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(available in a separate volume from the Polymer Research Centre)

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## Executive Summary

Fire continues to have a major impact on society causing deaths, injuries and property damage and in addition much personal suffering.

Governments world-wide are keen to maintain and, where possible, improve the fire safety of consumer products to help reduce fires. The role of flame retardants to help this is well recognised. However, some countries in Europe have expressed concerns about the use of flame retardants and claim that there are potential significant risks to human health and the environment with their use.

The Polymer Research Centre at the University of Surrey carried out independent research for DTI on the risks and benefits of flame retardant use in consumer products. The aim of the work was to inform debate on the relevant risks and benefits through the publication of a report.

### Conclusions

Despite falls in the numbers of fire deaths over the years, losses from fire are still a significant world-wide problem, particularly in dwellings and the home environment.

- In 1995 it is estimated there were about 750,000 house fires in England and Wales leading to 549 reported deaths
- up to 20% of these fires needed the attendance of the fire brigade
- the risk of death in fire is around 8 per 1000 reported home fires which equates to a risk of death in a fire of 14 per million of the population
- fire damage to property costs the UK about £350m per year and the gross cost of fire in Europe is estimated to be about 1% of Europe's GDP
- the risks of death or injury from fires involving consumer products in the UK is highest for upholstery and covers, accounting for around 40 deaths and 413 non-fatal injuries per 1000 product fires.

Smoke alarms can help reduce the damage and the severity of injury by fires. Indeed, the risk of death in a fire reduces from around 9 to about 4 per 1000 fires when comparing fires not detected by alarms with those detected by alarms. However, the benefits of smoke alarms have not yet been fully realised in the UK, in part due to incomplete penetration of alarms into households, but significantly due to the low numbers of fully functioning and well positioned alarms in operation. For example in 1995:

- only 11% of dwelling fires were detected by smoke alarms
- though 79% of households owned an alarm and 73% had them installed, 66% of fitted alarms did not respond to fires for various reasons.

Further, in 1997 smoke alarms were absent in the fire area of 70% of home fires involving around 400 deaths and a further 9,700 non-fatal injuries. In recognition of these difficulties the UK Home Office is launching a healthy smoke alarm campaign in the early part of 1999 to improve the use and maintenance of smoke alarms.

In the UK 40% of deaths in fires are caused by people being overcome by smoke and toxic gases with up to a further 20% by burns and gas/smoke inhalation. The main cause of death in such cases is inhalation of carbon monoxide. In contrast the longer term effects of acute exposure to toxic gases such as carbon monoxide, carbon dioxide and hydrogen cyanide are not fully understood despite considerable research in this area to date. Any health problems that emerge from this will add to the overall risks and “cost” of fire.

The major hazards of most fires arise from the existence of the fire and not the materials burned and there is no evidence that flame retardants contribute to the direct human health risks arising from toxic gas effects.

This report examined the currently available literature on the toxicology of a number of the more common flame retardants in use in consumer products in order to put the risks and benefits into context:

- Information available suggests that the benefits of many flame retardants in reducing the risk from fire outweigh the risks to human health
- Many flame retardants do not pose a significant threat to human health and the environment.

However, it is not possible to readily generalise the above to the large number of flame retardants available, although many are not widely used and a substantial number are not used at all in consumer products. A detailed risk assessment is currently being undertaken under the EU Existing Substances Regulations on the evaluation and control of the risks of existing substances. In particular, the assessment of the commercialised polybrominated diphenyl ethers (PBDPEs) should be completed early in 1999.

The risks associated with new and existing chemicals, including flame retardants, need to be considered in the context of other risks that people face and the benefits conferred by taking those risks.

Direct interventions to reduce fire risk include extinguishing or reducing the size of the fire, delaying or suppressing ignition and also slowing down the rate of development of the fire. Fire performance testing and the analysis of fire statistics show that there are significant benefits to be gained from using flame retardants particularly in relation to higher fire risk consumer products. Such analysis suggest that the risk of death or injury from a fire involving consumer products, such as upholstered furniture, can be reduced by 30% to 90% or more.

## Way Forward

Continued reduction of fire losses can be achieved using a number of complementary tools:

- introduction of mandatory or voluntary fire safety controls
- active promotion of fire safety devices such as smoke alarms and sprinklers
- general education of consumers in fire prevention and escape
- designing-out fire risk by reducing the inherent fire risk of consumer products by product modification (e.g. using flame retardants or low flammability materials) particularly for higher fire risk items such as furniture and televisions
- research to understand and minimise fire risks (e.g. long term health hazards of exposure to toxic fire gases)

The future use of flame retardants in consumer products is a very important part of any overall strategy to reduce the impact of fires. Risk assessments showing the balance of risk advantage which take account of product life-cycle and the environment need to be carried out on the more common flame retardants used in consumer products and when new flame retardant compounds are being considered. The more research that is done to assess these risks, the greater the opportunity will be to exploit the benefit of these compounds to improve consumer safety, whilst safeguarding public health and the environment.

It is equally important that research is done to demonstrate that significant reductions of fire losses can be achieved by using flame retardants, including the saving of lives. Probably the best example to date is the huge savings which have been delivered by the use of flame retardants in upholstered furniture in the UK to meet the Furniture and Furnishings (Fire) (Safety) regulations 1988.

# 1 Background to the Report

Internationally, most countries are interested in establishing and sustaining high levels of fire safety in consumer products and the role of flame retardants in providing part of the solution is well recognised. However some countries in Europe have expressed concern about the use of flame retardants and claim that they present potential unacceptable risks to human health and the environment.

In response to this concern, and in an effort to assist the development of UK policy-making in the field of consumer product fire safety, the Department of Trade and Industry Consumer Safety Unit in the UK commissioned the Polymer Research Centre at the University of Surrey to produce an independent report on the risks and benefits of flame retardant use in consumer products. Its purpose is to assist UK policy development and to act as a reference document to inform discussions within the European Union against a background of legislative developments concerned with consumer product fire safety and chemical safety.

This report is also written against the background of the report by Binetti (1992). This was commissioned by DGIII of the European Commission to provide comments on the toxicity and ecotoxicity of flame retardants used in upholstered furniture and related products. Unfortunately the commercially confidential annexes that supported the report have never been published. This report concluded (among other things) that from among commercially available flame retardants it would be possible to find some for use in upholstered furniture which in normal use would not be dangerous to human health and could be safely disposed of when products reached end of life.

During the writing of this report the Consumer Product Safety Commission (CPSC) in the United States also undertook a more limited review of the related issues in connection with the possible introduction of regulations governing the fire performance of upholstered furniture (CPSC, 1997, 1998a, 1998b). It is hoped that our report will further inform these developments in the US.

This report and its associated body of annexes utilised existing sources of information on the markets and use of these compounds in consumer products and the wide ranging literature on fire science, chemical toxicology and risk assessment, to present a comprehensive view of the risk and benefits associated with the use of flame retardants. Where possible, the report and its annexes provides full references to the scientific and technical sources used in its writing. The content of these annexes are given in Appendix 1.

