Invited Lecture

Industrial Fire Problems: An Overview

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ABSTRACT

Fires in industry impinge on the safety of workers, those living in the vicinity of the installation and on the environment. Though its control of industrial safety in the United Kingdom, the Health and Safety Executive (HSE) encounters a wide variety of fire problems. This paper examines the scope and magnitude of the problem and, by reference to examples from HSE's recent work, illustrates the wide range of situations which can occur. Methods for identification of the hazard are examined and the tools which can be used for its quantification are detailed. Reference is made to experiment and modelling of varying complexity. Particular attention is paid to the requirements of HSE. Finally suggestions are made for the most promising lines of research and the way in which safety standards can be maintained and developed in industry.

KEYWORDS: Industrial fires, experiments, testing, modelling, chemical plant, warehouses

INTRODUCTION

The Problem

In the United Kingdom the Health and Safety Executive (HSE) is charged with ensuring the provision of a safe working environment and protecting the public and surroundings from the harmful effects of work activities. Both a consideration of normal operations and the consequences of a departure from normality - the accident situation, are required.

It is this latter situation where fire studies impinge most closely on HSE's activities. Fire is one of the most common hazard or accident vectors encountered in the workplace. It is often accompanied by explosion. Thus, although the Flixborough disaster was due largely to an unconfined vapour cloud explosion, it was accompanied by a large flash fire, responsible in part for some of the effects. Similarly the Piper Alpha incident combined explosion and fire effects and the recent detonation of a commercial explosive in Peterborough was preceded by a small fireball and combustion of packaging. It is, therefore, sometimes difficult to ascertain the contribution of each component event to the total damage so much so that, in statistical analysis, fire and explosion effects are often bracketed together.

The Size and Scope of the Problem

Vilain[1] in a survey of accident statistics estimated that, in 1983, throughout the European Community, the total cost of fire averaged one per cent of member states' gross national product; a total of 26 billion ecu. Table 1 gives a detailed breakdown of these costs. It is interesting to note here that preventive measures represent 30% of this total whilst research consumes only 0.5%. Throughout the Community upwards of 5000 people die each year from the effects of fire.

TABLE 1 : Fire losses in the CEC

The overall cost of fire within the CEC amount to an average value of one percent of the gross national product, i.e. 26.10^9 ECU in 1983.

	%
- direct fire losses	30
- indirect fire losses	5
- human losses - deaths and injuries	5
- cost of administering fire insurance	15
- cost of intervention by fire fighting organisations	15
- cost of prevention in buildings	29.5
- cost of fire research, education and publicity	0.5

Some idea of the industrial problem is indicated by Table 2 taken from United Kingdom Home Office statistics[2]. This gives a compilation of United Kingdom fire data for 1988. Such data cannot present the total picture but shows that for occupied buildings some 30000 fires, 60 fatalities and 2000 casualties occurred in the non-domestic situation, where some work activity was taking place. Similarly a proportion of the external fires are of interest to HSE. Analogous data indicate also that in the same year there were 1160 fires involving explosions, the majority of these involving Liquefied Petroleum Gas (LPG) as Figure 1 shows.

Such figures do not, however, reveal the true impact of the large industrial fire or fire in a public place. Their consequences are societal rather than individual and, though of low frequency, they often produce high casualties, environmental damage or economic consequences. Incidents such as the San Juanito, Mexico City disaster (>500 fatalities), the King's Cross fire (31 fatalities) and the recent Italian Ferry disaster (140 fatalities) are examples.

The technology needed to address industrial fire problems is vast in scope. The situations for whch an understanding is required range in size from small localised spark ignition problems, laboratory test methods or small compartment models through to vast petrochemical plants with inventories of flammable materials running to thousands of tonnes. Similarly the range of materials involved is wide. Fuels may be solid, liquid, or gas and in any

TABLE 2 : Casualties from fires by location United Kingdom 1988

Location	Fatal casualties: Number of deaths	Fatal casualties: Deaths per 1,000 fires			Non-fatal casualties: Number of casualties	Non-fatal casualties: Casualties per 1,000 fires	No of fires
Occupied buildings	805	7.6			12,366	116.2	106376
Dwellings	732	11.4			10,178	158.5	64200
Private garages, sheds, etc.	8	1.2			179	26.0	6895
Agricultural premises	2	1.0			50	24.7	2026
Construction industry premises	-	-			34	50.0	680
Other industrial premises	11	1.6			454	65.8	6901
Retail distribution	6	1.6			226	58.4	3867
Hotels, boarding houses, hostels, etc.	6	3.2	196	104.7	1872		
Restaurants, cafes, public houses, etc.	4	1.3	200	64.0	3126		
Education	-	-			79	39.2	2016
Hospitals	7	2.9			80	33.1	2416
Recreational and other cultural services	-	-	44	31.0	1420		
Other or unspecified	29	2.6			646	58.9	11317
Fires outdoors and in derelict buildings	110	0.5			1,010	4.8	60048
Derelict buildings	5	0.5			95	10.2	280
Outdoor storage	1	0.8			72	56.4	1330
Outdoor machinery and equipment	-	-			98	25.2	3889
Road vehicles	75	1.5			378	7.7	48972
Caravans	4	2.9			79	58.0	1362
Ships and boats	5	12.1			43	103.9	413
Railway rolling stock	-	-			4	16.2	247
Grassland, crops, woods, etc.	1	1.1			29	26.3	1100
Other	19	0.2			212	1.9	2455

