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# Introduction

Fire has posed a risk to life and property ever since it was discovered. Throughout history, fire has been the cause of many injuries, deaths and property loss. Large fires, such as the Great Fire of London, caused massive widespread damage to entire cities and fires such as these led to the initial development of fire codes and regulations (Stollard, 1994).

Over the years, these rules and regulations have changed and evolved, especially after major fires have occurred. These changing rules and regulations have led to the development of the current building codes that are in place today. A summary of the current UK fire codes and regulations are shown below.

# Background

Without fire engineering involved in their design, many of the more modern and complicated buildings being designed and built currently would not be able to exist today due to the prescriptive requirements of building codes that they would have had to have followed.

Even with fire engineering approaches, the majority of building designs will take aspects from the rules and regulations. However, “cherry picking” (choosing bits that suit the project from different fire codes and using that) is generally considered bad engineering and under newer standards (BS 9999), discouraged.

Knowing the basics of the rules, regulations and standards is needed to look at fire engineering principles and fire protection methods as a knowledge of what each code and regulation requires is needed. Therefore the differences between regulations, standards and codes are addressed below.

## Current Legalisation

In the UK, there are various codes and management regulations that need to be followed to prove that a premises is deemed fire safe. Some of this legalisation is the put into effect when the building is constructed; others are only taken into account once the premises have been occupied and being used.

### Regulations

In the UK, buildings have to be built to follow the building regulations. However, as long as the building can achieve the requirements in the building regulations, it can be attained in any way. If a building does not follow the building regulations, it will be denied planning permission, until the regulations can be met. If the building contravenes the building regulations after modifications to an existing structure, then the local authority (or any other person), may take the person undertaking the modifications to court.

The regulations are split into many different areas, concerning various aspects, such as fire safety and toxic products. As the building regulations are large and complex, the Communities and Local Government have published a series of approved documents, each split down into topic areas that need to be covered. The easiest way for a building in the UK to achieve a building regulation compliant design is to follow the guidelines laid down in each approved document. The one relating to fire safety is Approved Document B: Fire Safety (ADB). This details basic layouts and basic guidelines for the application of fire safety in buildings. It is realised that the guidelines in this document are firstly very prescriptive and secondly, they result in simple, basic buildings. If an architect wishes to build a more innovative building, then ADB will restrict this.

### Standards

Standards describe the British Standards, set by the BSI (British Standards Institution), which specifies the performance and safety requirements of a product or system. Some British standards also provide an alternative method of meeting the building regulations with regards to fire, ‘BS 9999: Code of Practice for Fire Safety in the Design Management and Use of Buildings’ and ‘BS 7974: Application of fire safety engineering principles to the design of buildings: Code of practice’. These two standards lay down the requirements for meeting the building regulations without using ADB.

Other British standards relate to equipment and construction within the building – ADB, BS 9999 and BS 7974 requires equipment within a building to have achieved a level of performance described within the relevant British standard.

BS 7974 is a complete fire engineering based solution from first principles. It is used on the most innovative buildings, where they are unable to follow the guidelines in ADB to achieve the level of design the building architect wants. In this case, the rules within BS 7974 are followed to achieve a design that is based on performance design. Fire is studied from it’s beginning and the whole building is designed around this, to satisfy the building regulations.

BS 9999 is a half way point between ADB and BS 7974. When a designer wishes to make his design more complicated than ADB but does not want to employ the fire engineers needed to follow BS 7974, he can used BS 9999 to get a compromise between the two. BS 9999 is almost a performance based code as it takes into account the occupancy of the building it is being installed in and specifies various solutions based on the risk profile of a building. This allows different designs to accommodate for differing levels of risk within the property, something that ADB does not differentiate between – in ADB, for example, all industry buildings are deemed to be the same fire risk, regardless of what industry takes place within the buildings. For instance, the fire risks within a polystyrene factory and a furniture factory aren’t the same – a fire in the polystyrene factory will ignite and spread more easily than in a furniture factory. As BS 9999 takes this into account, the design for the furniture factory will be able to have extra benefits over the polystyrene factory such as larger compartment sizes due to the lower fire risk.

### Codes

Codes are the American version of the building regulations however the term is often used to describe the British building regulations as well. In America, the rules and regulations differ. In each state (and sometimes cities – New York City for example), there is an individual building code. This code is generally based off the International Building Code (IBC) with the state adding its own requirements and clauses. However the state code may not be updated as often as the IBC. Therefore in each state you must comply with the state building code, which will typically reference other codes such as NFPA 101 ‘Life Safety Code’.

### Regulatory Reform Order

Once a building is built and is occupied, it has to regularly be checked to make sure that the building remains fire safe. Hazards, such as occupants blocking escape routes, need to be found and corrected. This used to be undertaken by the fire service until the introduction of the Regulatory Reform (Fire Safety) Order, (known from here on as the RRO) in 2005.

Under the RRO, non domestic properties have to nominate a person as the “responsible person” and it is his/her duty to ensure that a risk assessment is carried out for the premises he/she is responsible for and steps are taken to reduce any fire risk highlighted by the risk assessment.

The RRO took many previous but different legalisation and regulations and combined them together to make it easier for businesses and for enforcing authorities to prevent fire. It focuses on performance based criteria rather than the previously prescriptive based legalisation that was used. This places a greater onus on the business to comply with the legislation than before, due to the risk assessments needed for the property.