The Polymer Research Centre appointed a multi-disciplinary research team at Surrey with experience of polymer flame retardancy, at an academic and industrial level, and toxicologists recognised in human exposure toxicology. This team also drew on other Surrey expertise in classic toxicology, environmental risk assessment and risk perception and made use of its contacts with international fire research, health and toxicology organisations.

This work has benefited from the cooperation of the flame retardant industry, its Associations in Europe (EFRA, EBFRIP) and the US (FRCA, BFRIP) and many other organisations and individuals who are acknowledged in annexe10.

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1 *Editorial Note: Throughout this report we have used the term “flame retardant” because it is the most generally used expression. However, we should like to point out that a more accurate description would be “fire retardant” because these compounds have the important function of reducing the incidence and propensity of all forms of fires including non-flaming smouldering fires.*

## 2 Report Objectives and Structure

The original objectives and scope of the report included the following:

1. *Identify and collate information on the types of flame retardants used in consumer products and assess the level of use (tonnages) of each principal retardant.*

For the purposes of this report "consumer products" are defined as any products that could be purchased by consumers and would exclude the structure and components used in the construction of dwellings (the so called built environment); the focus then is on the contents of dwellings.

2. *Review and evaluate published and unpublished information on the use of flame retardants in consumer products including reports already commissioned by the DTI, other UK government and European Commission bodies and trade/consumer organisations.*
3. *Summarise what is currently known about the mechanisms of action of the principal flame retardants in both the gas phase and in the solid phase of the host material.*
4. *Review and assess available data on the toxicity of the principal flame retardants.*

These reviews cover, as far as the available data allow, toxicology that is relevant to likely human exposure. This exposure may be by direct contact with consumer products containing flame retardants or by inhalation of the fire products from activated flame retardants during the ignition and post-ignition phases of fire. More complete life-cycle and ecotoxicology issues will be addressed in a separate report. The emphasis is therefore on identifying and evaluating what is currently known and to provide expert comment on what may be scientifically inferred from other toxicological experience.

5. *Review the fire safety value and effectiveness of flame retardants using statistical information to assess fire risks and how the incidence of fires is affected by the presence or absence of flame retardants.*

In writing this report it became apparent that people’s perception of the risks associated with flame retardants needed to be placed in the context of other risk experience and related to the different fields of chemical and fire hazard and risk assessment. Our actual approach to risk assessment of these compounds in their unactivated state should, in principle at least, be no different from that of other chemical compounds. The key difference is that when flame retardants are activated by fire they act to potentially reduce or counter fire hazards and risks but at the same time they may present additional hazards and risks from their presence in consumer products and from their involvement in fire. It is therefore important that all of these risks be considered relative to each other. Enumerating and reconciling these relative risks and comparing them with the potential benefits is at the heart of this report.

We also sought to produce a report that would be accessible to the non-expert and expert alike. So the main report has been structured to take the non-expert through the principal topics and issues that are relevant to understanding flame retardants and the often complex balance of risk arguments that impact these compounds. Likewise, it is hoped that the annexes will assist experts in different fields (and the interested non-expert seeking more information) to appreciate the fields of others and assist them to obtain a rounded out view of the subject. Of necessity not all topics have been covered in the detail we would have wished but we feel an adequate balance of our current understanding of the issues and challenges has been achieved.

Appreciation of the impact of fire on society, the nature of the risks from fires in dwellings and the need for passive fire countermeasures such as flame retardants is the subject of Section 3. Comparison of UK and US experience is also introduced here and is maintained throughout the report to broaden appreciation that the problems are global and can be tackled using international experience.

Understanding fire hazards and the potential impact of fire atmospheres on survival in fire is dealt with in Section 4. Current approaches to assessing the toxic hazard of fire atmospheres is considered in Section 5, providing a basis for comparison with the approaches taken to assess the toxic hazards of chemicals. This comparison also provides a means to judge the potential impact of flame retardants under normal conditions and when activated by fire. This brings together the areas of classical human exposure toxicology and fire-atmosphere inhalation toxicology.

Section 6 attempts to present our current understanding of the hazards of fire atmospheres and it identifies where areas of concern exist in relation to long term health impacts that are poorly understood. This is important because the available evidence indicates that the long term health effects of brief exposure to fire atmospheres may be more serious than exposure to unactivated flame retardants in consumer products. Thus any application of the precautionary principle should be even handed and applied to all of the short and longer term risk issues, not just those related to consumer exposure during the normal use of consumer products.

Section 7 deals with the toxicology of six flame retardants commonly used in consumer products. Within the scope of this report an exhaustive toxicological analysis of all of the flame retardant compounds and their combustion products was not possible. So, a generic group of the more important and widely used flame retardants was evaluated in more detail. These serve as examples to illustrate the potential strengths and weaknesses associated with more general assessments of toxicological impacts arising from the use of flame retardants and where uncertainties might exist in carrying out such assessments.

From an appreciation of the potential hazards from fires and flame retardants we move to an appreciation of how risk is perceived, compared and potentially controlled in Section 8. This acts as a scene setter for Sections 11 through to 13 and provides a basis for the comparison of risks arising from very different sources, such as risk of death or injury or long term health effects of fire atmospheres or exposure to unactivated flame retardants.

The action of flame retardants in reducing fire hazard and risk is considered in Section 9 which provides a background to understand how the flame retardants used in consumer products, as detailed in Section 10, function and what they can achieve in combating the dynamic development of fires. This provides a basis for understanding the use of flame retardants to mitigate the risks associated with unrestrained fire processes

Section 11 provides background on the bigger picture of progressive efforts to ensure the safety of chemicals in Europe and how flame retardants are a part of this under the new and existing substances regulations. This also provides an introduction to Section 12 which identifies the need for life-cycle risk assessment and shows how lives are being (and could further be) saved and injuries reduced by the use of flame retardants in higher fire risk consumer products.

With the background in place, Section 13 undertakes a balance of risk assessment for flame retardants. This compares the potential risk reduction benefits related to the use of flame retardants in consumer products with the possible human exposure risks, using three different end-point risk measures: death, short term injury and long term effects. These assessments are based on a conservative evaluation of the benefits of reduced fire risks and a pessimistic choice of the human exposure risks.

The main report is supplemented by one market and eight technical annexes which cover a number of subjects of core relevance to the report and the reader is referred to these for more detailed discussion beyond that of the main report. These are published separately from the main report and may be obtained from the Polymer Research Centre at the University of Surrey.

## 3 Trends in Fire Statistics in Residential Dwellings

Fire continues to have a major impact on society with loss of life, personal injury and loss of property involving significant direct and indirect costs and much personal suffering, particularly to those who experience fire in their homes.

### 3.1 International Comparisons of Fire Losses and Costs

It is a difficult task to undertake global and even European comparisons because the international reporting of fire statistical information is not standardised and no common international basis exists for the gathering and interpreting of such information.