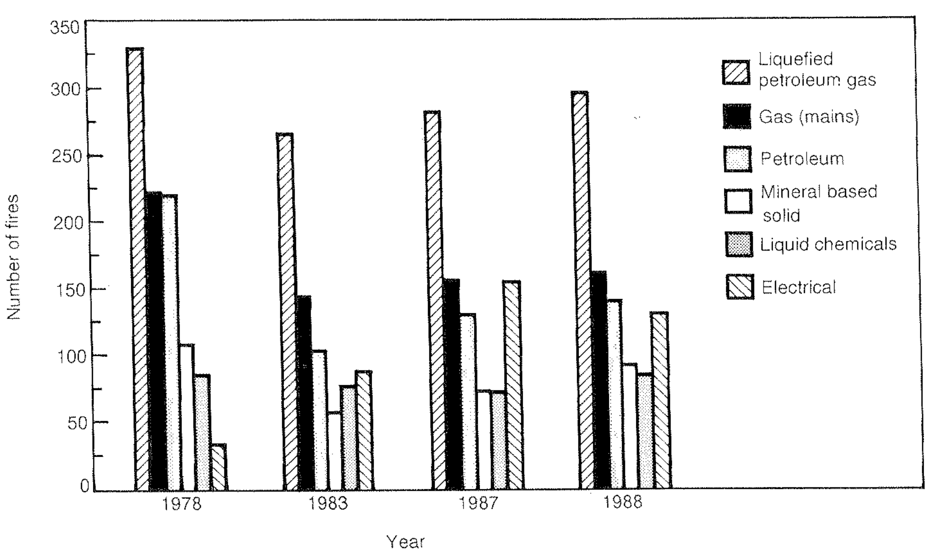

FIGURE 1 The number of fires with different materials which lead to explosions in the United Kingdom.

form; liquids for example may burn as pools or sprays. The combustion products may also appear as solids, particulate solids or vapours or, as at the Sandoz fire at Basle, may be washed away by fire water as a solution or suspension. The variety of environments also encountered is wide. Thus we must consider underground situations such as mines or transport tunnels for example, where fire consequences are made more severe by extreme confinement. Offshore locations are now of greater importance with the confined nature of oil production platforms posing greater fire hazards than onshore petrochemical plant. Large warehousing is a particular problem recently accounting for 40% of larger fires. They can contain a range of materials themselves toxic or which produce toxic combustion products. The complexity of the fire hazard continues to grow as society increasingly adopts high technology in new buildings and transport with the use of new materials and automated processes, these changes adding to the difficulties.

Fire Research: Need and Aims

The aim of fire research must be fundamentally to protect human life and reduce material damage. Central to this requirement is a thorough understanding of the hazard and an ability to quantify any resulting consequences. Furthermore a well-validated predictive capability is necessary so that suitable mitigation and protective measures can be defined, and also regulations and standards can be laid down. A knowledge base sufficient to allow informed forensic and post-incident investigations also permits the maximum benefit to be obtained from fire experience.

Regulations and controls play an important role. Legislated defences must take a wide form and research is an essential tool in identifying the underlying problems, in establishing the scientific and technical background and advising on technical options for legislative, educative and other solutions.

FIRE HAZARDS

The hazard of a fire is often defined as its potential to do harm to life and property. The potential depends on a combination of environmental, materials and initiating source properties. In the domestic situation the conditions are characterised by increased smoke concentrations, evolution of toxic products, oxygen depletion and increasing temperatures.

In the industrial sphere there are additional conditions to consider. Remote exposure is more important. Thus thermal effects on people and property over the fence must be considered and transport of toxic products in the atmosphere or fire water can occur. The former can arise directly from the fire, or be the product of some 'knock-on' effect, whereby on a chemical plant other neighbouring storage vessels become involved and fail due to fire engulfment or radiative heating from a distant source. Structural collapse is also of more relevance in the industrial context.

Overpressure is the obvious hazard of explosions. This may lead to structural collapse but also the generation of missiles, particularly if the source of the explosion is a storage or process vessel.

TOOLS AND TECHNIQUES

Fire is a complex phenomenon involving many disciplines and a wide variety of tools and techniques must be brigaded to permit identification and quantification of the hazard. However, the situation in many respects is a good deal better that it was a number of years ago due to our increased understanding of fire but some outstanding problems remain and new ones continue to arise.

Statistics

Perhaps the simplest tool is that of statistical examination of fire loss data. Both in the United States and the United Kingdom a comprehensive reporting system has been set up and can be used to assess the risk and hazard of a product. Thus these data can be used to identify causative factors, frequencies of occurrence and developing trends, and thus to focus research on areas of concern. Such data can also be used to aid the selection of relevant laboratory test methods. For example, the most important of the individual parameters in any of the encountered fire development scenarios can be identified so that a material can be properly assessed using the most relevant test.

Of course such data sets are not necessarily complete since successful mitigation will not always find inclusion. Currently Hymes and Flynn[3] are exploring this method for HSE to ascertain what information can be obtained on fires in warehouses.

Experiments

Experiments will always have their place in fire research since there is no real substitute for real fire experience. The wide use of experiment can embrace:

- Validation and extension of conclusions reached from fire statistics.
- Assessment of product fire performance.
- Development and validation of test procedures.
- Setting acceptability criteria.
- Generation of data for risk analysis.
- Development and validation of fire models.

However, they are expensive and difficult to perform and, therefore, only a limited number of physical situations can be tested. Experiments on a small scale have also proved difficult, since the number of important physical processes in fire is large, and thus the application of small scale experimental predictions to the real fire situation has often proved problematic, due to the large number of dimensionless variables involved. However, our understanding of fire processes has improved to allow partial modelling to be carried out with confidence in some situations.

Consequently a fire spread problem such as King's Cross was successfully partially modelled at one-third scale using a Froude modelling approach and a knowledge of the fire processes enabled corrections for fuel thickness to be applied.

However, it has been thought necessary to investigate a similar flame spread phenomenon through high rack storage in warehouses by the use of many full scale simulations using various stored materials. At the other end of the scale HSE has recently been involved in a successful simulation at one fortieth scale in a water channel. Linden et at[4] modelled the interaction of a stream of combustion products with a water spray barrier in a tunnel, where the actual combustion was of little importance.

