



TACTICAL FIREFIGHTING

*A COMPREHENSIVE GUIDE
TO COMPARTMENT FIREFIGHTING
& LIVE FIRE TRAINING (CFBT)*

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Paul Grimwood served 26 years as a professional firefighter, mostly within the busy inner-city area of London's west-end. He has also served in the West Midlands and Merseyside Brigades (UK) as well as lengthy detachments to the fire departments of New York City, Boston, Chicago, Los Angeles, San Francisco, Las Vegas, Phoenix, Miami, Dallas, Metro Dade Florida, Seattle, Paris, Valencia, Stockholm and Amsterdam. During the mid 1970s he served as a Long Island volunteer firefighter in New York State USA. His research into *international firefighting strategy & tactics* spans three decades and has resulted in over 80 published technical research papers and a book – FOG ATTACK (1992). In 1989 Paul Grimwood defined and introduced the concept of *tactical firefighting* as a means of bringing together a wide range of tactical options on the fireground. He also re-defined some already established techniques and procedures, as well as promoting research into various 'new-wave' methods being developed including 3D water-fog; PPV and CAFS. His proposal for a basic standard operating procedure (SOP) for first responders that prioritised tactical objectives in various situations was first published in 1992. This SOP was formulated with three things in mind –

1. A review into the causes of previous firefighter Line of Duty Deaths (LODD)
2. Ensuring that the wide range of tactical options are applied without conflict
3. Emphasising the 'safe-person' concept inline with recognised 'risk-based' assessment

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He is also a 'working' member of Cemac public services, a not-for-profit organisation, which advises and aids emergency services and other government organisations.



THE QUEST

The Assistant Chief Fire Officer stared me in the eyes.....'Do you honestly believe fire-fighters actually take the time to read this stuff you write?' I raised an eyebrow to this remark. It made me pause and think before answering.

'Yes sir, I really do believe there are some that have a strong desire to enhance their knowledge - to make themselves better firefighters'. He laughed.....'I wish I could share in your enthusiasm Paul but I honestly don't think they do'.

London 1993

'The lessons of others are here for you to learn'.....I said this in 1992 [4] and I say it again now. If only some of those who have died since then had read these words.....acted upon the advice.....learned to recognise dangerous conditions and circumstances.....I dedicate this book to all those brave souls and can only hope that someone, somewhere, uses this advice to good ends in future.



London 2003
Paul GRIMWOOD



II. CONTENT

I. ADAPTATIONS MADE	5
II. CONTENT	6
III. ABBREVIATIONS	8
IV. INTRODUCTION	10
V. THE BASICS OF FIRE FIGHTING	12
Fire explained	12
Explosions	18
Fire growth	22
Fire classes	26
VI. PERSONAL PROTECTIVE FIREFIGHTING GEAR	28
Structural firefighting gear	28
Fire fighting gloves	38
Comparison of NFPA and EN fire protective clothing standards	40
VII. COMPARTMENT FIRE BEHAVIOR TRAINING	45
CFBT simulator safety	49
Recent CFD research into fire simulators is flawed	52
The transition of CFBT to working structural fires	54
VIII. RAPID FIRE PROGRESS	57
Flashover	61
Flashover case histories	62
Backdraft	63
Backdraft case histories	65
Fire gas ignitions	67
Fire gas ignitions case histories	71
Website poll	75
Step & transient events	77
Firefighter's actions & warning signs	78
The under-ventilated fire	81
Flashover Phenomena – Questions & answers – Revision Aid	86
IX. 'NEW-WAVE' 3D WATER-FOG IN FIREFIGHTING	92
Flashover	94

3D water fog-applications _____	94
False assumptions _____	96
3D Offensive fog attack (Gas cooling) _____	98
Indirect (defensive) water-fog combination attack _____	100
Direct attack _____	103
Direct attack _____	104
Interaction of water sprays with flames and gases _____	105
Scandinavian research _____	108
Benefits of 3D water-fog applications _____	110
Flow-rates _____	111
X. TACTICAL VENTILATION _____	113
Natural ventilation _____	114
Positive pressure ventilation _____	116
Fire isolation (confinement) tactics (anti-ventilation) _____	117
Ventilation in practice _____	118
XI. TECHNICAL JARGON _____	120
XII. REFERENCES _____	126



III. ABBREVIATIONS

A

A	Alfa
ACT	Australian Capital Territory
AIT	Auto-ignition temperature

B

B	Bravo
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C

C	Charlie
CAFS	Compressed Air Foam System
CFBT	Compartment Fire Behaviour Training
CFD	Computational Fluid Dynamics

D

D	Delta
3D	Three-dimensional

E

E	Echo
---	------

F

F	Foxtrot
FGI	Fire gas ignition

G

G	Golf
---	------

H

H	Hotel
HRR	Heat release rate
HVG	High velocity gases

I

I	India
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J

J	Julliet
---	---------

K

K	Kilo
---	------

L

L	Lima
LEL	Lower explosion limit

M

M	Mike
---	------

N	
N	November
NSSC	Naval Sea Systems Command
NPP	Neutral pressure plane
O	
O	Oscar
P	
P	Papa
PPE	Personal protective equipment
Q	
Q	Quebec
R	
R	Romeo
RFP	Rapid fire progress
S	
S	Sierra
T	
T	Tango
TIC	Thermal Imaging Camera
U	
U	Uniform
UEL	Upper explosion limit
V	
V	Victor
VES	Vent Entry Search
W	
W	Whiskey
X	
X	X-ray
Y	
Y	Yankee
Z	
Z	Zulu



IV. INTRODUCTION

IV.1. Two tragic fires that occurred within a three-day period during February 1996, where three firefighters lost their lives in backdrafts, brought about a turning point in UK firefighting strategy. On 1st February 1996 in Blaina, Wales, a fire involved the ground floor kitchen at the rear of a two-storey house during the early hours. The initial crew of six firefighters were faced with the predicament of children reported missing and trapped upstairs. The building was heavily charged with smoke, which was seen to be issuing from the eaves on arrival. The firefighters chose to attempt the rescues first and in doing so, no *interior fire attack* or *fire isolation strategy* was undertaken. Two hose-lines (19mm hose-reels) were laid to the structure but neither was brought into use prior to the backdraft occurring five minutes after arrival. Flames were seen issuing from the rear kitchen window and the compartment fire had developed to a post-flashover stage. However, a distinct *gravity current* [20] was in progress with heavy volumes of thick black smoke exiting at the front entrance doorway. A fierce backdraft took the lives of two firefighters as the fire developed unchecked for several minutes.

IV.2. Just three days later another firefighter (female) was killed by an ensuing backdraft that occurred in a large super-market in Bristol. As four firefighters (including the victim) entered through the main entrance to tackle the fire the heavy black smoke layer was seen to be in motion, continually rising and falling. Just five minutes after entry an intense 'howling wind' was seen to enter the main entrance doorway causing flames to bend inwards. The resulting ignition of the fire gases moved across the wide expanse of the store both under and within the suspended fibre-board ceiling at an estimated five metres per second (high velocity gas combustion). The accompanying pressure wave knocked one firefighter off his feet. Should firefighters have entered these conditions in the first place? The continuous rise and fall of the smoke layer is most likely a result of the *pulsation cycle* caused by brief ignitions (oscillatory combustion) in the fuel-rich gas layers. This may also be linked to the 'puffing' phenomena noted by Sutherland [15]. As these ignitions occur intermittently the repeating thermal expansions of fire gases may cause the smoke interface to rise and lower and such a process must be viewed as a classic warning sign for backdraft.

IV.3. Sadly, just four years before this fire I had offered this warning [4] – 'The firefighter should attempt to seek out any structures in his/her locality where fibre insulating boards are used to any great extent and make a mental note of the back-

ulating boards are used to any great extent and make a mental note of the back-draft potential should a fire occur'....

IV.4. These two incidents were clearly seen to promote change in the way UK firefighters were to approach compartment fires in future. There was an immediate review of how national training programmes could be adapted to educate firefighters in the important aspects of compartment fire behaviour and flashover related phenomena. Inline with the philosophy of *safe-person* concepts and *risk assessments* at fires a new approach was formulated based upon the original Swedish training model (CFBT) I had introduced in the UK in 1991 [4]. It had been under similar circumstances that the Swedish fire service had embarked upon their national CFBT training project throughout the 1980s and several other countries were to realise the benefits of this 'new-wave' approach to training following similar LODD losses.



V. THE BASICS OF FIRE FIGHTING

IV.1. Before we start the review of the tactical aspects of firefighting we need to make sure that all the basics are understood. This section will therefore just be a reminder to some and a quick introduction to others. Nevertheless it is important to have some background knowledge of fire science before tackling the other aspects of tactical fire fighting [1].

Fire explained

IV.2. Several factors need to be present before combustion can occur. The first requirements are fuel and oxygen. **Fuel** can range from a forest to home furniture or from crude oil to gasoline. A fuel can present itself in any physical form i.e. gases, liquids or solids can burn.

IV.3. The **oxygen** required usually originates from the surrounding air. The oxygen concentration in normal air varies around 21%. If the oxygen concentration is lowered the combustion will be hindered and eventually stop. If, however the oxygen concentration is raised the combustion reaction will be more vigorous. An object can become saturated with oxygen and suddenly ignite when an ignition source is presented. Such a situation can occur in hospitals or other environments where oxygen is used. Another source of oxygen is the one contained in the molecule. In organic or inorganic peroxides the oxygen present in the molecule can sustain the combustion. This effect is used in gunpowder or in fireworks.

IV.4. In scientific terms one can describe a fire as being an **exotherm reaction between fuel and oxygen**. This means that the reaction produces energy, ie heat. Next to heat a fire generally produces light, combustion gases and soot.

IV.5. To initiate a fire a certain amount of **energy** is needed. One can visualise this parameter by referring to a simple test with gasoline and diesel fuel, a match has enough energy to light the gasoline but in the diesel fuel the match extinguishes. In chemistry the energy needed to start a reaction is called the **activation energy**. Chemical reactions need to surmount this activation energy before the reaction can

take place (enthalpy, thermodynamics). In a fire, the initial energy sources that cause the fire can be multiple e.g. a spark, an open flame, electricity, sunlight... Once the reaction is started however it generates more than enough energy to be self-sustaining, a **chain reaction occurs**. The energy given off in excess can be seen as light and heat generated by the fire.

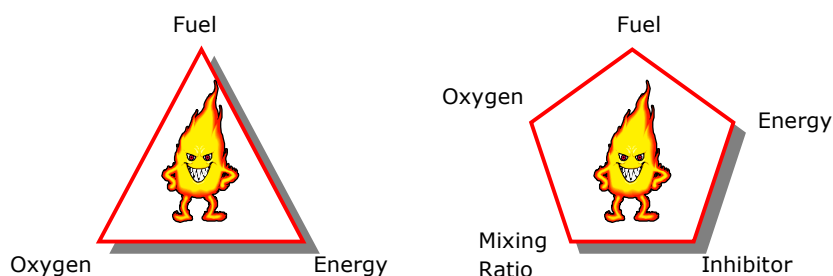


Fig. V.1 Fire triangle

IV.6. The energy liberated in the combustion process causes the **pyrolysis** and the evaporation of the fuel. In the pyrolysis process the chemical composition of the fuel is broken down into small molecules. These molecules evaporate and react with the oxygen in the air. Stoichiometric or complete combustion means that just enough oxygen molecules are present, to oxidise the fuel molecules. When hydrocarbons undergo complete combustion only water and carbon dioxide would be formed. Such conditions are however rare, therefore we need to note that other **combustion products** will also be formed. In the case of hydrocarbons the formation of carbon monoxide and soot increases with the oxygen deficiency. If other types of fuel are burned other toxic products are formed based on their molecular composition e.g. hydrogen chloride, hydrogen cyanide, hydrogen bromide, sulfur dioxide, isocyanates, ... A non-limitative list of these products and their possible origin is given in Table V.1.

IV.7. Combining the factors that we already mentioned above one can create the fire triangle, which symbolizes all the factors needed for combustion. However next to fuel, oxygen and energy one should also note the **mixing ratio** between oxygen and fuel. A log of wood will not sustain a fire if it's lit with a match, an amount of wood shavings however will. There is a better mixture between the fuel and the air, which favors the combustion. A much larger surface of the fuel is in contact with the air thus a greater **reaction surface** is offered.

IV.8. A further factor in the combustion process should be added which is called the **inhibitor**. In a combustion process a chemical chain reaction occurs, radicals of fuel react with radicals of oxygen heat and combustion products are formed. If one adds

a chemical molecule (inhibitor), which reacts with those radicals without sustaining the combustion process one can stop the fire. This principle is used in dry chemical extinguishers which contain e.g. potassium or sodium bicarbonate or in the now banned halon extinguishers. A catalyst has the opposite effect of an inhibitor, a catalyst is a substance, which promotes the reaction (without being altered or used in the reaction) e.g. adding metal shavings to oil rags aids their combustion. All five factors concerned in the combustion process are shown in figure V.1.

Toxicant	Origin	Toxicological effect
Carbon dioxide	Common combustion product	Not toxic, can deplete available oxygen
Carbon monoxide	Common combustion product	Asphyxiant poison
Nitrogen oxides	Common combustion product Cellulose nitrate, celluloid, textiles	Respiratory irritant
Hydrogen cyanide	Wool, silk, polyacrylonitrile, nylon (polyamide), polyurethanes	Asphyxiant poison
Hydrogen sulfide	Rubber, crude oil, sulfur containing compounds	Toxic gas, repugnant smell
Hydrogen chloride	Polyvinylchloride, some fire retardant materials	Respiratory irritant
Hydrogen bromide	Some fire retardant materials	Respiratory irritant
Hydrogen fluoride	Fluoropolymers	Toxic, irritant
Sulfur dioxide	Materials containing sulfur	Strong irritant
Isocyanates	Polyurethane polymers	Respiratory irritant
Acrolein and other aldehydes	Polyolefins, ... common product in combustion	Respiratory irritant
Ammonia	Wool, silk, nylon, melamine, normally only in small concentrations at building fires	Irritant
Phosgene	Chlorinated salts, some chlorinated hydrocarbons	Toxic, irritant, skin burns
Polyaromatic hydrocarbons	Common products in combustion, e.g. in soot	Long term effects
Dioxins	Combustion of PCB containing recipients, ...	Long term effects
Brominated dioxins	Some brominated fire retardants	Long term effects

Table V.1 Common combustion products

Ignition source	Temperature °C
Match	800
Match upon lighting	1500
Cigarette	300-400
Burning wood	1000-1400
Candle	700-1400
At 15 cm from the candle	200
Gasflame	1000-1500
Electric arch	4000
Glow-lamp	170-200
Alcohol flame	1200-1700
Oxy-acetylene cutter	2000-3000

Table V.2 Approximative ignition source temperatures

IV.9. The **ignition temperature** of a substance (solid, liquid or gaseous) is the minimum temperature to which the substance exposed to air must be heated in order to cause combustion. The lowest temperature of a liquid at which it gives off sufficient vapour to cause a flammable mixture with the air near the surface of the liquid or within the vessel used, that can be ignited by a spark or energy source is called the **flashpoint**. Some solids such as camphor and naphthalene already change from solid to vapour at room temperature. Their flashpoint can be reached while they are still in solid state. The lowest temperature at which a substance continues to burn is usually a few degrees above its flashpoint and is called **fire point**. A specific ignition temperature for solids is difficult to determine because this depends upon multiple aspects such as humidity (wet wood versus dry wood), composition (treated or non-treated wood) and physical form (dust or shavings or a log of wood). Common ignition sources are noted in table V.2.

IV.10. The **auto-ignition temperature** is the lowest temperature at which point a solid, liquid or gas will self-ignite without an ignition source. Such conditions can occur due to external heating - a frying pan that overheats causing the oil to auto-ignite, an exhaust-pipe from a car driving over dry grass or straw can cause it to auto-ignite- or they can occur due to chemical or biological processes - a silo fire can occur because of the biological processes in humid organic material. The auto-ignition temperature of substances exceeds its flashpoint. The auto-ignition temperatures of common solids are shown in table V.4.

Type	Auto-ignition temp. °C	Flash Point °C	Explosion Limits (vol. %)	Vapour density (in relation to air)
Acetone	600	-20	2-13	2
Benzene	500	-14	1,4-7	2,7
Diesel fuel	250-400	40-100	0,5-7	6-8
Ether	190	-41	1,7-48	2,6
Ethanol	460	10	3,3 -19	1,6
Frying fat	350	+/- 250-380	-	-
Gasoline	260	-45 to -18	1-7	3,5
Hexane	225	-22	1,2-7,4	3
Methanol	480	-6	6-36	1,1
Xylene	480	20-25	1-6	3,7

Table V.3 Properties of liquid fuels

IV.11. The flash points, auto-ignition temperatures, the explosion limits and the vapour densities of some common liquids are shown in table V.3.

Solids	Auto-ignition Temperature °C
Polyvinylchloride (PVC)	470
Nylon	450
Polyethylene (PE)	350
Polystyrene (PS)	490
Polyurethane (PUR)	420
Polycarbonate (PC)	570
Teflon	600
Wood	250-350
Paper	200-350
Hay	230
Straw	240
Wool	570
Matches	160-180
Coal	+/-350
Charcoal	140-300
Cotton	300-400

Table V.4 Approximative auto-ignition temperature of solids

IV.12. When considering vapour or gas explosions or fires it is important to look at their **vapour or gas density** relative to air. In this way air has a coefficient of 1. A substance having a relative vapour of 1.5 will be one and a half times as 'heavy' as air, while a substance with a relative vapour density of 0.5 is half as 'heavy' as air. Heavier than air gases or vapours stay low to the ground or enter lower-lying struc-

tures such as sewers or cellars. Via this downward spread a localised incident can cause effects at greater distances. To illustrate the effect of vapour density a test with a gasoline soaked cloth, a candle and a trough (as channel) can be performed. When you place the burning candle at the lower end of the tilted trough and you place the cloth at the upper end, gasoline vapours will flow downward through the trough, where they will ignite and flash back to the top of the trough.

IV.13. If you look at the vapour densities mentioned in table V.3 you 'll see that all of them are heavier than air. Only methanol's vapour density approaches that of air. Looking at table V.6 you can see that few gases have a relative density lighter than air. 'Lighter than air' gases have an advantage of self-dissipation, if the release is outside. Caution should of course always be taken.

IV.14. Next to vapour pressure when handling liquids their '**volatility**' is also important. Volatility refers to how readily a liquid will evaporate. The volatility of a product is closely linked to its boiling point. The higher the **boiling point of a liquid** the harder it will be for the liquid to evaporate. An amount of highly volatile fluid spilled will be of greater concern than the same amount of low volatile liquid, because of its ease to find an ignition source or because of the toxicity of the vapours. A more scientific term for volatility is the saturated **vapour pressure** of a liquid at a certain temperature, this is the pressure exerted by the vapour of at that temperature. The larger the vapour pressure of a liquid the more vapour is produced. The vapour pressure has an impact on the extent and area of the gas/air release. The vapour pressure of a liquid rises with the rise in temperature. The boiling point of a liquid is defined as the temperature at which the vapour pressure reaches 1 atmosphere. The lower the boiling point, the greater the vapour pressure at normal ambient temperatures and consequently the greater the fire risk. Vapour pressures at 20°C and 1 atmosphere are mentioned in table V.5.

Substance	Vapour pressure
Water	25 mm Hg
Ethanol	40 mm Hg
Gasoline	180 mm Hg
Acetone	180 mm Hg
Ethyl ether	440 mm Hg

Table V.5 Vapour pressures of liquids

Explosions

V.15. In case of a gas-air or a vapour-mixture an explosion can only occur in certain cases. An underground tank half full or near full with gasoline will not explode due to an above ground fire. The amount of vapour (density greater than air) present will cause a too rich mixture which will not ignite. If however the tank is near empty, air will already have entered the tank; otherwise the resulting vacuum would damage the tank (implosion). The amount of liquid left will dry out and gradually disperse, not generating enough vapour to reach a rich atmosphere. A spark or flame entering the tank at that point could cause the explosion. Modern underground gasoline tanks are fitted with a wire mesh flame guard at the air entry, hindering the introduction of an energy source. The range at which a vapour or gas can ignite and explode is known as the **explosive range (flammable range)** (figure V.2). The limits of the range are known as the **lower explosion limit (LEL)** and the **upper explosion limit (UEL)**. A mixture of flammable gas in air below the LEL will not ignite when brought in contact with an ignition source, it is said it's too 'lean' to ignite. A gas-air mixture above the UEL will also not ignite; it is too 'rich' in mixture. Only a few materials like ethylene oxide are able to decompose and burn when no oxygen is present.

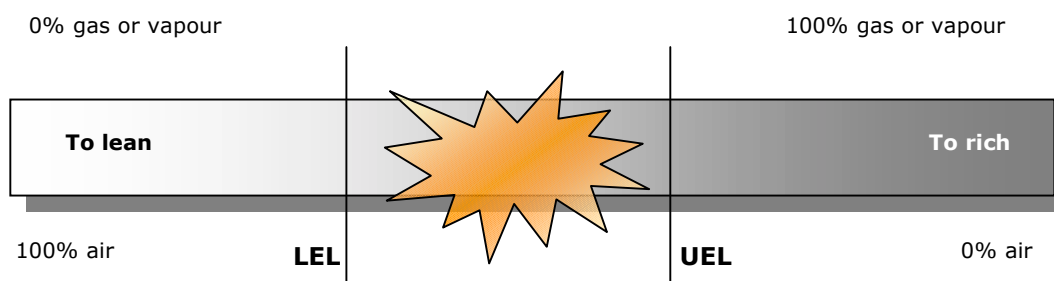


Figure V.2 The explosive range

V.16. A mixture of vapour or gas with air, within the explosive range, will ignite if the energy source presented has enough energy. The **minimal ignition energy**, which is the minimal amount of energy that is needed to set-off the explosion can be found in literature. The minimal ignition energy of a gas or vapour/air mixture varies between 0.01 and 0.30 milli joule. Gases like carbon monoxide, carbon sulfide, acetylene, ethylene oxide, hydrogen... have a minimal ignition energy below 0.1 milli joule. Sparks caused by normal tools mostly cause an energy above 0.1 milli joules. The energy given off by a flashlight, a cell phone, a doorbell... may be enough to cause the explosion. By limiting the temperature, or the energy of an appliance, or

by isolating the gases and vapours, one can build explosion proof equipment. Care should however be taken because European and American codes on what is 'explosion-proof' differ. Depending on existing safeguards fitted to an appliance one may use it safely in some conditions, and with some gases, although not in others; different classes of explosion proof equipment exist. Care should be taken when procuring such equipment.

Gases	LEL	UEL	Relative density
Natural gas	4	15	0,55
Acetylene	1,5	82	0,91
Butane	1,5	8,5	2,01
Propane	2,1	9,5	1,56
Hydrogen	4	75,6	0,07
Ammonia	16	25	0,58
Ethylene oxide	2,6	100	-

Table V.6 Explosive range of gases

V.17. A rise in ambient temperature causes the explosive range to broaden, enlarging the concentration range where an explosion can occur. This is shown in figure V.3. Next to a rise in temperature, an increase in oxygen concentration can also widen the explosive range of a substance.

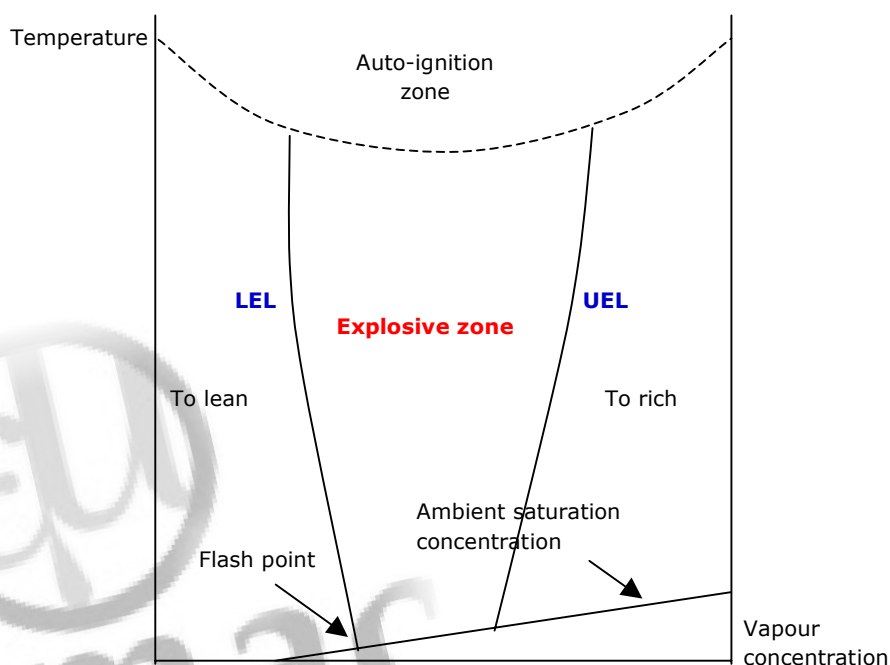


Figure V.3 Effect of temperature on the explosive range

V.18. The ferocity of an explosion depends on the speed of the flame front. If the flame speed remains lower than 340 m/s the explosion is called a **deflagration**. If this speed exceeds 340 m/s -and they can reach up to 1800 to 2000 m/s- one calls it a **detonation**. In laymans terms the differences are defined in being faster or slower than the speed of sound, respectively **supersonic** and **subsonic**. After the ignition the flame front passes upstream through the flammable mixture, propagated by the volume expansion of the exotherm combustion reaction. This volume expansion causes a pressure surge, which compresses the flammable mixture ahead of the flamefront. Due to the high temperature of the flame front, the radiation and compression cause the auto-ignition of the flammable mixture. In the case of a detonation the pressure wave and the flame front coincide causing supersonic speeds to be reached. A real detonation in gas-clouds is rare, except for explosive substances such as hydrogen or ethylene oxide. Hindering objects can however accelerate a deflagration to a detonation or near detonation.

V.19. Flammable dust from metals such as aluminium, or that of organic compounds such as sugar, milkpowder, grain, plastics, pesticides, pharmaceuticals, wood-dust etc... can explode. A dust explosion is an explosive combustion of a mixture of flammable dust and air. In other words it is a combustion reaction in a mixture of finely mixed dust and air, which starts due to a local heat rise and propagates itself through the complete mixture. A dust explosion is generally considered as a deflagration. The dust explosion range is more abstract than that of gas explosion because it is difficult to determine in real life. Next to the **concentration of dust in air** the explosion range depends on

- **Particle size**

The finer and more irregular of form the more explosive the dust (greater reaction surface), in reality a dust cloud is build of a mixture of different particle sizes.

- **Moisture content**

The larger the moisture content the more difficult the explosion becomes. The finer and drier the more explosive the dust becomes.

- **Hybrid mixtures**

The presence of flammable volatiles in the dust, as in polystyrene granules, in extracted soya beans or other seed waste or even wood-dust containing paint or varnish, can promote an explosion. In this case the ignition energy required is less.

- **'Dwell' time**

The time the dust remains in the air, and thus explosive, depends on its density.

- **Oxygen concentration**

The higher the oxygen concentration, the easier the combustion reaction.

- **Turbulence**

Is a factor which can speed up the flame front but it can also hinder the explosion.

- **Temperature**

The higher the ambient temperature the easier the ignition.

- **Inert particles**

The presence of inert particles as water vapour or inert dust slows the reaction.

V.20. As a **rule of thumb** guideline - 'If you are unable to see your hand you're your arm is fully stretched from the body, due to dust, the situation should be considered as explosive'.

V.21. 'A dust explosion can cause secondary explosions'; the fact that a primary limited dust explosion can cause further explosion makes dust explosions very deceiving. A small explosion in a room can cause dust, which had settled on surfaces to swirl, allowing it to be ignited by the primary explosion. In this fashion a chain reaction can occur which can continue throughout an entire installation/compartment if sufficient dust is present.

V.22. The ignition of a dust-air mixture requires **much higher ignition energy** than a gas-air mixture (around 10 milli Joule, hybrid mixtures require less). The above factors all influence the sensibility to ignition of the dust-air mixture. As common ignition sources one notes

- Open fire: welding, smoking, an earlier fire!!!
- Mechanical sparks or friction-heating: a transport rail guide which jams
- Hot surfaces: glow-lamp
- Spontaneous heating: due to biological or chemical processes
- Electrical sparks

V.23. The ignition temperature of common dust mixture lies around 330-400°C. This can easily be achieved by industrial hot surfaces. A layer of dust lying on a hot surface can start smouldering because of the upper layers insulate the lower ones causing the temperature to rise. The thicker the layer of dust the lower the temperature required to cause smouldering. A layer of 5 mm of flower only requires a temperature of 250°C to begin smouldering in less than 2 hours. Such a temperature is easily attained by the surface of a glow-bulb. Regular cleaning (up to 1mm of dust can be tolerated) of an installation is therefore a must.

V.24. When being called out to a fire in an installation where flammable dust is present one should beware of the possibility of a dust explosion and request information on the hazard. Check if the rooms are free of dust (less than 1mm of settled dust on surfaces). Use the rule of thumb (1 m visibility?). If the risk of a dust explo-

sion exists treat the situation as you would for a potential gas explosion. Do not enter rooms; limit the crew; fight fire from cover; never use a direct jet because it can stir the dust; if possible prepare a water monitor; seek escape routes. Specific advice when tackling the dangers of a dust explosion: wet the dust to prevent it from swirling, preferably using class 'A' fog or mist; preventive wetting of filters and transport systems should be taken in consideration; sometimes silo fires can be extinguished using dry ice, by lowering it down with a rope using a special knot. Take care of explosion vent openings. When arriving after a dust explosion has occurred: extinguish smouldering dust with mist; request information; be aware of structures which remained closed such as transport systems or filters, if possible wet them using fog.