With this major limitation in mind, Table 1 (and Annexe 1 in more detail) presents a comparison of the estimated direct national losses and costs of fire for a number of leading industrialised nations. This data is based on work by the World Fire Statistics Centre (Lloyds List 1995, Ramachandran 1995) and it has been updated using 1996 gross domestic product (GDP) data.

Table 1 Direct Fire Monetary Losses and Costs For 9 Leading Industrial Nations

| Country | 1996 GDP US$bn | Direct Fire Losses, %GDP | Direct Fire Costs, US$bn |
|---|---|---|---|
| USA | 7,580 | 0.17 | 12.9 |
| Japan | 4,564 | 0.14 | 6.4 |
| Germany | 2,377 | 0.19 | 4.5 |
| France | 1,550 | 0.29 | 4.5 |
| UK | 1,145 | 0.22 | 2.5 |
| Belgium | 255 | 0.40 | 1.0 |
| Sweden | 251 | 0.28 | 0.7 |
| Denmark | 175 | 0.28 | 0.5 |
| Norway | 147 | 0.31 | 0.5 |

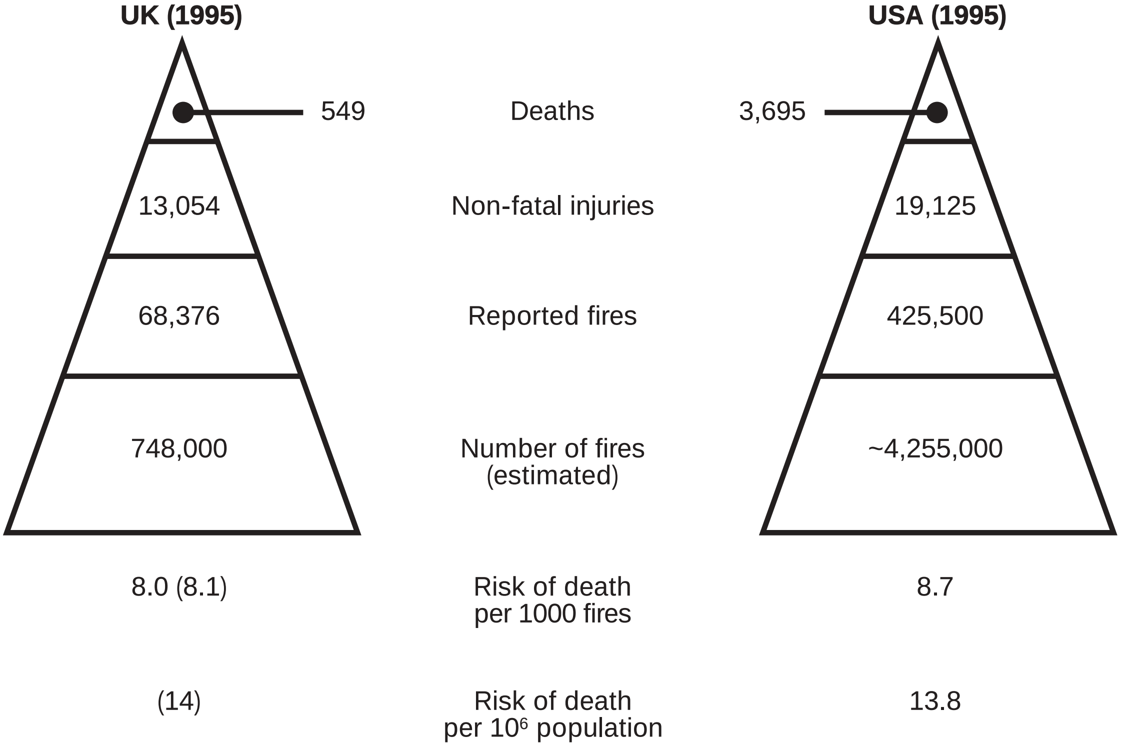
The direct costs of fire are large for every country and in the case of Belgium are disproportionately large in relation to their GDP and the losses experienced by similar sized economies. It has also been estimated that the gross costs of fire in the European Union are close to 1% GDP. If this is also true for these 9 countries, the gross losses for this group would amount to US$180bn; this is equivalent to the GDP of a small country such as Denmark.

### 3.2 A Comparison of UK and US Dwelling Fire Statistics

In our examination of current fire statistical and survey information from both the United Kingdom and the United States (see Annexe 1) it is possible to identify a number of similarities in fire-related deaths and non-fatal casualties in dwellings and residential environments where most consumer products are used. 1995 statistics were available for both countries at the time of writing this report and these are used in this comparison.

Top level comparisons focus on the human impact of fire as represented in the impact triangles shown in Figure 1. In this figure the base of each triangle represents the potential for experiencing fire with the top culminating in reported loss of life.

Figure 1 Human impact of fire for UK and US 1995 residential/dwelling fires (note: the risk of death figures inside the brackets are those reported in the statistics and those with no brackets are calculated using the statistics reported in the diagram).



According to the British Crime Survey, Fires in the Home 1995 report (Home Office 1997b) whose estimates are based on statistical polling, there were 748,000 home fires in England and Wales in 1995 of which only 12% to 19% were estimated to be attended by the fire services. The gross cost to householders of these fires was estimated to be £355m in 1995. In contrast, the UK fire statistics summary for 1995 (Home Office, 1997a) reported 68,376 accidental and malicious fires which were serious enough to be attended by the fire services and to appear in the statistics.

This comparison serves to illustrate the enormous potential for fire events in the home environment and the extent to which this can lead to potentially serious fire incidents causing injury and death. At the top of the triangle, the UK experienced 13,054 non-fatal injuries and 549 fatalities in dwellings. This equates to 8 deaths per 1000 reported fire and a UK annual average population risk of death by fire of 14 per million. The major cause of death is gas and smoke inhalation with around 37-42% of fatalities being attributed to being overcome by gas and smoke alone and a further 19-16% being attributed to burns and being overcome by gas and smoke, as reported in the UK fire statistics for 1995 and 1996.

The Consumer Safety Product Commission (CSPC) in the US published their 1995 Residential Fire Loss Estimates (CSPC, 1998a) with a focus on product-related fire losses based on information derived from data provided by the US Fire Administration (USFA) and the National Fire Protection Association (NFPA).

In 1995 the US experienced 425,500 reported residential fires which were attended by the fire service; it is estimated that this number represents only 10% of all residential fires, the majority being unreported. These fires resulted in an estimated 3,695 civilian deaths (8.7 deaths per 1000 residential fires), 19,125 non-fatal injuries and $4.4bn in property loss. When account is taken of the differences in population and GDP these losses are generally directly comparable to those in the UK, with the exception of the non-fatal injuries; the disproportionately low injury figure for the US is likely to be due to reporting differences.

These figures are not atypical of developed countries and a similar story is likely to apply to other nations in the European Union and indeed most advanced nations worldwide.