Laboratory Tests

In the recent past there has been a plethora of different national test methods for various fire properties, with the basic aim of predicting large scale behaviour. Since there were no rigorous studies or understanding of the link between bench and full scale behaviour, the tests generally failed in this, often only providing a crude ranking of products whilst excluding products of known generally unacceptable properties. Thomas[5] found there was often little agreement between the various national test methods. With the greater understanding of fire phenomena, this situation is rapidly changing and there has been particular progress in the area of the domestic compartment fire. The applicability of results from small scale ignitability, surface spread of flame and rate of heat release tests, recognised as the governing properties in determining compartment fire development, has been verified by using them by Brabauskas and Wickstrom[6] as input to a model to compare with a large scale fire, in this case the room corner facility. Once validated in this way, it is then possible to use test data and the model for predictive purposes.

There has been little progress in the industrial scene since the physical situations are often far more complex and varied. However, Brabauskas and Wickstrom[6] has outlined a scheme for devising useful, validated test protocols which points a way forward and can be applied generally to any product be it a flammable hydraulic fluid used underground or packaging material for transporting goods. There is a need for harmonisation of protocols and a concerted international approach in this area.

Mathematical Modelling

Models are based on the accumulated understanding of fire and fire properties of materials involved. The field of modelling presents perhaps the greatest potential for progress in the understanding of the fire processes.

Modelling can be carried out on various levels dependent on the needs of the exercise and knowledge of the phenomena involved.

(a) Simple correlations. These are generally used where understanding of a process is poor. They attempt to represent experimental data in a convenient form. They are of limited use since their validity is strictly limited by the particulars of the experiment. Thus zone models for compartment fires comprise combinations of empirical correlations of the type outlined by Mitler and Emmons[7].

(b) Phenomenological Models. These comprise simple equations derived from a intuitive understanding of the important processes involved and expressing the functional dependence of the important paramaters. The model constants are derived from experiment. They have wider validity than (a), but are again limited by the availability of experimental data. A typical example is provided by the relationships for fireball size and duration given by Roberts[8].

(c) Numerical Codes. This approach has great potential for predictive capability, being based, as outlined by Cox[9], on the conservation laws for fluid flow. It is also likely that our understanding of fire will be greatly enhanced by the application of such Computational Fluid Dynamics (CFD) codes as the factors and processes for which they will be able to account will increase as powerful computer hardware becomes more widely available. They are currently capable of describing the evolution of conditions in a compartment with a steady fire but now need to be extended to flame spread problems and prediction of burning. The addition of gas-phase combustion and Monte Carlo radiation models is pointing the way. A combination of this rigorous approach, small-scale test data and empiricism to allow for the non-homogeneous fuels encountered in the practical situation probably offers the best chance of advance.

Models are required for many tasks in the assessment of industrial fires. They may be required to examine a 'one-off' situation in a forensic investigation or as a research tool to improve understanding. In this case the CFD code are the most appropriate. However, they may be also required as part of a risk analysis of an installation in which case relationships for such parameters as received heat flux and explosion overpressure must be applied many times over to build up a picture of the hazard posed by the installation due to the many possible accident scenarios. These must be combined with models expressing the effect of the hazard on people and property. This is often accomplished through the probit approach of Eisenberg[10]. Simple models are most appropriate for this use. One of HSE's major activities is the development of the risk assessment tool (RISKAT), outlined by Hurst et al[11], which combines all the models necessary for computation of risks due to the use of flammable materials on major chemical plant.

SOME TYPICAL INDUSTRIAL FIRE PROBLEMS

In general the fire problems encountered by HSE fall into three main areas:

a) Problems connected with the storage and use of flammable materials. Flammable liquids or gases at a chemical plant are obvious examples.

b) Particular situations which render small and possibly trivial incidents a serious risk. The underground environment is of particular concern here. Thus mining activities are a constant concern and transportation tunnels are of increasing importance. The King's Cross fire indicated the possible severity of these types of incidents.

c) There are also problems where fire can act as a vector and transport hazardous toxic materials in the plume or indeed can lead to transportation in the fire water. The hazardous material may arise from the fabric of the building. There have been several recent warehouse fires in the United Kingdom in which asbestos fibres from roofing materials were carried downwind. Similarly the contents of chemical warehouses may decompose to give toxic products or hazardous materials such as pesticides may be transported unchanged.

Clearly such a classification cannot be completely rigorous. Offshore platforms, for instance, combine the storage and processing of flammable gases as are encountered in onshore chemical plant but complicated by the cramped nature of production platforms, which makes knock-on effects a major consideration.

Hazardous Materials

Ignition

Some of the materials which cause fires or explosions can ignite spontaneously. Contaminated ammonium nitrate-based fertilisers are an example. In this case the hazard arises from evolution of toxic gases, often denser-than-air, or explosion. The assessment of this hazard is then dependent on small scale laboratory tests to derive chemical kinetic reaction data and physical heat transfer parameters as input to models for the progress of the reaction front. A recent incident in Nantes in a bulk fertiliser store resulted in the evolution of large amounts of nitrogen oxides. Many tens of thousands of people were evacuated.

In some circumstances wood as suggested by Kollmann and Topf[12], can also spontaneously ignite, particularly if it has suffered prolonged exposure to low grade heating with the formation of pyrophoric carbon. This was the subject of considerable experimental investigation in the sixties when long-period, particularly difficult experiments monitored the chemical changes in the wood exposed to differing heat fluxes or maintained at a steady temperature. The current interest is in situations such as pottery kilns where structural timbers may be exposed, or indeed older and well-used sauna cabins where Jagger[13] has found that surface temperatures of ~120°C are not uncommon. Some up-to-date work in this area is still required.