Prevention as they say, is better than cure, and the RRO is seen as a step towards preventing fires occurring, thus allowing savings on fire fighter call outs.

The Government produce a range of guidelines and help documents on the risk assessment methods which are freely available for download on the Communities and Local Government website, http://www.communities.gov.uk/fire/firesafety/firesafetylaw/. These guides detail the outline of the risk assessment process for each different property type that needs to be risk assessed.

It should be noted however that even 3 years after the RRO became law in 2006, that the Fire and Rescue service is finding some premises and buildings are not complying with the RRO or are even unaware of its existence (Initial Evaluation of the Effectiveness of the Regulatory Reform Order, 2009). This research found that the Fire and Rescue service were reluctant to give help when requested, partly due to their nature of the enforcers of the RRO. It also found that many businesses, especially the smaller businesses did not have any awareness of the Government produced documentation on risk assessments. These results were also confirmed in a survey of the Fire Protection Association members (Wilkinson, 2008).

# Fire Protection Methods and Systems

Buildings that have fire protection installed are generally not protected by just one fire protection system. Often the fire safety strategy for a property can be made up of 3 of more fire safety systems that form the core fire safety strategy.

Some fire safety systems are required in the property through either the national building regulations (in the UK, ADB) or insurance companies that may require the building to have specific fire protection systems before they’ll insure the building. For example, Approved Document B states that all buildings over 30m should be equipped with a sprinkler system (Approved Document B, 2006). However a smaller building may want to install sprinklers to provide additional property protection.

Fire safety measures differ in how they act within the fire safety system. For example, alarms and detectors do not fight the fire themselves, however they warn occupants of a fire and allow them to escape, where as sprinklers, unless connected to a flow valve that sets off an alarm if they activate, do not automatically alert occupants within the building that a fire has ignited.

## Smoke Detection and Alarms

Most buildings except the smallest require a form of alarm system. This is to alert occupants that a fire is occurring within the premises, even if the occupants are not in the room of origin. Bigger buildings will have more complex alarm and detection systems that are able to pinpoint exactly whereabouts in the building the fire is taking place by having an addressable alarm system and a display panel which states what detector has detected the fire. This allows the fire service to very quickly locate the area of fire origin and start fire fighting operation as soon as they arrive on scene.

## Sprinklers

Sprinklers are a means of controlling fires and preventing them from spreading. However, sometimes sprinklers will extinguish the fire before the fire service arrive. However they are designed to keep the fire spread under control, meaning the fire service will have a smaller fire to extinguish upon arrival. There are various types of sprinklers systems which differ in operation methods. Wet pipe sprinklers are sprinklers where all the pipe work contains water. Dry pipe sprinklers are sprinklers where the pipe work does not contain water until a sprinkler is activated and then water enters the system. The wet pipe sprinklers are quicker to delivering suppression to the fire; however they are not suitable in cold climates where the water is likely to freeze in the pipes.

## Compartmentation and Passive Fire Protection

Compartmentation aims to prevent fire spread. This is to minimise the chances of conflagration of the entire building, prevent internal fire spread to allow other building occupants to escape (flats for example) and make the fire more manageable for firefighters to extinguish.

## Smoke Control and Pressurisation

Smoke control systems and pressurisation systems are not generally required in buildings except in certain circumstances, however if they are installed, extra benefits can be given to buildings, such as smaller corridor widths and longer travel distances (BS9999, 2008). Due to the benefits gained in the building design process due to extra fire systems being installed, part of the cost of installation maybe made up for in increased usable area inside the building.

Smoke from a fire does not remain in the same location as the seat of the fire. The smoke spreads throughout the compartment and if the compartment is not sealed against smoke flow, it will eventually spread into other compartments. Drysdale covers the factors affecting smoke movement in his book, An Introduction to Fire Dynamics (Drysdale, pp386- 392, 1998). Smoke moves around the compartment and thus out into the rest of the building via smoke buoyancy, expansion of combustion gases, the stack effect, via wind, the elevator piston effect and finally by heating, ventilation and air conditioning (HVAC) systems. Klote briefly mentions HVAC systems in his chapter in the SFPE Handbook For Fire Protection Engineering (Klote, pp. 4.274-4.291, 2002). In fires, HVAC systems are shut off to avoid getting air to the fire and allowing smoke and combustion products to be spread by the air systems. However, smoke will still be able to spread throughout the ducting naturally using the other effects mentioned above. Research has proven that HVAC systems will spread smoke and combustion products round a building faster and in greater concentrations than if the HVAC system was shut off and smoke spread via the other movement methods (Mowrer, 2004).