Fire growth

V.25. Now back to regular fires. The energy liberated during combustion can radiate back on the fuel substance, where it causes pyrolysis and evaporation of the fuel. It can also aid further pyrolysis of the products in the gasphase. The heat liberated by the fire also causes the surrounding materials to warm up. The **heat transfer** is accomplished by three means, usually simultaneously: conduction, radiation and convection.

V.26. **Conduction** is direct thermal energy transfer due to contact. The heat on molecular level means that the kinetic energy of molecules, their movement increases. This energy is then passed on from one molecule to the next. Materials conduct heat at varying rates. Metals are very good conductors while concrete and plastics are very poor conductors, hence good insulators. Nevertheless a fire in one sidewall of a compartment will result in the transfer of heat to the other side of the wall by conduction. If a metal beam passes through the wall this effect will be even larger. In ship fires, where most the walls are of metal, removing materials from the wall close to the burning compartment is necessary to limit the fire spread.

V.27. **Radiation** is electromagnetic wave transfer of heat to an object. Waves travel in all directions from the fire and may be reflected or absorbed by a surface. Absorbed heat raises the temperature of the material causing pyrolysis or augmenting the materials temperature beyond its ignition point causing it to ignite. Radiation from a fire plume is one of the major concerns when limiting a fire in an oil tank field, cooling of the tank on fire and the surrounding tanks is necessary to gain the time needed to mount an adequate foam attack.

V.28. **Convection** is heat transfer through a liquid or gaseous medium. This transfer is caused by density difference of the hot molecules compared to the cold ones. Hot air, gases expand and rise. Convection normally determines the general direction of the firespread. Convection causes fires to rise as heat rises.

V.29. Radiation, convection and conduction next to flame contact consist of normal **fire growth**. Burning embers carried by the wind, debris falling, breakdown of recipients containing flammable liquids or gases or the melting of lead pipes or plastics can cause firegrowth in an unforeseen direction.

V.30. Normal fire spread, once it breaches the compartment, is known as the **cube model** (fig. V.4). If all the compartment walls are equal, the first one breached will be the ceiling due to the exposure to the rising heat. A less likely fire spread will be the horizontal one, breaching the walls. And an even less probable fire spread will be the downward spread through the floor. All depending of course on the materials the compartment boundaries are made of.

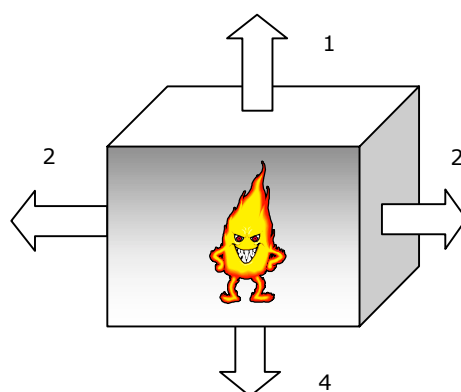


Figure V.4 Cube model of firespread

V.31. The temperature versus time plot of a normal compartment fire is shown in figure V.5. Three different fire phases can be distinguished namely the growth phase, the steady state phase and the decay phase. The early stage of a fire during which fuel and oxygen are virtually unlimited is the **Growth Phase**. This phase is characterized by an exponentially increasing heat release rate. The middle stage of a fire is the **Steady State Phase**. This phase is characterized by a heat release rate, which is relatively unchanging. Transition from the Growth Phase to the Steady State Phase can occur when fuel or oxygen supply begins to be limited. The final stage of a fire is the **Decay Phase**, which is characterized by a continuous deceleration in the heat release rate leading to fire extinguishment due to fuel or oxygen depletion.

V.32. **Flashover** normally is the culmination of the fire growth phase and occurs when the ceiling temperature reaches around 500-600°C, depending on the materials

present in the compartment and the geometric arrangement. After flashover, room temperature rapidly increases to reach up to 1000°C.

V.33. The same diagram can be redrawn more schematically to visualize fire growth in relation to time (figure V.6). In the first phase of the fire, shortly after the fire's ignition, the fire growth is limited to the object on fire and its immediate surroundings. The fire heats up the room slowly. Once however the fire gets a grip on its surroundings the fire shows a steep progress rate. All the objects in the room suffer from the intense heat radiating from the fire but mostly from the combustion gases and smoke produced, causing them to initiate pyrolysis, to evaporate or to heat up beyond their ignition point. At a certain point this effect causes **flashover**, to engulf the whole room in flames and thereby rapidly spread the fire until it reaches a **ventilation-controlled state**. At this point the fire growth slows, limited by the oxygen deficiency. If however the fire breaches the compartment walls, the new source of fuel and oxygen again allows a steep rate of fire growth.

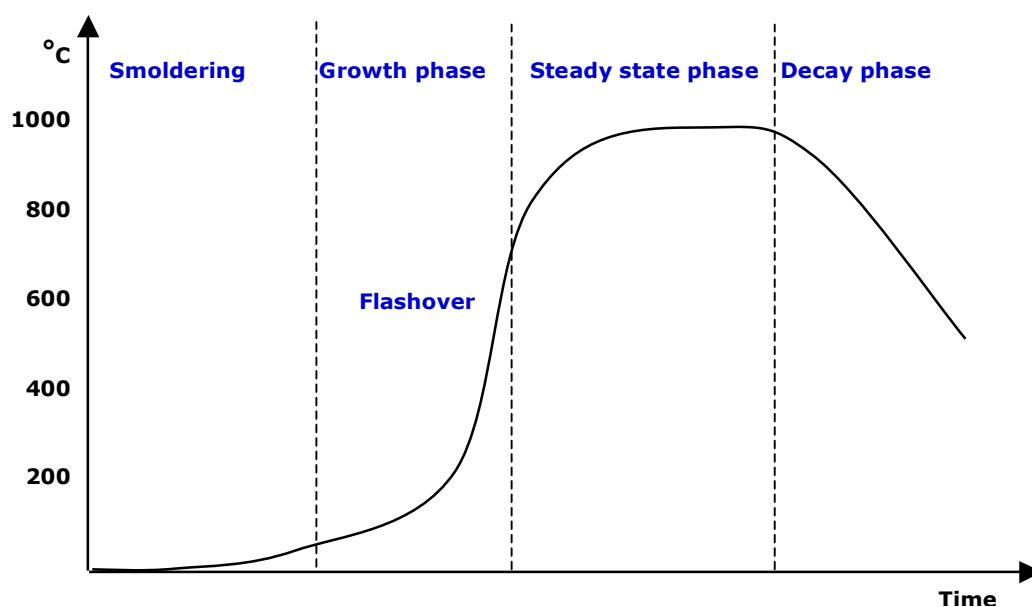


Figure V.5 Fire temperature versus time

V.34. Using this data to harness **fire prevention** concepts, one can easily deduce safeguards, which can be taken at different levels of fire growth. Preventing ignition can be done by eliminating energy or ignition sources (e.g. a smoking ban) or by removing/treating any easily ignitable materials (e.g. the use of flammable materials in upholstery etc). The fire growth phase can be slowed by installing automatic fire suppression; an automated fire detection system followed by an in house first response; by using materials which limit fire spread; by installing automated smoke and heat extractors or by the storage of flammable liquids in fire safe closets etc... The breach of the fire compartment can be slowed by using special fireproof doors or by using building materials with high fire resistance. Normally the breach of a

compartment can also be hindered by the intervening fire department, which at this point in time should have arrived on the scene.

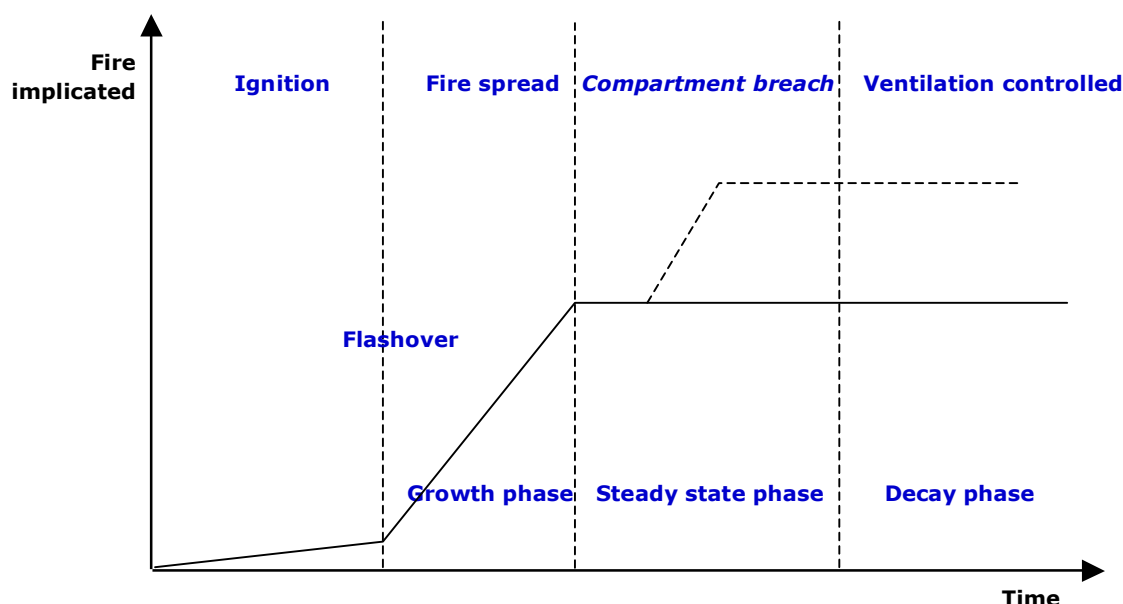


Figure V.6 Fire growth versus time

- V.35. Depending on the inflow or the amount of oxygen present in a compartment a beginning fire can evolve to flashover as described above but it may also slowly die out as a result of the lack of oxygen. This lack of oxygen inflow in a compartment is mostly due to modern heat saving construction utilising double or even triple glazing, which often maintains its structure so well during a fire. Furthermore, modern energy efficient doors and windows do not allow any air-drafts. Consequently in **modern buildings** a fire can smoulder due to the lack of oxygen producing large amounts of carbon monoxide and pyrolysis gases. Due to the high thermal insulation of modern buildings a major heat build-up may occur, even from a small fire. Due to the sudden opening of a door or window the sudden intake of oxygen enriched air can cause the combustible gases to explode in what is called a **back-draft**. This is not only a dangerous situation for intervening fire crews but it can be even more dangerous to an untrained occupant of the premises. In table V.7 we have grouped the warning signs of flashover and backdraft.

FLASHOVER	BACKDRAFT
<ul style="list-style-type: none"> ▪ Flames in the overhead, rollover ▪ Very high temperature, which forces you to crouch low ▪ Smoke layer is banking down 	<ul style="list-style-type: none"> ▪ Little or no visible flames ▪ High room temperature ▪ Blackened, windows with oily deposits ▪ Pulsating smoke from eaves ▪ Upon opening air rushes in ▪ Blue flames seen in the overhead ▪ A smoke-layer seen to be constantly rising and falling

Table V.7 Signals of Flashover and Backdraft

Fire classes

V.36. Fires are divided in classes depending on the materials that burn. Commonly the classes A, B, C and D are recognized. **Class A fires** are fires in ordinary solid combustible materials such as bedding, mattresses, paper, wood, ... Class A fires must be dealt with by cooling the fire below its ignition temperature. Most class A fires leave embers, which are likely to rekindle if air comes in contact with them. A class A fire should therefore not be considered extinguished until the entire mass has been cooled thoroughly. Smothering a class A fire may not completely extinguish the fire because it doesn't reduce the temperature of the embers below the surface.



Fig. V.7 The 3 most common fire classes symbols

V.37. A **class B fire** are those that involve flammable liquids such as gasoline, kerosene, oils, paints, tar, ... and other substances, which do not leave embers or ashes. Class B fires are best extinguished by providing a barrier between the burning substance and the oxygen. Most applied are chemical or mechanical foam. Depending on the type of substance, apolar (e.g. hydrocarbon) or polar, water soluble (e.g. alcohol), an adapted type of foam concentrate should be used. Extinguishing a small liquid fire with a water mist is also possible. This cools the liquid below its fire point or even flash point and puts out the flames; if however the heat source is not removed the fire can reignite.

- V.38. **Class C fires** involve gases like natural gas, propane, butane etc. Extinguishing such a fire equals shutting of the source of the gas. Putting out the flames without being able to reach the valve creates a dangerous situation where a spark can cause an explosion.
- V.39. **Class D fires** involving burning metals are less common. Combustible metals include sodium, potassium, lithium, titanium, zirconium, magnesium, aluminium, ... and some of their alloys. Most of the lightweight metal parts in cars contain such alloys. The greatest hazard exists when they are present as shavings or when molten. Fighting such fires with water can cause a chemical reaction or it can generate explosive hydrogen gas. Special extinguishing powder based on sodium chloride or other salts are available. Extinguishment by covering with clean sand is another option.
- V.40. **Class E fires** concern electric fires aren't really considered a true fire class. Electricity doesn't burn but e.g. a short circuit can cause a fire of the insulating material around the wires, which can propagate the fire. Extinguishing electrical fires is best done by using carbon dioxide or by using a powder extinguisher. The use of water is not advised, certainly not as a direct jet on apparatus remaining live. Water spray or mist might be used but with **great caution**. Due to the air between the water droplets a much larger resistance exists than when using a direct jet. Where possible the electrical supply should be isolated prior to applying water in any form.
- V.41. **Class F fires** are sometimes added for educational purposes. This is also not a true class but is used to emphasise the dangers when combating fires of molten fats or tars. The class F or Fat fires are particularly dangerous when tackled with water. The molten fat is lighter than the water, which sinks, heats up and vaporises, expanding enormously. As a result the molten fat is pushed out in very tiny droplets, which allows easy contact with the oxygen and causes the fire to produce a flame ball up to several meters high.

VI. PERSONAL PROTECTIVE FIREFIGHTING GEAR

- VI.1. Fire fighting gear has already come a long way, from the leather jacket to the modern synthetic materials fire-fighting gear is made of. This chapter doesn't try to give a complete overview of the available materials and the latest technology; it however tries to focus on some common hazards that are still sometimes overlooked. This chapter [2] was written using website data from fire departments and suppliers (Morning Pride, Lion Apparel). More information can be found on their websites.
- VI.2. When writing this would hope that all firefighters are provided with a full range of protective clothing meeting local minimum standards, including outer and under layers, gloves, boots, hood and helmet, eventually complemented with breathing apparatus. No firefighter should enter a fire building or training fire without these basics.

Structural firefighting gear

- VI.3. Entering a building on fire without protective clothing can lead to serious body burns as shown in Photo VI.1. No firefighter should attempt to enter a building on fire under any circumstances if not wearing his/her protective clothing.



Photo VI.1 Firefighter exposed to near flashover conditions without structural firefighting gear, heavy burns are visible on the back

Source : Domke, Jürgen. Universelle Feuerschutzkleidung für die öffentlichen Feuerwehren. Hintergründe, Entwicklungen, Leistungsmerkmale im Überblick, BRANDSchutz/Deutsche Feuerwehr-Zeitung 2/1998, 133-159. (www.atemshutzunfaelle.de)

- VI.4. **Burns are a function of time and temperature.** The higher temperature of the heat source and the longer the exposure time the greater the severity of the burns. First-degree burns occur when skin temperature reach 48°C; second-degree burns require 55°C skin temperature and above 55°C third degree burns can occur. Instantaneous skin destruction happens at 72°C degrees skin temperature. A simple wastebasket fire within the confines of a compartment can lead to temperatures capable of causing severe skin burns.

VI.5. Structural firefighting clothing is tested at high temperatures by TPP tests. However most burn injuries occur at far lower temperatures than those recorded at TPP levels and without direct flame contact. Heat can build up inside your clothing at relatively modest ambient conditions. This phenomenon, known as '*stored energy*', can lead to serious burn injuries, often without warning. This phenomenon is enhanced by the presence of water. Water is a very good conductor. Compare this with taken a hot pan from the stove, using a dry potholder this is feasible, using a wet potholder it becomes more difficult.

VI.6. *Water* can even cause a contact burn injury at temperatures that would probably not be as dangerous in dry clothing. Therefore structural firefighting clothing needs to be designed to prevent water absorption. Next to the exterior water exposure the design of firefighter clothing needs to take into account the amount of water produced by the firefighter. A firefighter can produce a substantial amount of moisture, sweating up to 1,8 l an hour. Once sweating has begun the likelihood of moisture related injuries increases rapidly.

VI.7. Next to wet clothing, the compression of clothing lowers their insulation factor. Compression increases the potential of heat conduction by displacing the insulated air between and within the layers of clothing. Compression burns can originate from your SCBA system, or from kneeling down on or contacting hot surfaces. However stretching, kneeling and other movements can compress clothing too, thus contact with hot surfaces is not always a necessity. To limit the effect of compression on the isolating qualities of the firefighters, some clothing manufacturers incorporate special padding e.g. on the knees. The combination of compression and wet clothing is of course not at all beneficial to the firefighters safety. Crawling on a floor through water or other liquids may cause thermal injuries. This type of injury is called *wet compression burns*.

VI.8. Water on the outside layers of firefighting clothing can provide a false sense of security when entering a dry high temperature zone. Because the evaporation of the water extracts heat from the garment a lower temperature is felt by the firefighter. If the heat present is sufficient to evaporate all the water, the cooling effect stops. The firefighter will however have advanced further in the danger zone, rendering him even more vulnerable. As drying occurs the protective clothing temperature may rise very rapidly, producing internal temperatures which can cause serious burns. J.R. Lawson called these *drying garment burns* in the 8/98 edition of Fire Engineering.

VI.9. *Steam burns* may occur when water sprays are directed on hot surfaces and the steam-produced envelopes back onto the firefighters. The steam will burn exposed skin directly and as it is a gas it will pass through the permeable components of the PPE.

VI.10. *Scald burns* occur when firefighters come in contact with a hot liquid that is flowing or dripping from or through the ceiling (liquefied tar, synthetic ceiling tiles, hot water), a puddle or liquid running on the floor or a burst pipe of an industrial installation or boiler set-up. The liquid burns exposed skin and can penetrate the protective clothing. Compression of the garment, as stated earlier, here also, facilitates the occurrence of firefighter burns.

VI.11. The environment at fires can be divided into three regions taking into account the thermal stress the firefighter and his protective equipment are put in. The chart below (fig. VI.1) shows the relationship between increasing thermal radiation and the resulting rise in temperature. The three regions are depicted as routine, ordinary and emergency.

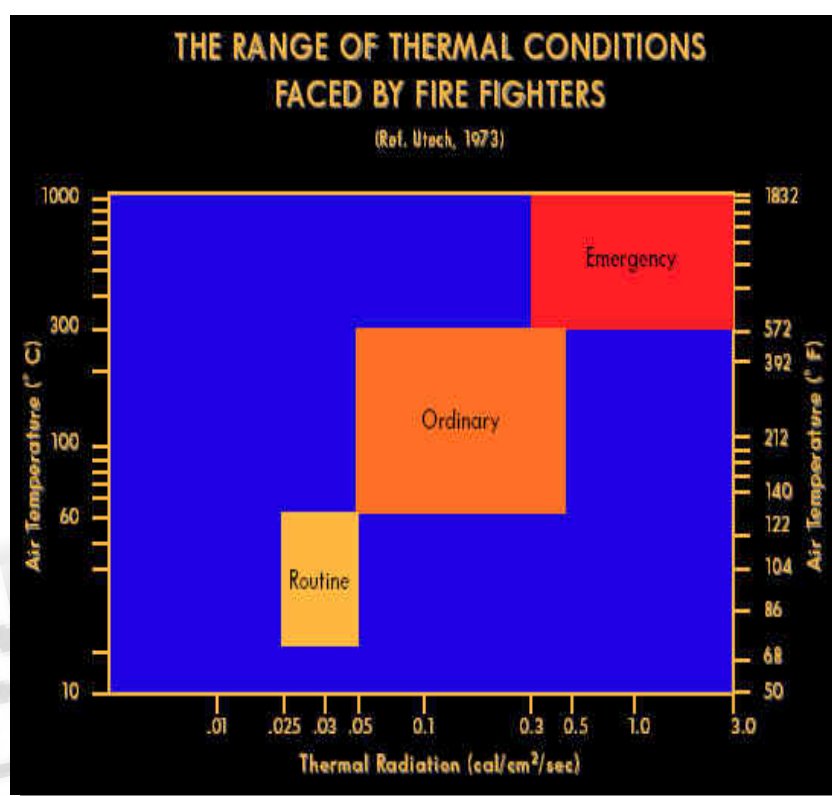


Figure VI.1 Range of thermal conditions, www.lionapparel.com

VI.12. The term '*routine*' could describe a condition when one or two items are burning in a compartment e.g. a chair or mattress that have just started to burn. Both the

thermal radiation and the resulting air temperature in the room may not be much higher than encountered on a hot summer day. Fire fighter protective clothing is more than capable of meeting this thermal load.

VI.13. The term '*ordinary*' describes a range of temperatures encountered when fighting a more serious fire, or perhaps if working adjacent to a flashed-over and vented room. Generally turnout clothing will provide lengthy periods of protection under 'ordinary' conditions. The higher end of this region is extremely hot and it is unlikely that a firefighter would be exposed to this condition for very long.

VI.14. The term '*emergency*' describes the most severe range of conditions firefighters are faced with when occupying a room or compartment bordering on, or exceeding flashover temperatures. Under 'emergency' conditions the thermal load can meet or exceed the 2.0 cal/cm² that is used in the TPP test and the air temperatures can stretch beyond the limitations of the individual textiles in firefighter PPE.

CFBT should rarely be allowed to enter 'emergency' conditions (*shoulder temperatures (crouching) in excess of 300°C*) Training in this region should never be allowed to progress more than a few seconds. Careful attention should be paid to a pre-set fuel load and a line on the floor should mark the limit of a 'safe' operating zone, beyond which no one should be allowed to cross following the ignition process.

VI.15. When a firefighter experiences *pain*, this signals the onset of skin destruction, a firefighter needs to make a decision with regard of the type burn he is going to get. At this point, it may simply require that the firefighter adjust any air-gap between clothing and skin to avoid a compression burn. However once pain is felt a firefighter has a one second window in which his actions in relation to the thermal environment can cause relief or serious burns. No real alarm time can be predicted as this depends from situation to situation, some *rules of thumb* however apply (J. R. Lawson, Fire Engineering, 08/98).

- When pain is felt, it must be assumed one has suffered a first-degree burn or greater.
- Once pain is felt time becomes a critical factor in reducing the severity of the burn injury.
- Remaining in the high temperature environment will increase the severity and the area of the burn.
- If a firefighter is able to exit this environment the heat contained in his garment is likely to increase the severity of the burns until the garments can be removed. A burn will increase in severity as long as the skin temperature is equal to or greater than 44°C.
- When hose streams are applied to extinguish a firefighter whose clothing is on fire or to cool burn injuries, there is a risk of producing scald burns. It is important if this kind of

action is required to first get the firefighter out of the high temperature area and consequently use massive amounts of water in order to cool the protective clothing as well as the skin tissue.

- Firefighters have indicated that they generally underestimate the severity of their burns while working, until they remove their protective clothing. This can be explained because human tissue becomes numb on reaching 62°C. Acting on first pain felt is thus necessary!
- The above discussions suggest that when a firefighter experiences pain from thermal exposure, the time for improving tactics to prevent injury has already passed and immediate action is required to reduce the threat of greater injury.

VI.16. In order to be able to rapidly discard the fire-fighting garment in order to limit further aggravation of burns, a 'panic system' was incorporated in the Dusseldorf and Berlin firefighting gear. The system is shown in figure... However adequate training is necessary as firefighters activate this '*Quick-Out*' system when putting on their turn-outs. An unwanted activation could have serious consequences when the jacket opens up in the fire-involved compartment.



Photos VI.2-3 Quick-out system

(www.Feuerwehr-duesseldorf.de)

VI.17. Next to burns, heat stress should be considered when wearing structural fire-fighting gear. In 1996, 44 of 45 firefighter on-duty heart attacks in the US were attributed to stress or overexertion and strain. Next to stress of the humid, hot and threatening environment firefighters wear heavy gear and have to perform hard labour. Dehydration can occur, which is the prime cause of heat illness. Heat stress or hyperthermia (body temperature greatly above normal) and dehydration can cause premature fatigue. In fact, in less than one hour under hot and humid weather conditions, muscle endurance is reduced. Alertness and mental capacity will also be affected. Fire fighters may find their accuracy suffering and others may find their comprehension and retention of information lowered. After 2 hours of the effects of heat stress –cramps, fatigue, loss of strength, reduced coordination- may set in. At

advanced levels, headaches, nausea, dizziness and serious fatigue can occur. At its most severe stage, hyperthermia can result in collapse, unconsciousness and even death.

VI.18. In hot hard-working conditions firefighters can lose up to 1,8 l of water in one hour. And sweat-laden skin and clothing reduce the heat dissipation normally performed by the body. Replacing body fluids lost during sweating, therefore, is the single most important way to control heat stress and keep firefighters fit, alert and safe. In most fire brigades a coolbox is kept in each pumper to provide drinks for immediate relief. Fluid replacement minimises the risk of heat injury, puts less strain on the cardiovascular system and prevents performance degradation.



Photo VI.4 Rehydration after CFBT

www.atemshutzunfaelle.de

VI.19. Some tips on re-hydration are mentioned here

- Drink before, during and after physical labour
- Anticipate conditions that will increase the need for water as high humidity, high temperature and difficult work...
- By the time you are thirsty you are already dehydrated.
- Drink cool water, because it is absorbed more quickly than warm or very cold fluids.
- Avoid coffee, tea or soda, which act as diuretics, further depleting the body of fluid.
- One litre of water a person should at least be present for CFBT (before and after).

VI.20. Modern structural firefighting gear consists of 4 layers, namely the outer shell, the moisture barrier, the thermal barrier, the inner liner, each having a function in the total concept. However one should not forget that the clothes you wear under the structural gear should also be considered in the total package of body protection. Wearing station gear or at least a cotton shirt is advised. Synthetic materials as nylons or polyesters should of course not be considered.

VI.21. **Outer Shell Criteria** - The outer shell probably has the most demanding role in the total configuration of textile materials. It has two critical functions: to resist ignition from direct flame impingement and to protect the internal layers from rips, tears, slashes, abrasion, etc. Some outer shell materials can have modest impact on TPP tests or can resist water absorption better than others. However, the real test

of an outer shell material is its ability to maintain its protective qualities under high thermal loads and stand up to the rough-and-tumble life on the fireground.

Information obtained from Southern Mills, Morning Pride, DuPont, Lion Apparel websites.

Nomex is an aramid fiber made by Dupont. Its unique molecular structure makes it inherently flame resistant.

Nomex III is 95% Nomex and 5% Kevlar.

Nomex IIIa is 93% Nomex, 5% Kevlar and 2% core-carbonfiber (anti-static). Nomex IIIa exhibits low flammability and high strength. Fabrics made from nomex IIIa maintain their integrity at high temperatures. Nomex will not melt, drip or char at temperatures below 675-750 degrees Fahrenheit (360-400°C). Nomex IIIa is the most economical of available outershells.

Nomex Omega is a turnout material developed by DuPont to offer high thermal protection and low heat stress. It consists of three components an outershell of a new Z-200 aramid fibre, a moisture barrier and a thermal barrier on Nomex substrate. Dyed Z-200 can discolour at 500°F (260°C) but the fiber will not degrade until 800°F (425°C). Z-200 doesn't have the cut resistance of a Kevlar blend and should be reinforced in high abrasion areas (e.g. knees). The Z-200 fiber is said to expand when exposed to extreme heat creating extra insulation.

Basofil products being marketed in the fire service are actually an engineered blend of 40% Basofil and 60% Kevlar. This outer shell offers exceptional heat blocking characteristics across a range of heat fluxes and thus will often allow the use of lighter liner systems. Basofil also appears to be exceptionally durable and comfortable. Basofil, however, does not offer all the advantages of the premium outer shells (PBI and PBO). Additionally, some competitive fiber providers have raised the issue of formaldehyde off-gassing with Basofil. The third party testing and research we have seen indicate this is NOT a valid concern. Basofil is an intermediately priced product.

Kevlar 60% / Nomex 40% This Kevlar Nomex blend product is probably the most durable outer shell and offers 300% improvement in char length over Nomex IIIa outer shells. Kevlar/Nomex stays flexible and supple, maintaining its integrity after moderately severe thermal exposure. While Kevlar/Nomex is a superior product to Nomex, customers are cautioned that the premium outer shells (PBI and PBO) offer strong comparative advantages. Kevlar/Nomex should be considered a Nomex upgrade rather than a PBI/PBO equivalent. Nomex/Kevlar is priced between Nomex and the premium shell alternatives. We believe Kevlar/Nomex is one of the best of the new products positioned between the premium shells and Nomex with very good comfort and durability characteristics.

PBI products being marketed in the fire service are actually an engineered blend of 40% PBI (polybenzimidazole) and 60% Kevlar. PBI has distinguished itself in some of the most active metro departments. The fabric was initially developed as part of the Project FIRES effort to provide non-charring protection at temperatures above Nomex's capabilities (approximately 750 degrees F). While Nomex remains an effective insulator charred, it can break away with movement and in the event of a continued or secondary exposure could allow a potentially serious breach in the protective envelope. PBI, in contrast, will resist charring up to temperatures that exceed the firefighters biological capabilities. Only PBO offers better anti-char performance than PBI. Black and dyeing the natural bronze color seems to dramatically reduce UV degradation problems and to improve durability. This is known as PBI (Black) gold.

PBO products being marketed in the fire service are actually an engineered blend of 40% Zylon (polyphenylenebenzobisoxazole) and 60% Technora. PBO is the newest of the premium outer shells, being commercialised only in early 2,000. PBO performs most like PBI but offers comparatively higher Taber abrasion test results (which should translate into better durability), lower water absorption tendencies, higher tear strength and better anti char characteristics (but PBI already offers such high anti char resistance that this latter point may be of suspect value). In fact, PBO offers the best performance in Taber abrasion resistance testing when compared to any other commercially available outer shell fabric. According to lion apparel the fiber is particularly sensitive to UV degradation.