In the UK the trends in fatalities and non-fatal injuries are reflected in progressive changes in these statistics across all age groups in the population over a 20 year period from 1974 to 1994. In the case of fire fatality the biggest reductions have occurred in the younger age groups (see Annexe 1).

Further consideration of the statistics concerned with the cause of non-fatal injuries, shows that the increase is mainly caused by gas and smoke inhalation against a background where there has been a reduction in the number of burn-related injuries, a decline which parallels the reduction in the number of fire fatalities.

### 3.3 Consumer Product Related Fire Statistics

Current British Crime Survey data indicate that in 1995 around two thirds of home fires took place in the kitchen with 41% of these associated with cooking appliances. However, around 21% took place in the lounge, dining and bedroom areas where we would expect the greatest involvement from consumer products in home fires and, as the statistics show, the greatest potential to cause loss of life.

Table 2 summarises the 1995 UK statistics for the proportion of fires, fire deaths and injuries associated with some of the higher risk sources of ignition or first material or item ignited.

The products most frequently involved as ignition sources or first materials ignited include - textiles and furnishings (deaths 21%, injuries 15%) - upholstered furniture (deaths 20%, injuries 8%) - space heating appliances (deaths 13%, injuries 6%) other electrical appliances (deaths 5%, injuries 7%). It is noteworthy that around 40% of all fatalities and 28% of injuries involve textiles, furnishings and upholstered furniture although only around 13% of fires involve these products. Smoking materials as an ignition source account for around 28% of fatalities and probably link with the first item ignited statistics for upholstered furniture, covers and textiles.

In contrast, cooking appliances accounted for the largest proportion of fires (42%) and injuries (43%) but a much lower level of fatality (11%).

Table 2 1995 product and cause related fire incidence, death and injury.

| Product | Numbers of Fires And Proportion (%) | | Number of Fatalities and Proportion (%) | | Number of Non-fatal Injuries and Proportion (%) | |
|---|---|---|---|---|---|---|
| Total (all products and sources) | 68,376 | | 549 | | 13,054 | |
| Smokers materials[1] | 5,580 | (8.2) | 152 | (27.7) | 1,926 | (14.8) |
| Cooking Appliances[1] | 28,545 | (41.7) | 61 | (11.1) | 5,671 | (43.4) |
| Space Heating Appliances[1] | 2,822 | (4.1) | 71 | (12.9) | 758 | (5.8) |
| Electrical Distribution[1] | 2,344 | (3.4) | 15 | (2.7) | 293 | (2.2) |
| Other Electrical Appliances[1] | 6,374 | (9.3) | 29 | (5.3) | 879 | (6.7) |
| Upholstery and Covers[2] | 2,645 | (3.9) | 107 | (19.5) | 1,092 | (8.4) |
| Other Textiles, Clothing and Furnishings[2] | 6,362 | (9.3) | 113 | (20.6) | 1,932 | (14.8) |

[1] reported by source of ignition - [2] reported as material or item first ignited

Note: the percentage values in this table do not and should not add up to 100% because the data are for both products and causes.

It is clear that only a small proportion of all fires involve products with a record of high lethality. For instance, upholstery, covers and textiles together present the greatest risks of death yet together they only account for 13% of fires. Similar disproportionality exists for smokers materials.

Interestingly, smoking materials as a cause accounted for only 8% of fires but a higher proportion of deaths (28%) and injuries (15%). However, on their own, smoking materials act primarily as the ignition source and other products such as upholstery, textiles and furnishing usually contribute to the development and spread of the resulting fire.

Further insight into these differences can be obtained by comparing the risks of death and non-fatal injury per 1000 fire experiences for the individual products; these are given in Table 3.

Table 3 1995 product and cause related fire death and injury risks.

| Product/Cause | Numbers of Fires | Fatality Risk (per 1000 product fires) | Non-fatal Injury Risk (per 1000 product fires) |
|---|---|---|---|
| Smokers materials | 5,580 | 27.2 | 345 |
| Cooking Appliances | 28,545 | 2.1 | 199 |
| Space Heating Appliances | 2,822 | 25.1 | 267 |
| Electrical Distribution | 2,344 | 6.4 | 125 |
| Other Electrical Appliances | 6,374 | 4.5 | 138 |
| Upholstery and Covers | 2,645 | 40.5 | 413 |
| Other Textiles and Furnishings | 6,362 | 17.8 | 304 |

The results discussed here and in Annexe 1 clearly show that the risks of death and injury for product related fires is highest for upholstery and covers. As ignition sources, smoking materials and space heating appliances produce similar risks to each other and to that of other textiles and furnishings (as combustible materials).

Long term trends in UK fatal and non-fatal injuries are discussed in section 12.4 where demographic changes are also taken into account. These data show that since 1988, following the introduction of the UK furniture and furnishing fire regulations, there has been a reduction in the number of fatal injuries per million of the population (pmp) in dwelling fires and a reduction in the rate of increase of non-fatal injuries pmp. Section 12 also discusses the significant reductions in television related dwelling fire deaths and injuries as a result of measures to improve the fire performance of these higher fire risk consumer products.

In contrast to UK experience, from 1980 to 1995 the number of residential fires in the US decreased by 44% and injuries decreased by 9%. In line with UK experience, the number of fire deaths decreased, in the US by about 33% over the 15 year period.

With some similarity to UK experience, the products and sources most frequently involved in fire deaths in the US are upholstered furniture (18%), mattresses/bedding (15%) and heating equipment (12%) accounting for 45% of all fire deaths; the corresponding injury statistics are respectively 9%, 15% and 10% for these products. However, the proportion of fires involving these higher risk products is disproportionately smaller with upholstered furniture accounting for only 3% of all residential fires and mattresses/bedding 6%.

In common with the UK, cooking equipment was the most frequent cause of residential fires and injuries (about 47%) followed by heating equipment (16%). Electrical equipment accounted for 36% of all residential fires, 21% of deaths and 33% of injuries primarily associated with cooking equipment and electrical distribution systems.

### 3.4 Spread of Fire

An important differentiating factor of dwelling fires in different countries is the number of fires that are confined to, or spread beyond, the room of origin. In the UK the trend in fire containment is seen in Table 4.

**Table 4** Fire containment trends in UK Buildings from 1985 to 1995

| | Total Number of Fires, x1000 | Confined to Room of Origin | | Spread Beyond Room of Origin | |
|---|---|---|---|---|---|
| | | No. x1000 | % | No. x1000 | % |
| 1985 | 104.7 | 95.2 | 91 | 9.5 | 9 |
| 1988 | 106.4 | 96.7 | 91 | 9.7 | 9 |
| 1991 | 107.4 | 95.6 | 89 | 11.8 | 11 |
| 1995 | 111.0 | 98.0 | 88 | 13.0 | 12 |

On the whole, fire containment is high in the UK (88% in 1995) compared with US and consequently the majority of fire deaths and injuries occur in the room of origin. However the trend indicates an increasing number of fires spreading beyond the room of origin from 9% to 12% over the 10 year period.