Smoke control systems, known as SHEVS (Smoke and Heat Exhaust Ventilation Systems), can be installed within a building and most buildings over a certain size or height will include some degree of smoke control within them. In ADB, the guidance is that all buildings over 18m require fire fighting shafts and to the design of BS 5588-5, which has been superseded by the regulations in BS 9999 and thus requires all fire fighting shafts over 30m to have a pressure differential system. Fire fighting shafts under 30m can be naturally ventilated. (BS 9999, 2008)

SHEVS can be installed for a variety of reasons. BRE 368 gives a list of design philosophies behind installing a SHEV system (BRE 368, 1999). It suggests that a SHEVS can be fitted for the following reasons:-

* Protection of Means of Escape
* Temperature Control
* Assisting fire fighting operations
* Property Protection

Protection of means escape is critical and thus the pressurisation systems usually seen, are those within staircases or the smoke reservoirs used in shopping centres to prevent smoke flow along the length of a mall area. Smoke has to be prevented from entering the means of escape from a building where ever possible or if it does enter, it must be kept above head height and ideally, much higher than head height, to prevent escaping occupants being subjected to thermal radiation from the smoke and also from inhaling the toxic products of combustion within the smoke.

Smoke from the fire is hot and rises. In the open, the smoke is free to be carried away under the fires thermal currents. However in a compartment, the smoke will build up, unless there is a means for it to escape. As it builds up, the area under the smoke is subject to radiative heat flux as the heat from the smoke is radiated downwards. This radiative heat flux will increase as the smoke temperature increases. This is part of the process that leads to flashover in a compartment (Drysdale, 1998). Therefore if the smoke can be removed from the compartment, the radiative heat flux from the smoke layer will decrease and flashover can be delayed or prevented. This can be used to help protect property. Flashover is less likely to occur within the fire compartment with the extraction of the hot combustion gases and thus less structural damage will occur, as the structural integrity of a compartment is impacted in the high intensity fire after flashover (Ramachandran, 1990).

## Modelling

Most large engineering companies will use modelling to help them in the design and engineering of a building during planning and construction. Computer modelling of fire hasn’t been used until recent advances in computer technology and computer models have made this possible. Even now, considerable time and effort is needed to design and run the computer model and to interpret the results.

There are various types of fire models available that offer different benefits and drawbacks to the end user. These are split into two types of models, zone models and field models.

Zone models are relatively simple models that can output answers quickly and with relatively little running costs. However because they are simple models, the results they give are not very accurate and cannot be used to show how smoke and fire is likely to progress throughout a building. Field models on the other hand take much longer to run and thus have a larger running cost associated with them but they do provide better estimates of fire growth and smoke movement, due to the many calculations they perform for each field within the model. These computational fluid dynamic models are the models most often used in the application of fire design, thanks to the more accurate results they are able to give. They require more training to use and require that the user knows the essentials of the program and of fire engineering to get the results needed from the program. (Cox, 1994)

Fire models are often used in the design of buildings, however research has been undertaken into using fire models to provide information to fire fighters whilst the fire fighters are at the fire fighting scene (Upadhyay *et al*, 2008). The Firegrid system proposed by Upadhyay *et al* relies on access to high performance computing (HPC) that can calculate changes in the building structure and the progress of the fire from data gathered within the building via sensor systems. The outputs of the model are then relayed to the fire service, allowing them to make informed and sound decisions on the situation at hand. This requires access to perform the calculations as the data needs to be gathered and calculated faster than real time to allow the fire fighters to receive the data when it’s of use to them on the scene.

As discussed above, zone models run quickly however do not give entirely accurate results. Comparisons between both field models and zone models have been carried out (Chow, 1995) and these show that the zone models give a good approximation of the actual smoke temperature and flow, but for more accurate results, a field model is best, though this will take much longer to run and gather the results.

Efforts have been made to try and combine the benefits of both zone models and field models. These models, known as HZAFM (Hybrid Zone And Field Models) use a field model to model the fire compartment itself and any vertical compartments such as staircases, whilst the rest of the smoke flow is modelled via zone models (Hua *et al*, 2005). This decreases the time of computation but gives results that are better than pure zone models but are less accurate that pure field models.

Three zone models, instead of the normal two zone models, have been experimented with, mainly in tunnel fire situations where the extended horizontal travel distance allows more entrainment of air into the smoke and thus more mixing will occur within the smoke (Charters *et al*, 1994). A standard zone model is based on two zones, a hot smoke layer and a layer of cool, ambient air below the hot layer. They generally have a uniform temperature across the smoke layer. In a three zone model, there is a third zone where the smoke and air mix. This intermediate zone represents the point where air is entrained into the smoke and the smoke mixes.

In Charters research, the three zone model was not applied to complicated models such as buildings and instead focussed on tunnels. However in a research paper published by Guo *et al*, a three zone model was applied to a building and was found to provide a closer fit to the results from a field model than the two zone CFAST (Consolidated model of Fire And Smoke Transport) model (Guo *et al*, 2009). The three zone model also followed the experimental data for this model better than the two layer model. With the three zone model that Guo *et al* used, there was an increase in computational time for the modelling scenario given but this increase was negligible compared to the time taken to run a full field model. However the more accurate results gained from the three zone model more than make up for the extra 10 seconds or so that it takes for the three zone model to run.

# Previous Research

## Effectiveness

However all systems within fire safety can be analysed to determine their effectiveness in regards to their role within the system. It should be noted that the effectiveness of an entire system depends upon the effectiveness of the individual components. If an alarm system is classed as very effective but the detection system installed alongside it is not and fails to detect the fire, the effective alarm system has been nullified by ineffective detection system.