VI.22. **Moisture Barrier Criteria** - The moisture barrier's main job is to keep the thermal protective properties of the system intact by preventing external water from penetrating into the critical air spaces of the garment. A dry system is safer, more dependable, and much lighter in weight than a wet one. All moisture barriers shed external water, but there are significant differences in their durability, thermal integrity, and long-term reliability. Another important aspect of moisture barrier protection is the ability to "breathe". A breathable barrier reduces the amount of moisture and body heat that can be trapped inside the gear. Highly breathable moisture barriers are intended to prevent water from entering the thermal layers, while allowing body vapor from sweat to escape outward. In addition, moisture barriers with high thermal integrity, or those well protected by other layers, are less likely to break open during "flash-over" conditions.

VI.23. **Air Layers and Thermal Barriers** - The protective value of the fabric composite is found in the air that exists between the fire fighter and the heat source. Air itself is the greatest single source of the insulative qualities in protective clothing. It weighs nothing and it's free! The most functional way to achieve the best protection is to use a multi-layer configuration in which each layer accomplishes part of the job. Highly efficient insulation can be gained by creating very thin air spaces between

the layers that supplement the air contained within the layers. It's important that none of these individual air spaces exceed 1.8 cm of thickness. Convective currents start beyond that thickness and may begin to quickly transmit heat. Similarly, air layers that are replaced by water can be unpredictably dangerous. Unlike air, water is an excellent conductor of heat.

VI.24. Thermal barrier systems that create multiple layers of air from multiple air spaces or that can resist absorption (water replacement of the insulating air) provide the most reliable protection.

VI.25. Another important consideration for thermal barriers is comfort and mobility. Thermal barriers that use slippery yarns on the "face cloth" next to the wearer are far less likely to bind and restrict the fire fighter's movement. The super-strong filament yarns that create this lubricity are also excellent at wicking perspiration away from the body.



Photos VI 5-6

Above: Berlin firefighters trying out their new protective gear.

Right: The effect of heat on the Nomex at $T > 250^{\circ}\text{C}$ the colour changed however without loss of protection, at $T > 500^{\circ}\text{C}$ charring occurred.

www.Berliner-feuerwehr.de

VI.26. Next to a good selection of all these layers, regular inspection and maintenance are required. Clothing is exposed to a wide variety of chemical and biological elements during work, such as hydrocarbons, polynuclear aromatic hydrocarbons, cadmium, chromium, chlorines, acids, alkalis, soot, body fluids, etc. These hazardous compounds can become embedded in the fibers of protective clothing. Clean your clothing as soon as possible; hose it down before returning to the station. Do not clean your turnouts at home or at a public Laundromat, it is against OSHA regulations and exposes your family to the dangerous compounds trapped within. In

some cases impregnation after laundry is required to maintain the water repellent qualities of the outershell.

VI.27. Next to maintenance, regular inspection of your thermal and moisture barrier is required. The thermal barrier provides the majority of your thermal insulation. The moisture barrier keeps the thermal liner dry and functioning at its best. These two layers play an extensive role in your safety. Be aware of their performance while you work or train. If you heat up or perspire more than normal, check your clothing for thin spots in the thermal barrier and for leakage in the moisture barrier.

VI.28. Virtually every material in your PPE will be adversely affected by sunlight. Do not store turnouts, stationwear or SCBA harnesses in direct or indirect sunlight (ie sunlight through windows). Never store your gear in your car or cab of the apparatus when exposed to sunlight. Store it in a locker, gear bag or cover it with a heavy dark cloth. Most outer shells and thermal barriers change color when they have been exposed to a significant amount of UV light. A dramatic change in color indicates your gear has not been stored properly and its protective properties may be compromised. An independent university laboratory study has shown that moisture barriers are not immune to UV damage. Further evidence reveals shielding on one side by an outer shell and on the other by a thermal barrier does not offer any more UV protection.

VI.29. The NFPA has issued a 'Standard on selection, care and maintenance of structural fire fighting protective ensembles', the NFPA 1851, 2001 edition, which incorporates requirements for proper care of turnout gear (and other PPE) as well as requirements for its selection and maintenance. Furthermore a complete 'User instruction, safety and training guide' can be downloaded from www.lionapparel.com. Regardless of the age, style, or make of your protective clothing always observe the mentioned 'common sense' guidelines.



Fire fighting gloves

VI.30. Fire fighting gloves are an essential part of the protective clothing. The gloves have to pass stringent criteria such as good thermal insulation; protection also when flame contact exists; good tactile qualities; resistance against abrasion and sharp edges; furthermore they should be waterproof. Because the combination of all these qualities in one glove are rare and because of the sometimes limited funds fire departments often utilise *simple leather gloves*. These gloves however *are not at all suited for firefighting*. Under heat stress they shrink and deform, leaving the hands with virtually no protection. Upon contact with water these gloves rapidly take up water. The effects of leather gloves in normal firefighting operations are shown in photos VI.7-8.



Photo VI.7-8 The effect of firefighting with leather gloves

Source : Domke, Jürgen. Universelle Feuerschutzkleidung für die öffentlichen Feuerwehren. Hintergründe, Entwicklungen, Leistungsmerkmale im Überblick, BRANDSchutz/Deutsche Feuerwehr-Zeitung 2/1998, 133 -159. (www.atemshutzunfaelle.de)

VI.31. In Germany the Dusseldorf firebrigade has conducted a wide range of tests in order to find the most suited alternative. Their requirements were good tactility, good thermal insulation and direct flame contact protection; furthermore price and easy maintenance (washable at 60°C) were also criteria. Firefighting gloves of various types, all meeting DIN EN 659, e.g. Seiz (Firefighter II), Eska (Jupiter), Crosstech (Fire-Dex), Oy B Hutha Ab (Finnland)... were tested.

VI.32. The tests were conducted during training burns to mimic real-life conditions and were accompanied by gasburner tests. In the gas burner tests gloves were worn, as local heating was applied. The inner temperature was measured by a thermocouple. Complete engulfment in the heat source was only conducted if the first test gave a 'good heat response'. The gasburner used was a propane burner, normally used by roofers working with bituminous materials. The temperature of the flame reached 850-1050°C and was directed straight on the glovematerial. The tests were conducted with dry and with sweaty hands. Some leather gloves showed only partial

shrinkage while others shrunk extensively. The gloves made of other materials as nomex or kernel didn't shrink, but however suffered greatly from the direct flame exposure as charring and deterioration occurred (Photo VI.9 A).

VI.33. The best-suited glove type, as selected by these tests was the Elk leather glove with innerfilling materials eg. Nomex or kevlar filling and air pockets for thermal isolation combined with a gore-tex or cross-tech membrane. These gloves provided good tactile qualities, extreme high heat resistance, an extreme low water infiltration rate (only after several hours), no shrinkage, ... The gloves can be machine washed without losing their properties. The temperature prescribed however is 40°C, which is lower than the criterium set by the Dusseldorf administration.



Figure VI.9 Gasburner tests conducted at the Dusseldorf firebrigade (Germany),

A structural degrading after flame exposure, B Elk leather gloves

(www.Feuerwehr-duesseldorf.de)

VI.34. Firefighters should be equipped with these kinds of gloves when tackling fires. The 'good' gloves should however also be kept for only this kind of call-out. It is not economical use them to clean roads, attend road traffic accidents or to respond to flooding... The good and expensive gloves should only be worn at fire calls or fire training. When attending to a fire keeping the gloves as dry as possible should be one of your concerns. When attending to other calls cheaper leather gloves, preferably with kevlar lining, should be used. PPE selection should each time be based on risk assessment.



Comparison of NFPA and EN fire protective clothing standards

VI.35. In this section we wanted to provide our readers with a short overview of the relation of standards in the US and in Europe. The information mentioned here is based on the text provided in the Morning Pride catalogue of 2002.

www.morningpride.com

VI.36. **CEN** has prepared standards on the major elements of the fire fighting protective ensemble, including:

1. Protective clothing for firefighters (EN 469)
2. Helmets for firefighters (EN 443)
3. Gloves for firefighters (EN 659)
4. Footwear for firefighters (EN 345, Part 2)
5. Hoods for firefighters (prEN 13911)

VI.37. CEN has also prepared a standard, EN 1486, on reflective protective clothing for specialized fire fighting (proximity fire fighting) which also addresses shrouds (hoods) and gloves. Also, efforts are underway for a new standard on wildland protective clothing in conjunction with ISO.

VI.38. Unlike NFPA, all four CEN standards have been developed by different committees or work groups. Consequently, the types of requirements and levels of protection are not consistent between ensemble elements. While many of the same kinds of tests are performed on each ensemble element, there are substantial differences in the way that these tests are conducted that make it nearly impossible to compare results from NFPA test to those from CEN tests.

VI.39. **Garment Requirements in EN 469.** For protective garments for structural fire fighting there are significant differences between EN 469: 1955 and NFPA Std. # 1971 (2000 Edition):

- No moisture barrier is required.
- There are no requirements for trim other than it not interferes with the function of the clothing.
- Substantially lower levels of thermal insulation are required. Testing is performed in two tests for flame transfer and radiant heat transfer. Performance is based on temperature rise with no relationship to predicted burn injury.

- Lower levels of thermal insulation are allowed for the lower torso as compared to the upper torso.
- Flame resistance testing is performed on the composite with examination of after-flame and afterglow, but no char length measurement is made.
- Heat resistance testing is performed in an oven at 355°F (180°C) instead of 500°F (260°C) as required in NFPA Std. # 1971. This permits the use of materials that melt, such as nylon.
- The thermal shrinkage requirement is more severe for EN 469 (< 5%) than for NFPA (< 10%), though testing is performed at a lower temperature.
- Cleaning shrinkage is limited to 3% by EN 469 while NFPA Std. # 1971 allows 5%.
- A liquid runoff test is used for assessing chemical penetration using a different battery of chemicals.
- Water penetration and breathability tests are optional.
- No wristlet performance requirements are specified.

VI.40. In 1998, a revision of EN 469 was accepted at the proposal stage. Even though the final revised standard has not been approved, CEN permits “certification” of clothing against the proposed revised standard. This revision of the standard (**prEN 469: 1998**) now allows two classes of thermal insulation performance for both flame and radiant heat transfer tests, with the new second level providing less protection than the original requirement. In addition, a moisture barrier is now required and must pass a water penetration test and breathability test. Extensive trim requirements were also added.

VI.41. **Helmet Requirements in EN 443.** EN 443 has fewer requirements than NFPA # 1971 for helmets. For example, EN 443-compliant helmets are not required to have chinstraps, neckguards, faceshields or ear covers. The majority of requirements parallel NFPA Std. # 1971 but use different test methods:

- Impact and penetration testing are conducted with a different mass and after different types of preconditioning.
- A different electrical insulation test is used.
- Strap elongation and breaking strength are measured in EN 433 while the entire retention system is evaluated in NFPA Std. # 1971.

Since there are fewer required components, there are fewer overall required tests.

VI.42. **Glove Requirements in EN 659.** EN 659 requires that minimum sizing of gloves be based on hand circumference and hand length to standard size designations. Gloves and glove materials are tested for:

- Abrasion, cut, tear and puncture resistance in accordance with EN 420 (mechanical properties of gloves);
- Burning behavior and surface contact heat resistance are tested in accordance with EN 407 (thermal properties of gloves);
- Heat resistance at 355°F (180°C);
- Maximum chromium and pH levels of glove leather.

Compared to NFPA Std. # 1971, EN 659 permits thinner, less insulative gloves without moisture barriers.

VI.43. **Footwear Requirements in EN 345-3.** Footwear requirements are mostly covered in EN 345, Part 2, but are also referenced in general footwear standards (EN 344 and EN 345). As with other European standards, similar tests are specified relative to NFPA Std. # 1971, but significant differences in test procedures and design requirements make comparison of products difficult. However, the thermal insulation and barrier requirements for EN 345-2 compliant footwear are relatively weak compared to the requirements in NFPA Std. # 1971.

VI.44. **Hood Requirements in prEN 13911.** With the exception of some differences in testing approaches, the proposed hood requirements in prEN 13911 are similar to the hood requirements in NFPA Std. # 1971. The completion of prEN 13911 is expected in late 2002.



VI.45. The total of NFPA standards concerning firefighting protective gear are mentioned below.

NFPA 1971-2000 Edition, Standard on Protective Ensemble for Structural Fire Fighting: Provides criteria for performance, design and certification of protective ensembles and materials used in structural firefighting including protective pants and coats, protective coveralls, helmets, gloves, footwear and interface components.

NFPA 1976-2000 Edition, Standard on Protective Ensemble for Proximity Fire Fighting: Addresses the performance, design and certification of protective ensembles materials used in proximity fire fighting including protective pants and coats, protective coveralls, helmets, gloves, footwear and interface components.

NFPA 1977-1998 Edition, Standard on Protective Clothing and Equipment for Wildland Fire Fighting: Sets forth performance, design and certification requirements for protective clothing and materials used in wildland firefighting activities including protective shirts, protective pants, protective coveralls, helmets, gloves and footwear.

NFPA 1975-1999 Edition, Standard on Station/Work Uniforms for Fire and Emergency Services: Describes testing, performance and certification criteria for clothing to be worn as station or work uniforms. This standard does not apply to garments intended to be worn as primary protection.

NFPA 1851-2001 Edition, Standard on Selection, Care and Maintenance of Structural Fire Fighting Protective Ensembles: Outlines procedures for the proper cleaning, care and maintenance of protective clothing compliant with NFPA 1971.

Information Southern Mills website

VI.46. The current edition of NFPA 1971 edition 2000 went into effect in February 2000. One of the significant new advancements in this revision is the inclusion of the Total heat loss test (THL) next to the famous thermal protective performance (TPP) test.

What is TPP?

TPP stands for Thermal Protective Performance. The TPP rating of a fabric or composite refers to its thermal insulation characteristics when protecting the wearer from fire. TPP is measured using a combination of flame and radiant heat sources with a heat flux of 2 cal/cm²-sec. The flame is impinged on the outer surface of a four-inch by four-inch area of the fabric or composite. The time required to reach the equivalent of a second-degree burn at the calorimeter on the other side of the sample is recorded. This time (in seconds), multiplied by the heat flux of the exposure, gives the TPP rating.

What is Total Heat Loss?

The body exhausts excess heat to maintain metabolic equilibrium. Some of this thermal energy is dry heat, but most of it is in the form of sweat. The evaporation of sweat is the body's most effective natural cooling mechanism. The Total Heat Loss number for a fabric or a combination of fabrics is the amount of energy that can be transferred through the system, from the inside out. The higher the THL value, the more the system allows excess body heat to escape.

THL is for the Basic Textile Composite

The NFPA requirement covers the turnout composite, but not the turnout suit. The test is run with the combination of the outer shell, the moisture barrier, and the thermal liner. The coat/pants overlap and areas that are covered with reflective trim, pockets, or additional reinforcements are not as breathable as the base composite. However, body heat can usually move around these relatively small barricades and escape (just as heat can escape through neck openings, legs openings, sleeve ends, etc.).

Does a High THL Mean a Low TPP?

Systems with extraordinarily high thermal insulation (TPP) ratings are usually thicker than average and do not allow body heat to pass through easily. There are a number of composites that provide excellent thermal insulation and exceptional THL performance. Each component of the turnout impacts a system's THL value, but the moisture barrier is the most important factor in determining a composite's Total Heat Loss characteristic. The choice of moisture barrier material can make a difference of more than 100 points in the THL rating, while having no appreciable impact on the TPP. The choice of thermal barriers has the greatest impact on TPP. It also makes a significant contribution to the THL performance. The type and weight of the outer shell have a minimal effect on a composite's THL and TPP.

What's the Best Balance Between THL and TPP?

There are many exceptional textile system choices available. The THL/TPP strategy chosen depends on the problem being solved and departmental approaches. The NFPA requirement for a TPP rating of not less than 35 is well established and proven. In the past, some departments selected their thermal barriers based on relative TPP values because no measurements were available of the stress-producing effects of turnout materials. Now, with a counterbalancing THL test which indicates the stress reduction characteristics of an ensemble, information is becoming available to help make judgments based on assessed risks, injury reports, fireground tactics, percentage of non-fire calls, departmental demographics, etc. In many cases, the best system offers a very high THL in the range of 260-300 W/m² to help maintain the metabolic equilibrium and a TPP that's in the range of 38-42. The tactical use of thermal reinforcements in the shoulders and knees, where compression and scald burns may occur, can complete the lightweight, breathable, and versatile protective envelope.

Information DuPont - Lion apparel website

VII.COMPARTMENT FIRE BEHAVIOR TRAINING

SAFE-PERSON CONCEPTS IN LIVE FIRE TRAINING

VII.1. Training for offensive (interior) firefighting operations is perhaps now more important than ever. The modern day firefighter needs both a theoretical and practical understanding of how fires develop and are likely to behave under a wide range of ventilation parameters, in a selection of single compartment, multi-compartment and structural settings. Such training should place great emphasis on how fire gases are likely to form and transport within a structure and must clearly define the term '*risk assessment*' inline with the hazards associated with flashover and backdraft phenomena and other forms of rapid fire progress. Further to this, the varying range of offensive firefighting applications including *Direct Attack* (using both water & CAFS); *Indirect Attack*; and 'new-wave' *3D water-fog* applications should be clearly explained and practiced under a broad range of firefighting conditions. This training may prove costly but is essential if the safety of firefighters is to be advanced. In countries such as Sweden, the UK and Australia, structured Compartment Fire Behavior Training (CFBT) programs have effectively reduced the life losses and serious burn injuries suffered by firefighters to various forms of rapid-fire progress and resulting structural collapse.



Photo VII.1 by Wayne Atkins (Australia)

VII.2. Past experience has demonstrated that live training burns in unoccupied or derelict structures can often breach the fine line drawn between 'realism' and 'safety', even where national guidelines and safety standards are closely followed. Such training fires also provide widely varying situations and a range of conditions that are often unpredictable and may be difficult to repeat or control for the sake of uniformity in teaching basic principles. In Europe it has long been recognized that purposely designed structures offering optimised fuel loading within a geometrically coordinated compartment, provide the safest environment in which to teach firefighters how compartment fires develop whilst also demonstrating a range of fire suppression and control techniques. Such facilities also offer the most economical option to train firefighters whilst effectively creating *realistic but controlled* conditions within.

VII.3. The steel shipping container offers versatility, adaptability and a ready made modular approach in constructing cheap but effective burn buildings and 'flashover' simulators. The single compartment observation; window and attack containers have been used in Europe for over 20 years to demonstrate fire growth; rollover; flashover and backdraft phenomena whilst enabling firefighters to witness fire gas formation, transport and ignitions from extremely close quarters with their safety being the prime concern. It is from such close quarters that firefighters are then able to practice and evaluate the various firefighting options and suppression techniques, offering them an unequalled experience and providing an element of confidence in relation to structural firefighting. The simulators are also used to teach door entry techniques whilst recognizing a range of fire conditions from the exterior, including the *under-ventilated fire*.



Photo VII.2 – Staffordshire Fire Brigade

VII.4. However, it is essential to remember that these modular trainers are only simulations of more realistic conditions and a training fire can never truly replicate the 'real' event for reasons of safety. There is no heavy fire loading during training evolutions and in reality the events experienced inside the simulators are likely to happen faster in the 'real' world in a compartmentalized environment that is genuinely unfamiliar to the firefighter. Even so, the modular simulators are as close to 'realism' as one would wish to take firefighters in a training environment, where temperatures at shoulder height (crouching) are regularly taken to 300 deg C for several seconds during the evolutions [20].

VII.5. It is also important to advance the CFBT training principles in stages from single compartment observation and attack units to the multi-compartment, multi-level designs now becoming popular. To assist the design of multi-module simulators the use of CFD modeling and past empirical research must be encouraged if such facilities are to remain *safe and effective*. Without multi-compartment training, using proven designs, the firefighter will fail to grasp an overall appreciation of how tactical venting actions are likely to affect surrounding and adjacent compartments (to the fire). The complete approach to a structural firefighting operation and any appreciation of realistic *fire gas transport* and involvement is therefore lost. CFBT principles are now being adapted into *existing training structures* along with '*smoke-scrubbers*' to purify the smoke and lessen the effects on the local environment.



Photo VII.3 by Tim Watkins (Australia)

Note :

Compartment Fire - Involves one room or space only.

Multi-compartment Fire - Involves more than one room/space, possibly on different levels.

Structural Fire - Involves multi-compartments/spaces where elements of structure have been breached or involved, thus threatening structural stability.

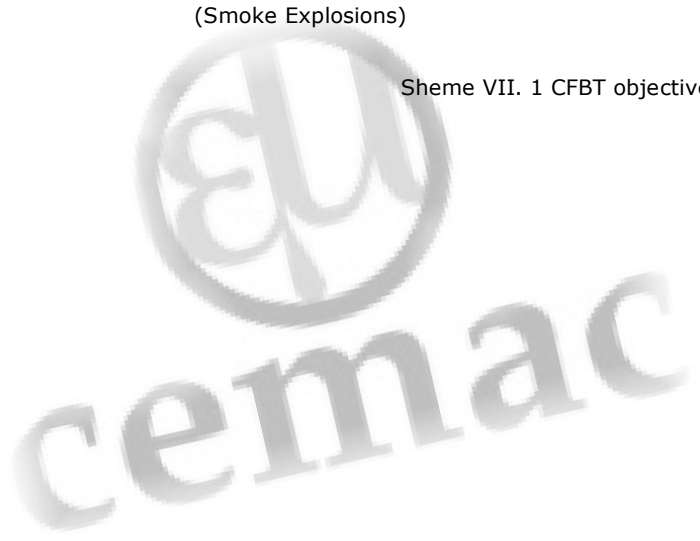
VII.6. **WARNING**

Single compartment systems are subject to limitations in that they can only prepare the firefighter for door entry procedure and one-room fires. To appreciate the operational implications associated with fire gas formations, transport and ignitions as well as tactical venting options/actions inline with crew advancement techniques in a 'structural' setting, the concept of CFBT training must be allowed to evolve into multi-compartment modular structures to provide an all-round approach.

VII.7. The use of LPG fuelled systems does NOT serve adequately to teach fire behaviour but does provide a facility where nozzle techniques may be practiced.



Scheme VII. 1 CFBT objectives in live fire training



CFBT simulator safety

VII.8. The concept for using redundant steel shipping containers to teach firefighters how a compartment fire is likely to develop and behave, under variable ventilation parameters, was introduced by Swedish fire officers Mats Rosander and Anders Lauren during the early 1980s [9]. The containers were designed to simulate, as realistically as possible, the formation and transport of fire gases within a compartment whilst demonstrating a range of phenomena related to 'flashover', backdraft and other forms of fire gas ignitions. These specific fireground hazards were increasingly becoming linked with firefighter deaths and quite often this was because they failed to understand the basic principles of fire development and fire behaviour within the confined state of a structure. The simulators also provided an opportunity to practice countering tactics for dealing with fire gases accumulating and igniting in the overhead. The introduction of 3D water-fog applications and tactical venting actions were central to the **'safe-person'** concepts and methods of operational risk assessment being developed in the UK and Sweden.



Photo VII. 4- ESSEX FIRE BRIGADE

VII.9. The methods and tactics used in the simulators were to vastly improve firefighter safety at fires over the following years and several fire authorities in Sweden, Finland, UK, Germany, Australia, Spain and the USA were the first to adopt the 'new-wave' approaches in dealing with confined and under-ventilated fires as well as

blazing 'reservoirs' of fire gases existing in stair-shafts, voids and compartments. Whilst gas-fired training facilities offered an environmentally friendly alternative to chipboard linings and 'real' fires the simulations were never truly realistic and failed to teach firefighters how a compartment fire was likely to develop under a wide range of venting parameters.

VII.10. As the training program developed, the safety procedures and simulator designs associated with Compartment Fire Behaviour Training (CFBT) advanced inline with much scientific research. The intention was to produce simulators that were safe but effective in offering realistic conditions. With the basic geometry of the steel containers being ideal for creating repeatable evolutions of igniting fire gases, a universal approach evolved in the design and use of such facilities to teach various aspects of fire behaviour. As an example, there are *observation* units for flashover; *window* units for backdraft; and *tactical attack* units where 'door entry' and 'crew advancement' techniques are practiced. The design specifications and methods of use vary between each type and may offer local adaptations, whilst still conforming to the original Swedish model.

VII.11. There are strict controls of safety [4] advised for the use of such units and these include the following points –

1. All firefighters should be fully hydrated before entering the simulators and re-hydrated at the end of training.
2. Both outer layers and undergarments of protective clothing should be of a high standard and include flash-hoods, ensuring all exposed skin is fully covered at all times. Clothing should be loose fitting, allowing an air-gap between undergarments. Damp clothing should not be worn inside the simulators.
3. There should be at least two hose-lines fitted with fog-nozzles available during the training. Separate pumps and supplies should feed them where possible. The interior line is managed by a maximum of 4-6 students whilst a safety officer and instructor manage the exterior line.
4. Personnel are assigned specifically to operate ventilation hatch controls.
5. There should be at least two points of exit available to firefighters inside the simulators.
6. The rear doors of observation simulators should remain open at all times during occupation of the facility.
7. Personnel should not occupy simulators used to demonstrate 'backdrafts' at any time during the training.

VII.12. In 1991 the Fire Technology Laboratory of the Technical Research Centre of Finland (VTT) carried out research [5] into the *operation and safe use* of container style compartment fire simulators. They carefully assessed the heat-flux and monitored temperatures at various locations, including those areas occupied by firefighters. They concluded that a 500mm x 500mm roof hatch was suitable and that the simulator design based upon the original Swedish model is safe and effective for use and occupation by firefighters as a method of teaching fire behaviour and gaseous-phase extinguishing techniques. **They emphasized the intention was to avoid any progression to full flashover whilst the unit remained occupied and that maintaining control of the environment by cooling the gases in the overhead was critical to safety.** They demonstrated maximum temperatures of 200 deg. C at shoulder height and up to 400 deg. C at top of helmet for a few brief (2-3) seconds were experienced by kneeling students during repeated ignitions of the gas layers.

VII.13. A further study by the University of Central Lancashire (UK)[6] reported maximum temperatures of 150 deg. C were experienced at the shoulders of crouching firefighters inside the observation simulators.



Photo VII. 3 Courtesy of the University of Central Lancashire (UK)


cemac

Recent CFD research into fire simulators is flawed

VII.14. There have been two recent research projects that have both attempted to use Computational Fluid Dynamics (CFD) to resolve situations of reported 'dangerous conditions' linked to excessive temperatures experienced at firefighter locations inside CFBT container style simulators. However, these research projects are seriously flawed in that CFD cannot (at this time) effectively model firefighting water applications. The research was further prompted by two fire authorities who apparently failed to follow the original Swedish guidelines relating to safe practice in the simulators.

VII.15. The first research report [7] appeared in the May 2002 edition of Fire Prevention & Fire Engineers Journal (UK) where Nick Pope reported 'overly high temperatures' within a flashover training simulator used by London Fire Brigade (at the Fire Service Training College - Moreton) had made the simulator 'dangerous' for use by trainee firefighters. He went on to describe how CFD was used to model conditions within the simulator and resolve the 'overly high temperatures' by increasing the ventilation hatches from one to three. What this research failed to account for was the water applications (*pulsing water-fog*) that are (*should be*) used to control the environmental conditions within the simulator, ensuring temperatures at firefighter locations do not become overly high. The report referred to temperatures at the entry point in excess of 600 deg. C but these were at ceiling level. Further still, the firefighters were reported as occupying an 'observation' unit and if this is the case, they would not enter AFTER the fire had been developing for some time (as stated) but would have occupied the compartment prior to ignition and observed the fire's development from its incipient stages through to 'flashover', whilst controlling the upper level temperatures with a pulsed application of water-fog. If the unit was an 'attack' unit then they would have entered sometime after the fire had begun, practicing door entry techniques and applying a cooling fog into the upper gas layers just prior to entry.

VII.16. The second research report [8] appeared in the November 2002 edition of FIRE Journal (Australia) and the authors admitted their research was prompted by the original 'Pope' report in the UK. The Australian Capital Territory (ACT) Fire Authority, following similar reports of 'dangerous conditions' existing inside a CFBT container simulator, initiated the Brammer & Wise research. Again they resorted to CFD modeling to provide solutions to excessive temperatures experienced at firefighter locations and again they altered the ventilation arrangements to 'improve' condi-

tions. However, again there is no mention of water applications or environmental control and it appears that the ACT firefighters were occupying the space without any water available to them at all as they observed a fire develop through and *beyond* its flashover stage!

VII.17. The two reports concluded with recommendations for improving conditions within the simulators and yet failed to reference previous research in this field that had already dealt with these aspects. The reports also failed to account for any cooling effect of water on the gaseous-phase state and the likely influence this might have for ensuring temperatures are controlled and maintained at safe levels. The fire authorities involved appear to have been using the training simulators outside of universally accepted safety guidelines, totally unaware of the design features and training objectives of the simulators in use.

VII.18. Such research can be totally misleading if allowed to stand alone, unchallenged, and these reports could form the basis of future design specifications of CFBT simulators, suggesting to current users that their own units may be dangerous. This would be far from the truth where the Swedish design and user model has been followed. It is also unnecessary and ineffective and fire authorities using such simulators in future would be well advised to acknowledge the long history of past experience and scientific research that already ensures that, if followed, the Swedish model of CFBT simulations remains the safest and most effective option. They should also ensure that instructors are both trained and qualified under the original Swedish model and that local adaptations in design, training or use of the units are carefully reviewed for safety, with the original specifications and training objectives in mind.



The transition of CFBT to working structural fires

VII.19. 'No two fires are ever the same'... is an old adage used by firefighters and it is true. It is well established that construction, structural layout, occupancy type, fuel load, weather conditions, water supply, fire location, occupancy location, structural integrity and ventilation parameters etc will vary widely, as will our own tactical approaches, at each incident. Whilst some firefighters are able to gain 'on the job' training simply through the high number of working fires they experience whilst observing and working closely with mentors, most of us must rely on the training we receive in live structural training burns or inside fire training facilities.