This increase, when linked with the increase in the total number of fires in dwellings in the UK, may account for the increasing number of non-fatal injuries related to people being overcome by gas and smoke. It is not clear in these statistics if this arises from toxic products that can move from room to room or results from a true migration of the fire beyond the room of origin.

**Table 5** 1989-93 US residential number of fires and fire deaths by item first ignited and the extent of fire spread

| First Item Ignited | Confined to Room of Origin | | | Spread Beyond Room of Origin | | |
|---|---|---|---|---|---|---|
| | Fires | Deaths | Deaths per 1000 Fires | Fires | Deaths | Deaths 1000 Fires |
| Upholstered furniture | 9787 | 197 | 20 | 6524 | 561 | 86 |
| Bedding | 9812 | 126 | 13 | 4833 | 281 | 58 |
| Structural members | 18189 | 24 | 1.3 | 18895 | 273 | 14 |
| Interior wall covering | 10432 | 34 | 3.3 | 8535 | 230 | 27 |
| Mattress or pillow | 14276 | 80 | 5.6 | 4026 | 162 | 40 |
| Multiple materials | 6324 | 29 | 4.6 | 8320 | 195 | 23 |
| Fuel | 11923 | 35 | 3 | 3765 | 130 | 34 |
| Contained accelerant | 5649 | 33 | 5.9 | 2658 | 116 | 44 |
| Floor covering | 7423 | 42 | 5.7 | 3824 | 94 | 25 |
| Cooking materials | 79863 | 27 | 0.3 | 4203 | 107 | 25 |
| Electrical wire/cable | 29382 | 14 | 0.5 | 5597 | 113 | 20 |
| Clothing on a person | 707 | 85 | 120 | 155 | 27 | 174 |
| Clothing not on person | 12484 | 33 | 2.6 | 3319 | 78 | 24 |
| Trash | 51239 | 19 | 0.4 | 5693 | 81 | 14 |
| Appliance housing/casing | 4125 | 8 | 1.9 | 458 | 12 | 26 |

This trend can be contrasted with the increase in the number of fires confined to the first item ignited in dwelling fires, from 39% in 1987 to 46% in 1997. This would suggest that the movement of toxic gases rather than movement of the fire is largely responsible for any growth in non-fatal injuries or that the trend in Table 4 is due to non-dwelling building fires, perhaps following the growth in open plan offices.

In the US, a recent report written for the Brominated Flame Retardant Industry Panel (with statistics prepared by the National Fire Protection Association (NFPA) (BFRIP 1997) has correlated the primary first source of fire incidents and fatalities in buildings with the degree of containment of the fire in the room of origin. The more significant results are shown in Table 5.

These findings reinforce the view that most of the more serious fire sources are consumer products and the majority of fire deaths in the US are associated with sources (i.e. first materials ignited) which create a fire capable of spreading fire atmospheres beyond the room of origin. This is a key point of difference between US and UK experience where in the latter case 88% of fires are confined to the room of origin. This is probably explained by the historic differences in building design and  construction.

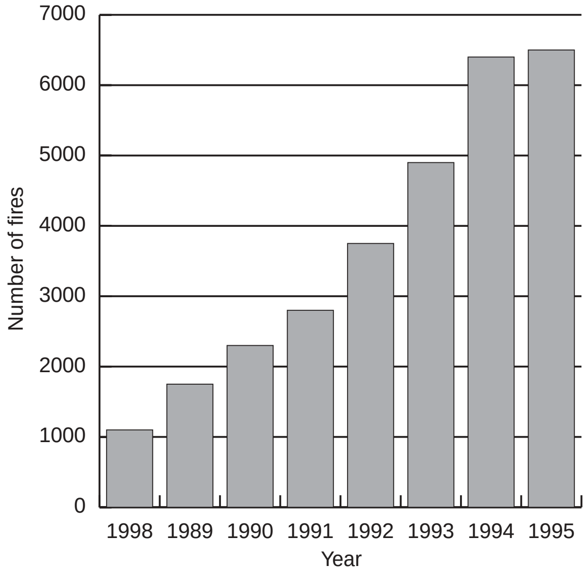
At a more detailed level, the US results also reveal that upholstered furniture fires as a group constitute the largest cause of fatalities and this product along with clothing and bedding produce the highest risk factors. This may reflect the lack of any federal regulations in relation to the fire performance of these products in the US; for upholstered furniture this is currently under review by the Consumer Product Safety Commission.

### 3.5 The Influence of Smoke Alarms in the UK

Smoke detectors and alarms offer an intervention measure which can reduce fire risks if they are able to provide early warning of the existence of fire on a timescale short compared with the rate of fire development and the time to achieve an untenable condition. Some people consider that smoke alarms are capable of offering adequate protection and remove the need to use flame retardants.

Figure 2 illustrates the increasing number of dwelling fires detected by smoke alarms; from 1,100 in 1988 to 6,600 in 1995. Other information indicates that detection times under 5 minutes currently apply to around 68% of dwelling fires (Home Office 1997a).

**Figure 2** UK dwelling fires discovered by smoke alarms from 1988 to 1995 (Home Office, 1997a).



Further analysis of the statistics indicates that smoke alarms have a beneficial effect on reducing fire fatalities with a death rate of 4 per 1000 fires when fires are detected by alarms in comparison with 9 per 1000 fires when fires are not discovered by alarms. This should be compared with the 1995 UK average of 8 deaths per 1000 fires.

However in 1995 only 11% of dwelling fires were detected by smoke alarms despite a MORI poll survey of the general UK public in January 1997 showing that 79% of households owned an alarm and 73 % of households had them installed. This compared with ownership levels of 70% in 1996 and 45% in 1994. Furthermore, the 1997 Fire Statistics Bulletin reported that smoke alarms were absent in the fire area of 70% of home fires involving around 400 deaths and a further 9,700 non-fatal injuries.

This disparity in detection versus ownership of smoke alarms is explained by the high number of alarms that were fitted but unable to detect the fire due to poor or inappropriate positioning or because they simply were not working. UK statistics indicate that 66% of fitted alarms did not respond to fires for these reasons.

Hence, the clear potential benefits of smoke alarms as an active fire-risk reduction measure could be seriously jeopardised in the UK if the low numbers of fully functioning alarm installations in dwellings continues. The same may be true for other European Union member states. In recognition of these difficulties the UK Home Office is launching a healthy smoke alarm campaign in the early part of 1999 to improve the use and maintenance of smoke alarms.

### 3.6 Social Factors in the UK

When considering the development of fire policy, the potential impact of intervention measures and the introduction or amendment of fire regulations, it is imperative to consider the social dimension of fire risk. The report of the UK Home Office British Crime Survey of Fires in the Home in 1995 (Home Office 1997b) examined risks in different neighbourhood groupings and different household types.