### Smoke Detection and Alarms

One of the most useful detection methods is smoke detection. Simple and easy to install, especially in the home environment. However smoke detection can be prone to false alarms when used in the wrong areas, as depending on the type of smoke detector, it can be activated easily by water vapour, other particles in the air (such as dust) and cooking fumes (Qiyuan, 2004). False alarms are an annoyance and increase the cost of fire fighting. False alarms cost the UK economy £81m in 2004 (Office of The Deputy Prime Minister, 2006). False alarms also cause disruption to commercial activities.

Smoke alarms have a different effectiveness on different age groups. In a study by Bruck, it was found that children are less likely to wake up for a fire alarm than the parents. (Bruck, 1999). This means that adults will then have to wake the child/children before escaping from the property, wasting time that could be used to escape.

The effectiveness of smoke detectors in Australia has been investigated by He and Nelson in 2008. They investigated the effectiveness of smoke detectors in both commercial properties and in residential dwellings. They found that smoke alarms were more effective in dwellings for adults but if the building occupant interactions are taken into account (such as trained staff working to help evacuate people as well as the alarms) then the commercial alarms were more effective than the dwelling alarms, especially at night, where the dwellings occupants would be asleep (He,2008).

### Sprinklers

The effectiveness of sprinklers is a crucial element within larger buildings and high rise structures. With a sprinkler system installed, these buildings are allowed additional design space beyond what would normally be allowed if they were not fitted with sprinklers. Therefore if the buildings sprinklers fail to operate or fail to contain the fire, then the building is liable to suffer larger amounts of damage (than if it wasn’t sprinklered due to the large floor area) or cause risk to occupants within the building that might be relying on the sprinklers to contain the fire and allow them time to escape before conditions within the building become untenable.

Sprinkler systems therefore need to be reliable (operate in a fire) and effective (contain the fire to the designed level). Previous research by Melinek shows that sprinklers are effective in reducing the probability of fires reaching an area greater than 100m2. However they have little effect on the probability of fire spread until the fire has reached 3m2. This suggests that a fire has to reach 3m2 before it will be hot enough to activate the sprinkler heads (Melinek, 1993a).

### Compartmentation and Passive Fire Protection

Passive fire protection is one of the easiest methods of protecting against fire spread of fire damage. Passive fire protection is defined by the Factory Mutual Research Corporation (Factory Mutual Research Corporation, 1991) as the protection through:-

* High resistance to ignition
* Slow and/or decelerating fire growth
* Low heat release rate and generation rates of fire products
* Short fire duration

Passive fire protection is used in various applications. Building compartments, built with fire resisting materials, are passive fire protection measures, as is the intumescent paint and other materials used to protect steel beams within buildings. These passive fire protection measures are designed to contain the fire, prevent its spread and prevent damage where possible from fire.

Recently, passive fire protection has been applied to concrete. Concrete is deemed as fire proof and is a common material in building construction. It is a Class 0 material, which means it is non combustible or of limited combustion, and is thus commonly used in escape routes to prevent fire spread (Communities and Local Government, 2006). Due to its wide use throughout the building industry, it has been subjected to fire on many different occasions and has been noted to undergo explosive spalling. This phenomena is seen when concrete is exposed to high temperatures which causes the water within the concrete to vaporise and move to the surface, destroying the concrete. In the Channel Tunnel fire in 1996, various sections of the tunnel suffered severe spalling and in places the concrete was almost reduced to the bedrock (Comeau, 1997). Due to spalling like this, passive fire protection has been applied to concrete to prevent the fire causing such damage. Various methods exist to protect concrete, the most effective of which is a thermal barrier (Khoury, 2008). The thermal barrier prevents heat reaching the concrete and thus prevents spalling. Another method in Khoury’s article is the addition of polypropylene fibres to concrete. These do not prevent the temperature of the concrete increasing but can minimise or even prevent explosive spalling from occurring. It can also be used to help protect structural steel beams and if the concrete spalls away, the steel will be subjected to the fire heat and will cause damage to the steel. Steel, when heated, can lose its strength and thus can cause building collapse.

Sustainability of buildings is a big design focus at the current time. With good building design, there is less emphasis on using secondary systems in the building such as HVAC systems that use energy and reduce the sustainability of buildings. Also sustainable buildings will make use of sustainable construction materials. Fire engineering, even in these sustainable buildings, is still essential. However research has been done on whether fire protection can be made more sustainable with the use of different and new fire protection materials. Fly ash from biomass burnt to provide power has some good properties that can be used for fire protection. A methodology has been developed by Vilches *et al* (Vilches, 2005) to test the new and different fly ash pastes that can be made with differing ashes from different biomass fuels. The pastes that perform well can then be further refined to create panel, similar to plasterboard. Leiva *et al* have studied the use of internal partition panels made with ash from biomass power stations (Leiva, 2009). They found that the panels had similar performance to that of gypsum plasterboard panels, in both fire conditions and in material properties. This could, in the future, be an alternative material for fire protection within buildings that is sustainable – using waste materials from sustainable power development.

In the research conducted by Remesh and Tan (Remesh & Tan, 2006), they found that smoke spread in a non partitioned flat unit was quicker than the smoke spread within a partitioned unit, meaning that the layout of a flat and building can affect the smoke spread and thus affect how quickly tenability limits are reached within a building. The basis of compartmentation is to prevent smoke spread around a building and this research gives a good indication of why compartmentation should be installed within buildings.