VII.20. The Compartment Fire Behavior Training (CFBT) principles, using redundant steel shipping containers, were introduced by Swedish firefighters during the early 1980s. The original Swedish model of training evolved on the principles of increasing awareness of fire gas formations, transport and ignitions. The objective was to demonstrate clearly how fires are likely to develop under variable venting parameters, teaching firefighters how to counter various forms of rapid fire progress and showing them the likely effects of their 'actions' or 'non-actions' at the simple one-room fire. The modular design of CFBT facilities has allowed a natural progression towards multi-compartment structures by adjoining containers in various configurations using L and H shapes in particular, as well as multi-level designs. This has taken CFBT to the next level in reality concepts and offers the fire service a safe, cheap and effective means of training firefighters in various tactical approaches.

VII.21. However, it is fact that the original Swedish model of training has been corrupted in both design and application in some parts of the world. The idea of firefighters simply 'observing' fire behavior whilst occupying containers, without the protection or use of water to 'control' the environment, is seen as dangerous and compromises the principles of safe operation. The use of straight streams, as opposed to 'pulsed' fog patterns, fails to demonstrate how the firefighter can assert control over interior conditions where the **fire remains hidden**. Finally, the use of gas-fired facilities, based on the container design, fails to teach how a fire develops and cannot therefore demonstrate fire gas behaviour in any realistic sense.

VII.22. A review of firefighter fatalities at structural fires shows up common errors that are generally the result of inexperience or a 'reactive' approach. The principles of CFBT *should* teach firefighters to be more 'pro-active' and anticipate likely 'events' ahead of time. They *should* also become more aware of *time frames* within the tac-

tical approach and their effect on the outcome if not addressed. For example, a common error is to neglect that **first-in hose-line**, or it's constant manning, in preference to other actions such as 'primary search'. Taken as a means of enhancing firefighter safety, CFBT has so far proven to be the safest and most effective method of achieving this aim. However, it is far from perfect!

VII.23. How many times have I heard comments from students - experienced fire officers and firefighters with twenty plus years of service - such as, 'wow, that training evolution was the most realistic and enjoyable I have ever had'! Now if you ask the same fire officer three weeks later how the training has prompted him to adapt the tactical approach of his crew and his-self he will say 'huh'?

VII.24. One fire authority, in the UK, recently spent nearly £500,000 over a two-year period on a CFBT program for it's 1,100 firefighters. When two of the CFBT instructors later formed part of an initial crew attending a 'basic' one-room apartment fire they failed to recognize the potential for smoke explosion where an adjacent room above the fire room became **smoke logged**. When fire extended into this room through a voided cupboard the ensuing explosion blew the walls and window out! An earlier venting action of the upper level may have alleviated this problem. The fire authority involved addressed this issue and asked if CFBT principles were truly effective in preparing their firefighters for 'real-world' fires. What they failed to address was the fact that they had only ever introduced single-compartment trainers and had failed to place any great emphasis during training on fire gas transport into adjacent areas, demanding a tactical venting action to remove such gases from the structure.

VII.25. Other fire authorities have simply covered the 'basics' of CFBT by introducing single-compartment facilities but have failed to place greater emphasis on the transition of the techniques into the real world. It can be seen that their firefighters have learned very little about how fire gases transport and ignite and their mental approach to compartment fires remains stagnant. This appears to be such a waste of resources and demonstrates a lack of conviction on behalf of those responsible for providing training. In the UK, for example, the view that CFBT has been effectively dealt with and is a 'done' project is widespread and this is dangerous. In the UK, as in Sweden and France, the principles of CFBT were introduced as a counter-action to several tragic losses of firefighter's lives in situations related to various forms of rapid-fire progress.

VII.26. It is important that fire authorities recognize the dynamic process of CFBT does not end

- a) With the single-compartment trainer; and
- b) Without recognition of the tactical approaches involved being written into department SOPs.

VII.27. The examination process and standards of competency of both trainers and students need to be addressed with some greater rigor if CFBT principles are to become part of the mind-set of the firefighter and enacted upon within the tactical approach to every fire. The whole process should address things like arrival on scene; water supply issues; tactical hose-line placement; crew accountability; size-up and calculated risk assessments; door entry procedures; tactical venting actions; priority actions to include first-in hose-line, primary search, back-up hoseline and secondary search etc. The principles of CFBT go way beyond sitting in a box and watching a fire develop through to flashover! It is important to address such issues at the outset of training for valuable resources and training time may be wasted without a greater emphasis on real-world transition.

VII.28. Venting fire involved cock-lofts (roof-voids) from above before cutting access in from below; placing and crewing a hose-line prior to primary search; emphasizing working as crews going in together, staying together and coming out together; controlling the interior environment through tactical venting or fire isolating techniques; clearing stair-shafts above prior to making entry into an under-ventilated compartment; applying correct door-entry techniques. These tactics should **ALL** be accommodated during CFBT in an effort to link that transition from container-simulator into the real world.



VIII. RAPID FIRE PROGRESS

VIII.1. The phenomenon of 'Flashover', in its generic sense, is a significant killer of firefighters. In the USA, NFPA statistics recorded between 1985 and 1994 demonstrated a total of 47 US firefighters lost their lives to 'flashover'. Of 87 firefighters killed since 1990 that reportedly died of **smoke inhalation** whilst operating inside structures, the major causes of injury were - *became lost inside the structure and ran out of air* (29 deaths); *caught by the progress of the fire, backdraft or flashover* (23 deaths); and *caught in structural collapses* (18 deaths, 10 of which were in floor collapses). All but one of these 70 victims was wearing self-contained breathing apparatus. (The one exception was a firefighter rescuing family members from a fire in his home.) Of 31 US firefighters who reportedly died of **burns** inside structure fires since 1990, 14 were caught or trapped by fire progress; *backdraft or flashover* and 12 were caught in structural collapses (NFPA). Three firefighters were killed when an Oregon auto-body shop roof collapsed in 2002 but witnesses reported hearing an 'explosion' seconds before the roof collapse – was it a backdraft or smoke explosion that caused the collapse? The Fire Chief on scene also reported that when firefighters tried to carve an opening in the building's ceiling, trapped gases that had heated found the oxygen they needed to flash into a blaze. The ceiling, floors and walls combusted immediately, causing roof supports to collapse.

VIII.2. '**Flashover**' (rapid fire progress) has often resulted in multiple life losses at fires. In 1981 a 'flashover' in the Stardust Disco in Dublin, Ireland caused the deaths of 48 young people. In 1982 two Swedish firefighters were killed in a smoke explosion. Following this incident the Swedish fire service developed Compartment Fire Behavior Training (CFBT) programmes to advance firefighter safety. Also in 1982 there were 24 deaths in the Dorothy Mae apartments flashover in Los Angeles. In 1987 thirty-one people, including a fire officer, lost their lives as fire gases ignited in the heart of London's underground railway (Metro) network and in 1991 eight Russian firefighters died in corridor flashovers that occurred during a major hotel fire in St. Petersburg. In 1994 three New York City firefighters died in a stair-shaft when a backdraft occurred as firefighters forced entry into an apartment on fire. In 1996 there were seventeen deaths as a flashover occurred in a Dusseldorf airport terminal fire. In 1997 three UK firefighters were killed in flashover related incidents and the UK fire service followed this with training updates and CFBT programmes. In the new millennium several firefighters have lost their lives to 'flash-over' during live training burns in 'real' structures, notably in Denmark and the USA, and in 2002 five Paris firefighters died trapped by two 'flashover' related incidents.

We may well ask - how many more must die unnecessarily? However, is the generic use of the term **flashover** to be encouraged and should firefighters gain a clearer understanding of other related phenomena?

VIII.3. The term 'flashover' was first introduced by UK scientist P.H. Thomas [38] in the 1960s and was used to describe the theory of a fire's growth up to the point where it became *fully developed*. Customarily, this period of growth was said to culminate in 'flashover', although Thomas admitted his original definition was imprecise and accepted that it could be used to mean different things in different contexts. Thomas then went on to inform us in UK Fire Research Note 663 (December 1967) that there can be *more than one kind of flashover* and described 'flashovers' resulting from both *ventilation* and *fuel-controlled* scenarios.

VIII.4. Thomas also recognized the limitations of any precise definition of 'flashover' being linked with *total surface involvement of fuel* within a compartment (room) where, particularly in large compartments, it may be physically impossible for all the fuel to become involved at the same time.

VIII.5. Throughout the period 1970 to 2002 there had been widespread use of the term 'flashover' and various attempts were made to redefine the terminology associated with such phenomena. It was also apparent that firefighters had failed to grasp a clear understanding of the various events that could occur at fires and the NFPA opted to record such occurrences simply as **Rapid Fire Progress**. An example of this confusion was demonstrated by a website poll [20] at www.firetactics.com in 2002 where, over a ten week period, in excess of 300 voters offered their opinion of what event was occurring in the picture below (photo VIII.1) – was this a flashover? backdraft? or perhaps another related event?



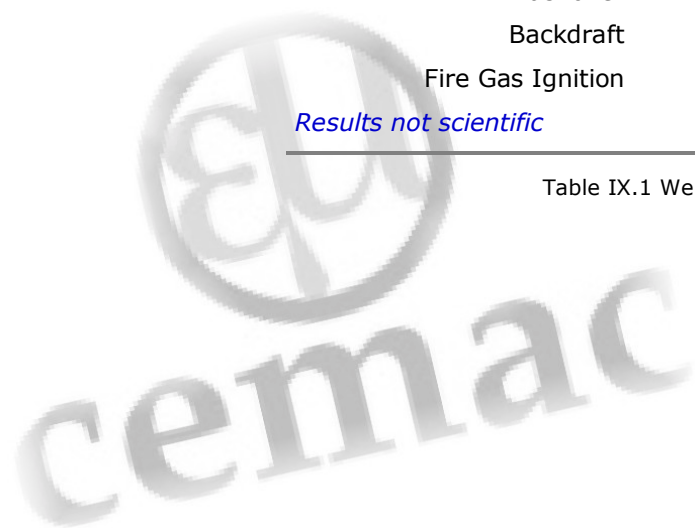


Photo VIII.1 by Glenn Ellman

VIII.5. The exercise demonstrated how difficult it was for firefighters to differentiate between the various phenomena –

Flashover?	Backdraft?	Fire Gas Ignition?	Votes
		Flashover	29% 91
		Backdraft	35% 108
		Fire Gas Ignition	34% 105
<i>Results not scientific</i>			304 votes total

Table IX.1 Website poll



VIII.6. There are many terms that are used by various authorities to describe 'flash-over' related phenomena. Some have scientific origins and are referenced universally whilst others have been introduced to the language by authors to describe events they have personally experienced at fires. It is common for different terms to sometimes mean the same thing. It is also a fact that English terms often fail to translate into other languages with the same meaning and terms have been amended to allow for this. However, this can cause further confusion when those terms are then re-introduced back into English in different formats! This can occur where scientific or training documents are translated back into English and new terminology appears.

VIII.7. It is perhaps more convenient to list such phenomena under three specific headings, describing universally accepted definitions; detailing case histories of interest; and demonstrating countering and preventative actions (defences) that can be used by firefighters, as follows.

RAPID FIRE PROGRESS

1. FLASHOVER
2. BACKDRAFT
3. FIRE GAS IGNITIONS



Flashover

VIII.8. 'In a compartment fire there can come a stage where 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. Given a source of ignition, this will result in the sudden and **sustained** transition of a growing fire to a fully developed fire.....This is called 'flashover'.....'

VIII.9. It is a significant feature of a 'flashover' that this transition to a state of total involvement is **sustained**. It has become further established that 'flashover', in its true form, is totally reliant upon variables such as thermal influences where *radiative and convective heat flux* are assumed to be the driving forces, although ventilation conditions, compartment volume and geometry, fire location and the chemistry of the hot gas layer also serve to influence any potential for a compartment fire progressing to flashover. Generally, such an event is physically defined as having been reached through flames exiting windows or door openings; gas temperatures of 600 deg.C at ceiling level; and heat flux to exposed items at floor level reaching 20 kw/m². It is worthy of note that '*rollover*', as an event that is seen to precede flashover by a few seconds, may also meet such criteria. As a scientist Thomas recognized the limitations of any precise definition of 'flashover' being linked with *total surface involvement of fuel* within a compartment (room) where, particularly in large compartments, it may be physically impossible for all the fuel to become involved at the same time. The spread of fire, in such a way, is generally linked with phenomena such as *flash-fires or flameover*.

VIII.10. In its generic sense the term 'flashover' is still used by many firefighters to describe a range of events that culminate in rapid escalation of the fire - rapid fire progress - or even an explosion with accompanying pressure wave that breaks windows or pushes walls down. Such generic use of the term should be discouraged.

VIII.11. In effect, flashover is generally a **heat-induced development** of a compartment fire. A fire that rolls 'lazily', although sometimes with great speed, across the ceiling, generally supports the event. It is rarely explosive although a pressure and combustion wave may break windows. It should be noted that there is potential for 'flashover' to be induced by an increase in compartmental ventilation where the *heat loss rate increases* as more heat is convected through the opening. There is a point beyond stability where ventilation may cause more energy to be released in

the compartment than can be lost through openings and this condition of 'thermal runaway' may lead to 'flashover' [12].

Flashover case histories

VIII.12.1. In the December 2002 edition of Firehouse magazine USA a company engine officer described how his crew attended a one-room house fire that had vented itself out of a rear window. Heavy fire was seen issuing from the window – the fire was post flashover. As the fire crew forced entry at the front they took out two windows either side of the entry door. As they advanced towards the fire they encountered moderate heat so they took out another window from the interior. At this stage the fire found them! At the same time the exterior officer ordered an immediate evacuation of the structure over the radio due to rapidly escalating fire conditions. Such were conditions inside the structure that they had to urgently evacuate out of the window they had just vented!

VIII.13. It must be remembered that fire will often head for an air supply – if that is behind you then you are in trouble! The more windows you take out behind you the more likely this is. Also remember that flashover conditions can be created or worsened by taking out windows, causing *thermal runaway*. If a window is to be vented it should be **ahead** of the hose-line being advanced, exterior wind conditions permitting!

VIII.14.2. A team of five firefighters arrived on-scene at a house fire and opted to place the primary search ahead of the fire attack. As the fire progressed unchecked for several minutes, without any form of isolation or confinement strategy, it developed beyond flashover and trapped two firefighters on the floor above. They survived but with serious burns.

Backdraft

VIII.15.'Limited ventilation can lead to a fire in a compartment producing fire gases containing significant proportions of partial combustion products and unburnt pyrolysis products (**under-ventilated fire**). If these accumulate then 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 backdraft (backdraught).'......

VIII.16.Use of the word backdraught (or backdraft) is not new - Steward described the phenomena as early as 1914 in an NFPA publication [41].

VIII.17.'These "smoke explosions" frequently occur in burning buildings and are commonly termed "back draughts" or "hot air explosions". Fire in the lower portion of a building will often fill the entire structure with dense smoke before it is discovered issuing from crevices around the windows. Upon arrival of the firemen openings are made in the building which admit free air, and the mixture of air and heated gases of combustion are ignited with a flash on every floor, sometimes with sufficient force to blow out all the windows, doors of closed rooms where smoke has penetrated, ceilings under attics, etc.'

VIII.18.In 1931 Deputy Chief Gamble (London) wrote [42] - 'Backdraught is the sudden ignition of inflammable dust in the air caused by organic substances that have become heated by the fire. Owing to lack of oxygen, combustion is delayed until a window is broken or a door opened. When the inrush of cold air containing its oxygen causes the sudden ignition of the heated air and an outburst of flame with such force as to give the effect of an explosion.....a dense mass of black smoke is usually seen issuing from the building a few moments before an outburst of this kind occurs'.

VIII.19.In 1936 Major C. Morris described the massive Crystal Palace fire in London [43] - 'as the wind veered round to the west the fire began to spread into the north transept. Two crews manning nozzles were sited therein in an attempt to halt the fire at this point. However, there was a grave risk of collapse and a back-draught of flame might occur....suddenly, in a flash, a huge sheet of flame travelled along under the roof and over their heads'....causing rapid evacuation of firefighting crews.

VIII.20. In 1992 C. Fleischmann [11] reported on the phenomena of backdraft - The purpose of his project was to develop a fundamental physical understanding of backdraft phenomena. The research was divided into three phases: exploratory simulations, gravity current modelling, and quantitative backdraft experiments. The term gravity current is used scientifically to describe two fluids of differing densities interacting in such a way that a vertical interface exists between the fluids, the resulting motion consists of the heavier fluid flowing horizontally beneath the lighter fluid. Such a flow is said to form a gravity current. Gravity currents are widespread in nature, and their common characteristics are observable in avalanches, heavy gas releases, turbidity currents, fresh and salt-water exchange, and sea breezes. However, the role they play in backdrafts is related to the movement of air into an under-ventilated fire compartment and is often referred to as an air-track by firefighters. It can often clearly be seen where smoke is pushing out of an opening or doorway with a clear interface below which clear air is entering the compartment or structure. The velocity of the air-track or the speed that the smoke is seen issuing is often a reliable sign as to the extent of under-ventilated conditions. However, a gravity current is not always distinct where heavy smoke exists down to the floor and a twister may sometimes be seen in the smoke at an entry point where a swirling pattern about the size of a soccer ball seems to be sucking air in through and along its path.

VIII.21. In effect a backdraft is a **ventilation-induced ignition** of the gases or combustion products. The event can result in a 'whoooooompf' or a 'bang' and can be violently explosive and damaging to structural elements. It generally produces a large fireball to the exterior of the building as fire gases are able to burn off in a plentiful supply of oxygen.

VIII.22. In the January 2000 edition of Fire Engineering magazine Brian White, a Captain with FDNY, put forward his own theory of a phenomena he termed - **high-pressure backdraft**. It was Mr. White's belief that wind effects upon buildings sometimes enabled excessive pressures to form within, as air entered through various openings on the windward side of a structure. He further suggested that when an opening was created elsewhere in the structure, the sudden unleashing of pent-up pressure sometimes worsened the effects of any rapid fire development as it stirred a large mass of high-velocity air-movement through the structure. He described several scenarios where rapid decompression of a structure occurred as windows failed, or vented, causing major increases in the burning-rate that were greater than normally anticipated '*fanning*' effects created by wind movement alone. These phenomena were also discussed by *Grimwood* in his book *Fog Attack* (1992) and his through own article, *momentum & inertia theory*, at www.firetactics.com

Backdraft case histories

VIII.23.1. At 1739 hours on 26th February 1994 London firefighters responded to a fire in a private cinema club in the central city area. On arrival four persons were seen trapped at a third storey window and one man had already jumped from this window prior to their arrival. As a ladder was sited for the rescue a further three men jumped from the window and another three were eventually assisted out and down the ladder. With reports of additional people trapped inside the structure firefighters in SCBA advanced a hose-line towards the interior stairs. As they reached the stairs a 'very loud roaring and intense fire' escalated in the stair-shaft and the crew were beaten back. A total of three people had jumped from the third storey and portable ladders and an aerial tower ladder were used to rescue a further 17. An additional six men died in the third storey cinema area. The classic 'roaring' sounds experienced by firefighters attempting to reach the upper floors by the interior stair-shaft demonstrated a backdraft situation where fire gases were burning off in the shaft as air rushed in from the access doorway.

VIII.24.2. On 1st February 1996 in Blaina, Wales, a fire involved the ground floor kitchen at the rear of a two-storey house during the early hours. The initial crew of six firefighters were faced with the predicament of children reported missing and trapped upstairs. The building was heavily charged with smoke, which was seen to be issuing from the eaves on arrival. They chose to attempt the rescues first and in doing so, no *interior fire attack* or *fire isolation strategy* was undertaken. Two hose-lines (19mm hose-reels) were laid to the structure but neither was brought into use prior to the backdraft occurring five minutes after arrival. Flames were seen issuing from the rear kitchen window and the compartment fire had developed to a post-flashover stage. However, a distinct gravity current was in progress with heavy volumes of thick black smoke exiting at the front entrance doorway. A resulting backdraft took the lives of two firefighters as the fire developed unchecked for several minutes.

VIII.25.3. Just three days later another firefighter (female) was killed by an ensuing backdraft that occurred in a large super-market in Bristol. As four firefighters (including the victim) entered through the main entrance to tackle the fire the heavy black smoke layer was seen to be in motion, continually rising and falling. Just five minutes after entry an intense 'howling wind' was seen to enter the main entrance doorway causing flames to bend inwards. The resulting ignition of the fire gases

moved across the wide expanse of the store both under and within the suspended fibre-board ceiling at an estimated five metres per second (high velocity gas combustion). The accompanying pressure wave knocked one firefighter off his feet. Should firefighters have entered these conditions in the first place? The continuous rise and fall of the smoke layer is most likely a result of the *pulsation cycle* caused by brief ignitions (oscillatory combustion) in the fuel-rich gas layers. This may also be linked to the 'puffing' phenomena noted by Sutherland. As these ignitions occur intermittently the repeating thermal expansions of fire gases may cause the smoke interface to rise and lower and such a process must be viewed as a classic warning sign for backdraft.

VIII.26.4. On March 28, 1994, the New York City Fire Department (FDNY) responded to a report of smoke and sparks issuing from a chimney at a three story apartment building in Manhattan. The officer in charge ordered three- person hose teams to make entry into the first- and second-floor apartments while the truck company ventilated the stairway from the roof. When the door to the first-floor apartment was forced open, a large flame issued from the apartment and up the stairway, engulfing the three firefighters at the second floor landing. The flame persisted for at least 6½ minutes, resulting in their deaths. The FDNY requested the assistance of the National Institute of Standards and Technology (NIST) to model the incident in the hope of understanding the factors, which produced a backdraft condition of such duration. The CFAST model was able to reproduce the observed conditions and supported a theory of the accumulation of significant quantities of unburned fuel from a vitiated fire in an apartment, which had been insulated and sealed for energy efficiency. This demonstrated that backdraft is not always, as commonly believed, a transient event involving short, possibly violent, releases of energy from the fire, which are not *normally* sustained!

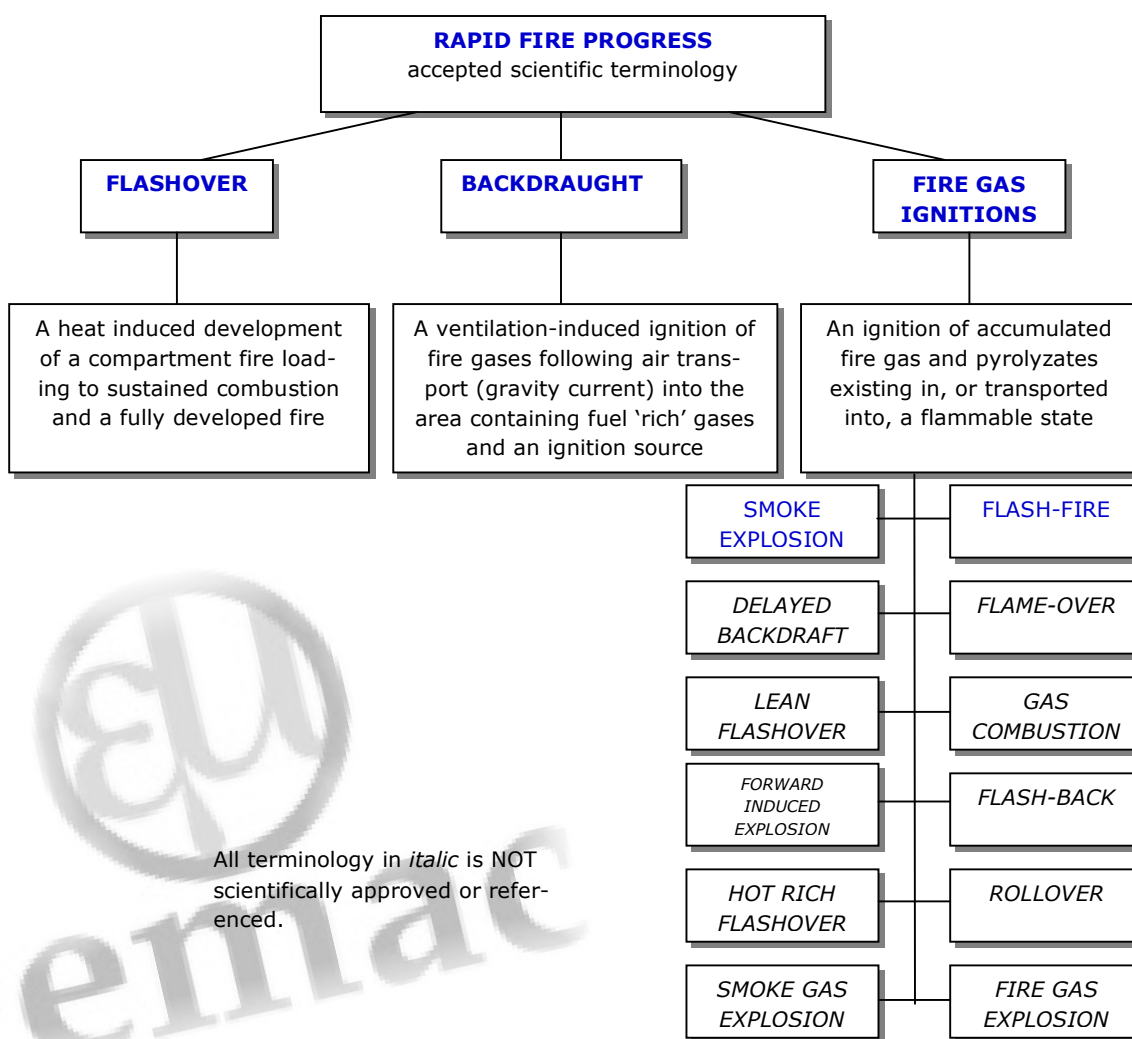
VIII.27.5. A fire department was using PPV in a pre-attack mode, in a house fire, to assist firefighters in locating the fire. The exhaust exit (window) in use was too small and a backdraft occurred as the fire gases ignited along the interface of the rich/lean mix.

Fire gas ignitions

VIII.28. There is a wide range of events that can be conveniently grouped under the heading Fire Gas Ignitions (FGI's) and such phenomena can generally be defined as – *'an ignition of accumulated fire gases and combustion products, existing in, or transported into, a flammable state'*. Any such ignition is usually caused by the introduction of an ignition source into a pre-mixed state of flammable gases; or the transport of such gases towards a source of ignition; or the transport of a fuel-rich mixture of gases into an area containing oxygen and an ignition source. The ignition is not reliant on the action of airflow/oxygen in the direction of an ignition source, which is clearly recognised as a backdraft event.

VIII.29. A look at the chart below (scheme VIII.1) will demonstrate how such phenomena can be conveniently grouped in such a way.

Scheme VIII.1 Rapid fire progress



VIII.29. There have been several scientific studies into the phenomenon of **smoke explosion** with the most recent by B.J. Sutherland [15] of University of Canterbury in Christchurch, New Zealand (1999). An explosion is defined in this study as the rapid propagation of a flame front with an accompanying pressure wave (Croft, 1980). Croft [16] suggests that pressures as high as 5-10 kPa could be produced during a smoke explosion. Pressures this high are large enough to break windows. It is the velocity of the flame front that determines the magnitude of the pressure wave. If the pressure wave is not formed or is negligible, then the phenomenon is known as a **flash-fire**, and not an explosion (Wiekema, 1984) [23]. This excellent report describes how smoke/gas layers may descend onto sources of ignition; how ignition sources may ascend into the gases and how a process termed 'puffing' may precede smoke explosions. This effect is thought to be similar to that of pulsating smoke – noted as a warning sign for 'backdraft'! The author also noted detached flaming in the overhead as a pre-cursor to some smoke explosions.

VIII.30. In his report Sutherland states there are three basic requirements that must be met before a smoke explosion can occur; they are:

1. A contained smoke layer that consists of enough unburned pyrolyzates that places the mixture within its limits of flammability. For example, the flammability limits for carbon monoxide are between twelve and a half and seventy-four percent, for methane the range is between five and fifteen percent (SFPE, 1995, 3-16).
2. To ignite the flammable mixture an ignition source is needed; there is a minimum amount of energy that will ignite the layer.
3. The last requirement is enough oxygen to support combustion.

VIII.31. At the Indianapolis Athletic Club fire [17] in 1992 it was suggested that the events that led to the firefighter and civilian deaths and injuries did not fit the accepted definitions of 'flashover' and further suggested that some form of **flash-fire** or **flame-over** was responsible for the rapid-fire development. This fire also demonstrated how flames might head towards new air supplies, at window openings, made or existing behind advancing fire crews. The term **flame-over** is used to describe the effect of flames, generally at ceiling level, travelling at high-speed across super-heated surfaces giving off flammable gases. This phenomenon is, in effect, not dissimilar to a flash-fire and is also sometimes confused with rollover, which is detached and sporadic flaming extending from the main fire plume in the overhead, often seen to precede flashover.

VIII.32. Floyd Nelson [18] (USA) introduced a further definition for a term he referred to as **Forward-induced Explosions**. In effect, this definition described the ignition of

pockets of fire gases as they transported throughout a structure/compartment. The phenomena differed from that of backdraft in that fresh air (oxygen) is the moving force in a backdraft whilst the gases themselves are the moving force in a 'forward-induced' explosion as they move towards a supply of air. This can occur in many ways inside a fire-involved structure, for example, where a collapsing ceiling forces fire gases to transport outwards from the area of collapse. On mixing with pockets of air they may come into the flammable range and can ignite with varying explosive effects.