The survey is reviewed in greater detail in Annexe 1 but its results confirm that for the poorer social groupings the risk of experiencing fire is up to 3 times higher than the best performers and 2.5 times the overall average. In this analysis the average risk of fire in the home was established as 4.1 per 100 households per year.

In general the poorer social groupings are less able, and in some cases less willing, to take steps to mitigate the potential for fire and to protect against it. It is also true that those households in financial difficulty have the highest risks. Interestingly, the reported statistics suggest that smoking has no greater influence than other key factors in causing household fires.

# 4 Fire Atmosphere Hazards

## 4.1 Types of Hazard

Principal human hazards from fires and the associated risks of death and injury arise from exposure to the toxic products in fire atmospheres and to a lesser extent from the thermal effects of fire (radiative and convective heat transfer). Of these, toxic fire atmospheres are the more frequent cause of death (Fardell et al 1987, see also Annexes 1 and 8).

Therefore, in what follows, we mainly concentrate on the potential toxic hazards of fire atmospheres and those related to systemic (largely narcotic gases and oxygen depletion) and irritant effects. The hazard of reduced visibility due to smoke with the consequent increased risk of people being trapped by the fire or having their escape impeded, should be noted, but these are not discussed in detail. These points are discussed in Annexe 5.

The irritant effects of fire gases are important because they produce rapid effects that impede escape from fire. However, since the effects vary greatly in different mammalian species the results of experimental animal studies should be interpreted with caution.

Survivors of fires may experience post-exposure lung complications which may be an inflammatory response to irritants and may lead to delayed death (Hartzell, 1996). Annex 5 also discusses the possibility of long-term effects from exposure to carbon monoxide, to other narcotic gases and to compounds such as carcinogens and dioxins in fire atmospheres.

The evolution of toxic gases and particles depends on:

- the stage of fire development, e.g. whether it is smouldering, flaming or at the flashover stage
- the type of material being burned, particularly in the early stages of fire development
- the supply of oxygen to the fire

These factors and the associated hazards are strongly affected by the kind of enclosure in which the fire occurs. The location of people within the enclosure also affects their degree of exposure to fire effluents. So the dose-response curve will be determined both by the fire dynamics and location, and the physiological characteristics of the individual.

The risk of exposure will be determined by the susceptibility of the individual to the received dose and their actions during the exposure experience. So when considering fire-hazard counter-measures and regulatory policies, we should be mindful of differences within the population and of the response of the most susceptible groups to toxic fire atmospheres.

## 4.2 Influence of Fire Development

As fires develop from one stage to the next the hazards due to the evolution of toxic gases change. In the non-flaming oxidative/smouldering stage with low to mid-range temperatures, fire effluents are rich in organic irritants and carbon monoxide (CO). Even when nitrogen is present in the source material, hydrogen cyanide (HCN) yields are usually low except at the lower temperatures (Purser, 1992a, 1995). Early well-ventilated flaming fires at mid-range temperatures produce mainly carbon dioxide ($CO_2$) with low yields of CO or organic irritants. The toxic potency is low unless inorganic acid gases are present. Under this condition organic nitrogen is released as nitrogen oxides ($NO_X$) or gaseous nitrogen ($N_2$).

Small oxygen-vitiated flaming fires and fully developed post-flashover vitiated fires at high temperatures produce high yields of organic smoke which is rich in CO and oxygenated organics. Under these conditions, organic irritants may also be released and organic nitrogen from the source material may produce high yields of HCN.

Consideration of exposure doses measured by mass loss in small-scale experiments have shown that with few exceptions the atmospheres produced by a range of common materials during the early flaming stage of fires is generally less toxic than at the non-flaming or post-flashover stages (BSI, 1994).

At any stage of fire development, the degree of exposure to potentially hazardous compounds depends on the rate at which products are being burned (i.e. mass loss rate in kg/min) and the volume dispersal of the hazardous materials ($kg/m^3$). Purser (1992a) suggests that the mass-loss rate, the volume dispersal and the toxic potency of the individual fire gases are the major parameters determining the development of hazard to life. For materials with a large surface area, such as wall coverings, drapes and carpets, the rate of heat release and the evolution of hazardous products depends on the rate of flame spread (Buszard 1996, 1998).

It is now widely accepted that collective fire hazards and risks, and particularly those due to the fire atmosphere, are directly related to the rate of heat release and rate of flame spread. For occupants in enclosed spaces or in a typical room in a small domestic dwelling containing the fire, then pre-flashover fires which lead to untenable fire gas concentrations are likely to present the greatest hazards and risks. For occupants remote from the room containing the fire in larger dwellings and buildings, hazards and risks are likely to be greatest following flashover.

### 4.3 Influence of the type of material and consumer product being burned

Historically, deaths from exposure to smoke and toxic gases increased approximately fourfold between the 1950s and the 1970s, a period during which there was a considerable increase in the use of synthetic polymers in furnishing materials. In this period the toxic hazard from fires was found to be increasing (Wooley and Fardell, 1977). Initially it was thought that the combustion products from fires involving synthetic polymers were more toxic than fire atmospheres from traditional materials. However, a more recent view is that the increased hazard arose more from the increased rate of combustion and rate of formation of toxic products than from the toxic nature of the products themselves. It is now evident that the nature and disposition of materials can influence the rate of fire development and the magnitude of the associated hazards. However, since all fires are potentially hazardous it has been said that the major hazards of a fire are more related to the fact that a fire exists at all than to the materials involved (ISO/IEC, 1989). This view is borne out by a number of workers (e.g. Levin 1987b, Hirschler 1994, Purser 1995, Hartzell, 1996).

An important fire atmosphere hazard parameter is the $CO_2$/CO ratio which is affected by the oxygen supply to a much greater extent than by the type of material being burned. In well ventilated fires the toxic risk from CO is low although the CO yield may vary by a factor as large as 60 according to the chemical nature of the material being burned (Tewarson, 1990). However, for under-ventilated fires, the effects of chemical structure on CO yield are not apparent at all.

Extensive literature reviews of the chemical nature and toxicity of the pyrolysis and combustion products of seven synthetic polymers has been summarized by Levin (1987b). The polymers were selected because of their use in consumer products and some of them contained additives which are commonly used in such products. Due to the widely varying types of test used, Levin's review was unable to rank the different polymers with respect to their hazard potential in fires. An exception was rigid polyurethane which was considered to produce an atmosphere containing an isocyanate. Other authors disagree with this observation. However, the precise balance between the production of hydrogen cyanide and isocyanates in these materials is likely to be related to fire intensity and oxygen concentration. However, Levin's overall conclusion was that none of the polymers produced unusually or extremely toxic pyrolysis or combustion products when compared with other synthetic or natural products such as Douglas fir.

## 4.4 Oxygen supply to the fire

Reduced oxygen supply is especially important at the flashover stage of fires and this is difficult to simulate in practical bench methods (Babrauskas et al 1991a). The predominant effect on fire atmospheres is to decrease the $CO_2$/CO ratio as oxygen levels fall below half the stoichiometric level (in relation to the concentration of volatile fuel). The increase in carbon monoxide yields with decreasing oxygen supply show the same trends across a wide range of fuel types, both natural and synthetic, of varying chemical structures.