Steel beams are a common building material, especially with high rise buildings. However, after the 9/11 attacks on the World Trade Centre, a lot of focus has been on protecting steel columns in fires, especially as NIST states that WTC building 7 “underwent progressive fire induced collapse due to structural failings due to fire” (NIST, 2008). Other fires have caused weakening of steel structural supports and deformed buildings, most notably the Broadgate Phase 8 fire in London, UK and the Windsor Building fire in Madrid, Spain. Both these fires, whilst not having significant structural collapse, showed the vulnerability of steel beams and structural steel parts within a fire. Therefore, these are protected within buildings to prevent a fire causing collapse of part of or the entire building.

Generally speaking, protection for steel is provided either by fire resisting materials such as plasterboard or with a gypsum based spray. Alternatively, intumescent paint and materials can be used to protect the steel. The aim behind the protection is to prevent heat reaching the steel beneath the fire protection. Steel loses its structural strength as temperature increases and at around 600°C; it will have lost almost half of its strength. Therefore preventing heat reaching the steel will mean that the steel will not lose any structural strength throughout the fire.

An interesting area of research in passive fire protection of steel is the use of ablative materials (Staggs, 2008). Currently in theoretical stages but the ideas behind it are promising. Ablative materials have been used for years to protect against heat on spacecraft, most notably the space shuttle. Using cheap ablative materials as fire protection isn’t a bad theory as after a fire, intumescent coating, if successful in preventing collapse, will have to be replaced due to the changes it undergoes doing heating, as would the ablative coating as it ablates during the fire.

In his paper, Inherently Safer Chemical Process Design, DC Hendershot (Hendershot, 1997) talks about improving chemical processes and manufacturer by using inherently safer options of chemical manufacture. He also discusses passive and active protection (in the chemical process aspect) for protection and this can be applied to fire engineering as well. He discusses the four methods of reducing the frequency or consequence of accidents. These are (in decreasing order of reliability and robustness) : -

|  |  |
| --- | --- |
| **Protection Method** | **Method** |
| Inherent | Eliminating hazards altogether |
| Passive | Equipment or protection doesn’t rely on activation or any functioning device |
| Active | Hazards are controlled by activation of protection system upon trigger |
| Procedural | Hazard is controlled via operating procedures and other management approaches |

Table – Protection Method Systems

Taking these protection steps, we can then apply these to fire engineering. Inherent safety in fire engineering is quite hard to achieve, however it can be done, usually at a cost of either aesthetics (concrete corridors are inherently safe but do not look pretty) or a larger cost to the building. Passive systems are easily built but need to be well maintained and provide unbroken protection, otherwise they are useless if fire and fire products can penetrate the passive barriers. Active measures require maintaining to make sure that they will activate in case of a fire. Procedural measures are not really applicable to fire safety. Having a person in control of alarm systems on there own is not a satisfactory system, however having people help control the alarm system ca be an extra level of protection, for example, manual call points alongside a detection system. However Hendershot does note that “business and economic factors must also be considered”. Therefore the best option safety wise may not be the best decision economically and thus a compromise must be met.

### Smoke Control and Pressurisation

Removing the smoke from buildings also allows escape under the hot layer of gases. Depending on how wide the corridor is and how deep the smoke layer is, the escaping occupants are subjected to differing amounts of heat flux (Wong, 2005). This heat flux will affect the occupants decision to escape via a smoke logged exit route. However in a shopping centre, it is unlikely that escape is possible without travelling under a smoke layer. This isn’t as much as an issue than within domestic and office accommodation due to the higher ceiling heights in shopping malls; however the smoke layer has to be significantly higher than the escaping occupants to prevent heat from the smoke causing injuries.

As smoke builds up, it causes visibility to drop and thus will affect escaping occupants and fire service personnel engaged in fire fighting operations. If the smoke can be removed from the building, then visibility will increase and the fire fighters are more likely to be effective in fighting the fire. In both America and Europe, fire fighters can use high power fans to clear buildings of smoke using positive pressure ventilation (PPV). In UK trials, PPV systems were found to be effective in clearing smoke and reducing temperature within a domestic fire however they were affected by wind conditions, as if the building was naturally ventilated. It’s use in staircases was found to be unpredictable and its use in large compartments was found to help speed up smoke clearance once the fire had been extinguished. It was concluded that PPV is just an extension of natural ventilation and thus should bear in mind that both the negative effects of ventilation (increased oxygen supply to the fire, spread of fire due to wind direction) will occur along with the positive effects (Rimen, 2000).

Buoyant smoke will rise under the pressure difference between it and the air around it. The smoke will continue to rise as long as there is a pressure difference caused by a temperature difference. Once the temperature difference does not exist or the smoke has reached the ceiling, the smoke will stop rising and will spread out horizontally. In large open buildings and rooms, such as atriums, the temperature at the top of the space maybe higher than that of the base of the space and thus the smoke may stop before it reaches the ceiling. This is called stratification and can cause problems with smoke detection. If an alarm system is installed within a building and on the roof, and the smoke doesn’t make it to the detectors, the alarm will not be triggered. Therefore the fire will spread before the alarm is raised and may cause extra damage and pose a threat to life safety. It is proposed by Fang and Yuan in the paper “Experimental Measurements, Integral Modelling and Smoke Detection of Early Fire in Thermally Stratified Environments “ (Fang and Yuan, 2007) that a light section detection system, coupled to a computer, would be able to detect the fire plume more reliably than the current beam or ionic/photoelectric detectors used. The light section detectors relies on using infra red detectors and light beams to detect smoke and activate the alarm, instead of waiting for the smoke to travel to the detectors.