VIII.33.Mr Nelson also discusses the effects of **high velocity gases** that may gain momentum in large spaces, corridors or shafts within a structure. Where the movement and ignition of super-heated fire gases are accelerated through narrow openings or corridors or are deflected the effects can be dramatic. The deep levels of burning (referred to in the UK as a *local deepening*) will cause unusual patterns of burn as if an accelerant has been used to increase fire intensity. On occasions, where high-velocity gases escape to the outside without being deflected, their flow is such that they may cross an entire street creating a flame-thrower effect from a window or doorway.

VIII.34.Swedish influence in fire behaviour training and language transitions have created terms such as gas combustion; hot-rich flashover; lean flashover; smoke or fire gas explosions and delayed flashover. Such terms are often confusing when applied universally as they already have meaning elsewhere.



Hot-rich flashover

Fuel-rich super-heated fire gases ignite immediately on contact with air, often to the exterior of a building but occasionally on exiting a compartment whilst still inside the structure. This effect has been previously termed **auto-ignition** by scientists.

Lean flashover

Relates to intermittent flaming in the gas layers at ceiling level. This effect is also termed '**rollover**'.

Gas Combustion

Relates to all situations where smoke or fire gases ignite as defined under the heading **Fire Gas Ignitions**.

Smoke-gas or Fire-gas Explosions

Defined and established in scientific terms as **smoke explosions**.

Delayed flashover/backdraft

This is a term used to describe an ignition that is delayed due to concealment of the ignition source. However, there are many different scenarios that may create this delay. Perhaps the fire involves a mattress that has its flaming restricted from underneath. If the fire smoulders, producing under-ventilated conditions, the sudden lifting of the mattress may introduce the ignition source to the accumulated combustion products – this may result in a **smoke explosion**. Another situation may lead to a build-up of flammable fire gases and combustion products in a compartment adjacent or some way from the original fire compartment. If an ignition source is introduced into this area the resulting **smoke explosion** can be extremely violent. This event could occur particularly in voided structures. It could be a situation where a fire breaches a floor to ignite accumulated fire gases on the floor above, forming in a flammable state. However, this again is a **smoke explosion** and should not be categorised as a flashover or a backdraft for these are different events. It is also dangerous to imply that only these type of ignitions may be 'delayed' for it is likely that all events associated with rapid fire progress may be subjected to delays for varying reasons, sometimes trapping firefighters following their entry and advancement into the structure.

Amongst other terms used by authors and scientists are **flash-back** – which is used to compare the effect of a Bunsen-burner with that of auto-ignition of fire gases at a point of exit (eg: window) burning back into the compartment; or, **blow-torching** – where a fire's intensity is increased by an exterior wind fanning the flames – an effect often mistaken by firefighters to be a 'flashover'.

Fire gas ignitions case histories

VIII.35.1. Firefighters were turning over debris after a small fire occurred in a cupboard involving some plastic and cardboard boxes. As they lifted a pile of debris a source of ignition was uncovered that ignited an accumulation of gases. The resulting explosion blew one firefighter into the hallway!

VIII.36.2. Whilst a PPV fan was being used to clear the smoke following a one-room house fire, the constant fanning effect from the PPV, after the main body of fire had been suppressed, caused a fast smouldering fire to occur in the debris and wall linings, resulting in an accumulation of fuel-rich 'under-ventilated' combustion products in the structure. The resulting explosion was caused as an ember or spark was convected up into these gases!

VIII.37.3. A fire in a Stockholm warehouse in 1986 had been extinguished but a heavy smoke layer in the large expanse of overhead went unnoticed above the firefighters heads. As debris was overturned an ember floated up into the smoke layer and a massive smoke explosion occurred with several firefighters receiving severe burns.

VIII.38.4. A fire in a warehouse caused two smoke explosions – firstly the un-vented smoke layer was fast approaching floor level when it came into contact with the flaming fire source. This ignited the smoke layer, which had formed into a flammable mixture. The second explosion occurred as a ceiling collapsed, pushing a fuel-rich-mix of fire gases outwards into other areas of the warehouse where there was a plentiful supply of air/oxygen. As the fuel-rich gases were diluted they came into contact with the fire and a further explosion occurred.

VIII.39.5. In 1973 a team of London firefighters was attempting to gain access into a basement area serving multiple occupancies in a six-storey building. The fire was in an under-ventilated state in the basement but all windows were intact. As the door was opened the gases **auto-ignited** on meeting fresh air. The fire burned above the firefighters heads for several seconds, trapping them in the open basement area outside the structure. They were not in immediate danger and were able to observe the gases burning off outside the compartment in free-air without any burning apparent inside the hallway. This effect may appear similar to that experienced at the NYC Watts Street fire (above) – if super-heated gases meeting fresh-air at a point of exit then cause the ignition it is not a backdraft. However, if the ignition occurred

inside the compartment first, as air entered, burning off in a fireball outside the compartment (Watts Street) then it is a backdraft – an ignition induced by ventilation. The two events may appear similar as they present themselves.

VIII.40.6. In 1997 a team of nine South Yorkshire (UK) firefighters responded to a fire in a car auto spares store. The building was tightly sealed with steel doors and windows boarded with timber and steel sheet. As the firefighters forced entry at the front of the store the conditions demonstrated moderate heat with only minor smoke issuing from the doorway. A water spray was directed into the overhead prior to entry. However, at this moment the doorway 'turned orange' and a fireball was seen heading out into the street. The explosion took out the entire storefront and buried several firefighters in front of the store in the street. Eight firefighters were taken to hospital – three of them seriously injured. It is most likely that the fire had burned for some time inside the sealed compartment and the fire gases and products of combustion had formed into an explosive mixture. On forcing entry a burning brand may have risen into the gases in the overhead causing a subsequent violent explosion. This was a difficult structure to ventilate due to re-inforced steel doors to the rear and boarded windows. The floor above served as a separate occupied residency. The introduction of water droplets into the overhead failed to suppress the smoke explosion in this instance. The lesson to be taken from this experience is to treat the frontage of such a structure as a shotgun barrel! This point was made in Fog Attack in 1992 where entry is being forced into a 'sealed' structure it is advisable to operate with the least number of firefighters in the danger zone as possible, using points of cover when able. At the time of this explosion all eight firefighters were situated directly in front of the building, just a few feet from the doorway.

VIII.41.7. Deputy Chief Thomas Dunne [44] (FDNY) presented a most interesting account of an event he termed '*delayed backdraft*'. He described how firefighters approached a fire in a two-storey and basement, 50' x 100' brick and wood-joint structure, in the Bronx. First arriving firefighters were faced with smoke (but no fire) issuing from the ground floor of a tire repair facility, which was the end one of three occupancies in the building. Initial actions were to lay 2 ½" hand-lines and open up all three occupancies at ground level, where it became obvious that the fire was restricted to the tire repair occupancy. Fire was located and almost suppressed in the basement of this part of the structure and adjoining occupancies continued to show clear of smoke or fire conditions. In fact a substantial firewall existed between the fire involved occupancy and the adjoining mattress store.

VIII.42. However, smoke issuing from the tire store suddenly started to increase rapidly and extended to the adjoining mattress store, causing the curtailment of interior firefighting operations. By this time a very large quantity of rubber tires were burning in the basement of the repair facility. An explosion (reported as a backdraft or smoke explosion), occurred some 45 minutes after first arriving crews had applied water to the fire. Immediately following the explosion a heavy amount of fire was seen to involve the ground floor level. As the fire continued to spread throughout the structure an exterior operation progressed through the night.

VIII.43. Deputy Chief Dunne then went on to explain that whilst firefighters are trained to recognise 'classic' warning signs of backdraft conditions on arrival, perhaps there is insufficient emphasis placed on the fact that such events can occur quite some time after fire suppression efforts have begun, possibly whilst the structure is occupied by firefighters. He advised that two incidents of this type had occurred recently in his assigned division and that firefighters should be wary of any enclosed space that is issuing heavy smoke and remains insufficiently vented.

VIII.44. The term '*delayed flashover*' was first introduced in Swedish firefighting training texts during the early 1980s and referred to situations where any likely ignition sources were isolated from accumulating flammable gas layers. This could occur where a smouldering fire existed in the same compartment as the fire gas accumulation or potentially where the gases were building in compartments adjacent to, or some way from, the fire compartment itself. The resulting explosion, when ignition source met with accumulated fire gases, was defined as a delayed action flashover. Later, during the mid 1990s, the same event was redefined in UK training texts [13] as a '*delayed backdraught*'. However, in both cases the definitions were incorrect in that these events are more correctly termed *fire gas ignitions* or *smoke explosions*. Experience has shown us however, it is perhaps more prudent to place greater emphasis on the fact that ALL events associated with rapid fire progress, be they flashover, backdraft or fire gas ignition, may occur quite sometime after initial firefighting operations have been initiated. Therefore the term *delayed*, along with the potential for delay, is applicable to all forms of rapid fire progress although perhaps even greater emphasis is needed in terms of fire-gas and smoke accumulations forming in adjacent or nearby compartments, rooms, voids or attics etc (*smoke explosion*). This form of explosion rarely presents itself with any form of warning signs whatsoever and is perhaps the firefighter's greatest hazard. Such explosions often occur when fire-gas accumulations form at their stoichiometric point - In terms of flammability limits of gas/air mixtures the stoichiometric mixture is the 'ideal' mixture that will produce a most complete combustion - ie; it is somewhere between the UEL (upper) and LEL (lower) explosive limits, and an ignition at the stoichiomet-

ric point may result in the most severe deflagration, in relation to those near the upper and lower limits of flammability.

VIII.45. A particular type of smoke explosion has been commonly associated with fires in saunas. This often occurs with some *delay* as a sauna is designed to retain heat! If a fire occurs inside the sauna, it is a *compartment within a compartment* if located inside a main building. Such fires progress extremely slowly in under-ventilated conditions, producing large amounts of smoke. The smouldering combustion process weakens the timber sauna structure and when firefighters direct a powerful stream of water at the sauna the structure fails and releases the ignition source into the surrounding atmosphere, which is most likely in a highly flammable state. The resulting explosion or ignition of the accumulated fire gases comes without warning and is often *delayed* until firefighters are occupying the space. This situation demands some form of tactical venting action prior to any attack on the fire taking place.



Website poll

VIII.46. In reality the phenomena of backdraft, flashover and fire gas ignitions are all closely linked and a firefighter who witnesses an event associated with rapid-fire progress may not be able to differentiate between specific situations. On other occasions it may be clearly apparent as to what actually occurred. The website poll exercise (2002) at Firetactics.Com demonstrated this fact quite clearly –

Flashover?	Backdraft?	Fire Gas Ignition?	Votes	
		Flashover	29%	91
		Backdraft	35%	108
		Fire Gas Ignition	34%	105
<i>Results not scientific</i>				304 votes total

Table IX.1 Website poll

VIII.47. **Flashover?** The 29 percent of voters who chose this option should remember that flashover is a *heat-induced development* of a fire where burning remains *sustained*. Although we only offered one picture from Glen Ellman's original sequence of seven for examination it is obvious that there is a major burn-off of fire gases taking place – once those gases burn-off the fire will rapidly subside.



Photo VIII.1 by Glen Elman

VIII.48. **Backdraft?** The ignition is occurring at an entry point, which suggests that an in-flow of air (gravity current) may have occurred. On arrival firefighters had reported a single storey frame house fully involved in the rear with fire showing through the roof. This fire was not demonstrating any signs of backdraft conditions and did not appear in an under-ventilated state. However, as Fort Worth firefighter Danny Morgan prepared to advance his 1 ¾" hose-line he 'felt it was going to flash'. He said 'there was heavy black smoke pouring out the top (of the doorway) and cool

air was being drawn inside in front of me....if we'd had one piece of protective clothing missing we'd have gotten burned'....A close study of the entire sequence of seven pictures shows the ignition of gases occurred as the door was opened for entry. Although the fire was well vented at the rear of the structure a build-up of fuel-rich gases was accumulating in the hallway at the front. As Danny Morgan and his colleagues opened the door a classic '*gravity current*' was set into motion. The resulting backdraft occurred within just a second or two! A more controlled approach to the door opening & entry procedure *may* have averted the ignition of gases (see end-notes).

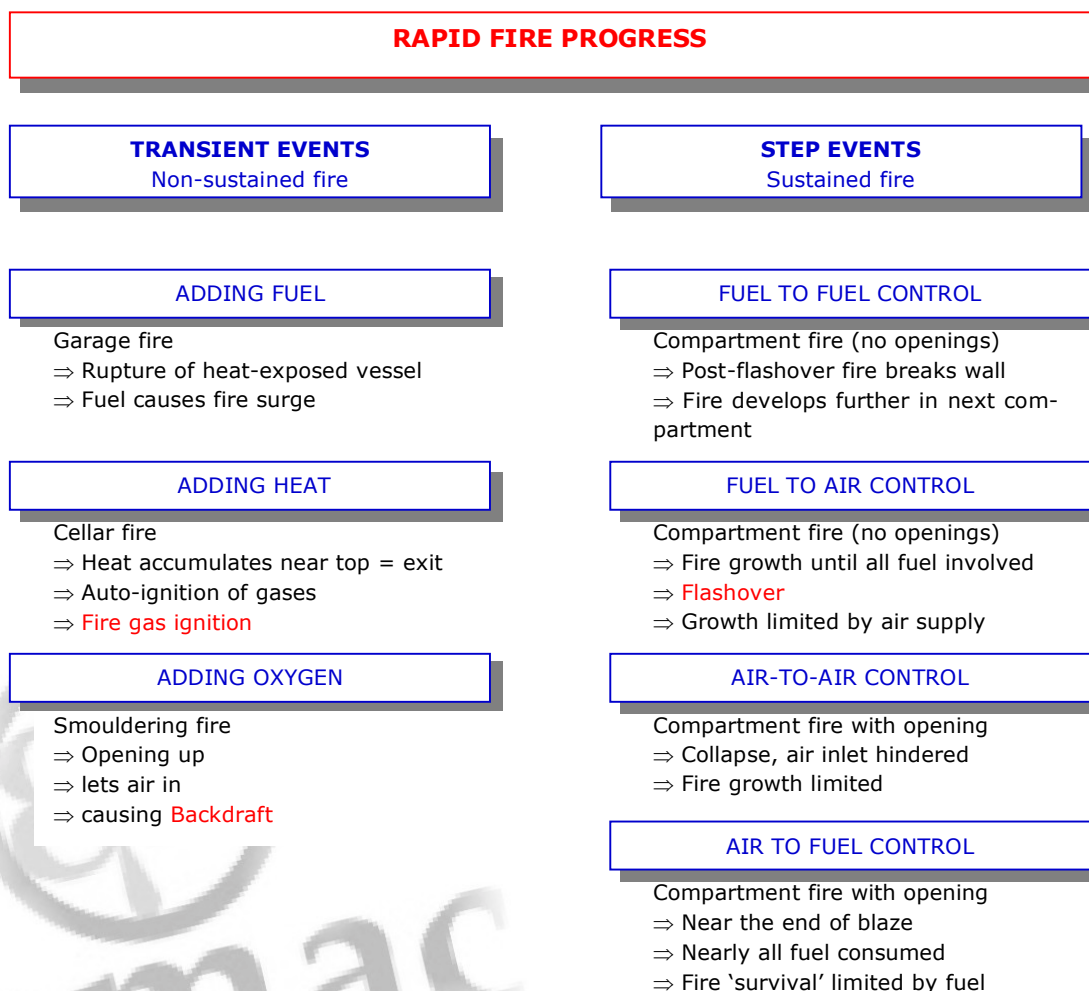
VIII.49. **Fire Gas Ignition?** The above photo, when placed aside on its own, may suggest that the ignition of gases was the result of a *smoke explosion* that occurred as a burning brand was convected or 'forced' into the gas layers on entry. Those that chose this option were not incorrect, based on the evidence provided!

VIII.50. **Is this relevant to the firefighter?** Does it really matter what caused the ignition? Well, the causes, tactical 'counters', and preventive actions for each specific event are different, as are the warning signs. It is important for the firefighter to understand the differences and also be able to recognize under what conditions they may occur. It is apparent that a backdraft can occur under a wide range of scenarios and a confined smoldering fire is not the only situation that can create 'under-ventilated' conditions. Warning signs may or may not present themselves but more importantly, the firefighter should anticipate worst-case-scenarios in each situation. It is the firefighter's actions that generate 'events' - perhaps a window or door is opened; or a hidden ignition source is uncovered; or an ignition source is pushed into a flammable fire gas layer by advancing firefighters. **The most important points are –**

- a) **Recognize obvious warning signs and don't commit crews into dangerous conditions except to save life;**
- b) **Utilise correct door entry procedure at all times; and**
- c) **Ensure correct tactical placement of hose-lines to protect escape routes, isolating the fire where water cannot immediately be applied.**

Step & transient events

VIII.51. There are several basic mechanisms which can involve a sudden change in the heat release rate of a fire in an enclosure - such changes can be divided into *step events*, where the heat release rate of a fire is sustained and *transient events* when the heat release rate returns to (approximately) its original value. There are seven ways [12] in which a sudden change may occur - four of these are step events representing transitions between fuel and ventilation controlled states whilst three are transient events corresponding to one of the components of the fire triangle (fuel, heat, oxygen). Flashover is usually a 'step' event whilst 'backdraft' is termed as a transient event, involving short, possibly violent, releases of energy from the fire, which are not *normally* sustained. It is possible for both step and transient events to occur at the same time.



Scheme VIII. 2 Rapid fire progress by step and transient events

Firefighter's actions & warning signs

VIII.52. The sudden opening of a compartment entry door may cause either a flashover, backdraft or potentially create a negative airflow into a stairwell, causing compartment windows to break inwards leading to rapid fire development. Use correct door entry techniques and 3D water-fog applications to lessen the risks. If possible, close all access points to the stairshaft on the fire floor prior to opening the compartment door.

VIII.53. Fires in concealed areas, roof spaces or in tightly sealed compartments with little ventilation are often prone to the hazards of backdraft where an accumulation of fire gases has slowly developed. Furthermore, smoke pushing out of the eaves of a structure is warning of a pressure build up inside. Tactical ventilation; 3D water-fog applications or *defensive actions* such as indirect water-fog attack from an exterior position are the most effective way of dealing with situations such as this.

VIII.54. Oily deposits on windows, hot doors and handles and pulsating smoke from around these areas are sure signs that backdraft potential exists on opening up. Again, a tactical venting operation coupled with 3D water-fog is required.

VIII.55. On entry, or during hose-line advancement into thick smoke, observe the smoke at the doorway. If a pulsation cycle is obvious with smoke flows sucking and pulsing back and forth or, if the smoke is black and rolling back into itself, retreat out of the area immediately behind a 'pulsing' spray of 3D water-fog into the overhead. A smoke layer that *constantly rises and falls*, as if on a pulsation cycle, is warning of an impending backdraft - evacuate the structure immediately!

VIII.56. Whistling or 'roaring' sounds are classic backdraft indicators - time to get out.....quickly!! Again, use the pulsing spray into the overhead to inert or quench any fire gases. Stay *away from the base of internal walls* if possible as high-velocity gases will generally 'bounce' off them at high speeds.

VIII.57. A further backdraft indicator [4] may be the presence of blue flames within the compartment. This may give warning of 'pre-mixed' combustion where air is rushing in a great speed to the fire source.....'pulse' and retreat!

VIII.58. Any sudden build-up of heat within a fire compartment, particularly if forcing the firefighter to crouch extremely low, is a warning sign of *imminent flashover*.

Pulse water up into the overhead, progressing a 3D water-fog application to effect gas-phase cooling.

VIII.59. The area immediately in front of a building such as a shop or factory-front should be considered a *high-risk* area. On creating an entry opening at the doorway (for example) the sudden in-flow of air, or the convection of a burning brand into a flammable gas layer, may cause a violent explosion! The resulting pressure wave and fireball may severely injure anyone who occupies this hazardous zone. *When siting fire engines or crews to work in this zone, be aware of the risk!*

VIII.60. If the smoke layer is rapidly banking to the floor and the fire is seen to be 'running' the ceiling, back out of the compartment behind a 'pulsing' spray into the overhead before a flashover occurs.

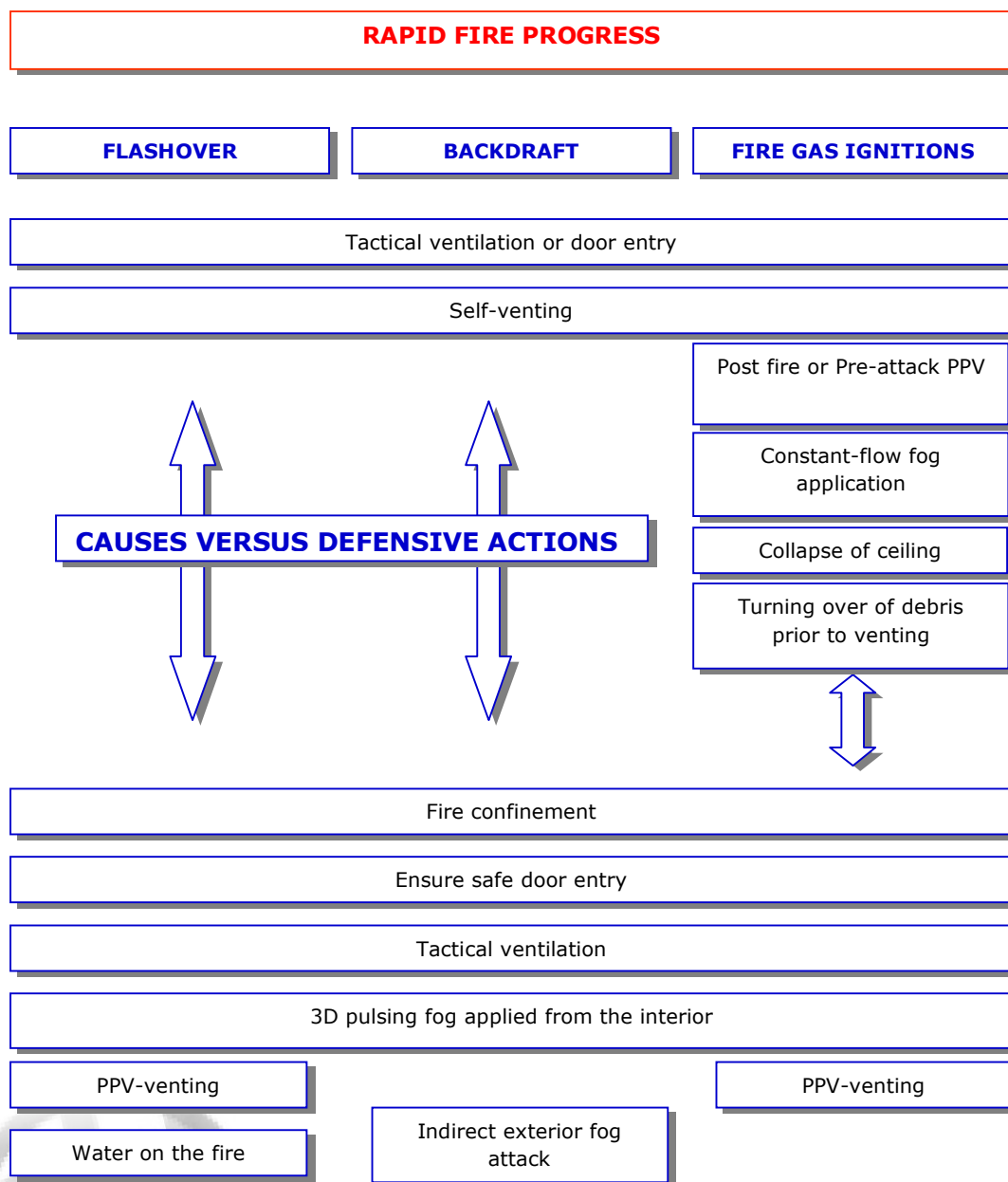
VIII.61. Great care to be taken when opening up walls, voids etc. Have a ready charged spray on hand to 'pulse' and cool any gaseous flows that may extend outwards or revert inwards.

VIII.62. Never anticipate the danger is over once the fire is under control and the overhaul stage is underway. Beware of accumulated fire gases in the overhead, *in cupboards, roof spaces, voids and adjacent compartments*. Ensure that all areas are effectively ventilated (prior to creating an internal opening if possible) under the protection of a pulsing spray application. Beware of using PPV under such circumstances where firebrands may be transported into the overhead!

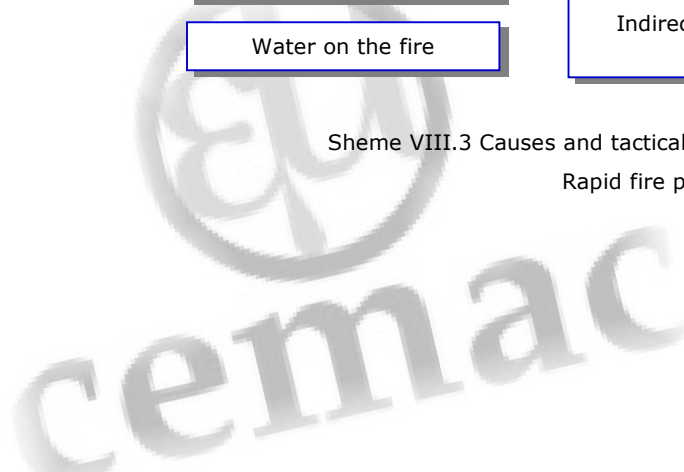
VIII.63. Signs of flaming in the gas layers above your head is a *flashover indicator* - 'pulse' pulse' pulse!!!

VIII.64. When forcing entry to a fire compartment serving a stair-shaft, ensure that the stair-shaft above the fire floor is unoccupied. If the fire is in an under-ventilated state the stair-shaft may serve as a *chimney* for igniting fire gases as they exit the compartment in a fireball!

VIII.65. When searching for fire, the raising of ceiling tiles hiding a ceiling void may cause either a backdraft or smoke explosion. Always consider vertical ventilation, where practical, prior to opening the void from below.



Scheme VIII.3 Causes and tactical defences of various forms of Rapid fire progress



The under-ventilated fire

VIII.66. Unlike the **ventilation controlled fire** an **under-ventilated fire** is not recognized as a 'burning regime' but rather a situation where 'fuel-rich' conditions (fire gases) have accumulated within a compartment (room or space). The situation may not involve a fully developed steady-state fire and is most likely in a state of smoldering. The fire itself may be confined behind a closed door or it may be somewhat open to hallways, stair-shafts and adjacent compartments, presenting conditions that may or may not offer warning signs related to backdraft. This type of incident is extremely familiar to firefighters but it presents one of the most hazardous situations they can face. There are important aspects of the tactical approach that the firefighter should be familiar with and training for this 'routine' type of fire has never been more relevant.

1. **The 'Size-up'**
2. **The 'approach'**
3. **The 'door-entry'**
4. **Tactical Ventilation**
5. **Fire Isolation**
6. **Gas-phase cooling & 'inertion'**
7. **Hose-line placements**
8. **Working above the fire**
9. **Adjacent Compartments**

VIII.67.1. The Size-Up

Upon entering any structure the firefighter should get a personal size-up locked into the mind. Don't rush in but DO take a second or two to **look up at the face of the building** - a lot can be learned. How many floors? How many windows? Smoke issuing? - from where? from the 'eaves'? Is the smoke under pressure? Are windows intact? Are there any windows open that show no signs of smoke issuing (may be feeding air to the fire). This information is 'locked in' with just a momentary glance - **practice it at EVERY fire** - even fire alarm calls! As you head into the building **look down to either side** - are there pavement lights or smoke venting points indicating a basement? On the way in look into the faces of people evacuating and gauge the urgency in their eyes! If they've seen, heard or experienced something bad it will show in a glance. Taking all this in will feed your mind and prime your senses, stabilizing your body with adrenalin for the tasks ahead.

VIII.68.2. The Approach

The 'approach' route to the fire is defined as a 'hazardous zone': either a hall-way, corridor or stair-shaft that leads to the room or apartment involved. This area needs to be treated with great caution and a risk assessment is needed to evaluate the situation. Is there smoke or heat on the approach route? Are there heavy smoke conditions? Is there gravity current in existence? This is an important indicator because **the presence of a 'gravity-current' suggests that the fire is not confined**, albeit that it may still remain in an under-ventilated state. The mere opening of the apartment door may initiate a gravity current, allowing smoke to exit under pressure at high level as air is 'sucked' in through the lower portions of the door, sometimes presenting a clear 'interface' where smoke meets air. The important point is, if there is smoke on the approach route this demands some action - if a clear gravity current exists then any exterior venting action of the apartment windows may worsen conditions further. There are alternative options in this situation - fire 'isolation' and venting of the approach route; or advancement in behind a 'pulsing' application of 3D water-fog to cool and 'inert' the smoke and fire gases. It may not be either possible or practical to 'isolate' the fire by closing the door to the fire compartment but this should always be considered in any approach. If the gravity current appears hazardous or backdraft indicators are present then isolating the fire and venting the approach route of smoke may be a viable and productive option. Signs of backdraft include heavy smoke staining or glass-crazing on windows that remain intact, harboring an under-ventilated fire; or heavy smoke conditions pushing from the eaves of a structure, possibly indicating a heavy pressure build-up within; or 'pulsing' smoke patterns at exit points as smoke flows rapidly reverse in direction, back and forth; a sudden in-rush of air (gravity current) creating a distinct smoke interface at a doorway or window; or a *'twister'* in the smoke where smoke is down to the floor and no clear interface exists, noted at a window or doorway, where a *swirling pattern about the size of a soccer ball* seems to be sucking air in along its path; or blue or 'dancing' flames that appear detached from the main fire within a fire compartment; or 'whistling' or 'roaring' sounds as air is being 'sucked' in at the entrance doorway or stair-shaft; or finally, heavy smoke conditions that appear to roll back into lots of tiny 'mushroom' shapes as the super-heated smoke exits a doorway or window. The isolation strategy can be taken further by closing any entry door on the approach route itself - this may support a **defensive** strategy by isolating the fire and venting the entire area prior to entry. However, if confirmed occupants remain within, an **offensive** approach may involve entry; isolation (behind you as you enter); 3D water-fog applications and search in unison with exterior venting when called for.