Reduced oxygen supply favours the production of HCN from nitrogen-containing fuels (Simmons and Metcalfe, 1987) and products of incomplete combustion such as formaldehyde and acrolein from other fuels ( Hartzell, 1996).

# 5 Methods of Toxic Hazard Assessment of Fire Atmospheres

During the late 1960s and early 1970s concern about the fire atmospheres produced by the newer synthetic materials led to new research in this area. This involved studies of individual fire gases and gas mixtures, together with the development of laboratory bench-scale tests (as fire models) for the decomposition of materials and the production of mixed combustion product atmospheres. These were used in conjunction first with animal exposures and later chemical analysis of the atmospheres to evaluate toxicity and toxic hazard.

## 5.1 Experiments and tests using animals

Early investigations, which sought to develop an understanding of the mechanisms of how fire atmospheres cause incapacitation, used rodents and monkeys. Later, when the emphasis changed to evaluating and classifying the toxic potency of the combustion products of different materials, rodents were used usually to establish lethality e.g. $LC_{50}$ (Hartzell, 1996).

The results of the first type of investigation indicated that the toxic effects of the fire atmospheres resulted from systemic poisoning, asphyxiation and irritancy caused by a relatively small number of major combustion products. This understanding led to the development of toxicity models based on chemical analysis of fire atmospheres. These toxicity models are of two types:

(i) bench scale chemical analysis tests to predict the toxic potency of the combustion products produced by individual materials; this approach replaced the use of rodents in small scale lethal toxicity tests

(ii) toxic hazard models designed to be used with large scale fire data to predict time to incapacitation and death in humans exposed to fire atmospheres (Purser 1996).

The latter is more relevant to human hazard and risk assessment.

## 5.2 Assessments involving chemical analysis of fire atmospheres

Approaches involving chemical analysis are based upon the concept that only a relatively small number of products are important in causing toxic effects in fires. This is borne out by the fact that most common materials, both natural and synthetic, fall into a small number of groups and within each group the toxicity of their fire effluents do not differ widely. This is the case despite hundreds of products being present in model and real fire atmospheres (ISO/IEC, 1989).

Humanitarian considerations, as well as cost reduction, favour the use of chemical analysis rather than direct tests on animals although it is acknowledged (Hirschler, 1994) that such use may result in products of extreme or unusual toxicity being missed. Recent test methods adopted by ASTM and ISO minimise or even eliminate the use of animals by using the fractional effective dose methodology (see Section 3 of Annexe 5) to calculate $LC_{50}$ values from analytical data (Hartzell, 1996).

### 5.3 Empirical models for predicting toxicity

Purser et al (1983a, 1983b and 1984) observed that the toxic effects of the combustion products of a number of natural and synthetic materials were related to the sum of the concentrations of a few gases. It was therefore feasible to express the toxicity of combustion atmospheres in empirical equations taking account as far as possible any synergism or antagonism in toxicity between the different gases. This led to the concept of Fractional Effective Dose (FED) measures to assess the impact and survivability of fire atmospheres (for more information see Annexe 5).

The toxic interactions between the gases are difficult to quantify experimentally but may be estimated from the physiological data of the individual gases (Purser, 1995). Nevertheless, there have been a number of studies of the effect of mixing gases on rat 30 minute $LC_{50}$ values (e.g. Doull and Bingham 1988; Levin et al 1994). Probably the most important conclusions from these studies are:

- the hyperventilatory effect of $CO_2$ increases the uptake of other gases so that 5% $CO_2$ approximately halves the $LC_{50}$ values of CO and $NO_2$.
- there is no evidence of synergism between CO and HCN although the hyperventilatory effect of HCN may increase the rate of uptake of CO. The effects of the two gases are assumed to be additive
- the toxic effects of $NO_2$ and HCN are antagonistic so that 200ppm of $NO_2$ increases the $LC_{50}$ of HCN by a factor of 2.4. This protective effect of $NO_2$ can be enhanced by $CO_2$ in tertiary mixtures of HCN, $NO_2$ and $CO_2$.

### 5.4 Comparison of results from bench scale and larger scale tests.

Comparisons of fire atmospheres from bench scale and larger scale tests have been carried out for upholstered furniture (Creyf et al 1995, Babrauskas et al 1991a,1991b, Babrauskas, 1998). The overall conclusion was that smaller scale tests did not accurately predict gas ratios and, in particular, tended to underestimate CO production compared with larger scale tests or real fires. It was suggested that the results do not support the contention that measurement of gases from cone calorimeter or furniture calorimeter tests could be used to define the life-threat from toxic gases.

The overall conclusions with respect to the ranking of products for their toxic fire behaviour were:

- it may be sufficient to measure the loss of source mass ($\Delta m$) in a room scale test
- $LC_{50}$ values derived by FED methods using room scale data are less valuable than $\Delta m$, heat release rate (HRR) or time to flashover values and these parameters have the advantage that they do not require measurement of toxic gas concentrations
- accurate prediction of full scale toxic fire hazard cannot be made from bench scale $LC_{50}$ values
- it would be appropriate to seek bench scale methods of the rate of $\Delta m$ or HRR as the basis of fire safety regulation.

This brief discussion indicates that care is required when interpreting the results of bench scale toxicity tests, particularly when no attempt has been made to relate the tests to large scale fire atmospheres.

# 6 Toxicology of Fire Atmospheres

It is important to bear in mind that the toxicity of fire atmospheres is a function of the rate of production of compounds as well as their concentration and their toxic potency. As discussed, the rate of production is driven by the heat release rate and mass loss of the source and this relates to the overall dynamics of individual fires. It must also be recognised that in some acute exposure situations irritant effects may be more important than systemic poisoning effects in impeding escape from fire.

In addition to acute exposure toxicity effects, evidence suggests there may be longer term effects from exposure to fire atmospheres that are currently incompletely understood. Both effects are discussed here, whilst a discussion of the wider life-cycle and environmental impacts of fires are discussed in Section 12 of the report.

From our review of the toxicology of the principal components of fire atmospheres it is clear that the shorter term acute effects can be prioritised according to the hazard and actual risks they present. These are:

- carbon monoxide
- hydrogen cyanide
- carbon dioxide
- oxygen depletion
- irritant gases
- solid and liquid particulates
- oxides of nitrogen
- products of extreme or unusual toxicity
- carcinogens
- dioxins

A brief review of each of these is helpful in understanding the severity of the hazards and risks presented by fire atmospheres. A more detailed discussion can be found in Annexe 5.

## 6.1 Carbon monoxide

It is widely acknowledged that CO is by far the most frequent cause of death in fire victims. The US National Research Council reported in 1988 that CO was the cause, or a contributory cause, of 80% of fire deaths (Tewarson, 1990) and 70% of fire victims in a Glasgow study were judged to have been incapacitated by CO (ISO/IEC, 1989).

