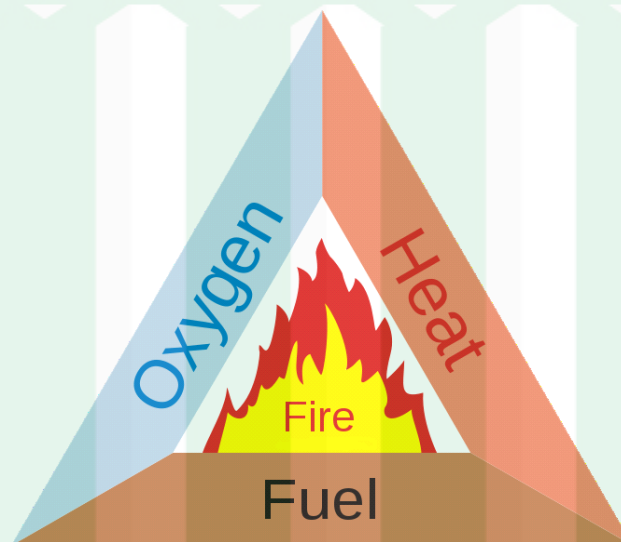
### Learning outcomes

On completion of this element, candidates should be able to demonstrate understanding of the content through the application of knowledge to familiar and unfamiliar situations. In particular they should be able to:

- 2.1 Explain the principles of the combustion process in relation to fire safety
- 2.2 Explain the principles and conditions for the ignition of solids, liquids and gases
- 2.3 Identify the classification of fires
- 2.4 Describe the principles of fire growth and fire spread
- 2.5 Outline the principles of explosion and explosive combustion.

### 2.1 THE PRINCIPLES OF THE COMBUSTION PROCESS IN RELATION TO FIRE SAFETY

The concept of the fire triangle



Fire is the chemical reaction called **COMBUSTION** i.e. oxidation resulting in the release of heat and light. Combustion is the scientific word for burning.

**Fuel** Combustible substances are either solid, liquid or gas. Solids and liquids do not burn but they produce vapours that do. The vapours mix in the air and then may ignite if they are in their flammable range. Dust is a solid that can ignite but usually an ignition source is needed.

**Oxygen** 21% or more in the atmosphere is normal in open air and this will readily sustain combustion. However a minimum of 10% oxygen will still enable some combustion to occur.

**Heat** The attainment of a certain temperature will normally be needed - once a fire has started normally it will maintain its own heat supply. The ignition sources needs a certain minimum temperature, energy and duration.

If all three ingredients of a fire come together there is the potential for a fire to start and then depending on the oxygen supply and fuel supply it may have the ability to sustain itself and

continue burning. Fire involves rapid chemical process that produce heat and usually light. Fire is neither solid, gas nor liquid but may involve substances in these variety of forms.

### **Complete Combustion**

Complete combustion is the term used when a chemical reaction that takes place with a substance burning and reacting with oxygen to produce heat and light energy. The most basic fire reaction is known as oxidization. Complete combustion is when a material burns fully and the chemical reaction is balanced or neutral. (This is based on the fact that matter is never created or destroyed it just changes its form)

$\text{CH}_4 + 2 \text{O}_2$  burns to generate  $\text{CO}_2 + 2\text{H}_2\text{O} + \text{heat} + \text{light}$

Methane + Oxygen generated + carbon dioxide + water vapour + heat & light

### **Incomplete Combustion**

If inadequate oxygen levels are present the fire may burn but the chemicals involved may not burn fully. For instance carbon monoxide is generated if a fossil fuel does not burn fully instead of carbon dioxide. Carbon monoxide is a toxic gas which can lead to headaches and loss of consciousness. Fire also generates heat and this may heat up other fuel sources and as such the fire may spread with yet more complete and incomplete chemical reactions occurring all at the same time.

Some substances may generate oxygen and this ensures the fire continues to burn, for example nitro-glycerine will burn or explode as it provides the oxygen needed for combustion.

$4\text{C}_3\text{H}_5(\text{NO}_3)_3$  leads to  $12 \text{CO}_2 + 10 \text{H}_2\text{O} + 6\text{N}_2 + \text{O}_2$

### **Exothermic reactions**

Exothermic reactions are reactions that result in the release of heat and energy. As the temperature increases, as does the pressure, this is why they can lead to fires and explosions. They involve changes in energy, usually evident as heat.

With exothermic reactions heat energy leaves the system, with combustion this also leads to the evaporation of water and the surrounding area or material will feel warmer.

### **Endothermic reactions**

These are reactions that absorb heat rather than generate it.

### **Oxidising Agents**

Oxidisers are substances which react with other materials, this may be at room temperature or with the application of heat. The resulting reactions mean the substance gains electrons from other chemicals.

Oxidisation involves the bonding of oxygen which will normally generate large amounts of heat even sufficient to cause an explosion.

A basic reaction is when metals oxidise and rust, they do this slowly and generate a small amount of heat over a period of time. However oxidisers can lead to extreme reactions, they may not be combustible themselves but they can liberate oxygen which causes other substances to burn or generate heat. Examples of oxidizing substances are nitrates, peroxides and some chlorates.

Oxidising agents supply oxygen to a fire so they cannot be put out by removing air via fire blankets or carbon dioxide.



## 2.1.1 Combustion Stages

There are a number of unique stages in a fire, including induction & ignition, fire growth, steady state and finally decay.

### Induction

Once a heat source has been generated and come into contact with a fuel source the fire is inducted or started. After that the burning process occurs in stages, an understanding of these is used by fire fighters as if they know what phase the fire is at they can determine how to best tackle the fire or even whether to tackle it at all.

The stages are depicted by varying differences in temperature and atmospheric conditions.

### Ignition Stage

Fuel, heat, and oxygen are all present. Fuel is heated to its ignition temperature.

There are three critical temperatures which effect whether a fire will be ignited. These are the flash point, fire point and spontaneous ignition temperature (also known as the auto ignition temperature).

The lowest temperature at which a fuel will give off vapours that will form a flammable mixture in air is known as the flash point. However, there must be a heat or ignition source for the material to flash. The range between ignition and flash point varies greatly.

The fire point is the lowest temperature at which heat from combustion of a vapour from a substance is capable of producing extra vapours to the combustion process to become self-sustaining. Once reached the fire will accelerate and burn quickly.

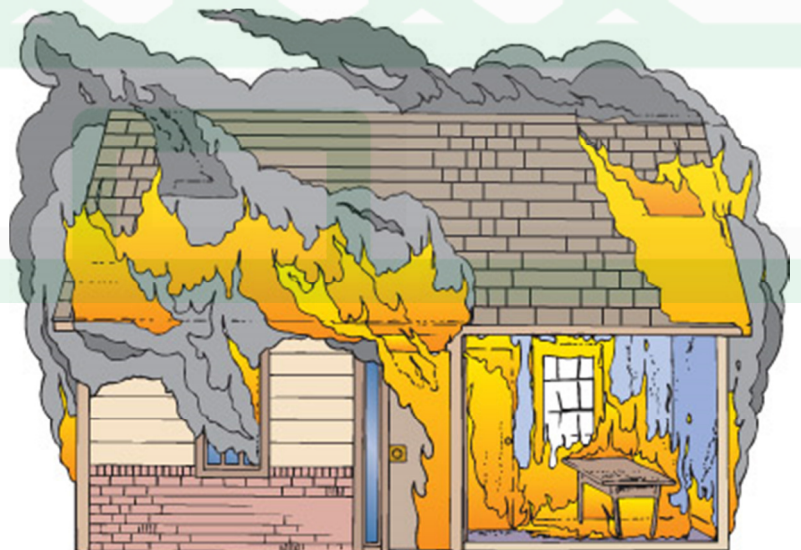
The spontaneous Ignition / auto ignition temperature is the lowest temperature at which a substance will ignite spontaneously without a flame or any ignition source.



### Growth Stage

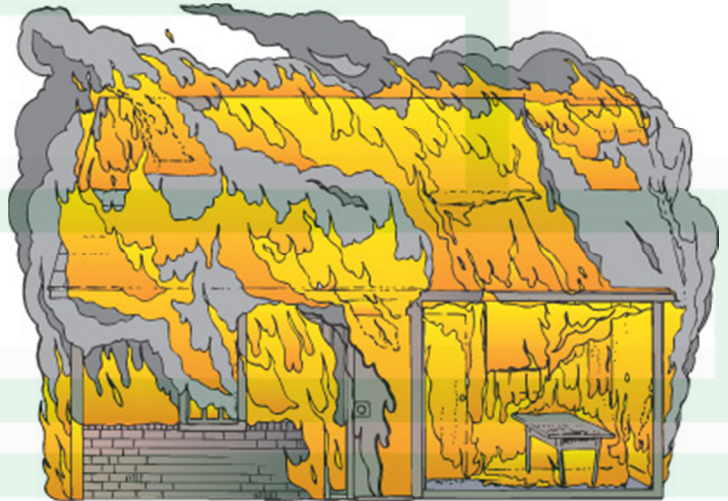
This phase, the oxygen content in the air has not been significantly reduced and the fire is producing water vapour, carbon dioxide, along with other gases including carbon monoxide.

Some heat is being generated, and the amount will increase with the progress of the fire. The fire may be producing a flame temperature well above 1,000°F (537°C), yet the temperature in the room at this stage may be only slightly increased.



## Steady State Stage

This phase of burning encompasses all of the free-burning activities of the fire. During this phase, oxygen-rich air is drawn into the flame as convection (the rise of heated gases) carries the heat to the upper most regions of the confined area. The heated gases spread out laterally from the top downward, forcing the cooler air to seek lower levels, and eventually igniting all the combustible material in the upper levels of the room.



This heated air is one of the reasons that firefighters are taught to keep low and use protective breathing equipment. One breath of this super-heated air can sear the lungs. At this point, the temperature in the upper regions can exceed 1,300°F (700°C). As the fire progresses through the latter stages of this phase, it continues to consume the free oxygen until it reaches the point where there is insufficient oxygen to react with the fuel. The fire is then reduced to the smoldering phase and needs only a supply of oxygen to burn rapidly or explode.