VIII.69.3. The Door-entry

Prior to opening any compartment door behind which there may be smoke or flames, it is essential to adopt an effective 'door-entry' procedure. This will include points such as positioning; opening the door 2-3 inches to insert and apply a brief burst of water-fog into the overhead; closing the door to allow the water droplets to take effect and possibly repeating the process again prior to entry. During this phase it is important to work under enough light to observe smoke conditions as the door is cracked, looking for smoke 'sucking' or 'pulsing' indicators, or again - a gravity current. The door can then be opened slowly and advancement made behind a 'pulsing' 3D water-fog application.

VIII.70.4. Tactical Ventilation

Strategically placed crews should give serious consideration to an exterior venting action. If several floors up, they may be able to vent windows from above or to the side using pike poles, hooks or axes lowered on a line/rope. Prior to entering the fire compartment the risk assessment carried out by firefighters may have suggested that warning indicators were prompting a venting action as an *essential primary* prior to door entry. They may, however opt to enter behind a 'pulsing' 3D water-fog application if the room is seen as 'approachable' and then call for the exterior venting seconds after having 'inerted' and cooled the gases in the overhead. Any such opening may serve to worsen conditions as well as relieve them! It is possible for a 'flashover' to occur as 'thermal runaway' occurs and the firefighter should be aware of this risk. It is also possible to worsen conditions if the wrong window is selected for opening, which serves an adjacent room/compartment that in turn, serves and is open to the fire room itself. Any venting action should be carefully coordinated and communicated between the Incident Commander, the fire attack team, the venting team and other firefighters occupying hazardous areas.

VIII.71.5. Fire Isolation (Confinement)

So many times, firefighters rush 'head-strong' into fires without considering tactical 'isolation' tactics. The mere act of closing a door may save lives! Always protect escape routes and where a hose-line is not being advanced towards the fire the closing of any such doors may avoid a dangerous gravity current and buy some valuable time. Always remember - **the most dangerous opening a firefighter might make is at the point of entry!** If possible it may be effective to ventilate or PPV smoke-logged areas once the fire is contained. It has been asked - "by isolating and confining a fire might we be creating backdraft conditions within" - I would say that this is possible. But better this and control the environment in adjacent compartments that may be occupied than allow a gravity current to develop un-checked. If

a hose-line crew are advancing on the fire then 'fire isolation' tactics become secondary, although still remaining a consideration.

VIII.72.6. Gas-phase Cooling and 'Inertion'

It has been scientifically proven that 3D water-fog applications, when applied in 'pulsing' fashion, using brief bursts at the nozzle, are the most effective way to cool or 'inert' dangerous gases in the overhead and possibly quench any likely ignition.

VIII.73.7. Hose-line Placements

The golden-rule of hose-line placements is to **site the first line in between the fire and the most seriously exposed** - this may be an escape route stair-way, for example. Another golden rule is to **stabilise the environment and attack the fire prior to**, or inline with, **internal searches as a primary action**. This rule is so often neglected by firefighters but it **means taking the fire before the search** and in areas of limited manning this is a choice that so often has to be made. If you choose to neglect either of these rules then you, and/or members of your crew may lose their lives.

VIII.74.8. Working Above the Fire

Prior to opening any door behind which fire is suspected, that serves or connects to a stair-way, ensure that no firefighters are working on the stairs above the door. Communicate to them to clear themselves from the area above - it's simple. Read the NYC Watts Street report to understand why!

VIII.75.9. Adjacent Compartments

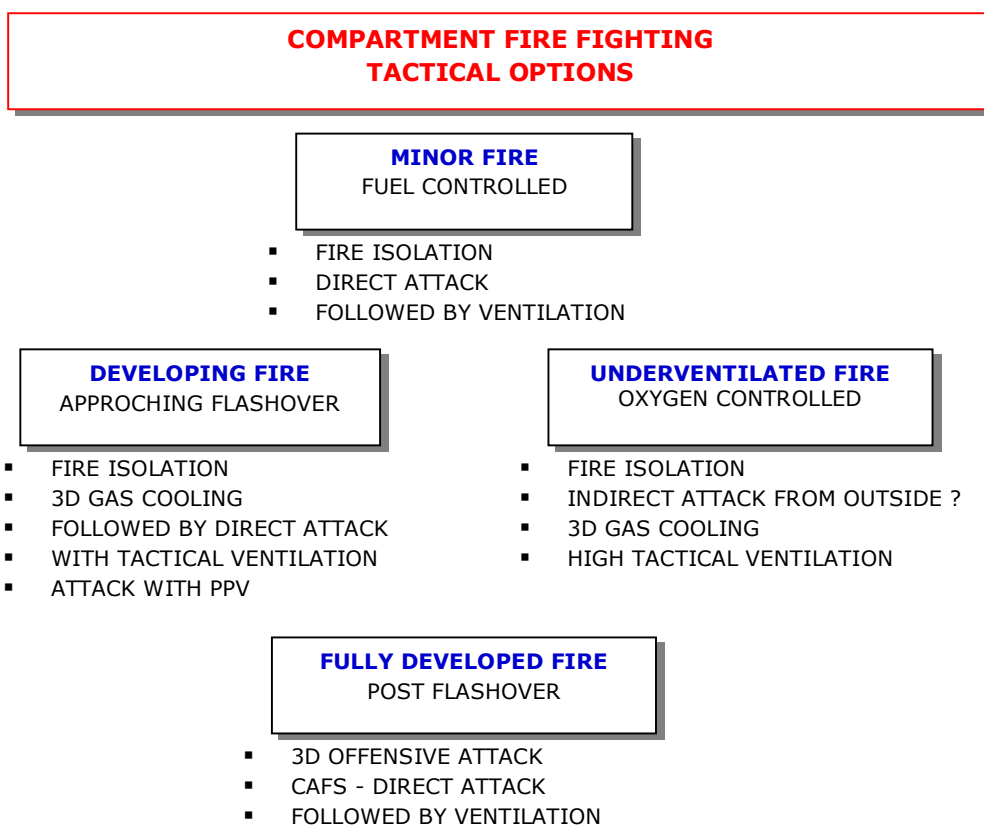
Adjacent compartments (rooms, stairs, shafts, spaces, cupboards etc) to the fire compartment, on the fire floor or at other levels in the structure may present a severe risk of 'smoke-explosion' if connected by voids or where 'off-gassing' has occurred above the fire. The introduction of an ignition source into this area may cause such an event if not carefully approached and vented, even where smoke conditions are reported as 'light to moderate'!

VIII.76.10. Fire Modeling in under-ventilated Apartment Fires

Interesting research by **Daniel Gojkovic & Lasse Bengtsson** [22] attempts to integrate theoretical CFD calculations with practical fire-fighting tactics used in Sweden, when arriving at the scene of an under-ventilated fire. It is shown that CFD has a great potential in creating a greater understanding of fire-fighting tactics. If burning has occurred in a lack of oxygen for a long time excessive pyrolysis products may have accumulated in the fire compartment. If air is suddenly introduced to the compartment a backdraft may occur. Different firefighting tactics are evaluated in-

cluding (1) Natural ventilation; (2) 3D offensive water-fog application with anti-ventilation; (3) Positive Pressure Attack (PPV).

VIII.77. **Conclusion:** There are options discussed in terms of entry procedures; approach route strategies; exterior venting actions; PPV; fire isolation tactics and 3D water-fog applications. The factors that will influence the selection of such options are a) risk assessment; b) existence of a strong gravity current; c) backdraft warning indicators; d) confirmed occupants within - promoting an 'offensive' approach that may place an exterior venting action as a secondary to entry, isolation and 3D fog applications in support of the search.



Scheme VIII.4 Compartment fire fighting – Tactical options



Flashover Phenomena – Questions & answers – Revision Aid

VIII.78. What is a flashover?

The term 'flashover' was introduced by UK scientist P.H. Thomas in the 1960s and was used to describe the theory of a fire's growth up to the point where it became *fully developed*. Customarily, this period of growth was said to culminate in 'flash-over', although Thomas admitted his original definition was imprecise and accepted that it could be used to mean different things in different contexts. Thomas then went on to inform us in UK Fire Research Note 663 (December 1967) that there can be *more than one kind of flashover* and described 'flashovers' resulting from both *ventilation* and *fuel controlled* scenarios. The term has been used in a generic sense by firefighters to describe various forms of *rapid fire progress* (RFP).

VIII.79. What other forms of Rapid Fire Progress (RFP) might firefighters encounter during structural firefighting?

There are several - **Flashover** is generally recognized as a *heat induced* form of RFP where the likelihood of a flashover occurring increases as the heat given off by the fire itself increases. **Backdraft** is an event that is generally *ventilation induced* where air/oxygen is suddenly introduced to an under-ventilated fire, often in a smoldering state. **Smoke Explosion (or Fire Gas Ignition - FGI)** is often confused with 'backdraft' but this type of event is distinctly different, where a pre-mixed 'pocket' or 'layer' of fire gases (in smoke), that are already within their flammable range, ignite on coming into contact with an ignition source. This could occur where a burning brand rises up into the flammable region, or where the smoke layer naturally expands and descends, as the fire progresses within a compartment, to meet an ignition source somewhere in the lower regions of the 'room'. It might also occur where a ceiling collapses (for example) or if a fog pattern 'pushes' the smoke outwards, forcing the fire gases towards ignition sources or into their ideally mixed states. These ignitions of the fire gases can take several forms - they may occur explosively, or they may be small events that can even set off a chain of similar additional events within a compartment. The fire gases may also ignite as they transport themselves through an opening, into an area that contains an abundance of air, for example near a stair-shaft or as they exit from a window or doorway. These ignitions may occur spontaneously in air, without an ignition source, where the gases are super-heated above their auto-ignition temperature and the flames will appear detached from the main fire plume (the burning items). Such ignitions may even *flash-back* into the compartment from where they came or they may continue to burn-off at the newly found air supply if conditions within are too 'rich' for gas burning to occur. Some smoke explosions have been particularly

damaging in their explosive effects and may occur in areas/compartments some way from the original fire compartment. In some instances, firefighters have occupied small rooms or storage areas and initiated a smoke explosion as they uncover an ignition source (ie; lifting a mattress with a small fire underneath) in an unvented area.

VIII.80. Do not confuse the increase in a fire's intensity or severity caused by external wind effects with that of a flashover or backdraft as they are not linked. This 'blow-torching' effect is common and occurs rapidly, without any warning whatsoever! The effects may appear the same but in reality, the cause is far simpler to comprehend - know the likely wind conditions prior to responding!

VIII.81. Can a 'flashover' be induced by an increase in ventilation?

Yes! There are occasions where the heat loss rate from the compartment increases as more heat is convected through the opening (eg window). However, there is a point beyond stability where ventilation may cause more energy to be released in the compartment than can be lost through the opening/s and this condition of 'thermal runaway' may lead to 'flashover'. It should be noted that on occasions several forms of RFP may occur and be closely linked together, making it difficult to realize which of the events actually initiated the ignition of gases.

VIII.82. Is flaming from a backdraft event normally sustained or is it usually a brief release of energy?

Scientists suggest that there are basic mechanisms which can involve a sudden change in the heat release rate of a fire in an enclosure - such changes can be divided into *step events*, where the heat release rate of a fire is sustained and *transient events* when the heat release rate returns to (approximately) its original value. There are seven ways in which a sudden change may occur - four of these are step events representing transitions between fuel and ventilation controlled states whilst three are transient events corresponding to one of the components of the fire triangle (fuel, heat, oxygen). Flashover is usually a 'step' event whilst 'backdraft' is termed as a transient event, involving short, possibly violent, releases of energy from the fire, which are not normally sustained. It is possible for both step and transient events to occur at the same time. However, there have been documented cases of 'backdrafts' occurring with sustained flaming over several minutes. One such event was the New York Watts Street fire where a backdraft occurred leading to flaming in the stair-shaft that lasted some 7 minutes as the fire gases burned off!

VIII.83. Are the various forms of RFP usually 'explosive'?

All forms of RFP may result in pressure or blast waves to varying degrees, ranging from a 'pop' to a 'whoooooompf' to a 'bang' that results in structural damage - an 'explosion'! On occasions the ignition of fire gases will be slow and can be seen to roll 'lazily' across the ceiling whilst on other occasions the ignitions will be forceful and occur with great speed.

VIII.84. Which of the three basic forms of RFP are firefighters most likely to encounter?

This is a common question but there are no real answers, as reliable statistics do not exist! In my experience as a firefighter, and of studying fires, I would suggest that a heat induced 'flashover' is the most common event but these frequently occur prior to firefighters arriving on-scene. Perhaps the 'backdraft' is the most likely event for firefighters to encounter as they are instantly creating ventilation openings (entry point) that are most likely to affect the fire's progress, or possibly the 'smoke-explosion' as firefighters advance towards the fire and upset/invert the thermal balance and fire gas formations by directing constant-flow fog patterns into the fire area, unknowingly pushing flammable gas 'balloons' directly onto an ignition source.

VIII.85. What warning signs should firefighters be looking for?

The warning signs are different for each occurrence - The onset of flashover is indicated by flames in the overhead running the ceiling (*rollover*); or sudden increases of heat forcing the firefighter to crouch low; or the sudden lowering of an existing smoke layer (*smoke interface*). Signs of backdraft include heavy smoke staining or glass-crazing on windows that remain intact, harboring an under-ventilated fire; or heavy smoke conditions pushing from the eaves of a structure, possibly indicating a heavy pressure build-up within; or '*pulsing*' smoke patterns at exit points as smoke flows rapidly reverse in direction, back and forth; a sudden in-rush of air (gravity current) creating a distinct smoke interface at a doorway or window; or a '*twister*' in the smoke where smoke is down to the floor and no clear interface exists, noted at a window or doorway, where a *swirling pattern about the size of a soccer ball* seems to be sucking air in along its path; or blue or '*dancing*' flames that appear detached from the main fire within a fire compartment; repeated rising and falling of the smoke layer; or '*whistling*' or '*roaring*' sounds as air is being '*sucked*' in at the entrance doorway or stair-shaft; or finally, heavy smoke conditions that appear to roll back into lots of tiny '*mushroom*' shapes as the super-heated smoke exits a doorway or window. The **existence of flammable smoke-layers** are rarely apparent but the firefighter must **ALWAYS** presume this layer is there - laying dormant in the overhead - both **DURING** and **AFTER** a fire has been extinguished!

VIII.86. What does the term High Velocity Gases refer to?

This phenomenon often occurs in large open compartments or where narrowing within a compartment occurs, for example in corridors or at doorways and stair-shafts etc. It is where the fire gases are igniting across a space at an increasing rate of burn before suddenly being stopped by a wall or narrowing of the opening, where the intensity of the burn rate appears to increase. Such phenomena may leave extremely severe burn patterns at the top and base of walls as well as at the points of narrowing. These burn patterns have been scientifically referred to as *local deepening's*.

VIII.87. Can tactical venting actions by firefighters prevent RFP?

There is much scientific research and debate concerning this topic as well as a whole host of fireground experience. Quite simply, the creation of openings **MAY** serve to **relieve** the conditions that cause RFP or they **MAY** actually **cause** RFP to occur! The events and conditions required to initiate them are unpredictable in the field and any such action by firefighters is often based upon a calculated risk - a gamble! Even the use of PPV (Positive Pressure Ventilation) may prevent RFP in some situations but initiate it in others.

VIII.88. The rule of thumb guidelines in tactical venting actions are this - **VENT FOR LIFE - VENT FOR THE FIRE - VENT FOR YOU!** This means - 'venting for life' actions are undertaken by firefighters who are practiced in the techniques and familiar with local construction and access points. The term **VES (Vent - Entry - Search)** is common in the USA and some parts of Europe - however, this form of tactical venting action is to access and save confirmed life by relieving conditions in the victim's location, knowing that such relief may only occur for a few vital minutes, or seconds! To 'vent for fire' means relieving conditions for interior attack and search teams and attempting to divert flame-spread from a horizontal direction to a vertical direction, or vice versa, in an effort to clear smoke, heat and fire from within by the shortest possible route. Such tactics **MAY**, on occasions, worsen the situation although, if correctly applied, will generally offer a positive outcome.

VIII.89. To 'vent for yourself' is something that all firefighters should be considering - in the one-room smoldering fire it is generally safer (for firefighters) to ventilate combustion products out of the compartment from the exterior **PRIOR** to forcing entry. Similarly, the approach route should be ventilated prior to entry being made into the fire compartment. However, where the door to the room is already open then a venting action **MAY** place an advancing attack crew in danger - it's a tough call - and only those on the inside should make that call! Communicate!!! However, al-

ways remember that water droplets and gas-cooling/gas inertions should ideally be applied into the overhead (and fire compartment where possible) prior to any external venting action.

VIII.90. **Is it true that RFP or 'explosions' may occur in compartments some way detached from the main fire compartment?**

Yes! This is something firefighters find difficult to comprehend! It is quite possible for fire gases to be transported into adjacent compartments either on the same level as the fire or on upper and even lower floors. They may exist in light to moderate smoke conditions and give the appearance that they are harmless. However, if an ignition source is introduced at any stage prior to their removal from the structure a smoke explosion may occur, possibly with structural damage resulting! Structural void extension or off-gassing of carpets above the fire have often been seen to cause such an event, sometimes after the main fire has been suppressed.

VIII.91. **Can the use of 3D pulsing fog patterns actually prevent ignitions of the gas layers?**

Yes! There are two ways in which they can do this - *gas-cooling* and *gas-inertion*. The use of 3D pulsing fog patterns can also be used to control and suppress burning gases in the overhead far more effectively than a straight stream. By resorting to brief bursts of water-fog, as opposed to a constant stream, you are less likely to 'push' fire gases towards ignition sources and more likely to maintain control of the environment. The effect of placing 'pulses' of fine water-droplets into the overhead is a three-dimensional (3D) process and is far more controlled (and safer) than using long bursts of water-fog which create large amounts of steam and force gases, fire and heat to transport, sometimes to great disadvantage. The 'pulsing' process ensures maximum cooling takes place *in the gases and NOT on super-heated surfaces* (walls & ceiling etc), optimizing any approach and reducing the likelihood of any RFP. The effect of gas inertion is not fully proven although scientists admit that the presence of fine water droplets suspended in a flammable gas layer is most likely to quench the effects of any subsequent gas ignition and potentially prevent such ignitions in the first place.

VIII.92. **How serious is the problem of firefighter deaths through various forms of RFP and how can we reduce these tragedies?**

Reported deaths through 'flashover' or other forms of RFP are difficult to locate. In the USA the NFPA report an average of five firefighters are killed annually by RFP and in other parts of the world there are constantly reports of serious incidents. Not only are there deaths, a few survived with terrible burns. **Many of the deaths occur during live 'training' burns in acquired unoccupied structures !** Even more important

are the number of incidents of RFP that go unreported! As events come to light it appears the problem is far more serious than one would first think. The big factor is that these events are associated with multiple firefighter deaths - RFP takes entire attack or search teams and the losses can be severe.

VIII.93. What is 'corridor flashover'?

Where fire gases are transporting into the corridor serving a room or compartment involved in fire, they may ignite. If the room itself has reached 'flashover' (total sustained involvement and flaming) then the air required to sustain flaming in the room may be provided to a greater proportion via the corridor. The flaming may extend out from the room into the corridor at ceiling level and the gases may ignite. Much will depend on whether the gases are 'fuel-lean' or 'fuel-rich'. If the gases are 'lean' the flaming will occur close to the ceiling and bring the surfaces into the ignition equation. If the gases are rich then flaming will occur at the lower boundary of the gas layer where air entrainment is taking place. Such an 'event' in the corridor leads to a restriction of air entering the room, resulting in 'fuel-rich' burning in the room, which in turn leads to an increase in the quantity of smoke produced. Corridor 'flashovers' are likely to be very intense, travelling with great speed. There is no protection for firefighters occupying the corridor where the narrowing of the space can turn a deflagration into a detonation. Two corridor flashovers in a St. Petersburg hotel in 1991 caused the deaths of eight firefighters - four were forced to jump from the seventh floor to escape the flames, only one survived. In 2002 five Paris firefighters were killed in similar corridor flashovers/backdrafts. These effects of rapid fire progress may not fit the normally accepted definition of 'flashover' as an event.

VIII.94. What is a 'flash-fire'?

An explosion is defined in the Sutherland [15] (1999) study as the rapid propagation of a flame front with an accompanying pressure wave (Croft, 1980). Croft [16] suggests that pressures as high as 5- 10 kPa could be produced during a smoke explosion. Pressures this high are large enough to break windows. It is the velocity of the flame front that determines the magnitude of the pressure wave. If the pressure wave is not formed or is negligible, then the phenomenon is known as a flash fire, and not an explosion (Wiekema, 1984). Wiekema's study [23] of sixty-eight fire incidents found that the presence of obstacles in a vapour cloud promotes the formation of an explosion and not a flash fire. Wiekema declares that obstacles cause turbulence, and turbulence is known to enhance flame speeds; thus, a pressure wave is generated.

IX. 'NEW-WAVE' 3D WATER-FOG IN FIRE-FIGHTING

IX.1. The tactical approach to structural firefighting, based around the concept of Lloyd Layman style 'indirect' attack has evolved over many years, although direct extinguishing techniques using narrow fog-patterns and straight streams is perhaps more widely used. The modern attack strategy is generally very aggressive and streams are applied from the interior whilst working at close quarters to the fire. This has sometimes caused firefighters to suffer from steam 'envelopes' and temperature inversions as thermal layers are often disrupted.

IX.2. In 1982, following the loss of two firefighters lives in a Stockholm flashover, the Swedish Fire Service introduced an innovative adaptation of the *Layman principles*, whilst working from an interior position, that negated all the problems previously associated with close-quarters fire combat and the compartmental use of water-fog. The 'new-wave' applications were termed '*offensive firefighting*' and later '*3D water-fog attack*' [4] when it was realized that the objective was to apply fine water droplets directly into the fire gases in the overhead. These three-dimensional effects were, in real terms, the exact opposite of the Layman approach that intended the evaporation to occur as water came into contact with the hot surfaces, walls, ceiling linings etc whilst targeting a 10 percent mix of water vapour within the compartment. Unlike the Layman approach, the effects of 3D water-fog applications were seen to rely far less on the *smothering* effects of excessive water vapour and more on the *cooling & inerting* effects that occurred in the gases.

IX.3. Around the same time a Stockholm fire officer [26] adapted a steel shipping container lined with panels of chip-board to demonstrate how fire gases formed and transported inside a 'fire compartment' before they eventually ignited in simulated rollovers, which would lead to flashover. This innovative use of a simple, cheap and freely available structure was further adapted for safety and effect and became known internationally as the 'flashover simulator' or 'can'. The design of the 'simulator' has been researched, developed and used worldwide to teach fire behaviour to firefighters whilst at the same time, enabling them to practice various nozzle techniques to deal with the fire gases building towards the *rollover* and *flashover* stages of development.

IX.4. In 1984 the use of 3D water-fog applications were researched operationally by west-end firefighters in London [4]. The 'new-wave' tactical approach became extremely popular although it was several years before the strategy was finally adopted officially by the UK fire service [13]. In 1988 and 1990 the US coast-guard [4], under the sponsorship of the navy's Naval Sea Systems Command (NSSC), researched what they termed as the 'short water-burst' technique and in 1994 the US Navy concluded their extensive research [27] into 3D water-fog applications for ship-board use. In 1997 the US Navy project team's research and recommendations were approved and the techniques were adopted officially as part of their operational attack plan NSTM 555-7.

IX.5. By the turn of the new millennium the 'new-wave' uses of 3D water-fog were being researched and deployed by many fire authorities across Europe, Australia, USA, and several other parts of the world. In the early part of February 2001 the Austin Fire Department in Texas USA completed 146 live training burns [36] in acquired structures and evaluated the 3D water-fog approach in every situation. Over 500 students utilized this form of fire attack and noted that the application of 'pulsing' water-fog droplets into the super-heated fire gases 'worked on the great majority of fires' The 'new-wave' applications developed throughout Europe since the 1980s were found to be particularly effective when traversing the approach route to fire-involved compartments. The improvements in visibility and maintenance of thermal balance when compared to smooth-bore attack appeared particularly outstanding. Austin firefighters noted that on a few occasions the fire would grow so rapidly that no amount of 3D fog application would control it and on these occasions even a smooth-bore application failed to reduce the fire's intensity, causing firefighters to retreat. This would suggest conditions where **air-tracks** remained uncontrolled and Heat Release rates (HRR) over-powered the lines and flows in use.

IX.6. One Austin Fire Officer stated [36]- *'I believe the 3D attack method worked very well and was the method of choice in the vast majority of the 146 fires we encountered in the training and are likely to encounter in the field. The use of 3D water-fog pulsing streams is the safest and most effective method compared to other applications although it is not suited to all situations. We are now teaching our firefighters these techniques'*.

IX.7. In 2002 the National Research Council (NRC) in Canada presented a review paper [45] that suggested further research into 3D water-fog tactics would most likely confirm the innovative potential of this firefighting strategy. They offered the view that in theory there was every reason to advance such an approach as 3D firefighting offered major advantages to the firefighter. They stated *'Compared to tradi-*

tional straight stream or narrow fog techniques, both experimental and analytical results show that proper use of the 3D water fog technique can have a better cooling effectiveness, generate less steam and lead to less disruption of the thermal balance in the smoke layer by using short discharges, fine droplets and wide spray angle'.

Flashover

IX.8. It was the loss of several firefighters lives in *flashover related events* that prompted the need for a review of firefighting strategy in Europe from 1980 onwards. It became obvious that firefighters did not have a clear appreciation of how compartment fires developed under varying ventilation parameters and little attention was being directed to the dangerous formations of flammable and explosive fire gases in the overhead. Sometimes these gases would transport into adjacent compartments or voids, some distance from the fire, and ignite under delayed circumstances, occasionally after the main fire had been suppressed. Several definitions of **flashover, backdraft and fire gas ignitions** were closely researched by scientists in the UK, Sweden and New Zealand and several events associated with rapid fire progress were clarified. This knowledge encouraged a reviewed approach to compartment firefighting and the flashover simulators (containers) were used to teach fire behaviour; fire compartment entry techniques from adjacent areas and 3D 'pulsing' actions at the nozzle to control conditions in the overhead.

3D water fog-applications

IX.9. There are three main applications, or uses, of 3D water-fog in compartment firefighting –

1. **Gas cooling** - used to cool the gases in the overhead below temperatures that support any progression to rollover or flashover situations.
2. **Inerting** - used to create an 'inert' atmosphere in the overhead - one of controlled steam OR suspended water droplets where no evaporation occurs - to prevent or suppress/mitigate any likely ignition of these gases in a backdraft or smoke explosion.

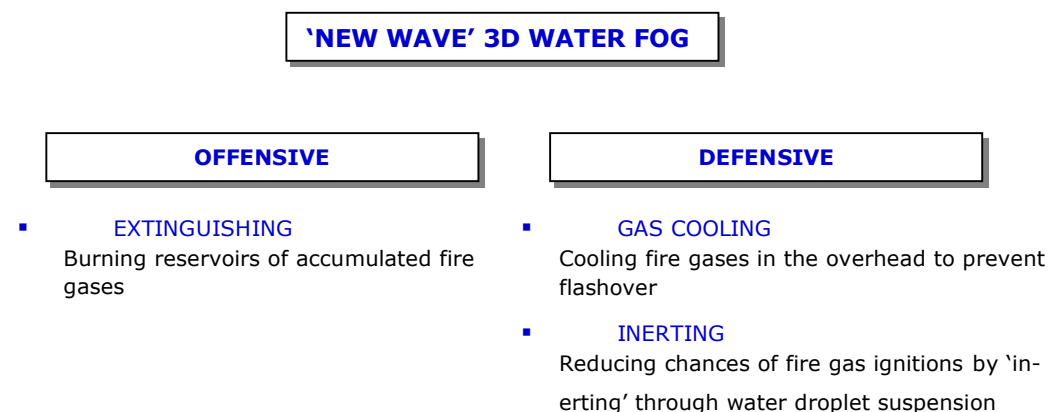
3. **Suppression** - used to extinguish burning reservoirs of fire gases that have accumulated and are burning off in geometrical voids such as stair shafts; attics or compartments etc.

IX.9. It should be clear that such applications are used - not (solely) to extinguish fires - but mainly **to make 'safe' the approach route to the fire** and reduce the likelihood of fire gas ignitions - flashovers - backdrafts etc. Neither are these techniques designed to replace the 'direct' style of fire attack utilising water in a straight stream setting but moreover, to complement existing forms of fire attack in an effort to increase the safety and effectiveness of firefighting teams.

IX.10. An interesting research project undertaken by a scientist [22] at Lund University in Sweden used a computer model to demonstrate the likely effects of actions taken at an under-ventilated compartment fire using

1. Natural ventilation;
2. PPV;
3. 3D water-fog application.

His conclusions demonstrated the 3D water-fog application as the safest option of the three.



Scheme IX.1 The new wave of 3D-Fog

IX.11. Three-dimensional tactics may be either defensive or offensive - the true qualities of 3 dimensional water-fog applications are realized in flashover & backdraft prevention (defensive). The 'pulsing' of water-fog into the overhead on the approach route using short rapid bursts at the nozzle serves to 'inert' the fire gas layers and will prevent or mitigate the potential for any ignition of the fire gases that may lead to such a major event. Such ignitions of accumulated fire gases may vary in their explosive force but it has been demonstrated that fine water droplets are able to offer a 'quenching' effect under such conditions and lessen

the explosive effects. However, again the applications are administered with a reasonable amount of precision and are dependant on equipment, firefighter awareness and training. The duration of 'pulses' and degrees of cone spread will vary according to the size of the compartment and the conditions presented therein.

IX.12. There are many ill-informed arguments and misconceptions mounted against the tactical use of three-dimensional water-fog, for example ...