Very few of the large number of substances that cause fires or explosions ignite spontaneously; they require a source of ignition. In most industrial and non-industrial environments, however, there are many such sources. They include: open flames; hot surfaces; small moving hot bodies such as frictional sparks; electrical sparks, of which there are a number of different types.

Our understanding of how such sources occur and how effective they are at causing ignitions varies considerably. Flames are probably the most reliable means of causing ignition, the reaction simply extends from the ignited to the non-ignited.

Where hot surfaces are involved the situation is more complicated and whether or not ignition occurs depends on a number of factors. For flammable gases and vapours mixed with air and enclosed by a hot surface, e.g. a vessel, temperature is the important parameter. Each substance has its own ignition temperature which is called the auto-ignition temperature. Such temperatures are a useful guide as to how easy it is to ignite a substance but the values can be misleading. For example, the auto-ignition temperature of methane is about 540°C but to ignite it with a 20 mm square surface of alumina requires a temperature of 1100°C. Reducing the area of alumina to 2.5 mm square increases the ignition temperature to over 1600°C.

Similar trends exist for other gases or vapours and the general rule is, the smaller the area of surface involved the hotter it has to be for ignition.

Friction and impact between two bodies can produce both areas of hot surfaces and sparks. The possibility of igniting a flammable atmosphere depends upon the size and temperature of the hot surfaces or particles. This is governed to a large extent by the materials in contact and the power or energy dissipated. Normally, one or other of the materials has to have a high melting point and sufficient energy must be dissipated to produce the required temperature.

A considerable amount of work has been done in investigating ignition by friction and impact. The general trends have been established but it is often not possible to predict with any degree of certainty whether a particular activity is ignition capable or not. In many circumstances there are simply too many relevant parameters, physical, chemical and mechanical.

By comparison, the description of ignition by electrical sparks is relatively straightforward. Such sparks are very small and very hot. In terms of energy required, they tend to be very efficient at causing ignitions - quoted values of minimum ignition energy are normally determined using electrical sparks. It is reasonable to assume that if a circuit is electrically capable of producing sparks of greater energy than that required to ignite a particular substance then ignition is possible.

As a consequence, electrical equipment for use where there are flammable atmospheres has to be designed to specified standards. Examples of the various concepts include: intrinsically safe, which inevitably is of low power; increased safety, which is designed never to produce sparks; flameproof, in which the spark producing parts are housed in an enclosure designed to prevent external propagation of flame.

Fires and Major Chemical Hazards

There has been much research in the field of chemical plant hazards stimulated by catastrophic incidents such as Flixborough, the Spanish Campsite Disaster at Los Alfraques and Mexico City.

The obvious hazard is that from thermal radiation causing severe skin burns and loss of eyesight in humans and ignition of other combustibles in the area. In addition, minor incidents have the potential for initiation of catastrophic fires and explosions. Thus a small liquid leak might form a pool which, if ignited, could engulf a pressurised storage vessel with possible more serious consequences. Consequently a study of heat transfer from such events is a topic of current interest. The major scenarios most often considered include:

- A jet or torch fire
- A flash fire in a large gas cloud
- A boiling liquid expanding vapour explosion (BLEVE) followed by a rising fireball
- Fires on liquid pools

To quantify the hazard from such events the most important parameters needed are the size of the ignited cloud, jet or pool so that the affected area can be determined, and the burn rate which governs the emitted radiative flux. Thus fireballs, which exhaust their energy in a matter of seconds have high levels of emitted radiation and are of particular concern.

The size of the release is determined mainly from fluid mechanical considerations. It is often reduced to specifying the rate of flow of material from a pipe or the behaviour of an instantaneously-released/storage vessel inventory. The material may be a liquid or a gas or the release may comprise a two phase mixture of vapour and liquid droplets. Single phase releases are relatively well-understood. A combination of small scale experiment and theoretical modelling has led to the formulation of predictive models which give reasonably good agreement with the few larger scale experiments. Vilain[1] has pointed out that the scaling laws are also relatively simple. There is less confidence regarding two phase releases. Ewan and Moodie[14] have shown that these are difficult to investigate experimentally, so that the few models available cannot as yet be adequately validated.

Fundamental research has yielded much information on the way gases and liquids burn. Thus there is a large body of data on the mechanism of pool fires. It is well known that back radiation from the flame controls evaporation, whilst air entrainment sustains the combustion. For cryogens, however, heat transfer from the substrate is also important. Thus measured regression rates for hydrocarbons fall in the range 5 - 10 mm min^{-1} and extensive studies of the flame size and shape have been undertaken yielding simple correlative models. In addition, there are measurements, from radiometry of surface emissive power suggesting typical values averaged over the flame of 60kW m^{-2} for propane and 150kW m^{-2} for LNG. On this basis the simple models and more recent computational fluid dynamics-based simulations of the type detailed by Bouhafid et al[15] are in good agreement but there still remain some problems.

Particularly with large or elongated pools the base can break up into separate burning patches or combustion is not uniform across the base since air is consumed at the periphery forming a fuel rich core. Smoke and soot formation remains a problem and of current models only the most complex take this into account in a crude way. This is an important parameter in determining the emissivity and hence radiation from the flame. Also there is a need for further experimental work on configurations other than circular or square. For example there is evidence that elongated pools burn with emission of far higher levels of radiation that those conventionally accepted.

Pool fires can initiate further more serious releases. Moodie[16] has shown that pool fire engulfment of storage vessels has been the subject of extensive experimental and modelling attention in an attempt to predict the heat transfer and response.