Flashovers as occurred in the Kings Cross fire tend to occur at the end of the growth phase and start of the steady state stage. Flashover occurs when a room or other area becomes heated to the point where flames flash over the entire surface or area. (This is covered later in this element).

## Decay Stage

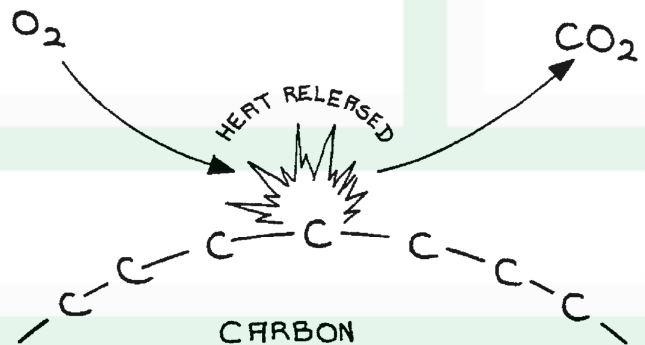


In the final phase, flames may cease to exist if the area of confinement is sufficiently airtight and the oxygen has been used up. In this instance, burning is reduced to glowing embers. The room becomes completely filled with dense smoke and gases to the extent that it is forced from all cracks under pressure. The fire will continue to smolder, and the room will completely fill with dense smoke and gases of combustion at a temperature of well over 1,000°F (537°C). The intense heat will have vaporized the lighter fuel fractions such as hydrogen and methane from the combustible material in the room

## 2.2 THE PRINCIPLES AND CONDITIONS FOR THE IGNITION OF SOLIDS, LIQUIDS AND GASES

Combustion takes place most readily between oxygen and a fuel in its vapour or other finely divided state. Solids are most easily ignited when reduced to powders or vaporised by the application of heat but, except in a few cases, the temperatures required for the vaporisation of solids are well above normal ambient temperatures.

When wood, paper, fibres or similar materials are involved in fires they decompose; the term used to describe thermal decomposition is pyrolysis. Pyrolysis decomposes solid material into solids, liquids and gases. The solid produced is mostly carbon.



Liquids act in a different way, some will give off dangerous quantities of flammable vapours well below normal room temperature; others do so at points only slightly above room temperature, and still others at much higher temperatures. This variable level is a major factor in enabling liquids to be classified into various risk levels (flammable, highly flammable or extremely flammable). The flash point is the lowest temperature at which a fuel will give off vapours that will form a flammable mixture in air.

### Example Flash points

Fuel Type	Temp (Deg C)
Acetaldehyde	-37.78
Acetone	-17.78
Benzene	-11.11
Carbon Disulfide	-30
Diesel Fuel (1-D)	37.78
Ethyl Alcohol	12.78
Gasoline	-42.78
Iso-Butane	-82.78
Iso-Pentane	less than -51.11
Kerosine	37.78-72.22
Methyl Alcohol	11.11
n-Pentane	less than -40
n-Hexane	-21.67
Propane	-104.44
Styrene	32.22
Toluene	4.44
Xylene	17.22

If a liquid is ignited and continues to burn, the heat causes more of the liquid to evaporate and burning continues. If we look carefully at the liquid fuel it shows that in the gap between the liquid surface and the flame, the vapour concentration is above the upper flammable limit.

Liquids and gases, however, burn by quite a different method. In solids the oxygen has to contact the solid for the reaction to occur, but with gases they can diffuse away and search out oxygen with which to react. In fact, liquids burn by exactly the same method, except they

must turn to a vapour first. Liquids, as such, do not burn, they first form a vapour that burns; it is due to this that such combustion is known as vapour phase reaction (VPR).

The VPR describes exactly what is happening; the reaction (combustion) is taking place in the vapour phase. The reaction occurs as flames and the reaction propagates through the atmosphere with emission of heat and light, so where flames are seen it is an indication of the presence of burning gases. In fire situations where the supply of air has been limited, the combustion of vapour is incomplete and oily liquids condense on cool surfaces. This produces the oily, corrosive smoke damage seen at many fires. Apart from solid and liquid fires, we must also consider the possibility of fires occurring when a combustible in the form of dust is mixed with air. All that is needed to cause an explosion is a spark.

Incomplete combustion reactions are hazardous as they cause smoke (carbon and unburned fragments of material) and produce toxic gases, e.g. carbon monoxide. *This occurs* because there is a lack of oxygen (air) or oxidant to fully react with the fuel. Once a fire has started the exothermic reaction can supply heat to other materials and the fire will spread.

### 2.2.1 - Important Definitions and Concepts

**Spontaneous Combustion** – when material reacts with the air to produce an exothermic reaction i.e. produce their own heat and will ignite spontaneously without any heat source e.g. oil soaked rags, carbon, coal, fertilisers and oils can all produce their own heat.

**Ignition Temperature (Ignition Point)** - The minimum temperature at which a fuel/vapour/air mixture will burn after ignition. This will depend on temperature composition mixture, pressure and nature of ignition source.

**Flash Point** - The lowest temperature at which a fuel will give off vapours that will form a flammable mixture in air. However, there must be a heat or ignition source for the material to flash. The range between ignition and flash point varies greatly, the flash point of petrol is much lower than that of paper, but its ignition temperature is higher.

**Auto ignition Point / Spontaneous Ignition** - The lowest temperature at which a substance will ignite spontaneously, the substance will burn without the addition of a flame

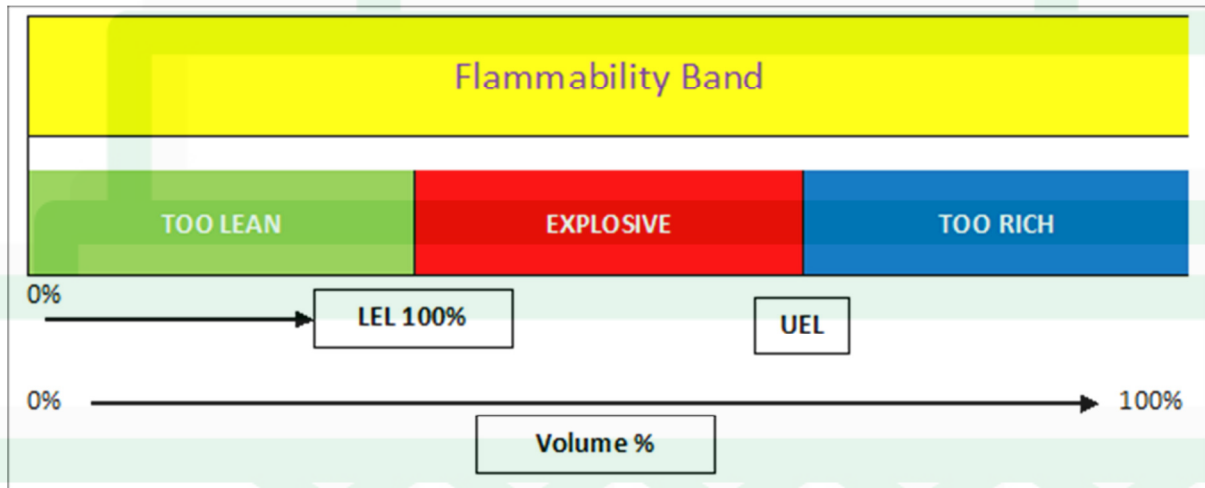
**Lower Explosive Limit - Upper Explosive Limit** - This is where the concentration of the vapour will support fire and burning. If the concentration is too high/low then fire will not be able to start or sustain itself. An increase in temperature increases the flammability range by decreasing the lower and increasing the upper limit.

**Vapour (Relative) Density** – the weight of a unit volume of gas or vapour compared to (divided by) the weight of an equal volume of air (or, sometimes, hydrogen). The density of vapour relevant to air (e.g. heavier than air gases tend to lie low to the ground as opposed to ones lighter than air which rise). Weight of vapour/gas. A vapour density of 1 or more means the gas is heavier than air, a vapour density of less than 1 means the gas is lighter than air. The result of this is that heavy substances gather together in low lying areas. Whereas low density substances are more mobile will lift into high areas. They are more likely to disperse and be diluted. Examples Methane = Lighter & Carbon Dioxide = Heavier than air.

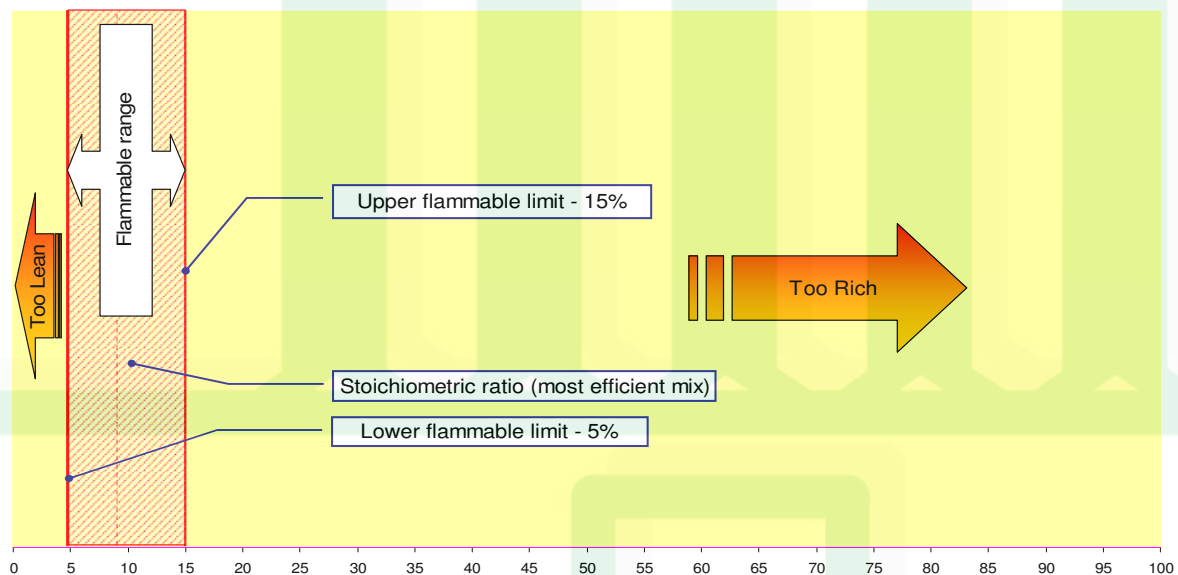
**Vapour Pressure** – this is Pressure of vapour given off by solid or liquid. The molecules escape and normally rise from the surface. The more volatile the substance such as a solvent the more vapour will be generated, this will have a higher vapour pressure. The vapour pressure may increase with increase in temperature.