## Cost Effectiveness

### Measuring Cost Effectiveness

In the paper, Principle for Risk Evaluation and Expected Cost to Benefit of Different Fire Protective Measures in Industrial Buildings, the underlying principle behind the cost effectiveness of a protection measure is raised – a protective system should not cost more than the potential loss in a fire (Thor and Sedin, 1980). A system that costs more than the loss it is liable to prevent is not a cost effective option.

Fires cost money. Not just to the company/owners of a building where a fire occurs but to the whole economy. The cost of fire to the British economy for 2004 was estimated at £7.03bn, 0.78% of the national GVA according to the Office of The Deputy Minister (ODPM, 2006). This cost includes the cost of the fire brigade, insurance administration, prevention and protection measures installed within buildings and property loss amongst others.

The aim of a cost benefit analysis in relation to fire is to make sure that the fire safety systems proposed for a building are cost effective. Not all fire regulations require all fire safety systems to be installed into one building; however the owner or occupant may want to install other non required systems if these are cost effective ways of reducing risk to their building and occupants. There are various ways of measuring the economic performance of the safety systems installed within a building. ASTM International have written a standard for the measuring the net benefits and saving of buildings and building systems (ASTM, E1074-09). As a fire alarm or sprinkler system counts as a building system, this standard can be used to work out the economic viability of installing a system. This also takes into account the Value of Statistical Life (VSL) of occupants within the building; however it points out that the methods of choosing a VSL can lead to very different choice in a value for the VSL. If the value is worked out according to present earning potential, it can give a different figure for the old and young with the middle age being the highest earning members of the community. A paper by Baker (Baker, 2009) describes a method that can be used to negate the effects of this calculation and use a mean value of the statistical life across the board – as even using the willingness to pay method may result in vastly differing values due to the spread of wealth across the community as a wealthy person is more likely to pay a higher percentage of there income to lower his risk of death than a poorer person.

The SFPE handbook for Fire Protection Engineers also contains a section on the economics of fire technology (SFPE Handbook for Fire Protection Engineers, 2002). This section describes the basics of economics for fire protection systems, which are covered in greater detail in other literature.

The economics of fire protection systems is covered in greater detail within Ramachandran’s book, the Economics of Fire Protection. (Ramachandran, 1998). In this book, Ramachandran details the cost benefit analysis models, the VSL within a fire engineering context, the consequential and indirect losses associated with a fire within a building, decision analysis of a project once the cost benefits of each project is described and utility theory.

Costs can be split into direct and indirect costs. Direct costs are costs incurred from damage to buildings, contents and means of transport. Indirect costs are costs caused by lack of production, loss of sales and things such as loss of customer respect. A study in Denmark on the socio-economic costs of fires showed that Denmark had lowest socio-economic costs in out of the UK, Denmark, Canada and the US (Møller, 2001). However Denmark does have a lower cost of rescue services and has a low cost of fire prevention. However the report stated there was a lack of research into the indirect costs of a fire. While these may be substantial, there is no easy way to work out the indirect costs, especially ones such as damage to the companies reputation. The report also briefly looks at whether there is a correlation between direct and indirect costs. However it was found that “no statistical correlation between direct and indirect costs could be shown”.

Direct costs will affect a business but for the majority of these costs, the business will be insured against (minus the deductible or excess). However the indirect costs may be significant and against these, the company is not likely to have insurance.

### Smoke Detection and Alarms

In the United States, safety programs educating and fitting smoke alarm systems have been researched to check the cost-outcome of the safety programs. These studies did not do a cost-benefit analysis but a quick comparison of the overall costs of the safety programs compared to the statistical value of life (which vary depending on the literature), shows that the program could be classed as cost effective. However this would need further research and a more detailed economic analysis of both the benefits of having smoke detectors and the number of injuries prevented and live saved (Parmer *et al*, 2006).

### Sprinklers

While sprinklers aren’t required under building regulations, a building owner or occupant might wish to install them to provide additional property protection, as sprinklers are proven to reduce the probability of fire spreading beyond 100m3 by a factor of 5 in commercial and industrial applications. (Melinek, 1993a)

However the probability of it restricting the fire growth may not be enough incentive to some companies and in the case of residential sprinklers, homeowners may not consider this saving worth the investment as the property areas for a dwelling is much less than that of an industrial premises.

Cost benefit analysis has been undertaken in previous research to show the benefits and costs that a sprinkler installation is likely to incur should sprinklers be considered for installation into a building.

NIST (National Institute of Standards and Technology) in America has investigated residential sprinklers and researched if it made economic sense to install sprinklers in residential properties throughout America. They concluded that if a multipurpose network design of sprinklers was installed, the system was economical for all three housing types they tested it in (Butry, 2007). Benefits gained were reduction in injuries and fatalities, lower insurance premiums and lower uninsured direct property loss whilst the costs were the initial purchase and installation costs – maintenance costs were classed as negligible due to the type of system installed. The results are also summarised in Fire Technology (Butry, 2009).