There is little data and fewer models available on the subject of flash fires. In general these are unconfined quasi-deflagrative clouds with flame speeds of a few metres per second. The few tests available such as those carried out by Shell at Maplin Sands and the United States Department of Energy at China Lake, respectively described by Hirst and Eyre[17] and Koopman[18], have indicated erratic behaviour. The flame has been seen to propagate upwind, jump across the cloud, stop or bifuricate. Much of this can be ascribed to non-uniformity and intermittency in the cloud. Due to this erratic behaviour radiation measurements are scanty but indications are that the levels are much higher than for pool flames. Measured fluxes for LNG exceed 200kW m^{-2} possibly due to the more efficient combustion in the premixed cloud or the greater emissivity due to increased optical depth. Clearly, however, this is an area for further experiment and theoretical study.

The behaviour of torches and jet fires is of considerable current interest due to their potential to initiate further more serious events. The characteristics depend strongly on the source term characteristics be it a plume, momentum jet or two phase jet. In general it would appear that, the more turbulent the release, the higher the combustion rate and flame temperature. Models of such flames have assumed that the LFL contour of the release governs the steady state extent of the flame, though Vilain[1] has contradictory evidence on the validity of this assumption. Work on small scale laboratory burners can be applied to single phase jet flames but there is little data to validate their use. More recently a series of experiemnts carried out by Shell and British Gas have greatly enhanced our knowledge of jet flames. They have examined some large jet fires of both propane and LNG and also examined the heat transfer from the flame to a tank placed at a varying distance from the nozzle. The results have been used to develop a model useful for hazard analysis purposes, but indicate that the surface emissive power from the flame exceeds 300kW m^{-2} and heat transfer levels to the tank are also high with both radiative and convective components separately dominant. The importance of this topic for chemical plant safety will ensure that further work is undertaken.

Fireballs are rapidly and intensely burning clouds which give high radiation pulse for some seconds. One of the largest fireballs occurred during the explosion of the Challenger Space Shuttle. The commonest way to generate a fireball is by BLEVE of a tank of liquefied fuel above atmospheric pressure. Any blast which arises originates primarily in the expansion of the vapour phase alone. Many such experimental release have been carried out but due to economic and practical considerations they have tended to be small releases of a few hundred kilogrammes at most. Even these data are contradictory. Surface emissive powers tend to the 2 - 300kW m^{-2} range though some recent data obtained on 2Te propane releases reported by Cowley and Pritchard[19] indicated values as high as 400kW m^{-2}. Emissivities in general fall into the range 0.8-1 and it appears that ~ 30 - 40% of the available energy appears as radiation (for common hydrocarbons). There is particular need for further experimental work on fireballs, particularly at higher inventories, but also on substances other than the common hydrocarbons. Materials such as chlorinated hydrocarbons, explosives/propellants are relevant. Models which have been proposed are simple phenomenonological relationships for duration and size as a function of mass released, derived from simple dimensional arguments. Model constants are obtained from the sparse small scale data. Clearly there is scope for a more rigorous approach. No attempt has been made to model the turbulent combustion process so that it is necessary to use experimental values of surface emissive power and emissivity in computing consequences. Figure 2 shows a fireball produced by 250 Kg of LPG.

The computation of the effects of such combustion events in hazard analysis studies uses the simple view factor approach. This can be applied at varying levels of complexity, being computed algebraically or programmed, as by Hankinson[20] with the emitting surface being partitioned to allow for path length, varying emissivity atmospheric humidity and temperature. In general the simple algebraic approach breaks down close to the source. Further sophistication is becoming available in the form of the Monte Carlo techniques, and described by Wilkes et al[21], being incorporated alongside computational fluid dynamics models.

HAZARDOUS ENVIRONMENTS

Underground

Fire underground still remains one of HSE's concerns. Historically the mining context dominated but the King's Cross incident showed the increasing importance of the transport industry and the arrival of the Channel Tunnel has emphasised this. The hazard here comes from evolution of smoke and toxic products rather than thermal effects.

The effort in the coal industry to minimise the hazard involves the testing of materials and equipment used underground to strict fire resistance standards. One particularly common hazard involves the use of flammable hydraulic fluids in cutting machinery and vehicles. In such circumstances it is the usual procedure to develop a small scale or laboratory test method. This test should be closely controlled and reflect the end use and conditions of material. The problem then becomes one of setting an acceptability criterion. For this it may be possible to apply scaling rules so that hazards may be predicted in use. However, with so many variables in the fire context and the wide range of environmental conditions encountered in mines, it is more sensible to calibrate the test

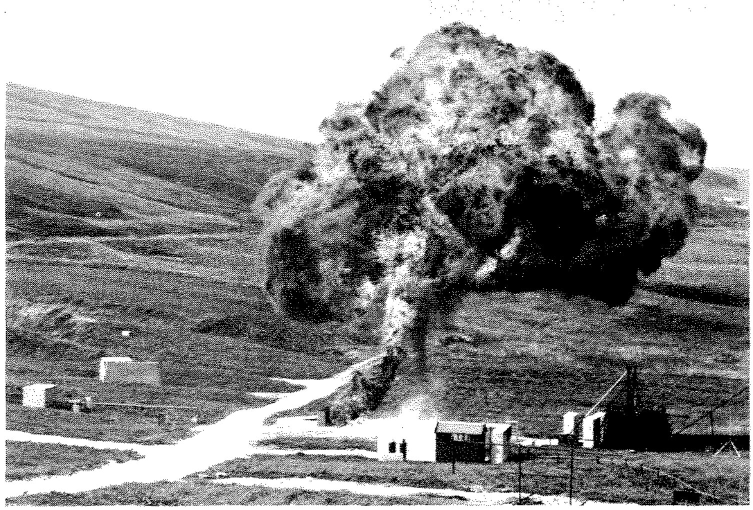

FIGURE 2 A typical fireball obtained by engulfing a liquefied petroleum gas container in fire.

method using materials of definite unacceptability and those with desirable fire resistant properties.