**Oxidation** - Fire is the rapid oxidation of a material in the exothermic chemical process of combustion, releasing heat, light, and various reaction products. Slower oxidative processes like rusting are not included by this definition.

### 2.2.2. Lower and Upper Flammable Limits



For gases to burn they need a certain amount of oxygen, for different gases they will burn more or less effectively depending on the mixture of gas and air (or pure oxygen). This is known as their flammability limit or explosive range of flammability. If there is too much oxygen and too little gas the mixture may be too lean, if there is too much of the gas and too little oxygen the mixture may be too rich to burn.



*Diagram Flammable Limits for Methane*

The diagram above shows the flammability range of methane. This is a substance that will burn readily if there is a ratio of gas to air of between 5 and 15%. Its most effective burn ratio is 9%, this is known as the stoichiometric ratio. However if there is more than 15% of the gas the mixture is too rich and will not burn.

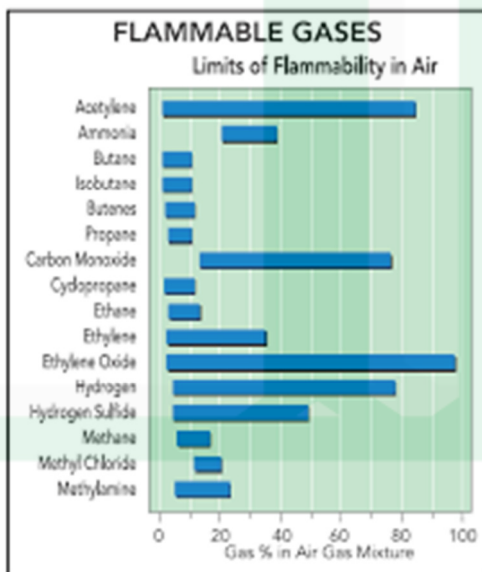
Table Example Flammability Limits

Gas	Lower limit	Upper limit
Acetylene	2.5	80
Hydrogen	4.1	74
Carbon Monoxide	12.5	74.2
Ethylene	2.7	28.6
Methane	5	15
Butane	1.5	9
Petrol	0.6	8

If we dilute a mixture with more oxygen/air there comes a point where there is insufficient fuel to sustain combustion. This is known as the lower flammable limit (LFL). There is also an upper flammable limit (UFL) where there is too much fuel for combustion to occur.

In pure oxygen or oxygen-enriched atmospheres, the limits become wider than they are for air - thus it is more likely for a mixture of gas or vapour to be within the flammable range and fires are correspondingly more difficult to extinguish.

Conversely, if the air or oxygen is diluted with an inert gas such as nitrogen or carbon dioxide, the limits become narrower until they converge together and there is no flammable range. Such dilution typically would reduce the oxygen content to 8%-10% (the same limit below which an atmosphere would be irrespirable and unable to support life).



In the practical situation of a leak involving petrol, dispersion and natural dilution in still air would reduce the vapour content below the lower flammable limit at a distance of about 12 m from the leak; this is known as the **safe dilution point** and gives an indication of the size of zone which would be needed to control sources of ignition in order to prevent a fire. A dangerous condition is usually indicated when one third of the lower flammable limit concentration is reached.



### 2.2.3 Liquefied petroleum gas (LPG) – For further details see Element 3.

Extra precautions are needed for highly flammable materials with a flash point of below 32°C, this includes many solvents, LPG, flammable gases and oxygen cylinders.

- If there is a release of liquid to gas it expands rapidly (butane 1:230)
- 2-10% gas in atmosphere = fire / explosion risk
- knocks out oxygen
- cold liquid - skin burns
- asphyxiate
- narcotic
- lighter than water



Flammable liquids are in common use in many industries, yet they have the power to destroy very easily if appropriate precautions are not taken. Substances with low flash points represent the highest risk. It is normally the flammable vapour which the liquid produces which is the fire hazard, mixed with air these can ignite very rapidly to give an explosion.

Almost all highly flammable (HF) vapours are denser than air, this means they will accumulate at the lowest point available possibly at some distance from the flammable liquid itself. The use of correct and suitable equipment for the storage, use and transfer of these liquids is essential if the risks are to be minimised.

Good ventilation in storage areas is essential, openings to provide ventilation should not ventilate into surrounding structures. Typically an opening of just 1% of the floor and wall area is sufficient but this may need to be up to 2.5% for flammable gases and oxygen.

## 2.3 THE CLASSIFICATION OF FIRES



### Class A

These are fires involving solid materials normally of an organic nature (compounds of carbon) in which combustion generally occurs with the formation of 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 may be divided into two groups:

- those that are miscible (soluble) with water; and
- those that are immiscible (insoluble) with water.

Depending on the type of liquid involved the extinguishing agents include water spray, foam, light water, vaporising liquids, carbon dioxide and dry chemical powders.

### Class C

These are fires involving gases or liquefied gases in the form of a liquid spillage, or a liquid or gas leak, and these include methane, propane, butane, etc. Dry chemical powder can be used to control fires involving shallow liquid spills. (Water in the form of spray is generally used to cool the containers.)

### Class D

These are fires involving metals e.g. magnesium, potassium & aluminium. Extinguishing agents containing water are ineffective, and even dangerous; carbon dioxide and the bicarbonate classes of dry chemical powders may 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 fusing powders have been developed for fires involving some metals, especially the radioactive ones.

### **Class F**

These are fires involving fats and oils. A wet chemical extinguisher has been developed specifically for these fires and is identified by a canary yellow band around the extinguisher.

### **Electrical Fires**

It is not considered, according to present day ideas, that electrical fires constitute a class, since any fire involving, or started by, electrical equipment must, in fact, be a Class A, B or D. The normal procedure in such circumstance is to cut off the electricity supply and use an extinguishing method appropriate to what is burning. Only when this cannot be done with certainty will special extinguishing agents be required which are non-conductors of electricity and non-damaging to equipment; these include vaporising liquids, dry powders (low voltage) and carbon dioxide.

## **2.4 THE PRINCIPLES OF FIRE GROWTH AND FIRE SPREAD**

There are a range of factors that influence fire growth rates and smoke movement:

- building design (such as cavities, ducts, shafts)
- insulated core panels
- construction materials
- internal linings
- ventilation levels
- contents of the premises

The materials the building is made of or contains will have different limits of flammability, some such as metals may conduct heat readily. Some may resist the passage of smoke and flames. All of these may affect how quickly a fire takes hold and can affect the success or failure of a "Means of escape".

The design of the building itself can also impact on the effectiveness of materials during a fire, the main factors include:

- The size of the building
- Compartmentalisation
- Layout of escape routes
- The behaviour of the material if it is burning
- The hazards created by the burning of the materials.

### 2.4.1 Cavities and voids

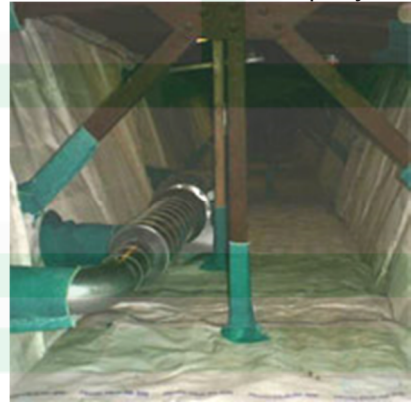
Cavities and voids are primarily by their very nature out of sight and as such can conceal a fire of considerable proportions before it becomes apparent.

They can form channels or passageways through which heat and smoke can move rapidly and unseen to other parts of a building often at considerable distance from the original fire. Fire fighting in such areas can prove problematic due to their inaccessibility.

Cavities and voids may be present in cavity walls between constructional walls and cladding between external walls and linings or as part of the internal divisions of the building between floors and ceilings and between structural and false ceilings.

Measure to reduce the risks associated with cavities and voids include:

- Ensuring separation between cavities and spaces is fire resisting.
- Providing fire resisting barriers e.g. above the structural or partition wall in the space between false and structural ceilings.
- Providing appropriate dampers in ducting which are activated by fire detection
- Ensuring the linings of such areas are non-combustible. Metal components which will afford heat transfer by conduction are enclosed in fire resistant cladding.
- Limiting size / cross communication and ensuring they do not compromise fire
- Compartmentation.
- Ensuring that combustible materials are not stored in voids.



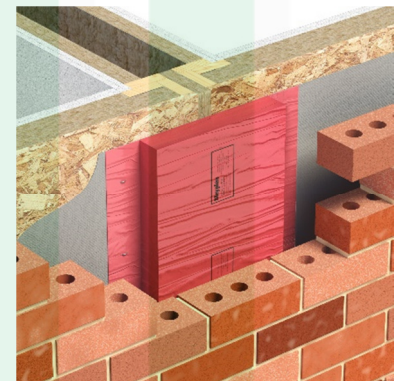
### 2.4.2 Construction Materials

A variety of different materials will be used in the building of a structure, these can effect fire spread and smoke movement.