Sprinkler systems can be installed almost anywhere. In New Zealand, the possibility of installing sprinklers into car parking areas was looked at by Li and Spearpoint (Li and Spearpoint, 2004). It was found that it was uneconomical to install sprinklers into New Zealand parking buildings due to the expected number of fires each year. However the results relied on the critical variables of usage ratio (how often each car parking space is used) and unit fire damage from a fire. For both of these variables, there was limited data. They found the usage ratio would have to be significantly higher than current values if sprinklers were to be economical.

Sprinklers as life safety protection methods have also been investigated. Melinek found that “sprinklers substantially reduced the number of deaths in both multi-fatality and single-fatality fires”. (Melinek, 1993b) However he found that by taking the value of statistical life, that sprinklers in the home were not economical. It should be noted however, that this paper was published over 10 years before Butry’s more recent study and the decline in costs of sprinkler systems have changed this as Butry’s report shows.

### Compartmentation and Passive Fire Protection

In a paper by Tyldesley *et al*, they investigate the cost effectiveness of compartmentation within chemical warehouses (Tyldesley, 2004). They found that compartmentation was not the most cost effective means of fire prevention within chemical warehouses. They did investigate various materials as the compartmentation materials to see if this had any effect on the cost effectiveness but they found the only effective measure was reinforced concrete. The two other materials tested, block work and stud partition walls of plasterboard were not as effective as the reinforced concrete and could not protect against fire spread caused by certain cases such as explosive destruction of chemical storage containers. They concluded that AFD (automatic fire detection) was a more cost effective method of protecting chemical warehouses.

### Smoke Control and Pressurisation

# Fire Engineering Design

Previous methods of protecting against fire have revolved around using prescriptive codes to specify fire protection measures.

# References

(2009), 'ASTM E1074 - 09 Standard Practice for Measuring Net Benefits and Net Savings for Investments in Buildings and Building Systems', ASTM International, Technical report, ASTM.

Baker, R.; Chilton, S.; Jones-Lee, M. & Metcalf, H. (2009), 'Valuing Lives Equally in a Benefit-Cost Analysis of Safety Projects: A Method to Reconcile Theory and Practice', *Safety Science* **47**(6), 813–816.

Bruck, D. (1999), 'Non-awakening in Children in Response to a Smoke Detector Alarm', *Fire Safety Journal* **32**(4), 369 - 376.

(2004), 'BS 5588 - Fire Precautions in the Design, Construction and use of Buildings —Part 5: Access and Facilities for Fire-Fighting', BSI Global, BSI.

(2008), 'BS 9999: Code of Practice for Fire Safety in the Design Management and Use of Buildings'(9999), BSI Global, BSI.

Butry, D. T.; Brown, M. H. & Fuller, S. K. (2007), 'Benefit-Cost Analysis of Residential Fire Sprinkler Systems', Technical report, NIST.

Butry, D. T. (2009), 'Economic Performance of Residential Fire Sprinkler Systems', *Fire Technology* **45**(1), 117-143.

Charters, D. A.; Gray, W. A. & McIntosh, A. C. (1994), 'A Computer Model to Assess Fire Hazards in Tunnels (FASIT)', *Fire Technology* **30**(1), 134 - 154.

Chow, W. K. (1995), 'A Comparison of the use of Fire Zone and Field Models for Simulating Atrium Smoke-Filling Processes', *Fire Safety Journal* **25**(4), 337 - 353.

Comeau, E. & Wolf, A. (1997), 'Fire in the Chunnel!', *NFPA Journal* **March**.

Communities & Local Government. (2006), *Approved Document B: Fire Safety*, NBS.

Communities & Local Government. (2009), 'Initial Evaluation of the Effectiveness of The Regulatory Reform (Fire Safety) Order 2005', Fire Research 3/2009.

Cox, G. (1994), 'The Challenge Of Fire Modelling', *Fire Safety Journal* **23**(2), 123 - 132.

Drysdale, D. (1998), *An Introduction to Fire Dynamics*, John Wiley and Sons.

Factory Mutual Research Corporation. (1991), 'Small-scale testing: The Role of Passive Fire Protection in Commodity Classification', *Fire Technology* **27**(3), 266-272.

Fang, J. & Yuan, H.-Y. (2007), 'Experimental Measurements, Integral Modeling and Smoke Detection of Early Fire in Thermally Stratified Environments', *Fire Safety Journal* **42**(1), 11 - 24.

Guo, S.; Yang, R.; Zhang, H.; Narayanan, S. & Atalla, M. (2009), 'Development of a Fire Zone Model Considering Mixing Behavior', *Journal of Thermophysics and Heat Transfer* **23**(2), 327 - 338.

He, Y. & Nelson, D. (2008), 'A Comparative Study of Effectiveness of Smoke Alarms in Two Types of Buildings', *Journal of Fire Sciences* **26**(5), 415-434.

Hendershot, D. C. (1997), 'Inherently Safer Chemical Process Design', *Journal of Loss Prevention in the Process Industries* **10**(3), 151 - 157.