Such a test has been developed at HSE's Explosion and Flame Laboratory by Yule and Moodie[22] to assess the flammability of hydraulic fluids. It reflects the characteristics of probable in-site releases of such materials in that the fluid is sprayed closed chamber. Ignition is by a carefully controlled propane pilot flame. The hazard level is assessed on the basis of heat release rate, flame length and smoke generation. Choosing a suitable test duration implicitly includes a consideration of flame stabilisation effects. The test currently is capable of ranking fluids in order of hazard but the next step will be to relate the test outputs to full scale fire conditions to assist further in the choice of materials.

CFD codes could be used, in the mining context, to predict the consequences of a fire in a piece of machinery or on a conveyor system, allowing a computation of downstream temperatures and concentrations of smoke or toxic gases at least in the near-field or in a simple tunnel system. These codes are becoming more accessible with advances in computer hardware. Currently they comprise finite volume turbulent fluid flow codes with body adaptable grids. Their treatment of combustion remains in the gas phase only and is rather crude and there are few attempts to incorporate realistic chemistry or soot/smoke formation. There is also a great need for validation studies comprised of global assessments of code performance of output predictions against measured data, and also closely controlled experiments on different scales to test component models, applicability of boundary conditions and simulations of small scale test apparatus for example.

The King's Cross investigation, described by Moodie and Jagger[23], was the first instance in which HSE employed such a code. In this incident a fluid flow code without combustion or radiation components was used to predict the general form of the flows from a fire in an inclined tunnel containing three escalators. The size and progress of the fire was prescribed by reference to damage patterns and a knowledge of material fuel properties. This application both demonstrated the potential of this approach and the further work necessary before it can be regarded as an engineering tool. The model was able to give an indication of the flows in the tunnel and gave a clue as to the progress of the fire. However, experiment was necessary to confirm these indications and a one third scale model was built. In this case model and experiment were in qualitative agreement, though any quantitative correspondence would have been fortuitous. At that stage the model was and indeed still is not capable of predicting the spread of flame and hence fire growth in even a single compartment. Work in this area is continuing, particularly the incorporation of cone calorimeter and similar test data in computational models. The King's Cross investigation, incidentally, also demonstrated the need for well validated models since the difficulty of performing fire simulations on a small scale was clearly shown. Analysis showed that the smallest scale at which any test would give meaningful results was 1/4 to 1/3 given other practical constraints. Thus the tests were carried out using Froude scaling criteria at 1/3 full size, with considerable difficulty and expense. Figure 3 shows model predictions of surface temperatures and particle tracks and Figure 4 shows a view of the experimental simulation.

There are, however, some problems underground for which CFD is not applicable but we must still employ modelling techniques. If we wished to

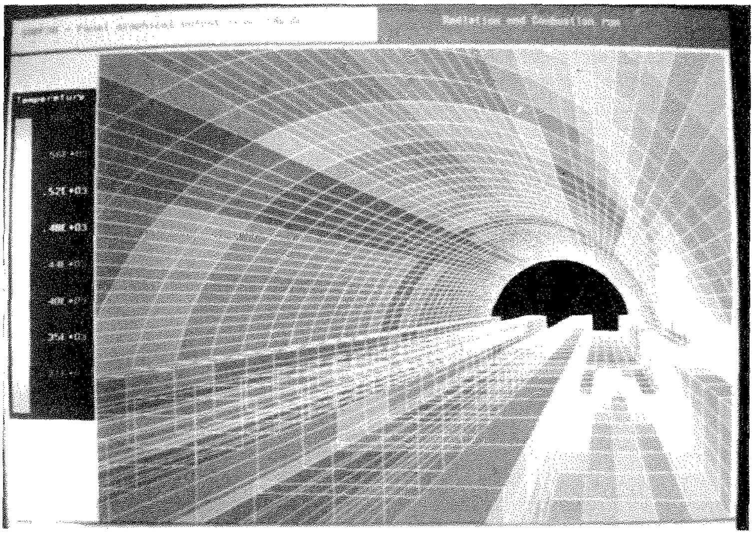

FIGURE 3 A computational fluid dynamic model simulation of the King's Cross Fire.

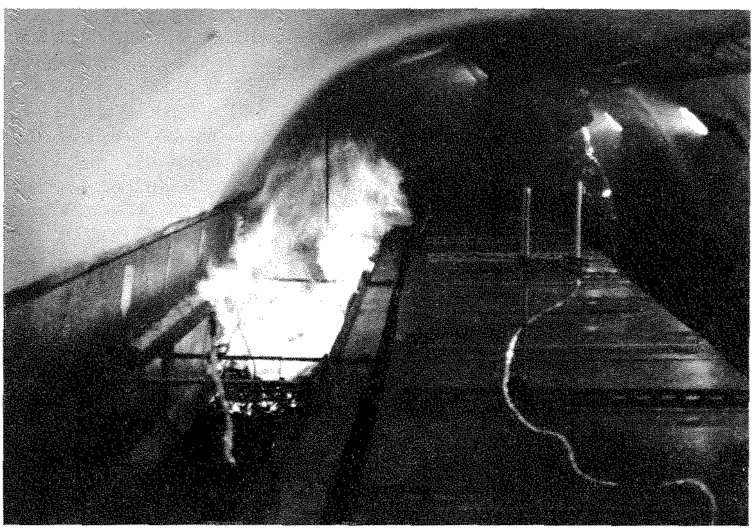

FIGURE 4 A one-third scale simulation of the King's Cross Fire.

model the spread of smoke in a complex network of interconnecting multilevel passageways under forced ventilation, such as that which forms a coal mine, or indeed a large underground station, it would, except in the near-field, be computationally too expensive to apply CFD and also take too long to set up the grid. In this situation a simpler physical representation must be applied. A suitable method is the ventilation network model Edwards and Greuer[24] used in mining. In such a model the network is divided into a large number of closed meshes and iterative calculations are performed until pressure losses and flows around each mesh are consistent. Any fire is regarded as a perturbation to this flow and is allowed to modify the ventilation flows. Such models have some scope for wider application outside the mining field.