False assumptions

IX.13. **The stream from a smooth-bore nozzle can be used just as effectively to 'cool' gases in the overhead by utilising a 'Z' pattern - FALSE.**

It has been scientifically proven in several independent research studies that fine water droplets WILL cool gases in the overhead far more effectively than a straight stream application. The US Navy tests [27] (for example) clearly demonstrated this fact under strict scientific monitoring.

IX.14. **The application of water-fog causes steam burns to firefighters and pushes fire ahead of the stream - FALSE.**

This will not happen where a 'pulsing' action is used at the nozzle, using short bursts to place about a 'cup-full' of water-droplets into the overhead with each brief 'pulse'. The water will then evaporate in the gases and not on super-heated surfaces such as walls and ceiling. This cooling effect causes the gases to CONTRACT and move away from the nozzle operator. The compartmental pressure is more negative than positive and steam production is 'dry' as opposed to cloudy 'wet'. There is not enough 'force' from the 'pulses' to push fire ahead of the 'stream'.

IX.15. **The use of water-fog upsets the thermal balance - FALSE.**

The actual effect where three-dimensional applications are used is exactly the opposite! The smoke layering is maintained and visibility is optimised by 'pulsing' water-fog into the overhead. This has constantly been demonstrated in scientific studies, including the US Navy tests, when compared to the stream from a smooth-bore nozzle.

IX.16. **The flow-rate required for gas-phase cooling is dangerously low - FALSE.**

But with a select-a-flow combination nozzle you have higher flows immediately available at the flick of a switch! Gas cooling can also be effected with high-flow

automatic nozzles. You have to adjust your applications to suit the equipment and flow-rates you normally work with.

IX.17. **Water-Fog tactics are optimised in non-ventilated spaces - FALSE.**

This is most certainly not true of three-dimensional water-fog applications, which are effective in both ventilated and non-ventilated compartments.

IX.18. **The 'pulsing' actions at the nozzle may create dangerous water-hammer effects - FALSE.**

The views of major fire pump manufacturers suggest that there is no danger of causing damage to fire pumps by using 'pulsing' actions at the nozzle. Since introducing these techniques in Sweden, the UK and Australia there has been no noticeable increase in pump/nozzle maintenance/repairs although there has been some problems with bursting hoses (booster lines) when 'pulsed' at 500 psi pump pressures. This problem has now been resolved. There are also engineering solutions available in terms of pressure relief valves and hydraulic retarders that can be fitted to pumps and nozzles where any concern exists.

IX.19. The 'tactical solutions' and training implications associated with applying water to control environmental conditions within a fire compartment/structure go way beyond nozzle techniques. The training concepts create a greater awareness of fire growth and development; fire behaviour patterns; formations and behaviour of flammable fire gas layers; environmental and tactical risk assessment; the effects of compartmental geometry and layout; and, the tactical approach to varying situations including opening & entry procedures and the effects of tactical venting actions. This style of approach is being adopted worldwide and cites **firefighter safety** as the prime concern. In Queensland, Australia a Swedish 3D-fog firefighting specialist [29] was detached for one year to help structure and develop their entire training program whilst similarly in Paris, UK specialists were sent to train French firefighters.

3D Offensive fog attack (Gas cooling)

IX.20. Defined as an application of water-fog discharged in short controlled bursts (pulses) where the water droplet range is critical. The objective (defensive use) is to suspend the droplets into the fire gas layers to cool, inert and dilute them, bringing them outside their *immediate* range of flammability in an attempt to prevent or quench subsequent ignitions. The effects of 'gas-cooling' serve also to reduce thermal feedback and heat-flux into the compartment, preventing the onset of flash-over. This form of application may also be used to knockdown fire-gas formations (offensive use) that are burning off inside a compartment under a ventilation-controlled regime (where the amount of fire gases burning off, inside the compartment is dictated by the quantity of oxygen/air entering through ventilation openings). The applications are made on a three-dimensional basis into a cubic volume of fire gases inside an enclosure (compartment or room) and the strategy is applied at close quarters - with firefighters occupying the compartment at the time of attack. This application of water-fog may be utilised both inside vented and un-vented compartments. The calculations [4] used to quantify effect are based upon volumetric suspension (Cu. Metres etc) and would vary according to the conditions and size of compartment involved.

IX.21. To achieve effective results the '**fog-cone**' and application angles are as important as the practical aspects of nozzle '**pulsing**'. As an example [4], a 60 degrees fog-cone applied at a 45-degree angle to the floor into an average room (say 50 cubic metres) will contain about 16 Cu.m of water droplets. A one second spurt from a 100 lpm flow hoseline will place approximately 1.6 litres of water into the cone. For the purposes of this explanation let us suggest a single 'unit' of air heated at 538 deg. C weighs 0.45kg and occupies a volume of one cubic metre. This single 'unit' of air is capable of evaporating 0.1kg (0.1 litre) of water, which as steam (generated at this, a typical fire temperature in a compartment bordering on flashover) will occupy 0.37 Cu.m. It should be noted that a 60-degree fog-cone, when applied, will occupy the space of 16 'units' of air at 538 deg. C. This means that 1.6kg (16 x 0.1kg), or 1.6 litres of water can be evaporated - ie; the exact amount that is discharged into the cone during a single one second burst. This amount is evaporated in the gases before it reaches the walls and ceiling, maximising the cooling effect in the overhead. It may be seen, where droplets are over-sized or over-drenching occurs, that too much water will pass through the gases to evaporate into undesirable amounts of steam as it reaches the hot surfaces within the compartment.

IX.22. Now, by resorting to Charles Law calculations we are able to observe how the gases have been effectively cooled, causing them to contract. Each 'unit' of air within the cone has now been cooled to about 100 deg. C and occupies a volume of only 0.45 Cu.m. This causes a reduction of total air volume (within the confines of the cone's space) from 16 Cu.m to 7.2 Cu.m. However, to this we must add the 5.92 Cu.m of water vapor (16×0.37) as generated at 538deg.C within the gases. The dramatic effect has created a negative pressure within the compartment by reducing overall volume from 50 Cu.m to 47.1 Cu.m with a single burst of fog! Any air inflow that may have taken place at the nozzle will be minimal (around 0.9 Cu.m) and the negative pressure is maintained. Overall, there is no expansion whatsoever, however, the mass of gases are not stable and are constantly in motion and in a state of transition. It is important, therefore, that nozzle operators continually assess conditions following each burst, or series of bursts (pulses) so that adjustments in pulse duration and cone pattern may be made.





Photo IX.1-4 Narrow pulse techniques
Photos by John McDonough NSWFB AUSTRALIA

Indirect (defensive) water-fog combination attack

IX.23. Defined as an application of a water-fog (or spray) where the droplet range is not so critical, the objective being to apply the water (usually from the exterior, *arguably* in a defensive mode) so that the droplets reach super-heated surfaces including the walls and ceiling. This creates a massive amount of hot wet steam that smothers the flames, sometimes to extinction. The calculations involved in this style of application are based upon area drenched (Sq.metres etc). Such applications are often used to great effect when under-ventilated or backdraft conditions are prevalent.

IX.24. **Chitty** [12] informs us - *Giselsson and Rosander present a calculation to explain the action of indirect firefighting attack (the application of water to hot surfaces to*

create a steam rich atmosphere, displacing oxygen, and controlling a fire), this has been taken up by Grimwood, with a few corrections in his book 'Fog Attack'. The explanation needs some embellishment to aid understanding due to a lack of rigour in the original (for example a statement such as $90^\circ = 380\text{kW}$ is nonsensical). In addition some steps in the calculation and associated values are missing.

IX.25. This is an attempt to rewrite the indirect fog attack example calculation clearly.

Consider a room with a 40 m^2 floor area, 2.5 m high filled with hot fire gases.

If we apply brief spurt of water fog to a hot surface, this water will evaporate and form steam. When our water comes from a fire hydrant we can suppose it is delivered to the pumper at 10°C . If we want to create an 'hypothetical' atmosphere containing 10% water vapour at 180°C , **we can calculate how much water we needed to apply as follows...**

To heat water from 10°C to steam at 180°C energy a certain amount of energy must be provided to:

- To raise the water temperature from 10° to 100°C
- To change the liquid water at 100°C to water vapour at 100°C
- To raise the water vapour, steam temperature from 100°C to 180°C

If we now calculate backwards we need to start by calculating the amount of steam present...

$$\begin{aligned} 40\text{ m}^2 \times 2.5\text{ m} &= 100\text{ m}^3 \\ 10\% \text{ of } 100\text{ m}^3 &= 10\text{ m}^3 \\ \text{our volume of steam at } 180^\circ\text{C} &= 10\text{ m}^3 \end{aligned}$$

If you consider this as heated water vapour, a heated gas at 180°C and you know that a gas expands when heated, you can calculate it's volume at 100°C , using the ideal gas law, taken into account that the general pressure change in the room is considered negligible $P_1=P_2$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

V_1 = vapour volume at 100°C

V_2 = vapour volume at $180^\circ\text{C} = 10\text{ m}^3$

T_1 = $100^\circ\text{C} + 273 = 373\text{ K}$

T_2 = $180^\circ\text{C} + 273 = 453\text{ K}$

Calculating gives $V_1 = 8,23\text{ m}^3$, which concurs with our knowledge that gases shrink when cooled. One may however not forget that this volume equals 8230 l of vapour at 100°C .

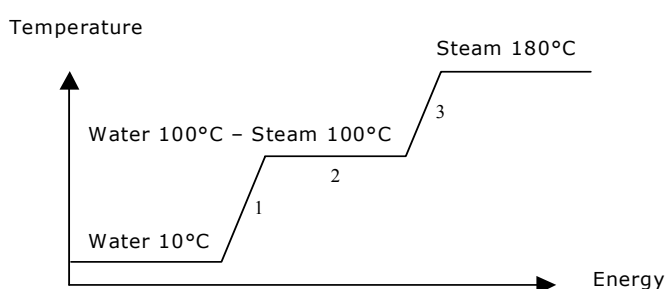
We already calculated that we had 8230 l of steam at 100°C.

Science tells us that 1l of water (liquid) can turn into a volume of 1700l of steam at 100°C (gas) when heated. Hence to create the 10% steam atmosphere one needs
 $8230/1700 = 4.84$ l

Thus we only had to vaporise 4,38 l of water to create a 10% atmosphere of water. How much energy is needed to create these 10 m³ of steam ? Or if rephrased – **To what extent do we cool, when we create 10 m³ of steam ?**

To heat 4.84 litres (= 4,83 kg, as the mass of 1 litre of water is 1kg) of water from 10°C to steam at 180°C energy must be provided to:

- To raise the water temperature from 10° to 100°C (1)
- To change the liquid water at 100°C to water vapour at 100°C (2)
- To raise the water vapour, steam temperature from 100°C to 180°C (3)



1. Using the specific heat capacity of water $C_{p(H_2O, l)} = 4180$ J/kg/K

We can calculate the energy needed in the first heating step.

$$E_1 = C_{p(H_2O, l)} \cdot m \cdot \Delta T_1$$

$$E_1 = 4180 \text{ J/kg/K} \cdot 4,84 \text{ kg} \cdot (100-10)$$

$$E_1 = 1820808 \text{ J} = 1821 \text{ kJ}$$

2. Using the latent heat of water (2260 kJ/kg) we can calculate the energy needed in step 2.

$$E_2 = L \cdot m$$

$$E_2 = 2260 \text{ kJ/kg} \cdot 4,83 \text{ kg} = 10938400 \text{ J} = 10938 \text{ kJ}$$

3. Using the specific heat capacity of steam $C_{p(H_2O, g)} = 2020$ J/kg/K

We can calculate the energy needed in the third heating step.

$$E_3 = C_{p(H_2O, g)} \cdot m \cdot \Delta T_1$$

$$E_3 = 2020 \text{ J/kg/K} \cdot 4,84 \text{ kg} \cdot (180-100)$$

$$E_3 = 782144 \text{ J} = 782 \text{ kJ}$$

If we now add up $E_1 + E_2 + E_3$ we get the total amount of energy E_{tot} needed to heat up 4,83 l of water from 10°C to steam at 180°C.

$$E_{tot} = 13541352 \text{ J} = 13541 \text{ kJ} = 13,541 \text{ MJ}$$

Giselsson and Rosander assume that in the first instance all this heat is in the first 1 mm of the wall. The available energy in this slab of wall may be found from:

$$E_{\text{wall}} = \rho \cdot A \cdot d \cdot C_{p_{\text{wall}}} \cdot \Delta T$$

ρ = Density of the wall material

A = Area of wall or ceiling

d = Depth

$C_{p_{\text{wall}}}$ = Specific heat capacity of the wall material

ΔT = Temperature change of the wall

Assuming an initial wall temperature of 500°C and final temperature of 180°C, a density of 1000 kg/m³ and a specific heat capacity of 1000 J/kg/K using the assumed depth of 1mm, **the area required to provided the required amount of heat is:**

$$A = E_{\text{wall}} / (\rho \cdot C_{p_{\text{wall}}} \cdot \Delta T)$$

$$A = 13.5 \text{ E}+6 \text{ J} / (1000 \text{ kg/m}^3 \cdot 1000 \text{ J/kg/K} \cdot 0,001 \text{ m} \cdot (500-180))$$

$$A = 42.2 \text{ m}^2$$

Therefore around 4.9 litre of water should be applied to approximately 42 m² of wall to achieve the required concentration of steam.

What results in an application of 0.11 litre/m² as calculated by Giselsson and Rosander and reproduced by Grimwood.

A transient model for heat losses from the walls could significantly improve this analysis as the reheating time and hence the time between applications and the duration of subsequent applications of the spray could be estimated.

Several **fire suppression/control actions** have occurred, firstly as stated by Giselsson and Rosander the **oxygen concentration** in the room is **reduced** inhibiting combustion reactions. In addition the **compartment temperature** will have been **reduced** decreasing thermal feedback to the fuel surface and the heat losses to the boundary increased. These thermal factors may be sufficient for the fire to jump to a lower stable equilibrium (a reverse of the flashover mechanism).

Giselsson and Rosander continue to warn of the effects of **over drenching** (causing the wall temperature to fall below 100°C, which causes the condensation of the water) and observing that **fuel rich atmospheres** will require less water since they will be oxygen depleted already and leaner mixtures will require more.

It is then stated that the opening should be kept as small as possible during this fire fighting procedure, presumably to reduce incoming oxygen and to hinder steam rushing out. The reignition hazard is emphasised.

In order to apply this technique special piercing fog nozzles have been developed, however in a regular European home the walls are not from plaster or wood, but from solid bricks thereby limiting its use. This technique is also commonly applied to fight ship fires in the cargo holds.

Direct attack

IX.26. Made directly at the base of the fire-plume to reach the source of the flames, using either a smooth-bore nozzle or straight-stream or narrowed fog pattern from a combination nozzle. This attack may be either offensive or defensive, depending upon the level of fire spread involved.

IX.27. MECHANISMS OF EXTINCTION BY WATER OF CLASS 'A' FIRES

The suppressive effects water may have on Class 'A' fires are -

- **Fuel Cooling** - *Cooling of the combustible solid fuel surface*, which reduces the rate of pyrolysis and thus the supply rate of fuel to the flame zone. This reduces the rate of heat release by the fire; consequently the thermal feedback from the flame is also reduced and this augments the primary cooling effect of the suppression agent. The application of a water spray to the fuel bed is typical of this method;
- **Flame Cooling** - *Cooling of the flame zone directly*; this reduces the concentration of free radicals. Some proportion of the heat of reaction is taken up by heating an inert substance (such as water) and therefore less thermal energy is available to continue the chemical break-up of compounds in the vicinity of the reaction zone. One function of the new water mist technology is to act in this manner, the fine droplets providing a very large surface area per unit mass of spray in order to increase the rate of heat transfer;
- **Flame Inerting** - *Inerting the air feeding the flame* by reducing the oxygen partial pressure by the addition of an inert gas (eg N₂, CO₂, H₂O vapour). This is equivalent to the removal of the oxidiser supply to the flame by the production of water vapour. This is the dominant mechanism by which water mists can suppress large confined fires.

In a discussion of water-mist fire extinction mechanisms Mawhinney added to the above the possibilities of **thermal radiation attenuation, dilution of the flammable vapour/air mixture and quenching the combustion radicals (by interacting with the free radicals water lowers their energy level).**

Interaction of water sprays with flames and gases

IX.28. The use of fine water droplets for gaseous phase fire suppression has been studied for at least 50 years. Herterich identified a need for consistent terminology when discussing firefighting sprays, especially when considering the characteristic 'size' of the droplets. Average sizes of droplets that appear of most interest in firefighting terms fall within the range of 100-1000 microns (0.1-1.0 mm). A spectrum of **drop sizes** classes them into five categories –

1. **Colloidal** (Below 1 micron - appears as smoke);
2. **Dust** (between 1-10 microns) appears as oil or sea fog;
3. **Fine** (between 10-100 microns - appears as clouds or mist);
4. **Average** (between 100-1000 microns - appears as drizzle or rain);
5. **Coarse** (1000-10000 microns - appears as coarse heavy droplets).

IX.29. The **cut off between sprays and mists** appears somewhat arbitrary and the US NFPA has recently suggested a practical definition of 'water-mist' as a spray in which 90 percent of the water volume is contained in droplets less than 1000 microns (1.0 mm) in diameter. An alternative definition of 'water-mist' has been advanced by Ramsden who suggests the NFPA definition may be too 'loose', recommending a finer droplet range of 80-200 microns diameter is more suited to water-mist systems.

IX.30. In firefighting terms the size of an individual droplet, or some mean drop size within a spray, is of great importance when discussing other attributes of the spray as the resistance offered by the surrounding air to the forward motion of the droplets is proportional to the droplet diameter. Therefore the carrying power, or penetration, of the spray is strongly dependant upon the drop size distribution. The efficiency of heat transfer to water droplets, which is fundamental to their use in firefighting applications, is also dependant on droplet geometry and in particular the ratio of the total surface area of the spray to its volume; maximising this ratio is beneficial in promoting rapid absorption of heat from the environment and subsequent evaporation of the droplet. The practical penetration achieved by a particular spray is governed by the relative magnitudes of the kinetic energy of the initial liquid and the degree of aerodynamic resistance offered by the surrounding gas. All other things being equal, the penetration of a spray is much greater than for an individual drop, since the leading droplets impart forward momentum to the surrounding gas, reducing the air drag on the following drops and thus creating a 'pathway' for them, resulting in better overall penetration. There is a growing body of contemporary research concerned with the interaction between water droplets

and buoyant fire plumes. The literature suggests there may exist a critical heat release rate above which a given drop size would not contribute to fire extinguishment due to its failure in reaching the relevant 'cooling' zone. With this in mind it has been noted in numerous studies that the 'ideal' water droplets for gas-phase cooling and gaseous suppression applications by firefighters fall with the 200 - 400 (0.2-0.4mm) micron range.

IX.31. The Annual BFRL Conference on Fire Research in 1998 produced an interesting (NIST) paper from Alageel, Ewan and Swithenbank - University of Sheffield UK - that investigated the *Mitigation of Compartment Jet Fires Using Water Sprays*. The main objective of the study was to investigate the interaction of water-sprays with a ceiling jet fire in a ventilation controlled state and close attention was paid to the effectiveness of different spray angles, droplet diameters, stream velocities and water flow-rates. It was generally observed that water applications into the gas layers utilising different spray angles of 30, 60, 75, 90, 120, 135 and 150 degrees produced varying reductions in compartmental temperatures but spray cones within the 60-75 degree range were found to be most effective in reducing the overall temperature. For these angles the limiting behaviour due to the effectiveness in penetrating the flame indicated that spray velocities in excess of 18 metres/second (40 mph) should be used. The mean droplet diameters of 100 to 600 microns were analysed and it was further noted that droplets within the 300 micron (0.3mm) range maximised any cooling effects within the compartment. In terms of flow-rate it was reported that, for these compartmental dimensions (which were the same as a standard 'simulator' container being 35 Cu.m), the optimum flow-rate was between 120-180 lpm (32-48 gpm). Where this flow rate was exceeded the compartmental temperatures were not reduced any quicker and much water was observed as 'run-off' whereas at flow rates below 120 lpm the overall cooling of the gases was seen to be much less effective.

IX.32. As an extinguishing medium it has been stated that water has a theoretical cooling capability of 2.6 MW per litre per second although in practical terms of direct attack, its capability is more likely to be around 0.84 MW l/s. It is prudent to try and match your flows with the likely heat release rates that may be encountered on initial entry in structures sited within your locality. The average one roomed residential fire is likely to reach intensities in excess of 7MW at flashover and a minimum flow of 500 lpm (132 gpm) will be required to handle this situation safely and effectively. However, such a flow-rate is too high for an optimised gas-cooling application and a flow of around 100-150 lpm (26-40 gpm) will be more suited to the same fire during its pre-flashover stage where gas cooling/inerting is relevant. To avoid bringing in larger streams and playing 'catch-up' as the fire escalates, the firefighter might

ideally be equipped with an initial attack hoseline that provides this flow range of 100-500 lpm with a [selectable flow option at the nozzle](#). An alternative combination nozzle, of fixed flow or automatic design, may be used where a flow control facility enables *pulsing* actions at lower flows by just *cracking* the flow handle/trigger on and off.

IX.33. Using a computer model Rasbash attempted to estimate the heat transfer between flames and water sprays and produced a plot of *convective heat transfer rate* against *drop velocity* for drop sizes ranging from 50 microns to 2 mm whilst assuming a flame temperature of 1,000 deg C. In general, higher velocities and smaller droplet diameters were found to increase the heat transfer rates. For example, a 2 mm drop at 0.07m/s (terminal velocity in still air) produced a heat transfer rate of 167 kW Sq.m while the same drop travelling at 2 m/s achieved a value of 293 kW Sq.m. For a 50 micron drop at velocities of 0.01 m/s and 0.5 m/s the corresponding heat transfer rates were 1.7 MW Sq.m and 2.5 MW Sq.m respectively. An estimation of droplet penetration was also presented and it was noted that drops of larger initial size were able to penetrate further into the flame before complete evaporation occurred. More recent implementations of this type of model have been developed where input data include details of the hot gas layer and empirical drop size data from a range of commercial sprinklers and water mist nozzles where individual droplet behaviour may be studied within an overall simulation of spray/fire interaction.

IX.34. Of interest, the IFEX 3000 one litre impulse gun (<http://www.ifex3000.de>) discharges its 'burst' of 2-200 micron droplets at 120 m/s with a maximum throw of 16 metres but having tested it during container simulations firefighters have reported it may lack deep penetration into the superheated gas layers within the confines of a structure fire. Whilst its cooling capability appeared to be effective at close range its interaction with the buoyant fire plume seemed to affect the tiny droplets ability to penetrate gases in the overhead.

IX.35. In terms of *droplet penetration* the influence of nozzle exit pressure is disputed by some and the use of high-pressure systems as a means of increasing the throw of fine sprays appears to be questionable. The effect on drop size may also be contrary to expectations where an increase in pressure may result in a larger droplet rather than a smaller range. However, further research in this area is suggested.

Scandinavian research

IX.36. In 1995 a four-year research project [31] was completed by Finland's Fire Technology Laboratory (VTT) where Dr. Maarit Tuomisaari used computer analysis and live fire tests to study the fire suppressive qualities of water sprays, when applied into gaseous combustion, in compartmental firefighting. The research compared 'indirect' applications onto hot surface linings using 'sweeping' motions against intermittent 3D bursts (pulses) directed into the burning gases of post-flashover fires. It was noted that the amount of water used and the average water droplet size were the two most influential factors to affect fire control times. In line with many other studies of this nature the droplet range of 0.2 – 0.6 mm (200 – 600 microns) was found to be the most effective for fire suppression of the burning gas layers. Whilst indirect 'sweeps' of the linings were effective in cooling and suppressing the burning gases the disruption of the thermal layer is seen to be an undesirable effect when compared to intermittent *pulses* applied directly into the gases, where thermal disruption is non-existent and a positive balance is maintained. The use of intermittent pulses of water-fog are also seen to optimise the actual amounts of water injected into the overhead and the nozzle operator is more likely to maintain control of the conditions and reduce undesirable steam expansion.

IX.37. Water being sprayed into the fire compartment can generally be divided into three main parts –

- a part of the water (*small droplets*) is blown away through failure to penetrate the up-draught in the compartment and thus does not take part in the suppression;
- a part is vaporized (*ideal droplets*) in the combustion gases;
- and a part reaches internal surfaces (*large droplets*) and the fuel in liquid form where it is vaporized or flows to pool on the floor.

To optimise 3D gaseous fire suppression the amount of vaporization must be maximised. To ensure the vaporization effects are positive towards firefighters and victims occupying the compartment the vast majority of vaporization should occur in the gases and not on wall or ceiling linings. The resulting contraction of the gases will overcome any expansion of the water vapour providing droplets are within an acceptable range and the nozzle operator is not over zealous in the application of water.

IX.38. In 2000 a further research project [32] was completed in Sweden at the request of the Stockholm Fire Brigade when Anders Handell, of Lund University, evaluated various firefighting fog/spray streams using computer aided technology and live-fire experience to compare the effectiveness of a wide range of nozzles in cooling the super-heated gaseous conditions that exist in the overhead of a fire-involved compartment. It is worth noting that this was also the objective, in part, of the earlier VTT research and that *both research projects* concluded that the most effective nozzle pattern for gas cooling and burning gas suppression was provided by equipment from Task Force Tips (USA). As a result of this research the Stockholm Fire Brigade initiated a nozzle replacement program in 2001 to change to the **TFT Ultimatic**, a nozzle also used by London Fire Brigade since 1992. The Lund research again paid close attention to water droplet size, stream patterns, flow and velocity of firefighting nozzles as well as application techniques. This was a turning point in that the North American nozzle was seen to out-perform the TA Fogfighter that had previously been considered as the most effective nozzle for 3D gas-cooling applications throughout the Swedish fire service since the early 1980s.

IX.39. It is beyond doubt that the transition to 3D offensive style water-fog attack using 'pulsing' applications of fine water droplets into the super-heated and gaseous overhead has saved firefighter lives. Statistics have demonstrated that 'new-wave' methods of preventing or reducing the potential for any ignition of forming gas layers in subsequent rollovers, flashovers, backdrafts or smoke-explosions whilst dealing most effectively with post-flashover burning gas reservoirs have drastically reduced the death and injury rate of firefighters caused through such rapid fire propagation. Remember, this 'new-wave' use of water-fog in compartmental or structural firefighting is complementary to traditional firefighting methods, such as direct straight-stream attack. **The firefighter who is able to assess the risk and recognize the application that is optimal for the fire conditions as they present themselves is the one most likely to succeed.**



Benefits of 3D water-fog applications

IX.40. Proven scientifically to be the most effective way to cool gases in the overhead in comparison to any other form of fire attack, including smooth-bore, indirect-fog, class 'A' foam and CAFS methods. This fact is supported by several independent studies around the world.

- 3D water-fog applied correctly will have an inerting effect in the gases, rendering them less likely to ignite (*Inerting the air feeding the flame* by reducing the oxygen partial pressure by the addition of an inert gas - eg N₂, CO₂, H₂O vapour). This is equivalent to the removal of the oxidiser supply to the flame by the production of water vapour. This is the dominant mechanism by which water mists can suppress large confined fires.
- The injection of water droplets into fire gases is seen to *narrow their limits of flammability* and further reduce the likelihood of ignition.
- **Flame Cooling** - *Cooling of the flame zone directly*. Some proportion of the heat of reaction is taken up by heating an inert substance (such as water) and therefore **less thermal energy** is available to continue the chemical break-up of compounds in the vicinity of the reaction zone. One function of the new water mist technology is to act in this manner, the fine droplets providing a very large surface area per unit mass of spray in order to increase the rate of heat transfer. From a chemists point of view this could also be seen as the lowering of the number of effective collisions (leading to combustion) of the radicals present in the combustion process. The water molecules -which are inert in this process- collide with the radicals thereby lowering their energy and thus leading to less effective collisions -for which a certain amount of reaction energy is needed. One could say the water has a quenching effect.



Flow-rates

IX.41. There have been several international research projects over the past 50 years that have attempted to produce an engineered solution to water flow-rate requirements for structural fire-fighting purposes. These studies have been generally based upon scientific data associated with heat release rates from compartment fires along with empirical research investigating actual flow-rates used by fire brigades when tackling fires in a wide range of occupancy types. This information is most useful for grading fire-fighting water flow requirements in-line with building codes. It is also of use to the operational fire officer who must assess the resources required at a particular incident to suppress any structure fire of a known or estimated size.

IX.42. Before my own study in 1990 [4], the most established research to date had been completed in the USA [33] although there had been several small-scale laboratory studies investigating theoretical flow-rates to suppress minor compartment fires. The conclusion of my research covering 100 major fires in London 1989-90 demonstrated a recommended flow-rate that appeared controversially low in comparison to those used in the USA and caused a debate that prompted further research. This research occurred between 1994-97 when Lund University Sweden supported London Fire Brigade in a 307 fires study that culminated in the Sardqvist report [34] in 1998. The flow-rates reportedly used by London firefighters in this study were substantially higher than those I had calculated in 1990, but why did this happen? – Were my findings somehow underestimated or did the Lund 7003 report produce an over-estimate?

IX.43. It is beyond any doubt that the nozzle flow estimates provided by London Fire Brigade upon which Mr Sardqvist based his calculations were not representative of actual flows achieved on the fire-ground. In fact, I have calculated that these theoretical and unrealistic nozzle flows actually resulted in the Lund 7003 flow-rate curve demonstrating a 40 percent overestimate. As a serving operational firefighter in London during part of this research period I am able to attest that flow-rates detailed in SRDB Codes at that time were rarely, if ever, achieved on the fire-ground due to a number of factors including hydrant flow capabilities, frictional losses and nozzle reaction forces. There is no mention in the codes of nozzle/hose sizes, or reaction forces that would have direct impact on the amount of water an interior attack hose-line could effectively flow.