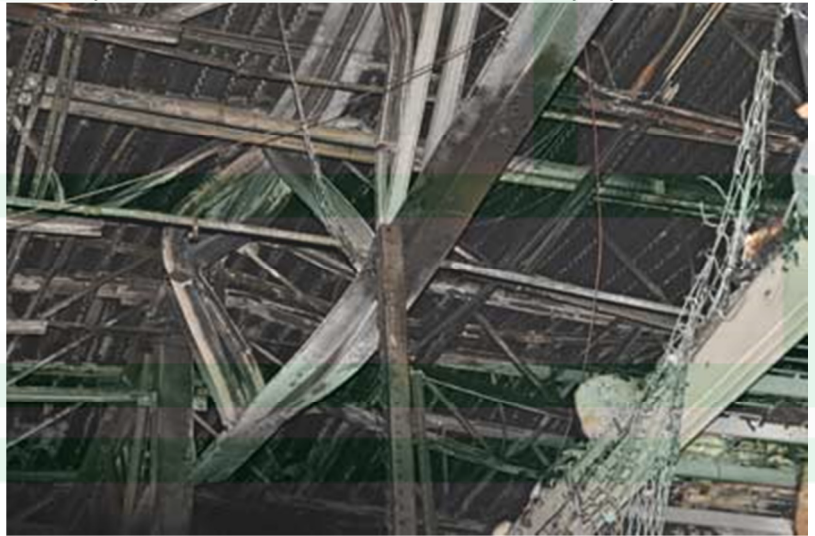
**Bricks** – These are normally made from fired clay, the thicker the brick the better the protection that is given to the structure. Any imperfections and air in the bricks means they may crack and allow smoke to travel through.

**Concrete blocks** – these are heavier than bricks and have a higher fire resistance. Concrete itself has low thermal conductivity, it heats up slowly but it will spall (See image showing cracking and falling off this is known as spalling) depending on the silica in the mix. When cold fire water is used to cool the structure it will contribute to spalling, pieces of concrete can fall off and expose other surfaces which may then weaken or spread the fire further. Concrete blocks will not collapse easily. Concrete is used as a reinforcement material, it may be coated on the reinforcement rods. If heated the steel rods may puncture through the concrete, weakening the structure significantly.

**Gypsum** – this is chemically bonded with water to form a solid layer. As it heats up the water content will evaporate. This slows down the heating process. Basic gypsum is low density and may crack at high temperatures exposing other building components. Some gypsum can be reinforced with an inner mineral core which makes it stronger for longer.

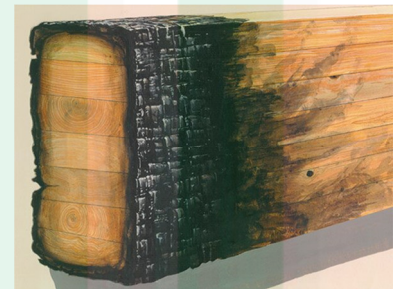


**Metals** – these will heat up and as this happens at different temperatures, strength of the metal will reduce, it will expand and eventually melt. Metals conduct heat and may spread the fire to other parts of the building. Carbon Steel loses its strength when it reaches the temperature of 300°C, at 800 °C it will start deforming. Stainless steel expands as it heats up to 1200°C, it conducts heat less well than carbon steel. More fire resistant steels have been developed that retain their strength at higher temperatures. Metals may be covered with other less combustible materials to protect them. As steel expands if there are steel bars or rods inside the structure, the bars will expand and puncture out through the concrete or brick work.



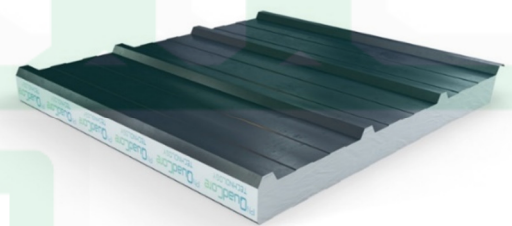
**Plastics** – Thermosetting plastics are formed by heat and compression they will not soften but they will decompose. Thermoplastics are moulded, they will melt easily.

**Timber** – Wood burns but in fact can withstand fire for a significant period of time. The thicker the wood the more difficult it is to burn. Denser woods are thicker and will burn more slowly. Flame retardant coatings may be used to limit burning. Burned timber chars, as this occurs it loses some of its strength, underneath there will be a second layer known as the pyrolysis zone. Moisture will evaporate from the wood drying it out and making it more brittle. More charring the higher the loss of strength. Wooden floors and panels may need to be supported from all sides to reduce the risk of failure when they weaken.



### 2.4.3 Insulated Core Panels

Insulated panels (as depicted here) normally consist of two metal facings either side of an insulating core. The core is either bonded to the facings using an adhesive. There is no air gap between the core and the facings. The panels are manufactured in a factory and delivered to the construction site as a single piece unit. Panels are generally 1 m in width and are delivered to site in lengths from 1 m to 20+ m. Insulated panels are generally regarded as non-structural although they are strong rigid units that act compositely when under load.



Since the Grenfell fire the spot light has been on the quality of cladding and how it can contribute to the spread of fire on the outside of the building. Issues to take into account when deciding to use panels of this type are:

- The type of panel and its core insulating material
- Whether the panel is securely fixed or free-standing
- Factors that have a direct influence on the scale of the fire i.e. type and magnitude of the fire load of the contents of the building

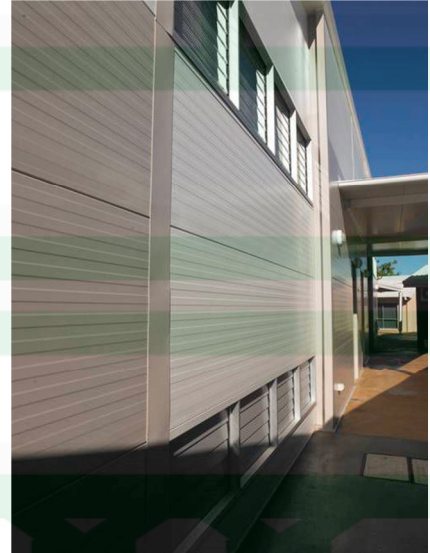
- Other factors such as open edges or cut holes that expose the core and could influence the contribution of any combustible core material to the fire and which might affect the Fire Risk Assessment.

Image: Panel Use

In a fire the following may occur:-

- Production of smoke
- Buckling and delamination of the facings but not necessarily collapse where the facings are fixed to the framework
- Charring and burning of non-melting combustible materials

Additionally burning, shrinking away from the steel and melting of combustible materials such as polystyrene (PS) will occur at the early stage of the fire. As the fire impinges on the panel the fire will grow, the fire will generally be localised and the temperatures lower.



#### 2.4.4. Building Contents

A typical building will have various different plastics, foam, fabrics and paper based materials either stored or used in the buildings structure.

Some everyday products burn extremely fiercely in the quantities found in manufacturing and distribution premises. Examples are foamed plastics such as polystyrene, polyurethane and polyethylene, polyester wadding used in clothing and bedding, and bubble wrap. A large surface area in the product itself, a tendency to melt, and high racked storage are potent hazards.

Like hay, wood or coal plastic materials contain large amounts of carbon and hydrogen with a corresponding calorific value. This means that plastic materials are inflammable and can burn in the presence of oxygen. In this respect, any plastic material constitutes a certain fire hazard when used in contact with or in the vicinity of a potential source of fire. In electrical networks, this can be switching contacts, connection and disconnection contacts, as well as all kinds of electric and electronic components which can heat up to dangerous levels as a result of faults, fatigue or injection of external energy.

Research by the HSE identified that plastic is more easily ignited than wood, the time it takes for a fire to spread upwards is far quicker and the flames spread further. The intense heat from plastic burning is likely to cause violent spalling of concrete e.g. nearby walls or floors which may weaken the structure of the building.

Large fires involving plastics produce copious quantities of black smoke, such smoke is likely to be more toxic than smoke from a fire involving wood, and would render escape and firefighting very difficult.

Textiles can be easily combustible, loose materials have low density fibres and therefore burn very easily. Deposits of fluff and dust (fly) - dust on light fittings is a particular risk.

## 2.5 - THE SPREAD AND EFFECT OF FIRE

Once a fire has started and there is sufficient fuel and oxygen to sustain it, there are four recognised ways in which it can spread within the building – direct contact, convection, conduction and radiation.

The actual materials used in the construction of buildings are as important as the building design itself in minimising the potential effects of convection, conduction and radiation in the event of a fire.

Materials that are fire resisting, i.e. resistant to conduction and radiation (and are of limited combustibility) are therefore used in building construction, e.g. in floors, partitions and doors to restrict the spread of fire.

The development of a fire under free burning conditions and a fire in enclosed conditions

- Variations in the direction of fire spread occur if air currents deflect the flame.
- The total material burned reflects the intensity of the heat and the duration of the exposure to the heat.
- An adequate supply of oxygen must be available to fuel a free-burning fire.
- Many fires in buildings burn the contents of the structure, but do not involve the structure itself.
- Most modern rooms are heavily loaded with materials made of plastics and synthetic materials. These produce dense smoke that can be highly toxic.
- Newer upholstered furniture is more resistant to ignition from glowing sources, but it has little resistance to ignition from flaming sources.
- Finishes used on walls and ceilings can burn readily. This can increase the intensity and spread of the fire.

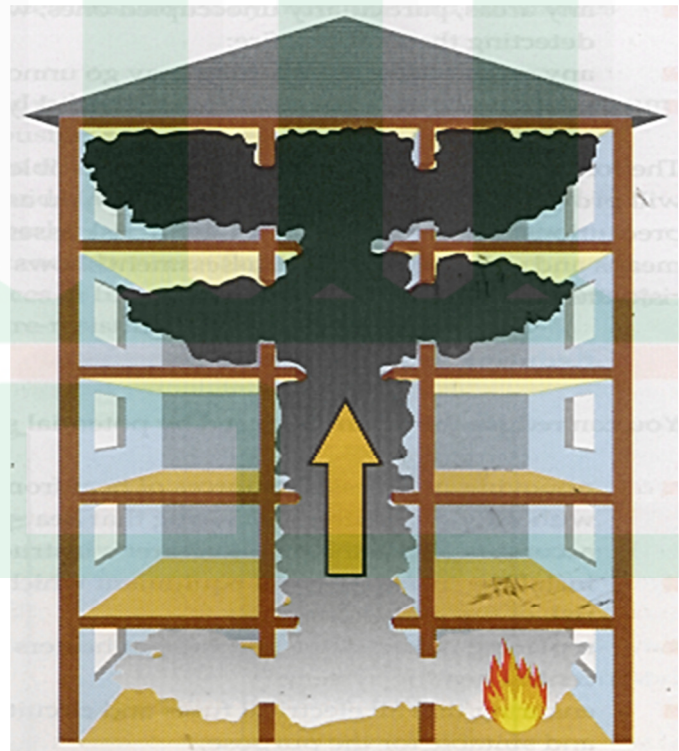
### 2.5.1 Direct Contact Via Flame

This is where the flames or heated particles directly come into contact with a new fuel source. Burning fragments may fly from the fire onto nearby objects setting them alight.