Bulk Storage of Flammable Solids

Flammable solids such as artificial fibres and fabrics, plastic foams and paper can pose a serious industrial hazard if stored in large quantities in unsuitable circumstances. For example in 1987 a fire at a Plymouth printing works claimed three lives. A sudden, rapid spread of flame across stocks of reeled paper led to workers being trapped in a fire of great intensity that quickly destroyed the whole building.

In this and other industrial fires involving flammable solids stored in bulk, the hazard stems from the combination of two factors:

1) The potential for very rapid vertical spread of flame and high rates of heat release for some stacked materials.

2) The early transition to a developed compartment fire where fire loads are high.

The first effect has generally been investigated in full-scale tests on stacked commodities. Some typical examples of results from this kind of work are shown in Table 3. The time taken for fire to engulf vertical stacks of goods may only be a few tens of seconds and the resulting rates of heat release are high.

TABLE 3: High Stack Material Fires

Commodity	Max heat release (MW/m2)	Time to 1MW (s)
Wood pallets (5 m high)	17	75 - 125
P.U. insulation foam (5 m)	2	8
Polystyrene foam (5 m)	3.3	6
Cardboard cartons (5 m)	1.7	60
Assorted garments (4 m rack)	-	21 - 42
Rolled P.E. film	6.2	40
Paper (6 m vertical rolls)	-	16 - 28

The development of compartment fires involving stacked goods is difficult and expensive to study experimentally. In domestic fires the burning of a single item e.g. a sofa, is often sufficient to cause flashover in a living room. This is fortunately less common for stacked goods in large industrial premises: usually lateral fire spread away from the first

ignited fuel stack is necessary to cause flashover in the compartment as a whole. This lateral fire spread is usually much slower than the initial spread in the vertical.

There are a number of factors which can lead to rapidly developing fires in large compartments. Situations with very high fuel loads per unit area, lack of adequate lateral separation between stacks, ie. no fire breaks, or lack of adequate clearance between the top of high stacks and the roof are of principal concern. The latter can lead to early horizontal flame extension under the ceiling and the possibility of fuel-rich flames. Clearly also the presence or otherwise of frangible skylights to vent the fire or automatic detection and suppression system will have a controlling influence.

In assessing the likely hazard associated with the bulk storage of a given material in the UK industry, the HSE has developed a medium scale room/corridor test. This test uses of order 5 kg of test material cut, packed or baled in a way that corresponds as closely as possible to storage conditions. It has been recognised that most industrial stores contain potential sources of ignition such as discarded packaging, so the test is started with a British Standard No 7 Crib - with a heat output approximately equal to that from four burning sheets of crumpled newsheet. The criteria used for the assessment are the rate of fire development and the volume of smoke produced in the test. The development of new materials makes such a continuing programme of research necessary. Two of the most important recent examples are combustion-modified polyurethane foams and thermally-bonded polyester waddings.

Assessing the likely influence of building layout and construction on fire development and smoke movement can only be systematically attempted using CFD.

Fire as a Vector

Fire also has the capability to transport hazardous material away from the source of the fire and so expose a wider population and the environment to contamination from a hazardous material. Figure 5 shows a fire in a phosphorus store producing phosphorus pentoxide fume, but in this instance no serious consequences occurred.

A number of serious fires in Europe and the US involving the release of toxic materials has drawn attention to the risk to workers, firemen and the wider population from such accidents. The materials involved include toxic or potentially toxic agrochemicals such as pesticides and ammonium nitrate; general chemical toxics such as isocyanates; biological materials and asbestos. Fire fighting must also be taken into account as the Sandoz warehouse fire at Basle showed.

Sensible regulation of such hazards must be based on an assessment of the overall risk to the public, taking account of all possible occurrences. Consideration only of the consequences of the worst conceivable accident may suggest preventative measures that actually increase the overall risk. For example, the provision of fire resistant, segregated stores for toxics, away from large quantities of palleting, packaging, work areas etc. is clearly an advantage - the risk to the public is reduced when the probability of all possible incidents is weighed with their consequences.

However, if one bases an assessment only on the consequences of the escape of a large fraction of the stored toxic from a segregated store, the overall risk to the public may be increased.

Following the alert due to the Sandoz fire, the European Commission expressed concern over this issue as evidenced by a recent amendment to the Seveso Directive controlling the use and storage of major hazard chemicals. The European Commission have also stimulated research on the topic.

Clearly control of public safety near premises storing toxics requires a particularly broad range of scientific inputs; from combustion chemistry of toxics through fire dynamics and dispersion of buoyant releases to toxicology and behavioral studies. With support from the European Commission, a number of research projects in this area have been initiated. In one of these, led by HSE, a consortium of nine European research organisations will undertake a wide range of experimental and theoretical studies to address the fundamental scientific issues: these include micro-scale combustion experiments, small and medium scale tests of material flammability, zone and field modelling of fire development in buildings, wind tunnel modelling of plume lift-off and near field dispersion, and field-scale experiments on stacked commodities. Of particular interest is the behaviour of the building fabric and the performance of mitigating measures such as smoke vents and sprinkler systems. In contravention of usual procedures it may be beneficial, in incidents of this type, if the fire is allowed to grow and mitigating devices such as sprinklers disabled and fire fighting suspended so that the fire reaches sufficient size and

FIGURE 5 A typical incident fire in a chemical warehouse here illustrated by a phosphorus store.

breaks through the building roof. In this way plume lift-off is ensured, with wider distribution of any escaping toxic material. Such studies and issues will feed into the end products of this project - a risk assessment tool for warehouse fires, to allow the computation of risks posed to the public and environment from any store containing hazardous chemicals and an expert system to allow sensible decisions to be made on the tactics and methods available to combat the fire in such a manner as to minimise exposure of fire fighters, public and environment to the toxic material. Atkinson[25] has described an initial attempt at such a model in an attempt to identify the major controlling parameters. As the project proceeds and information becomes available this model will be improved.