Hua, J.; Wang, J. & Kumar, K. (2005), 'Development of a Hybrid Field and Zone Model for Fire Smoke Propagation Simulation in Buildings', *Fire Safety Journal* **40**(2), 99 - 119.

Khoury, G. A. (2008), 'Passive Fire Protection of Concrete Structures', *Structures & Buildings* **161**(3), 135-145.

Klote, J. H. (2002), *Smoke Control - SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, chapter 4-12, pp. 4.274-4.291.

Leiva, C.; Vilches, L. F.; Vale, J. & Fernández-Pereira, C. (2009), 'Fire Resistance of Biomass Ash Panels Used for Internal Partitions in Buildings', *Fire Safety Journal* **44**(4), 622 - 628.

Li, Y. & Spearpoint, M. (2004), 'Cost-Benefit Analysis of Sprinklers For Property Protection In New Zealand Parking Buildings', *Journal of Applied Fire Science* **12**(3), 223 - 243.

Melinek, S. (1993a), 'Effectiveness of Sprinklers in Reducing Fire Severity', *Fire Safety Journal* **21**(4), 299 - 311.

Melinek, S. J. (1993b), 'Potential Value of Sprinklers in Reducing Fire Casualties', *Fire Safety Journal* **20**(3), 275-287.

Møller, K. & Danish Emergency Management Agency. (2001), 'The Socio-Economic Costs of Fire in Denmark', Technical report, Danish Emergency Management Agency.

Morgan, H. P.; Ghosh, B. K.; Garrad, G.; Pamlitschka, R.; Smedt, J.-C. D. & Schoonbaert, L. R. (1999), *BRE 368: Design Methodologies for Smoke and Heat Exhaust Ventilation*, Construction Research Communications Ltd.

Mowrer, F. W.; Milke, J. A. & Torero, J. L. (2004), 'A Comparison of Driving Forces for Smoke Movement in Buildings', *Journal of Fire Protection Engineering* **14**, 237-264.

NIST (2008), 'NIST NCSTAR 1A: Final Report On The Collapse Of World Trade Center Building 7', Technical report, National Institute of Standards and Technology.

Office of The Deputy Prime Minister. (2006), *The Economic Cost of Fire: Estimates for 2004*, ODPM Publications.

Parmer, J. E.; Corso, P. S. & Ballesteros, M. F. (2006), 'A Cost Analysis of a Smoke Alarm Installation and Fire Safety Education Program', *Journal of Safety Research* **37**(4), 367 - 373.

(2003), 'PD 7974: Application of Fire Safety Engineering Principles to the Design of Buildings - Part 3: Structural Response and Fire Spread Beyond the Enclosure of Origin', BSI Global, BSI.

Qiyuan, X.; Hongyong, Y. & Huiliang, G. (2004), 'Experimental Analysis on False Alarms of Fire Detectors by Cooking Fumes', *Journal of Fire Sciences* **22**(4), 325-337.

Ramachandran, G. (1990), 'Probability Based Fire Safety Code', *Journal of Fire Protection Engineers* **2**(3), 75-91.

Ramachandran, G. (1998), *The Economics Of Fire Protection*, Taylor and Francis Group.

Remesh, K. & Tan, K. H. (2006), 'Field Model Analysis and Experimental Assessment of Fire Severity and Smoke Movement in a Partitioned and a Non-partitioned Dwelling Unit', *Journal of Fire Sciences* **24**(5), 365 - 391.

Rimen, J. G. (2000), 'The Use of Positive Pressure Ventilation in Firefighting Operations'(81), Technical report, Home Office Fire Research and Development Group.

Society of Fire Protection Engineers. (2002), *SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association.

Staggs, J. (2008), 'A Theoretical Appraisal of the Effectiveness of Idealised Ablative Coatings for Steel Protection', *Fire Safety Journal* **43**(8), 618 - 625.

Stollard, P. & Johnston, L., ed. (1994), Design Against Fire : An Introduction to Fire Safety Engineering Design, E & FN Spon.

Thor, J. & Sedin, G. (1980), 'Principles for Risk Evaluation and Expected Cost to Benefit of Different Fire Protective Measures in Industrial Buildings', *Fire Safety Journal* **2**(3), 153 - 166.

Tyldesley, A.; Rew, P. & Houlding, R. (2004), 'Benefits of Fire Compartmentation in Chemical Warehouses', *Process Safety and Environmental Protection* **82**(5), 331 - 340.

Upadhyay, R.; Pringle, G.; Beckett, G.; Potter, S.; Han, L.; Welch, S.; Usmani, A. & Torero, J. L. (2008), An Architecture for an Integrated Fire Emergency Response System for the Built Environment, *in* 'Proceedings of the Ninth International Symposium: Fire Safety Science', pp. 427 - 438.

Vilches, L. F.; Leiva, C.; Vale, J. & Fernández-Pereira, C. (2005), 'Insulating Capacity of Fly Ash Pastes Used for Passive Protection Against Fire', *Cement and Concrete Composites* **27**(7-8), 776 - 781.

Wilkinson, P. (2008), 'Order Status', *Fire Risk Management* **September**, 48-50.

Wong, L. (2005), 'Hazard of Thermal Radiation from a Hot Smoke Layer in Enclosures to an Evacuee', *Journal of Fire Sciences* **23**(2), 139-156.