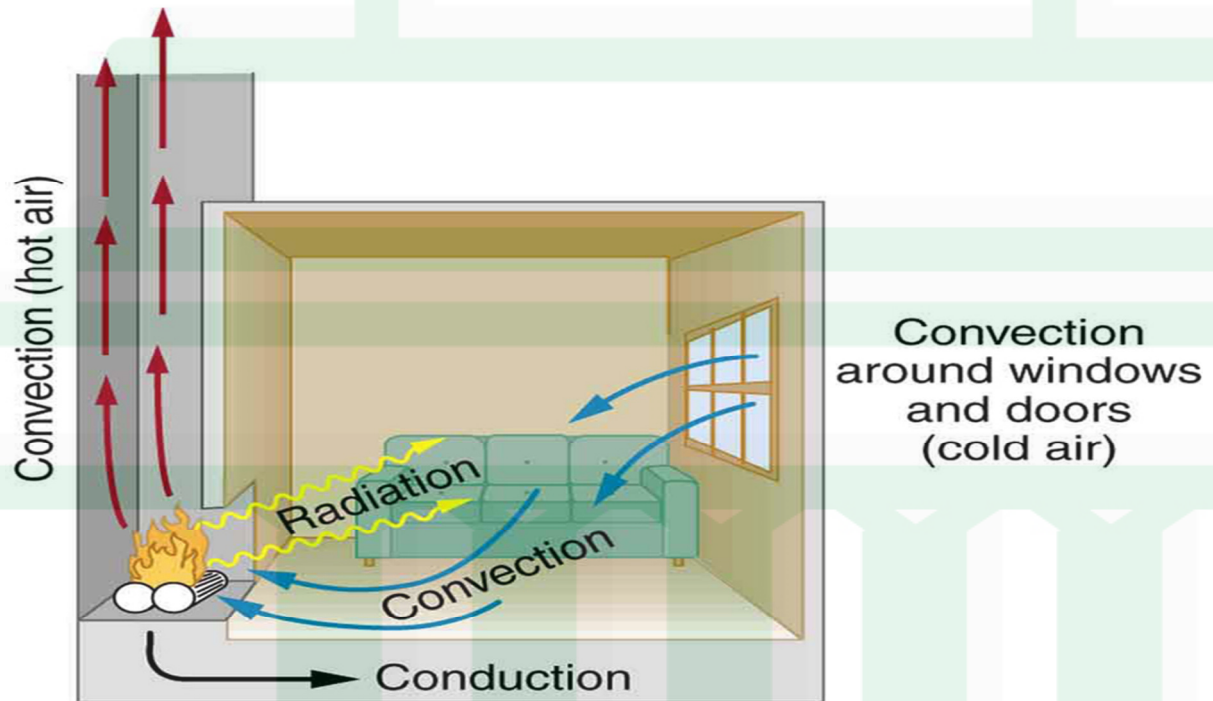
### 2.5.2 Convection

Convection is the transfer of heat via moving air currents. When heated, air becomes less dense and rises, as the fire burns, fumes are given off which mix with the air to form smoke. The smoke rises in a plume forming a layer at ceiling level which then spreads out horizontally. As the temperature of that layer increases, heat is radiated downwards and may ignite other combustible materials in the vicinity.

The further from the fire that the layer spreads, the more it will cool and if the compartment (room) is large enough, it will lose buoyancy and sink, creating a "mushroom" effect. The rising gases are replaced at the



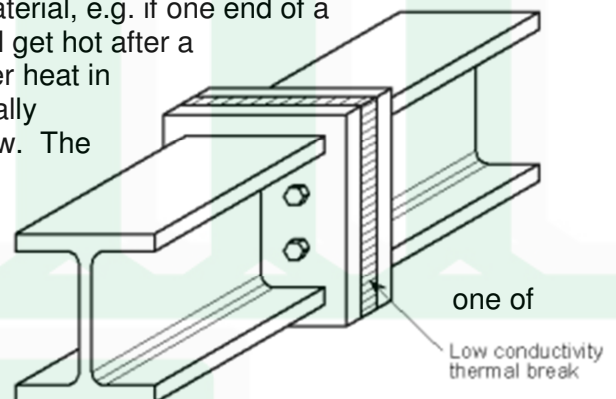
base by cooler air. In a building, fire can spread to higher floor levels by hot gases from a fire "convecting" up enclosed stairways. This process will be assisted if fresh air is allowed to enter at the foot of the stairway via doors or windows. The hot gasses, smoke and fumes also spread via lift shafts and ventilation systems.



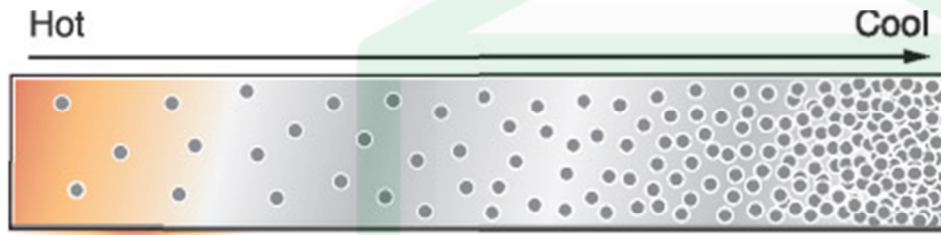
### 2.5.3 Conduction

Conduction is the movement of heat through a material, e.g. if one end of a metal bar is placed into a fire the opposite end will get hot after a period of time. Materials which are able to transfer heat in this way are known as conductors, they are normally metals which allow free electrons to move and flow. The ability of conductors to transfer heat varies considerably according to the type of material, e.g. metal is a much better conductor than brick.

Most metals are conductors of heat, copper being the best. Therefore, a fire in one compartment (room) can spread to adjacent compartments through heat being conducted via metal pipes and via frames used in the building construction. Non-metallic solids, liquids and gases are generally accepted to be poor conductors of heat.







### 2.5.4 Radiation

Radiation is the transfer of heat energy as electromagnetic waves which heat solids and liquids (but not gases) encountered in their paths. Sun rays are an example of radiated heat.

Heat from fire in a building may be radiated to an adjacent building by passing through windows and igniting combustible contents in the second building. Glass has very little resistance to radiated heat.

### 2.5.5 Flashover

This is the sudden ignition of all contents of a room, if a person is present at the time there is minimal chance of survival. Flashover often occurs just as fire fighters arrive on the scene.

- Flashover is a heat-driven phenomenon. Without heat, the interior contents won't off-gas and reach their ignition temperatures.
- As the Growth-stage of the fire occurs if there is no fire cooling the likelihood of a flash over increases. If the area cannot be cooled two of the three things needed for a flashover will be present: heat and fuel (fire gases).
- Changing conditions. A rapid increase in the heat level may be a good indicator of impending flashover. More smoke is also a contributory factor as this is loaded with unburned fire gases that ignite under the right conditions.
- The hot gases rise and fill the room from the top, they get hotter and hotter via convection, this gas ignites and the heat will be so intense it burns everything else in the room
- Rollover. The term "flashover" is often misused when interior fire crews see a rollover, which is the ignition of the fire gases in the upper ceiling area. This is the last warning



sign before a flashover occurs. It's very important to be aware that you may or may not see the rollover prior to flashover.

### 2.5.6 Back draught

This is an explosion that occurs when oxygen is suddenly admitted to a confined area that is very hot and filled with combustible vapors. A backdraught is where limited ventilation can lead to a fire in a compartment producing fire gases containing significant proportions of partial combustion products and unburnt pyrolysis products. If these accumulate, the admission of air when an opening is made to the compartment can lead to a sudden deflagration. This deflagration moving through the compartment and out of the opening is a backdraught. The force of a backdraught has the potential to damage building elements resulting in an unstable structure.

Fire gas ignitions may occur when gases from a compartment fire have leaked into an adjacent compartment and mixed with the air within this additional area. This mixture may then fall within the appropriate flammable limits that, if ignited, will create an increase in pressure either with or without explosive force. Where this process occurs it is not necessary for an opening to be opened for such ignition to take place.

- **Usually occurs when a fire is smoldering**
  - Room is filled with carbon monoxide and other products of combustion.
  - Sudden introduction of air will explosively feed the fire.
  
- **Signs of an impending backdraft:**
  - Little or no flame visible
  - Smoke emanating from cracks
  - No large openings
  - "Living fire" visible
  - Unexplained change in color of smoke
  - Glass smoke stained or blackened
  - Signs of extreme heat
  
- **Prevention of backdrafts:**
  - Ventilate at a high level to allow superheated gases to escape.
  - Well-coordinated fire attack



## 2.6 THE PRINCIPLES OF EXPLOSION AND EXPLOSIVE COMBUSTION

An explosion is a rapid violent release of energy usually from a chemical reaction, this will normally lead to heat, light, noise and a shock wave, as well as potentially the release of a toxic or hot substance. Flying debris and missiles can also result.

Explosions tend to be caused by dust or gases, where there is the right ratio/ mixture and sufficient temperature to give enough energy to start the reaction.

As mentioned previously for gases for an explosion to occur there has to be a substance (dust or gas normally) which is present in the air within its explosive limits or ratio.

**Fire-** A slow form of deflagration

**Deflagration** - Propagating reactions in which the energy transfer from the reaction zone to the unreacted zone is accomplished through ordinary transport processes such as heat and mass transfer. Normal subsonic combustion. There is a flame front propagating at 300 metres per second through unburnt material, this heats up unburnt materials and ignites it, then this occurs again and again. E.g. chip pan fire.

**Detonation / Explosion** - Propagating reactions in which energy is transferred from the reaction zone to the unreacted zone on a reactive shock wave. The velocity of the shock wave always exceeds sonic velocity in the reactant. This is super-fast (2000 metres per second) during propagation shock wave travels through material and air. This may set fire to other materials E.g. explosion.