CONCLUSIONS

Because of the range of industrial fire problems, fundamental research must play an important role so that the underlying science is well understood. Figure 6 gives diagrammatic respresentation to a scheme of maintaining and establishing standards in industry. Research provides the essential information to identify the hazards and the tools to allow computation of consequences and risks of these hazards. It also provides the necessary background for the enforcement and updating of regulations such as the Building Regulations, Fire Precautions Act, Control of Major Industrial Accident Hazards and Control of Substances Hazardous to Health Regulations impinging on HSE work. HSE also relies on its Inspectors in the field who regularly inspect premises to identify new situations or materials which require fresh consideration. Thus the process is a cyclical one so that constant vigilance is maintained.

Clearly such a strategy as described is capable of maintaining standards and reducing casualties. Further progress toward this end will be enhanced by the increased consciousness of fire science among architects and designers so that fire safety engineering becomes an integral part of the design process of all products be it a building or vehicle or whatever.

Research into fire involves both experiment and theoretical analysis. The nature of the industrial situation often involves large events, so that the experimental investigation is both difficult and expensive. Scaling is also difficult to the extent that Williams[26] has identified twenty-nine dimensionless groups appropriate for modelling. Thus the application of results obtained at small scale to full scale events is often difficult. However, as the King's Cross work has demonstrated, progress can be made by experiment. In addition small-scale testing is often the only available way of assessing material hazards, though where possible they should be confined to determinations of fundamental material properties. Despite the fact that experiment will never be totally replaced the greatest potential for progress is currently in the field of CFD based modelling techniques. Such models can in no way yet be regarded as engineering tools since they are in need of much further development and validation.

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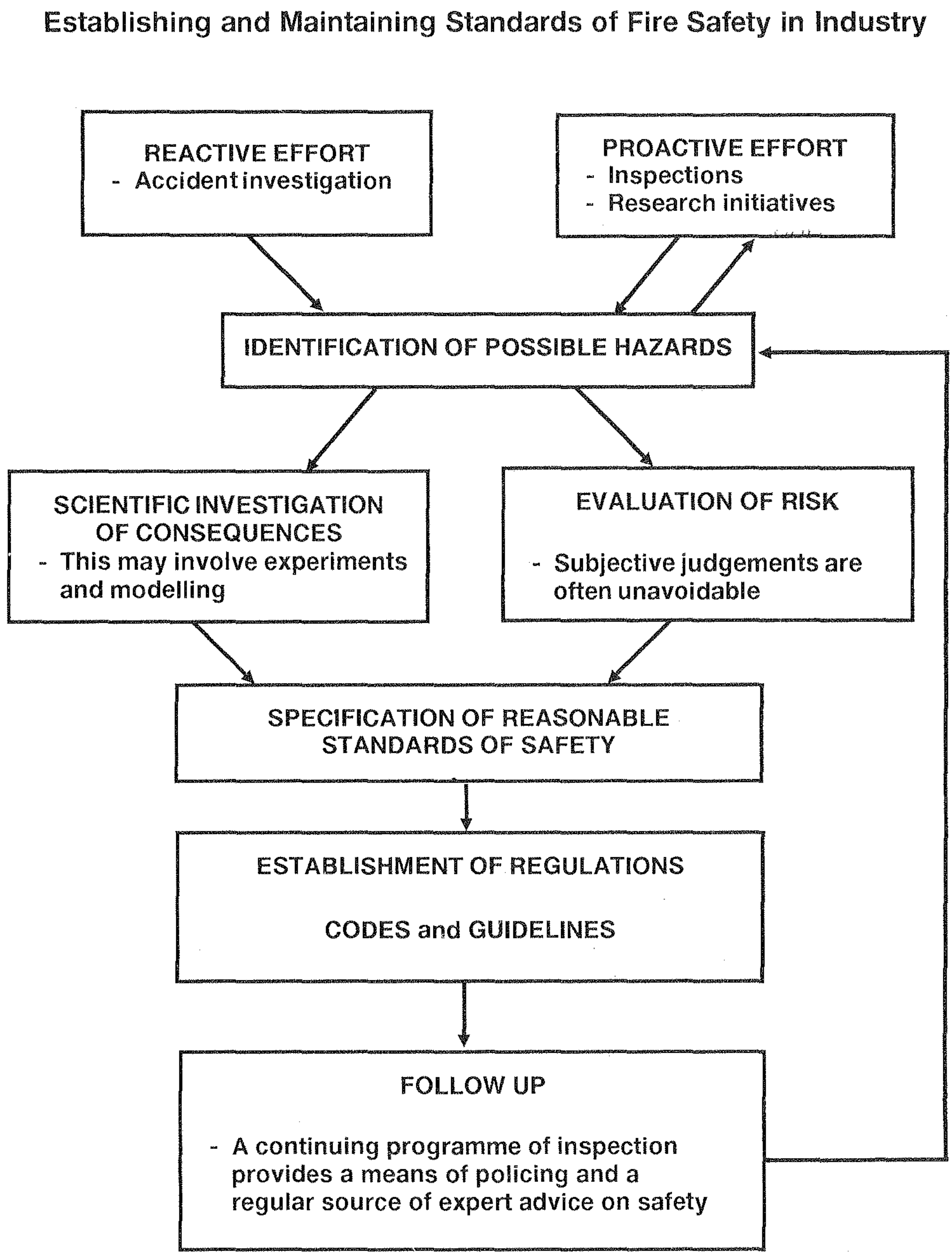

FIGURE 6 A schematic view of how fire standards can be derived and maintained in industry.

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