IX.44. As an example, any attempt to flow an attack hand-line at 870 LPM would produce a nozzle reaction force that could not possibly be handled safely by an interior attack team. Further still, to suggest that pressures of 5 bars are regularly achieved at the nozzle is generally unrealistic and often impractical as it is well established that UK firefighters traditionally underpump their attack hose-lines with pump pressures of 4-5 bars being common. My practical experience at that time would suggest that maximum flows of 200 LPM from a 12.5 mm nozzle; 450 LPM from a 20 mm nozzle and 700 LPM from a 25 mm nozzle on interior attack hose-lines were far more realistic than those suggested by the theoretical SRDB Codes, as used in the Lund research. At large incidents the flow-rates may even have fallen below these estimates due to hydrant capability at the grid.

IX.45. In 1994 a further study completed by Barnett [35] in New Zealand produced scientific data, supported by much empirical research that provided a foundation for the *MacBar Fire Design Code* in 1997. This research produced a flow-graph that is closely correlated to my own earlier work and interestingly, where the Lund 7003 flow graph is amended as demonstrating a 40 percent over-estimate, this too falls much more inline with both the Barnett and Grimwood research findings.

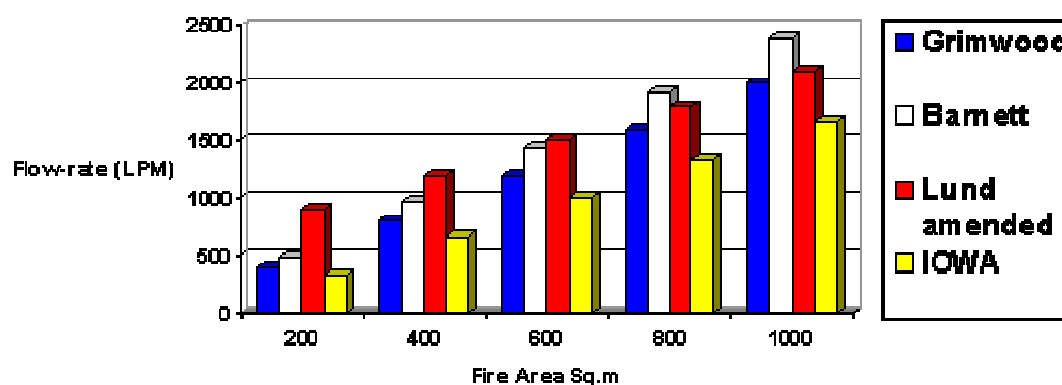


Chart IX.1 Flow- rate in function of fire area

IX.46. When converted to an area formula my original calculation, based on a mean average for comparison to Lund 7003, for minimum (and realistic) fire-ground flow-rate requirements (based on office compartments with 2.5 metre high ceilings) suggests that $A \times 2 = \text{LPM}$ (where A = area in Sq. m). If *high-risk occupancies* are involved then my own 1990 calculations converted for area flow-rate ($A \times 4 = \text{LPM}$) appear far less controversial, especially when applied to fires involving up to 100 Sq. m of floor space. Interestingly, the Barnett 1994 and Grimwood 1990 studies demonstrated a flow-curve directly proportional to the area of the fire and not roughly proportional to the square root of the area of the fire as suggested by Sardqvist in 1998.

X.TACTICAL VENTILATION

X.1. Paul Grimwood (1989) introduces the terminology & defines 'tactical ventilation' - *'venting actions by on-scene firefighters, used to gain control of a fire building's internal environment to the advantage of firefighting and rescue teams working within. Such actions may include attempts to release or direct smoke, super-heated and burning gases from the building by either natural or forced means via vertical or horizontal openings made or existing in the structure. These actions may also include the 'closing down' of a structure in an attempt to reduce the flow of air towards the fire. This tactic is termed 'Anti-Ventilation' by the Swedish Fire service'. It is essential that firefighters remember the most dangerous opening they may create in the structure exists at the point of entry to the building'.*

X.2. The 'opening up' or 'closing down' of a fire involved structure to gain tactical advantage during firefighting operations is a strategy that is fraught with controversy and opposing views. The North American philosophy has demonstrated the benefits of releasing super-heated and dangerous fire gases from a building and the reduction in levels of smoke logging to be achieved when horizontal & vertical openings are made. They have also shown us how such combustion products may be forced from a structure ahead of advancing firefighters by the use of positive pressure fans. The European philosophy has strongly promoted the concept that in certain situations greater benefits may be derived where openings in the building are avoided, placing a greater responsibility on firefighters to control conditions inside a structure using 'anti-ventilation' techniques. That's not to say that UK firefighters fail to acknowledge exterior venting actions as part of an overall firefighting strategy and one only has to look at London's lengthy efforts to ventilate the Tooley Street warehouse fire in 1971, where natural openings were non-existent, to accept that the strategy is occasionally employed, if only during the latter stages of firefighting operations.

X.3. Perhaps the greatest benefits in fireground strategy may be realized by firefighting forces who are trained and able to recognize changing conditions and situations that will dictate which of the above two approaches is likely to be most beneficial in any particular situation. It is probable that tactical venting actions are currently over-used in the USA and under-used in Europe and greater attention is needed to support a strategic firefighting approach that demands an in-depth understanding of compartment and structural fire behavior and the dynamics of fire

development under varying ventilation parameters. Perhaps greater attention is needed in the UK and Europe specifically where the initial move towards a wider acceptance of tactical venting actions during the early stages of firefighting operations has failed to progress due to a lack of training; the failure to equip firefighters with additional forcible entry tools; and an ongoing reduction in manpower and aerial ladder capability, particularly in city centre areas. Whilst PPV has become a popular concept in the UK, this has often been introduced prior to any form of training in compartment fire dynamics and 'basic' tactical venting actions, ie; the implications and advantages (or disadvantages) of creating, or utilizing existing, openings in a structure to release combustion products and hot gases.

Natural ventilation

X.4. The decision to create openings within a fire-involved structure to gain tactical advantage should be carefully considered for the outcome may be irreversible. Under certain circumstances such actions may prove most effective whilst in others they may prove disastrous. In some situations the openings will serve to release combustion products whilst others may simply provide dangerous airflows heading in towards the fire. It is often the case that the most influential (dangerous) opening a firefighter can make is at **the point of entry to the structure**. This opening is often seen as a necessity and is not considered as part of the venting plan. However, the airflow provided at this point of entry may serve to intensify the fire and may indeed allow it to escalate beyond the capability of initial attack hose-lines.

X.5. Tactical openings made to release combustion products may serve to reduce smoke logging, lower compartmental temperatures, prevent flashovers and backdrafts and generally ease the firefighting operation. However, it is also possible that such openings may achieve undesirable and opposing effects, causing temperatures to rise with resulting escalations in fire spread leading to flashovers, backdrafts and smoke explosions.

X.6. A Swedish scientific research study suggested that fire officers should gain a clear understanding of how pressure build-up develops within a fire building and how gases flow out through various types of opening in different situations. The causes of such pressure build-up may be divided into a number of categories

- Inhibited thermal expansion
- The buoyancy of hot gases
- Normal temperature difference between inside and outside air
- Wind
- Mechanical ventilation.

It is important also to appreciate how openings may become inlets (for air) as these internal pressures move nearer equilibrium with the outside pressure. Eventually, as smoke and fire gases begin to clear from the vented area, air will enter and mix with the remaining gases and may allow the fire to intensify. It is possible that some form of flashover or backdraft may occur at this stage.

X.7. Richard Chitty's excellent report [12] posed the potential of a 'flashover' being induced by an increase in compartmental ventilation where the heat loss rate increases as more heat is convected through the opening. However, there is a point beyond stability where ventilation may cause more energy to be released in the compartment than can be lost and this condition of *'thermal runaway'* may lead to 'flashover'.

X.8. A situation has been noted where venting actions have often resulted in devastating effects where buildings are designed with a normal point of entry through the front at ground floor level, whilst having the rear basement 'spilt-levelled' so that it too appears at ground level from the rear of the structure. This can occur where land to the rear of a residence is actually one storey lower than at the front and a basement from the front is not seen as so from the rear. Where initial openings made at ground level (front) for entry are followed by venting (or further entry) actions at the rear basement level, rapid fire propagation has often occurred. Usually, this situation occurs whilst firefighters are occupying the space.

X.9. It is always essential to consider the wind direction and any effects this is likely to have on fire spread. This is particularly important where wind is entering the point of entry - such an effect may be either useful or hazardous to interior fire-fighting crews advancing on the fire. A further situation that may lead to unfavourable conditions could occur where ventilation openings are made in a **room adjacent** to the fire compartment. Where airflows are set up through the fire compartment itself the conditions may improve but where the natural path of ventilation is

through room adjacent, temperatures and smoke logging may actually **increase** throughout both compartments.

Positive pressure ventilation

X.10. As a post fire strategy the use of Positive Pressure Ventilation (PPV) by trained and experienced operators is generally proven to safely and effectively remove smoke and dangerous gases from within the fire compartment and structure, enabling firefighters to complete overhaul and mop-up operations with ease. When used to force-vent a structure/compartment during the actual fire attack stage PPV has been found to relieve conditions for firefighters; improve visibility; remove smoke and dangerous gases quickly and effectively and reduce temperatures within the structure. However, such use of PPV demands a more intensive level of training and a comprehensive understanding of fire behaviour, air dynamics and fire gas transport within a structure.

X.11. **Before using PPV** during the attack stages of a fire it is **imperative to know where the fire is located**; to **what stage** the burning regime has developed and if the fire compartment is in an **under-ventilated state**. Where the fire exists in an under-ventilated state or where any warning signs preceding backdraught are apparent then PPV should not be used if the structure is likely to remain occupied. It is well established that the addition of air into an under-ventilated compartment could possibly trigger a backdraft, smoke explosion or even a flash-fire. If the fire has reached a ventilation-controlled regime, with steady state burning, it may be safe to initiate PPV but firefighters should be aware that the airflow from the fan/s could still possibly create a build-up of dangerous gases or combustion products within compartments. This could occur as super-heated wall and ceiling linings and hot embers/'bulls-eyes' combine in the increased airflow to form a hazardous environment.

X.12. Also, firefighters should gain an understanding of how air-dynamics in **stair-shafts** and corridors could potentially create negative pressures that may actually 'pull' fire, smoke and gases into such areas. The potential for fire spread into other areas where elements of structure have been breached always remains a concern and PPV should be used in association with firefighters operating thermal image cameras (TICs) to monitor any such fire spread into internal shafts or roof voids. The siting of adequately sized smoke outlet points is of course a major factor of any successful PPV operation.

Fire isolation (confinement) tactics (anti-ventilation)

X.13. The concept of 'anti-ventilation' addresses, not an opposing view to creating openings to rid the structure of dangerous heat, smoke and gases but rather, a **complementary** approach to suit certain situations. It is sometimes safer to achieve control of the existing **gravity currents** or air-pathways [36] in a fire-involved structure to gain tactical advantage. The 'opening-up' of a structure relinquishes some control of airflows and allows heat, fire and gases to transport and perhaps escalate/ignite as they mix with air. This may sound simple, straight forward and basic - but how many instances of rapid fire spread have occurred as a direct result of uncontrolled 'gravity currents or pathways', occasionally causing the loss of firefighters lives! You know the scene - perhaps a large escalating fire with multiple entry points being created to advance hoselines through. I ask you to analyze each of these situations as they occur and ask yourself if a greater element of control over inflowing air-tracks may have slowed the fire's progress and made for an easier and safer approach?

X.14. Greater control of airflows and fire spread can be initiated instantly simply by closing a door, preventing vital air from feeding the flames. It may be safer and more effective, under certain situations, for firefighters to **'close-down'** - for example, where obvious backdraft conditions prevail with thick black 'rolling' smoke emitting from the upper portion of an entry point (doorway) the partial or complete closing of the door may be enough to prevent a backdraft or any rapid fire propagation from occurring. At this point any subsequent actions will be dictated by circumstances related to fire location, structural/compartmental dimensions etc. An indirect application of water-fog may suit; or openings made elsewhere in the structure to relieve conditions may be a better option prior to entry.



Ventilation in practice

X.15. The CHERRY ROAD fire in Washington DC in 1999 presented a ferocious form of rapid fire progress that resulted in two firefighters losing their lives and a third being seriously burned following a venting action. The thermal conditions experienced at this incident have since been reproduced in NIST scientific simulations and the tactical venting action carried out by firefighters at this incident appeared to have **initiated a flow of high velocity gases** into the first floor room that was occupied by the searching firefighters (above). Extensive reports are available of these simulations at <http://fire.nist.gov/6510/6510.htm>

X.16. In '**Flashover & Nozzle Techniques**' (1999) Paul Grimwood wrote.....

X.17. *"As we crawled into the room the fire's roar was somewhat disconcerting. The thick smoke from the fire's plume was banking down setting an 'interface' at about 1.5 metres from floor level and the heat radiating downwards from the ceiling could clearly be felt through the substantial layers of our protective clothing. I looked directly above our position, into the darkness of the smoke, and noted some yellow tongues of flame rolling the ceiling, detaching themselves from the main body of fire that blazed in the furthest corner of the compartment. We had advanced about 1.5 metres into the room as I reached for the nozzle of the high-pressure hosereel line and discharged the briefest 'pulsation' of water-fog into the upper strata above our heads. There was no drop-back in terms of water particles and the series of 'popping' sounds suggested that the fog was 'doing its thing' in the super-heated gas layers. The tongues of flame dispersed for a few brief seconds before resuming their eerie 'snake-like' dance towards the open access point (doorway) situated behind us. "Hold the water" shouted Miguel over the BA comm's radio. As we inched further into the room I realised then that I was placing my deepest trust in the man.*

X.18. *The smoke continued to bank down around us and I watched in awe as several 'balloon-like' pockets of fire gases ignited, each for a brief second, in front of my eyes about one metre from the floor. I could sense the moment of compartmental 'flashover' was fast approaching and I instinctively reached for the nozzle again. "WAIT", shouted Miguel - he laughed as he reached back and kicked the access door almost shut. I felt extremely vulnerable but then, as if turned off by a tap, the fire suddenly lost its 'roar' and the rolling flames in the plume above dispersed completely. Everything went dark as the fire 'crackled' and the smoke banked right down to the floor. There was an eerie silence within this blinding experience that*

*seemed all too familiar to the 'firefighter' in me. Miguel took the nozzle out of my hands and discharged several brief 'pulsations' of water-fog, on a wide setting, into the upper portions of the room. Again, there was no 'drop-back' and you could almost sense the minute particles of water suspending themselves within the super-heated flammable gas layers. The steam 'over-pressure' and humidity was negligible and any air movement went unnoticed. More importantly, the thermal radiation from above had lessened considerably reducing the likelihood of a flashover. Then I heard Miguel's voice over the comm's calling for an exterior tactical venting action and almost instantly the smoke layer began to rise as firefighters in the street vented the window serving the room. The fire in the corner of the room became visibly active again as it increased in intensity, however this time the tongues of flame in the ceiling layer were heading towards the open window and **away** from our position".*

X.19. Here was a typical example of how **anti-ventilation (fire isolation)** techniques can be used to slow the fire's development whilst following such a 'close-down' with a well-coordinated and precise tactical venting action to direct the fire plume away from advancing firefighters. It is normal for the fire's plume to head in the direction of an air supply. If such a supply exists behind the firefighters at the entry point then the fire plume may travel directly towards the advancing firefighters!

X.20. What remains critical under all circumstances is that any tactical advantage gained by venting actions can only be achieved by ensuring that the entire operation is disciplined, carried out with great precision and carefully coordinated between interior and exterior crews. The ultimate key to all this is communication!



XI. TECHNICAL JARGON

Auto-ignition temperature – Is the lowest temperature at which point the vapours of a liquid or solid will self-ignite without an ignition source.

Backdraft (Backdraught) - The closest definition to date is perhaps 'the explosive or rapid burning of heated gases (unburnt pyrolysis products) that occurs when oxygen has been introduced into a compartment or building that has a depleted supply of oxygen due to an existing fire'.

However, there is also a further range of conditions that have been associated under this definition such as 'smoke explosion' and 'blow-torch' effect as examples that may not necessarily require the addition of oxygen for such phenomena to occur.

Blue Flames - Noted by Grimwood (4) as a warning sign preceding backdraft.

Dancing flames - See Ghosting flames.

Diffusion flame - Most flames in a fire are diffusion flames - the principal characteristic of a diffusion flame is that the fuel and oxidiser (air) are initially separate and combustion occurs in the zone where the gases mix.

Explosion range - applies generally to vapors and gases and is defined as the concentration range in which a flammable substance can produce an explosion or fire when an ignition source (such as a spark or open flame) is present. The concentration is generally expressed as percent fuel by volume.

Above the **upper explosion limit (UEL)** the mixture of substance and air is too rich in fuel (deficient in oxygen) to burn. This is sometimes called the upper flammable limit (UFL).

Below the **lower explosion limit (LEL)** the mixture of substance and air lacks sufficient fuel (substance) to burn. This is sometimes called the lower flammable limit (LFL).

Fire phases - One can characterize most fires by one, or a combination of three unique phases related to the fire's rate of heat release. These are the *Growth Phase*, *Steady State Phase* and *Decay Phase*.

The early stage of a fire during which fuel and oxygen are virtually unlimited is the **Growth Phase**. This phase is characterized by an exponentially increasing heat release rate.

The middle stage of a fire is the **Steady State Phase**. This phase is characterized by a heat release rate, which is relatively unchanging. Transition from the Growth Phase to the Steady State Phase can occur when fuel or oxygen supply begins to be limited.

The final stage of a fire is the **Decay Phase**, which is characterized by a continuous deceleration in the heat release rate leading to fire extinguishment.

Flashover - A generic term that may have several scientific references or definitions. The term is used in general by firefighters to describe an element of rapid fire progress although scientists are somewhat at conflict as to any specific meaning. The originator (P.H. Thomas) admitted the term is imprecise and may be used to mean different things in different contexts.

Flammability of Fire Gases - Fire gases are capable of burning in both diffusion and pre-mixed states. The smoke given off in a fire is flammable. Particulate smoke is a product of incomplete combustion and may lead to the formation of a flammable atmosphere that, if ignited, may lead to an explosion.

Flammable limits – See explosion limits

Forward Induced Explosion - Floyd Nelson (USA) introduced a definition for a term he referred to as Forward-induced explosions. In effect, this definition described the ignition of pockets of fire gases as they transported throughout a structure/compartment. The phenomena differed from that of backdraft in that fresh air (oxygen) is the moving force in a backdraft whilst the gases themselves are the moving force in a 'forward-induced' explosion as they move towards a supply of air.

This can occur in many ways inside a fire-involved structure, for example, where a collapsing ceiling forces fire gases to transport outwards from the area of collapse. On mixing with pockets of air they may come into the flammable range and can ignite with varying explosive effects.

Fuel Controlled Fire - Free burning of a fire that is characterised by an air supply in excess of that, which is required for complete combustion of the fuel source or available pyrolysates.

Ghosting flames - A description of flames that are not attached to the fuel source and move around an enclosure to burn where the fuel/air mixture is favourable. Such an occurrence in an under-ventilated situation is a sure sign that precedes backdraft. Also termed Dancing flames.

Gravity Current - also termed gravity wave - An opposing flow of two fluids caused by a density difference (termed by firefighter John Taylor as an air-track).

In firefighting terms this is basically referring to the under-pressure area where air enters a building or compartment

and the over-pressure area where smoke, flame or hot gases leave.

Heat Release Rate - The amount of energy (fire intensity) released by burning materials is recorded in Kw or Mw/sq.m.

In a compartment fire a minimum level of HRR is normally required before 'flashover' can occur - this can be increased by - (1) an increase in the area of the ventilation opening; (2) an increase in the compartment size; (3) an increase in h_k which depends on the thermal conductivity of the compartment boundary.

High Velocity Gases - Where the ignition and movement of super-heated fire gases are accelerated through narrow openings, corridors etc, or are deflected, the effects can be dramatic.

The deep levels of burning (referred to in the UK as a *local deepening*) will cause unusual patterns of burn as if an accelerant has been used to increase fire intensity. On occasions, where high-velocity gases escape to the outside without being deflected, their flow is such that they may cross an entire street creating a flame-thrower effect from a window or doorway.

Hot Layer Interface - Often referred to as the NPP (neutral pressure plane) - it is assumed that the hot smoky upper layer that forms below the ceiling and the lower cool layer that shrinks as the hot layer descends are joined at a distinct horizontal interface (computer model). This is obviously a simplification because the turbulence within a fire compartment would prevent any true formation of such an interface.

Also, highly turbulent plumes and hot layers, as well as strong vent flows, may cause the destruction of a clear interface. However, a noticeable change in conditions from the upper layer to the lower has been observed in many compartment fire experiments. The hot layer *interface* plane and *neutral* plane are not the same. The interface is the vertical elevation within the compartment, away from the vent point, at which the discontinuity between the hot and cold layer is located. The neutral plane (or point) is the vertical location *at the vent* at which the pressure difference across the vent is zero.

Local Deepening - See High Velocity Gases.

Pre-mixed flame - In pre-mixed burning gaseous fuel and oxidiser (air) are intimately mixed prior to ignition - the flame propagation through the mixture is a deflagration (eg; Smoke explosion).

Pulsation Cycle - An indication of the presence of unburned fuel vapours within a compartment with the potential for pre-mixing and a potential explosion - A warning sign for backdraft as smoke 'pulses' intermittently in and out at a ventilation/entry point

Pyrolysis – Is the chemical breakdown, due to heat, of solid materials e.g. when exposed to the radiant heat of the fire. This process gasifies the fuel making it more easily combustible and filling the room with combustible breakdown products. The chemical decomposition of natural (eg wood) or synthetic polymers creates a toxic atmosphere containing various toxic products.

Certain combustible solids such as sodium, potassium, phosphorus, and magnesium can even be oxidized directly by oxygen in the air without the need of pyrolysis.

Rapid Fire Progress - An NFPA definition of all types of rapid fire escalation that may occur and be linked to the above described phenomena as flashover, backdraft and their associates.

Regimes of Burning - (1) Fuel controlled; (2) Ventilation controlled; (3) Stoichiometric.

Rollover - The extension of the fire plume or tongues of flame that have become detached ahead of the plume at ceiling level signalling the effect of 'rollover' - a recognised warning sign that the compartment fire is rapidly progressing towards 'flashover'.

Smoke Explosion - The ignition of a pre-mixed pocket of fire gases and oxygen that may occur when an ignition source is introduced. This may occur, for example, when a hot brand or spark is directed via convection into an area, possibly near the ceiling, where the pre-mixed gases exist, or where an ignition source is uncovered in an area that is harboring such a gas/air mix.

Step Events - The Heat Release Rate (HRR) is either controlled by the supply of fuel or the supply of air. Therefore, in principle, four transitions (steps) are possible –

1. Fuel control to new fuel control;
2. Fuel control to air control;
3. Air control to new air control;
4. Air control to fuel control.

In each of these cases the new fire is SUSTAINED. The event defined as FLASHOVER is usually related to Step 2 although it may also occur through an increase in ventilation (Step 3).

Stoichiometric - In terms of flammability limits of gas/air mixtures the stoichiometric mixture is the 'ideal' mixture that will produce a complete combustion.

This means that for every molecule of fuel the right amount of oxygen molecules is present for a complete chemical reaction, i.e. combustion generating, ideally combustion products as carbon dioxide and water.

Tactical Firefighting - Paul Grimwood introduced the concept of tactical firefighting in 1989 to affirm the combination of various tactical options on the fireground. These included 3D offensive water-fog; smooth-bore/straight stream (direct) attack; indirect attack; tactical ventilation including 'open-up', 'close-down' and PPV methods. The key lies in careful risk assessment, recognition of specific conditions, application and TRAINING! All these various tactical options have a place on the fireground but the experienced firefighter will recognise specific conditions and utilise the most effective option, or combination of, for each individual scenario, ensuring tactical options are used effectively without conflict or breach of safety.

Tactical Ventilation - A concept of safe practice originally introduced and defined during the 1980s by Paul Grimwood as *'venting actions by on-scene firefighters, used to gain control of a fire building's internal environment to the advantage of firefighting and rescue teams working within. Such actions may include attempts to release or direct smoke, super-heated and burning gases from the building by either natural or forced means via vertical or horizontal openings made or existing in the structure. These actions may also include the 'closing down' of a structure in an attempt to reduce the flow of air towards the fire. This tactic is termed 'Anti-Ventilation' by the Swedish Fire service'. It is essential that firefighters remember the most dangerous opening they may create in the structure exists at the point of entry to the building.*

Thermal Balance - The degree of thermal balance existing in a closed room during a fire's development is dependant upon fuel supply and air availability as well as other factors. The hot area over the fire (often termed the fire plume or thermal column) causes the circulation that feeds air to the fire. However, when the ceiling and upper parts of the wall linings become super-heated, circulation slows down until the entire room develops a kind of thermal balance with temperatures distributed uniformly horizontally throughout the compartment. In vertical terms the temperatures continuously increase from bottom to top with the greatest concentration of heat at the highest level.

Transient Events - These are short, possibly violent, releases of energy from the fire which are NOT sustained -

1. adding fuel;
2. adding air/oxygen (backdraft);
3. adding heat (smoke explosion).

Under-Ventilated Fire - Unlike the *ventilation controlled fire* an *under-ventilated fire* is not recognised as a burning regime but rather a situation where fuel-rich conditions have accumulated within a compartment. The situation may not involve a fully developed fire and may only be in a state of smouldering. The conditions may or may not present warning signs related to backdraft.

Ventilation Controlled Fire - Sometimes referred to as an 'under-ventilated fire' although this may be incorrect (see '*under-ventilated' fire*') - most fully developed fires that occur under confinement or within a compartment are ventilation controlled and burn under fuel-rich conditions. In these situations the highest temperatures are normally noted at the ventilation openings. The rate of air supply is insufficient to burn all the fuel vapours within the compartment, possibly leading to much external flaming.



XII. REFERENCES

- [1] Fire officers course, Belgium with personal adaptations
- [2] Website data, as mentioned in text
- [3] Tewarson – Observations on experimental fires in enclosures – Combustion Flame 19 (1972)
- [4] P. Grimwood – Fog Attack – DMG (FMJ) Publications UK (1992)
- [5] Johan Mangs and Hakan – VTT Finland - Fire International Magazine (UK) December/January 1992 p32-38
- [6] K. Roughley - University of Central Lancashire (UK) – Research dissertation
- [7] N. Pope - Fire Prevention & Fire Engineers Journal (UK) (May 2002 (p33-36)
- [8] Brammer & Wise - FIRE Journal Australia – November 2002
- [9] K. Giselsson & M. Rosander – Fundamentals of Fire – Girobrand ab 1978
- [10] PDC Steward – Dust & Smoke Explosions – NFPA Q.7(4) (1914) – 424-428
- [11] CM Fleischmann – University of California – NIST GCR-94-646 1994
- [12] R Chitty – A Survey of Backdraught – FRDF 5/94 1994
- [13] Fire Service Manual – Volume 2 (1997) – Compartment Fires & Tactical Ventilation – HMFSI
- [14] Lars-Goran Bengtsson – Report 1019 – Lund University Sweden – 1999
- [15] BJ Sutherland – Smoke Explosions - University of Canterbury NZ - 1999
- [16] WM Croft – Fires involving Explosions – Fire Safety Journal 3 (1980/81) 3-24
- [17] Indianapolis Athletic Club Fire – Report 063 – USFA
- [18] F Nelson – Qualitative Fire Behavior – ISFSI 1991
- [19] Dr M Thomas – Report into the Blaina Fire – 1996
- [20] P Grimwood – www.firetactics.com
- [21] Stn.O P.Hall – Shropshire Fire & Rescue (UK) – Personal communication
- [22] D Gojkovic & L Bengtsson – Lund University/Helsingborg FD – Theory & Practice of Backdrafts
- [23] BJ Weikema – Vapour Cloud Explosions – Journal of hazardous Materials 8. 295-329 1984
- [24] L Laymen – Attacking and extinguishing Interior Fires – NFPA 1955
- [25] P Grimwood – Flashover & Nozzle Techniques – 1999 www.firetactics.com
- [26] Anders Lauren
- [27] JP Scheffey, CW Siegmann, TA Toomey, FW Williams, JP Farley – 1994 Attack Team Workshop Phase 2 - Full-scale Offensive Fog Attack Tests – US Navy
- [28] Personal E-Mail Communication – www.firetactics.com
- [29] Tommy Torling
- [30] Grant & Drysdale – The Suppression and Extinction of Class 'A' Fires Using Water Sprays - FRDG 1/97
- [31] Maarit Tuomisaari – VTT Finland – Suppression of Compartment Fires with a Small Amount of Water – 1995
- [32] A Handell – Lund University Sweden Fire Safety Engineering – Report 5065 (2000)
- [33] $LxWxH/100=NFF$ (gpm) Royer Nelson IOWA 1959 – or $LxW/3=NFF$ (gpm) NFA USA
- [34] S Sardqvist – Lund University Sweden – Report 7003 (1998)
- [35] CR Barnett – Fire Cell Floor Area Limits – MacBar Fire Design Code 1997

- [36] www.firetactics.com
- [37] A Hay – FRDG 6/94 UK – A Survey of Fire Ventilation
- [38] PH Thomas – FRS Note 663 – UK 1967
- [39] John Taylor – North Yorkshire FRS UK – IFE Scholarship published 1993
- [40] Shan Raffel – Queensland FRS Australia – CFBT Techniques in Queensland 1998
- [41] Fleischmann C.M., Pagni P.J., Williamson R.B., "Exploratory Backdraft Experiments", Fire Technology, Vol 29 No 4 p 298-316 1993
- [42] Sidney G. Gamble – Outbreaks of Fire – Their Causes & Means of Fire Prevention 1931 London
- [43] Major CCB Morris – Fire (p102) London – Date unknown
- [44] Deputy Chief Thomas Dunne (FDNY) – Fire Engineering Magazine – December 2002
- [45] Z.Liu, A.Kashef, GD Loougeed and N.Benichou – National Research Council (Canada) – Research Report RR124 – 3D Water-fog Review