### 2.6.1 Dust Explosions

There are a few basic rules to observe to see whether a dust is capable of causing a dust explosion:

- The dust must be combustible.
- The dust must be capable of becoming airborne.
- The dust must have a size distribution capable of flame propagation.
- The dust concentration must be within the explosible range.
- An ignition source must be present.
- The atmosphere must contain sufficient oxygen to support and sustain combustion.

If all of these criteria are fulfilled then a dust explosion can occur. The best way to avoid dust explosions is to invalidate as many of these properties as conditions allow.

Historically the first recorded incidence of a dust explosion was at an Italian flour mill in 1785, although it was almost certainly not the first to occur. Dust explosions have been a risk in the grain industry for as long as people have made bread, and will continue to be for as long as people eat sandwiches.

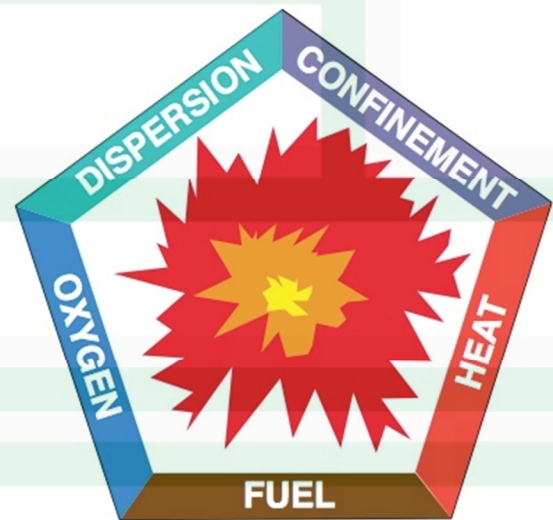
A dust explosion is very similar to a gas or vapour cloud explosion, i.e. when a volume of a flammable mixture is ignited, resulting in a rapid pressure increase and fire moving through the cloud. A dust explosion occurs when a combustible material is dispersed in the air forming a flammable cloud and a flame propagates through it.

This of course also depends on the supply of oxygen to the fire, and the concentration of the fuel, if either of these are in too high or low then the explosion will not occur. The explosion occurs in three stages, devolatilisation (where volatiles are evaporated from the particles, or the particle is vaporised), gas phase mixing and gas phase combustion.

## Factors Affecting Ignition Sensitivity and Explosion Violence

Although particle size/specific surface area is the main factor in the estimation of the likelihood of a dust explosion there are other factors that will influence it:

- Chemical Composition of the dust (and its moisture content)
- Chemical Composition, pressure and temperature of the gas
- Particle shape and size distribution
- Degree of dispersion of the dust cloud
- Concentration distribution in the dust cloud
- Turbulence in the dust cloud
- Amount of turbulence caused by the explosion in unburnt parts of the cloud
- Flame front disturbance by mechanisms other than turbulence

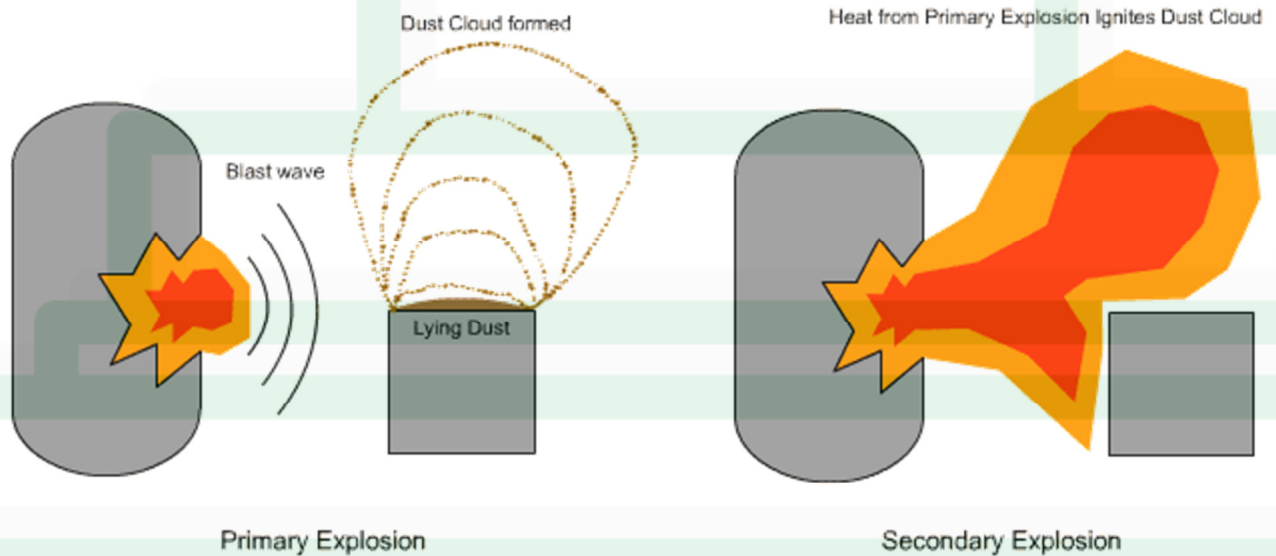


*Figure: The result of a dust explosion*

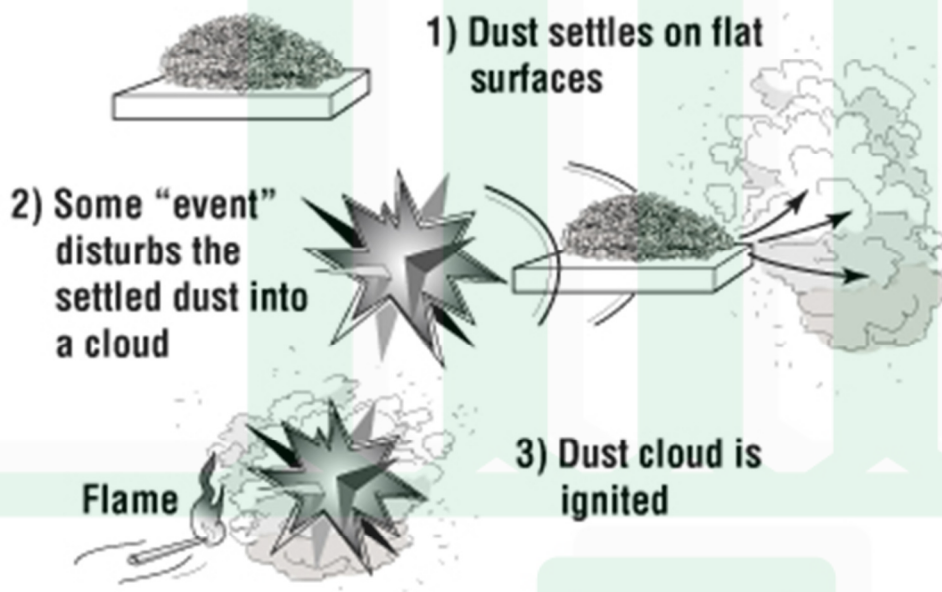
### Primary and secondary explosions

When combustible dusts ignite, there are often two explosions known as primary and secondary explosions. The primary dust explosion is the first explosion. It occurs when there is a dust suspension in a confined space (such as a container, room, or piece of equipment) that is ignited and explodes. The primary explosion will shake other dust that has accumulated. When this dust becomes airborne, it also ignites, this is known as the secondary dust explosion is often more destructive than the primary one.

An important aspect of dust explosion avoidance is the limiting of the possibility of primary explosions, however more important is to reduce the possibility of a secondary explosion occurring.



The problem is that small amounts of lying dust occupy very little space, but once disturbed can easily form dangerous clouds. A 1mm layer of dust of  $500\text{kg/m}^3$  can give rise to a 5m deep cloud of  $100\text{g/m}^3$  dust.



### Dust Chemistry and Moisture Content

Moisture content of a dust will affect the ability of a dust cloud to be ignited and its ability to sustain an explosion. Increasing moisture content pushes the ignition energy up exponentially with some dusts. The moisture works in several main ways. The heating and evaporating of the moisture provides an inert heat sink. Once evaporated the water vapour mixes with pyrolysis gases and makes them less reactive, and can also increase intermolecular cohesion of the dust meaning a larger effective particle size.

## Particle Size and Specific Surface area

No matter how combustible the powder, if it's in big lumps it isn't going to cause a dust explosion.

## Dust Concentration

Dust cloud explosions can only occur if the dust concentration is within certain limits. This is analogous with the concept of upper and lower flammable limits of mixtures of gas (or vapours) and air. In general the lowest concentration of dust that can give a dust explosion is around 50-100g/m<sup>3</sup> and the maximum is 2-3kg/m<sup>3</sup>. These limits are dependent on the particular chemical in question and on the particle size distribution.

## Turbulence

A more turbulent cloud will result in a more severe explosion as, due to the more homogenous concentrations and lower degree of dispersion, the flame will move more quickly through the dust cloud. However a less turbulent cloud is more easily ignited, as heat dissipation is at a lower rate so the initial heat release is more locally concentrated, leading to a higher probability of ignition from an input of energy.

## Oxygen Content of Oxidising Gas

Less oxygen in the air causes the explosion to be much less severe as it limits the rate of combustion of the dust, thus limiting the oxygen in process vessels can minimise the possibility of a dust explosion (fire can only be sustained if oxygen concentration is greater than 10% in air).

## Degree of Dust Dispersion

Dispersion and degree of agglomeration (collection together) affect the combustion as they change the effective local dust concentrations and the effective particle size respectively. A more evenly dispersed dust will burn more easily. The degree of dispersion is usually dependent upon the method of dust dispersion and the turbulence in the system.

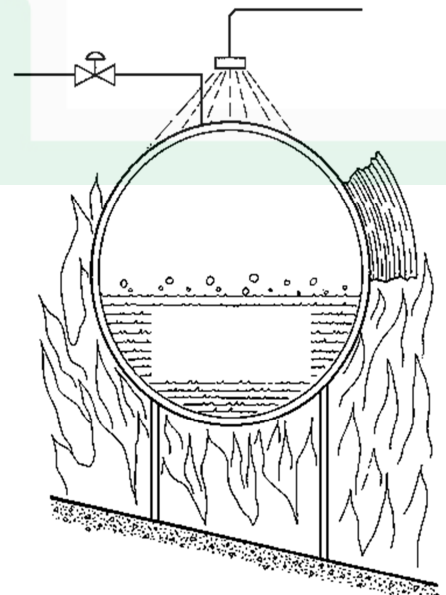
## 2.6.2 GAS EXPLOSIONS - BOILING LIQUID EXPANDING VAPOUR EXPLOSIONS (BLEVES)

Explosions can involve gases as well as dust, these may be confined in a room or building, unconfined as in the case of Buncefield or from the heating of a storage tank or vessel.

A boiling liquid expanding vapour explosion occurs when a pressure vessel containing flammable liquefied gas becomes exposed to fire or heat. This can either weaken the vessel or build up the pressure, both situations may cause a BLEVE.

The most common example of this type of explosion is the explosion of butane or propane gas cylinders which are damaged. Cylinders, if not stored correctly, can present a serious risk of injury. A BLEVE is likely to occur if there is a rapid release of vapour, this is normally LPG. If a gas cylinder is heated the metal container loses its strength, in addition the liquid inside the container heats up and starts to expand, and will rupture. At the rupture stage the vapour is released and will ignite if an ignition source is available.

The emergency vents in the vessel with blow off allowing the pressure to be released but the gas will normally continue to burn and the cylinder will eventually rupture and explode. The vapour released will ignite and can cause a major explosion. Debris may be thrown in all directions. A 15 metre

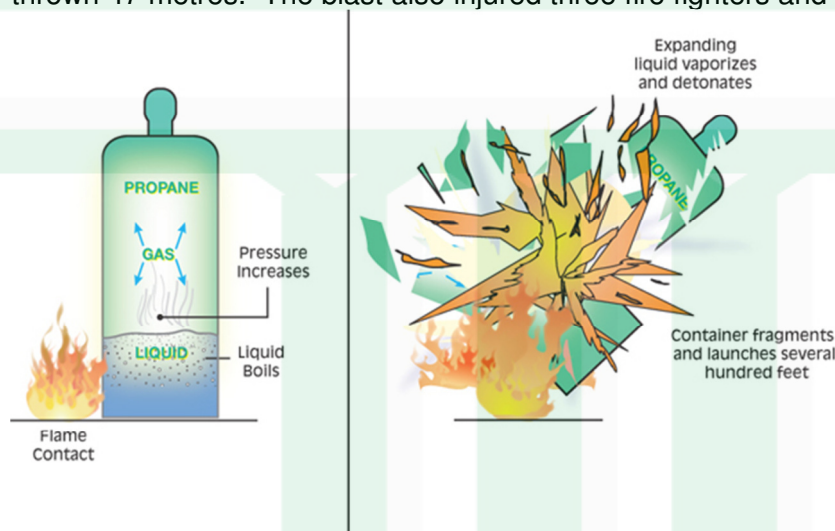


sphere of LPG could cause blast damage up to 5000m from the container. Once the liquid in the container becomes a vapour this type of explosion is inevitable. The critical temperatures for Propane are 97°C and for butane 153°C.

Pressure can build up in drums due to the difference between the filling temperature and the ambient temperature. If the ambient temperature is higher, ejection or splashing of the liquid contents or vapour release may occur on opening exposing the operator to the risk of ~~slashing~~

Liquid heats up and converts to vapour

In June 1993 at Ste. Elizabeth de Warwick, Quebec, Canada, the fire brigade responded to large cattle barn fire. A 4,900 litre propane tank was close to the fire with its relief vent operating, shooting flames over 5 metres into the air. The fire fighters applied water to the LPG tank in an effort to cool it, but the tank BLEVE'd and split into two large pieces. One piece was blasted into an open field while the other one travelled over 47 metres, struck a fire engine, then travelled a further 232 metres where it struck a passing vehicle trapping the occupant. Four fire fighters were killed when the metal struck the fire engine, one being thrown 47 metres. The blast also injured three fire fighters and four members of the public.



### 2.6.3 AVOIDING EXPLOSIONS

The table below gives an overview of ways of preventing (stopping the explosion from occurring) and mitigating (minimising the damage of an explosion) dust explosions:

<b>Prevention</b>		<b>Mitigation</b>
Preventing Ignition Sources	Preventing Explosible Dust Clouds	
Smouldering combustion in dust	Inerting by N <sub>2</sub> , CO <sub>2</sub> and rare gases	Partial inerting by inert gas
Other Open Flames	Intrinsic Inerting	Isolation
Hot Surfaces	Inerting by adding inert dust	Venting
Electric/Electrostatic Sparks	Dust concentration outside of combustible range	Pressure Resistant construction
Heat From Mechanical Impact		Automatic Suppression
		Good Housekeeping

	(cleaning & dust removal)
--	---------------------------

Prevention falls into two categories, preventing ignition and preventing the formation of a dust cloud. Mitigation can be achieved in several ways which either stop the explosion or relieve the pressure it causes before it can do too much damage.

### **Preventing Ignition Sources**

For most processes where the minimum electrical spark of ignition energy of the working dust is considerably greater than 10mJ, elimination of ignition sources is a satisfactory protection against dust explosions. These ignition conditions are present in the actual process and hence need to be solved in a multitude of ways.

#### **Open Flames**

Open flames are most easily avoided by rigorously enforcing a no smoking policy within the process area. Hot work must not be carried out in an area unless it, and any area that could be directly or indirectly affected, is entirely free from dust. Gas cutting torches that use excess oxygen should be avoided as they can cause ignition to be easier than it would be in air.

#### **Hot Surfaces**

Dust lying on hot surfaces can be ignited, as can dust clouds, thus leading to dust explosions. Dust lying on hot surfaces also acts as a layer of insulation which can cause equipment failure. Following these measures can help minimise the chance of ignition from hot surfaces:

- Removal of all dust before performing hot work
- Prevent / remove dust on hot surfaces
- Shield or isolate hot surfaces
- Only use electrical equipment approved for use in the presence of combustible dust
- Use equipment with low chance of overheating
- Regular and thorough inspection and maintenance procedures

#### **Self-Heating and Smouldering of Dusts**

There are several ways to minimise the chance of self-heating occurring:

- Control dust temperature, moisture content etc. before putting into storage
- Make sure no heated bodies are in contact with the stored dust
- Monitor temperature of stored dust carefully
- Monitor dust storage for combustion gases
- Inerting of bulk material with a suitable inert gas (e.g. nitrogen)

#### **Electrical / electrostatic sparks**

Electrical sparks are best minimised by observing the regulations for electrical equipment in dusty areas and ensuring that any installed electrical items comply. Making sure that workers are aware of the electrical items and how to use them safely is also wise.

Electrostatic sparks are less well understood and there are many ways to try to minimise their formation. It has been recommended that:

- Use conducting materials for plant items to avoid charge build up
- Earth any equipment that may become charged



- Earth workers if the dust is easily ignitable
- Earth coarse non-conducting powders via an earth rod through their storage vessel
- If in doubt, earth it.

### Segregation

Materials which could create an explosion risk need to be carefully managed and controlled. They need to be segregated from other materials and stored away from buildings and plant so that damage will be minimised if an explosion were to occur. Where a suitable safe distance is not possible from the storage area to work areas, they will need to be separated by compartmentalisation. The walls will need to be strong enough to withstand an explosion.

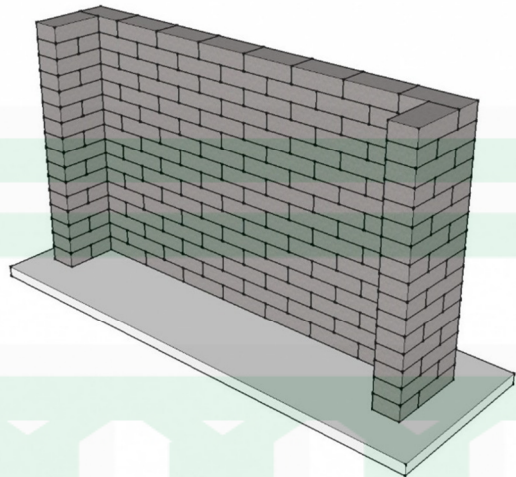


Diagram – Explosion Wall

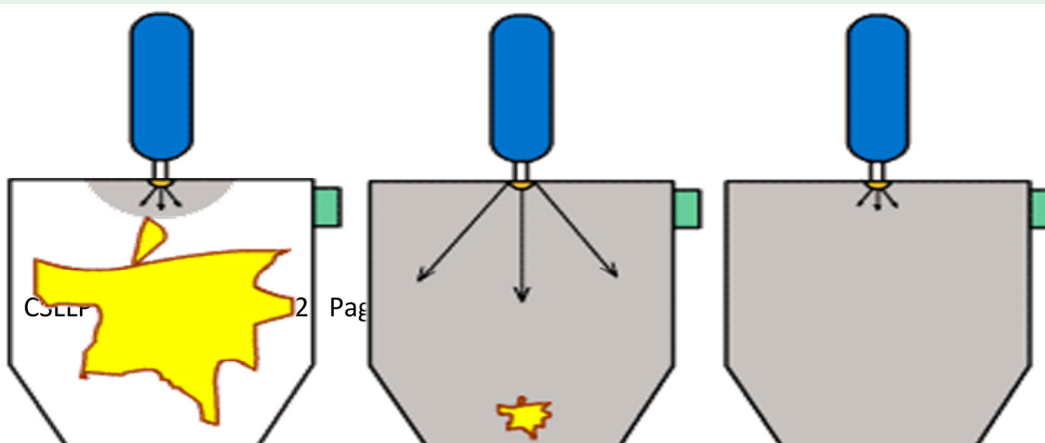
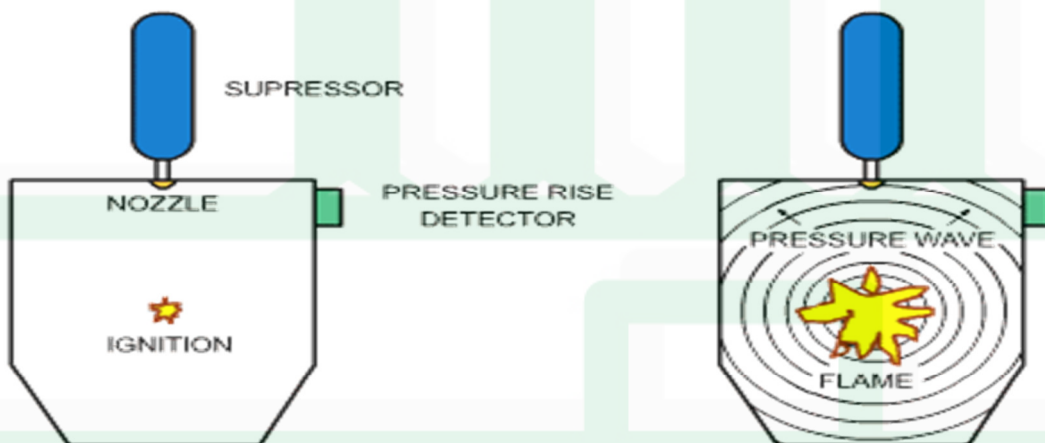
### Ensure that the dust is outside of explosible concentrations

This is extremely difficult to do in practice and is not generally used as a technique as the dust concentration in vessels is too unpredictable and very hard to measure accurately.

### Suppression - Add Inerting Dust

This method of avoiding forming explosive dust clouds is used successfully in coal mines. A layer of rock dust in the working area is entrained by the blast wave and, as it forms an incombustible atmosphere, it extinguishes the flame. This means of inertion is not usually

available due to the contamination of product that it causes.



## Explosion Isolation

Isolating an explosion can restrict the amount of damage caused in several ways. Primarily it stops the explosion from reaching other areas of the plant through the process ducts or pipes, but also it stops the possibility of flame jets that can occur at the end of long pipes and stops the pressure from the primary explosion making secondary explosions in further vessels even more violent.

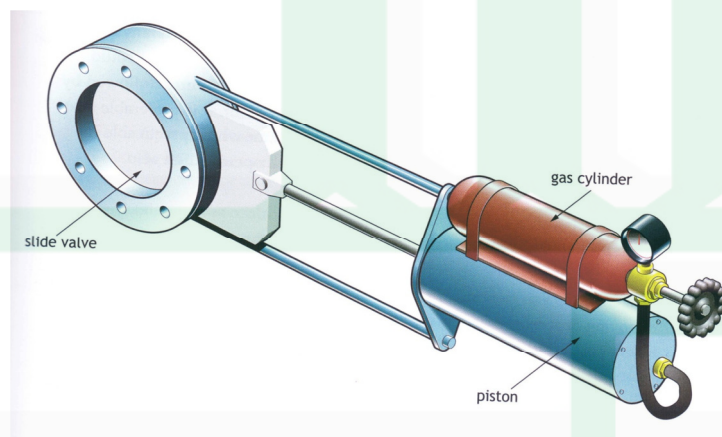
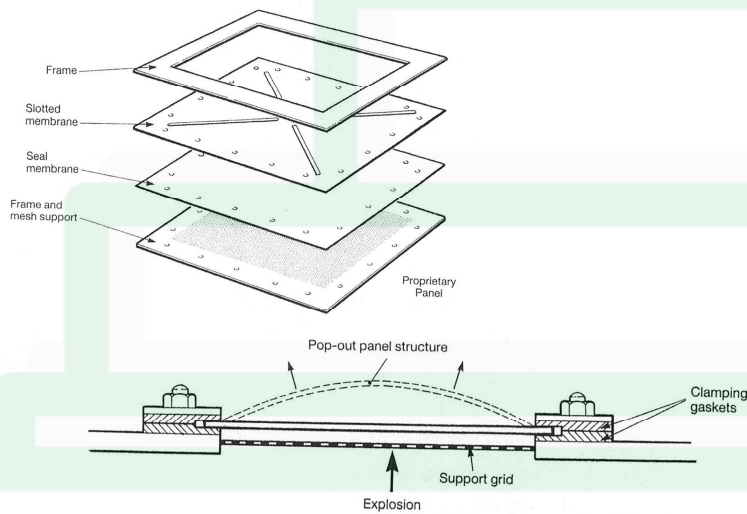


Figure 6. Mechanical Containment

### **Mechanical Containment** – This is

connected to a valve which detects any changes in pressure in the system or its pipelines. Within milliseconds of detecting the pressure the valve activates stopping the pressure wave or heat from travelling further into the system.

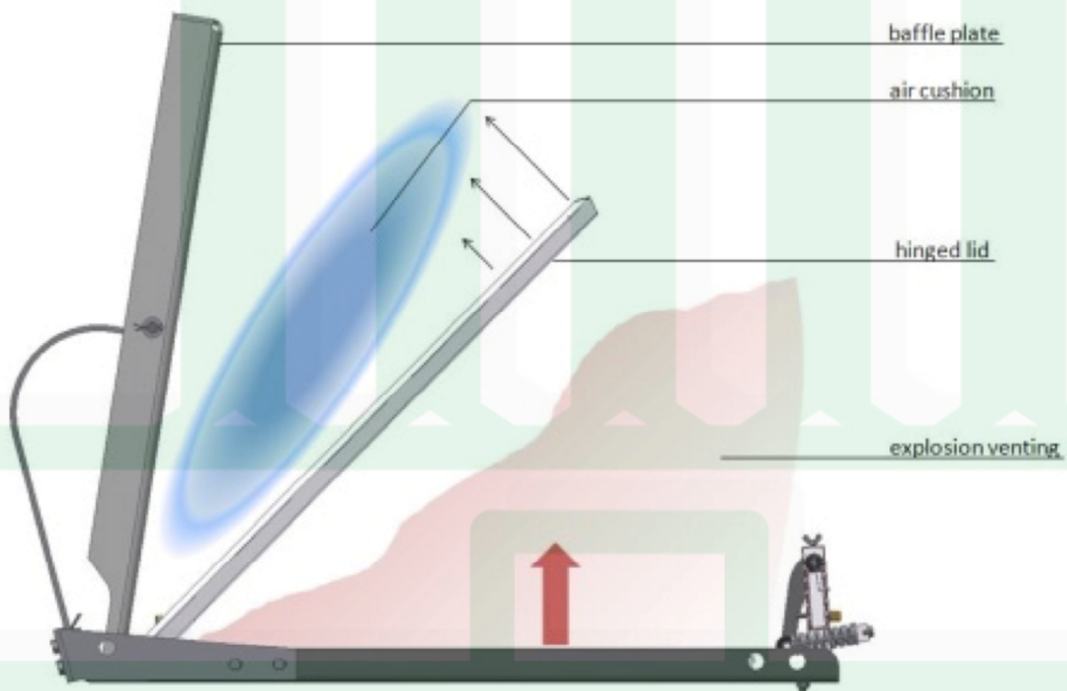
## Explosion relief panels



Explosion panels to allow the excess energy out when pressure of sufficient force occurs. They should not be located where they could fly off and hit employees.

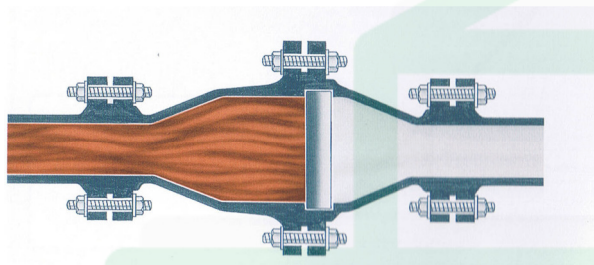
## Explosion Vent closures

Vents may need to be shut for regular use but the use of hinged flaps can allow energy from the explosion to be released where the explosion pressure is detected. It is important that the hinged vents do not themselves become projectiles.



## High speed isolation valves

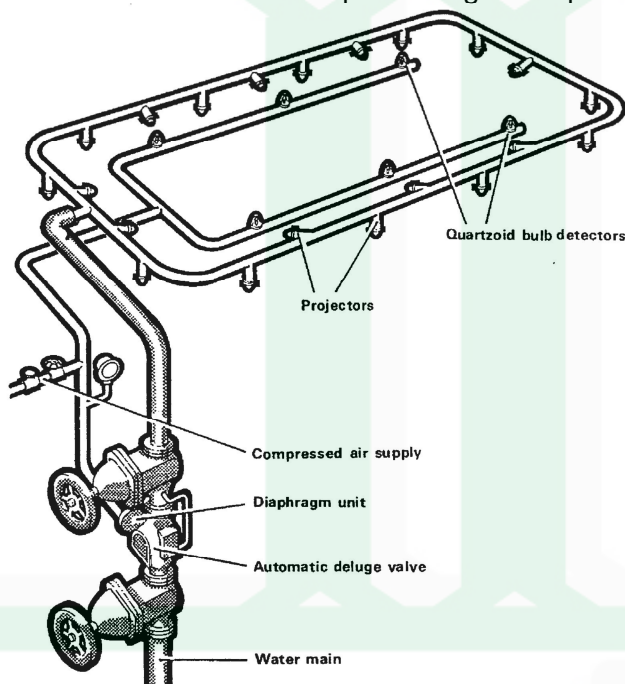
This is similar to explosion proof panels, where sections of plant containing explosive substances can be isolated from each other by automatic super quick reacting valves which operate when they detect the initial pressure wave generated by the explosion.



**Flame Arrestors** – stopping fire going through a pipeline by breaking up the energy from the explosion.



**Bursting Disc** allows excess pressure or contents to be released preventing the explosion.



**Deluge Systems to cool down LPG**

tanks

**Dust extraction local exhaust ventilation systems** – where local exhaust ventilation systems are in use they will extract dust and gases from plant. The LEV systems this needs to be designed so that it covers only one item of plant and does not connect to the ventilation systems for all the other parts of the plant as well. This will prevent an explosion in the vents of one system propagating through to the entire plant. Long lengths of ducting over 3 metres may need to be protected with explosion vents to prevent a build-up in any one area. Vents or pop out panels will also be needed by bends or changes in direction of the ducting. It is also important that the duct air velocity is sufficient to stop dust settling in the ducting where a primary explosion could release it potentially leading to a larger more devastating secondary explosion.