There are large differences between reported effects to different exposures to CO (Hirschler 1994) and it is possible that these differences may be due in part to the duration of exposure to CO as suggested by Hardy and Thom (1994). According to Hirschler (1994) any carboxyhaemoglobin (COHb) > 20% may be lethal but 50% is not necessarily lethal depending on the age and physical condition of the person. However, Christian (1993) in a study of fire victims in the UK, did not find any evidence that age or pre-existing disease affected the lethality of CO. He suggested that deaths involving relatively low levels of COHb could be due to enhancement effects of other fire gases. Incapacitation by CO is also more rapid if the victims are exerting themselves or are of relatively low body weight Purser (1995).

The evidence is that CO has effects on the central nervous system and the importance that this might have on the ability of people to escape from fires has lead to a number of neuro-behavioural studies.

Benignus (1993 to 1996) has reviewed a large number of his own and other workers studies of the short term neuro-behavioural effects of CO in rats and human volunteers. He concludes that, with respect to the short term neurobehavioural effects of CO, there are too many statistically significant findings to ignore and too many non-replicants to believe them.

Besides the short-term neuro-behavioural effects there is clinical evidence from actual human exposures of a wide range of delayed neurological effects (Hardy and Thom, 1994).

Christian (1997) and Hardy and Thom (1994) discuss the evidence that there are long term neurological effects of exposure to CO by hypoxia. Hardy and Thom (1994) list nearly 400 cases (not all of them fire victims) of people who had been acutely poisoned by CO, had apparently recovered and then within 2 to 40 days had developed delayed neurological sequelae (DNS). The incidence of DNS is related to some extent at least to the duration of unconsciousness during the acute stage of intoxication.

Another cause for concern is the incidence, discussed by Christian (1997) and Hardy and Thom (1994) of teratogenic effects in women acutely intoxicated by CO during pregnancy. Sixty cases have been reviewed in which there is a correlation between CO exposure and foetal death or toxic effects in the foetus including anatomical malformation and functional alterations. The indications of teratogenic potential for CO are apparently supported by animal data but it is not clear from our present information whether this is an effect specific to CO or whether it is a general effect of acute intoxication. The difference between these alternative possibilities is important for pregnant women who may be exposed to CO at levels below those which cause acute intoxication.

Despite the existence of a sizeable medical literature on the toxicity of CO, the long term effects of acute exposure and the possible occurrence of long term sequelae are not well understood. Consequently, this is a major area of potential concern for all surviving victims of serious fires and is a subject worthy of further in-depth investigation.

## 6.2 Hydrogen cyanide

HCN has high acute toxicity. It does not appear to follow Habers law in that the time to incapacitation is much less at concentrations about 200ppm and higher, than at lower concentrations (Purser 1995). This may account for the sudden knockdown effect in fire victims. In humans 50ppm for 30-60 minutes is generally tolerated. Exposures which are generally fatal in humans are 100ppm for 30-60 minutes or 180ppm for 10 minutes.

Inhaled HCN is rapidly distributed throughout the body water and it inhibits cellular respiration. HCN causes hyperventilation and thereby increases its own toxic effect and that of other toxic gases. The effect of the inhibition of cellular respiration is mostly seen in the brain where it produces depression of central nervous system activity, slowing down of the heart rate (bradycardia) and cardiac arrhythmias. Death is generally due to respiratory arrest caused by depression of the central nervous system. Besides its action in blocking cellular respiration HCN exerts its toxic effects by inhibiting other enzymes, by causing an accumulation of calcium in neurons, by initiating the release of catecholamines from the adrenals and adrenergic nerve terminals and by causing the release of excitatory brain neurotransmitters (Smith, 1996).

The possibility of longer term effects from exposure to HCN is indicated by the occurrence, in survivors of cyanide poisoning, of lesions of the central nervous system characteristic of hypoxia or ischaemic injury (i.e. tissue injury due to deficiency in the blood supply). Effects may include delayed Parkinsonism/dystonia (Anthony et al, 1996). Our present reading of the literature gives no indication of whether or not any longer term effects from exposure to fire atmospheres could be attributed to HCN. However, as in the case of CO we consider this to be worthy of further examination.

## 6.3 Carbon dioxide

$CO_2$ itself has low acute toxicity. However, $CO_2$ causes hyperventilation and this is likely to be the most important mechanism for the observed synergism between the toxicities of $CO_2$ and CO and enhanced inhalation of other fire atmosphere products. Inhalation of $CO_2$ can produce adverse psychological effects including panic in susceptible people (Gorman and Uy, 1987). It would appear that the toxicology of $CO_2$ may be more complicated than its action as a simple asphyxiant and respiratory stimulant. This too is worthy of further study.

## 6.4 Oxygen depletion

Reduction in the normal concentration of oxygen (21% by volume) has acute effects in humans. Motor coordination is impaired at about 17% in people not exercising vigorously; persons display faulty judgement and become rapidly fatigued at 14% to 10%; unconsciousness and death may ensue within minutes at 10% to 6%. During periods of exertion these symptoms may occur at higher oxygen concentrations (Hartzell, 1996).

## 6.5 Irritant Gases

Halogen acid gases and many oxygenated organic compounds produce irritant hazards in fires. Sensory irritation does not depend on an accumulated dose but occurs immediately upon exposure and usually lessens somewhat if exposure continues or if people have prior experience of exposure to irritants.

Some investigators believe that irritant effects may make escape from fire difficult while others believe that the effects provide a strong incentive to escape and might almost be beneficial (Purser 1995). It would appear probable that the outcome of exposure to irritants may depend on the rate at which the concentration increases as well as on the fitness and ability of exposed individuals. The outcome is likely to be less serious if the concentration increased relatively slowly and the exposed individuals were fit and not confused about escape methods.

### 6.5.1 Hydrogen chloride and hydrogen bromide

An important consideration in interpreting the results of small-scale and intermediate sized toxicity tests on these acid gases is that in real fires they tend to react with building surfaces and are not entirely available in the atmospheres. Consequently, the toxicity of the effluent of burning PVC decays rapidly (Hinderer and Hirschler (1990). We have not seen any evidence that the tendency of these acid gases to be removed from fire atmospheres has been taken into account in experimental assessments of hazard.

Hydrogen chloride (HCl) and hydrogen bromide (HBr) exert similar effects in fire atmospheres. The major effects are sensory irritation to the eyes, nose, throat and lungs especially in humans and other primates because the anatomy of these species does not protect the respiratory tract to the same degree as in rodents. Besides sensory irritation, exposure to these gases produce mucosal lesions in the mouth and pulmonary haemorrhage in primates (Hartzell, 1996). This latter effect sometimes causes deaths in fire victims (ISO/IEC, 1989).

In summary, the major effects of HBr and HCl are likely to be through sensory irritation although these acid gases are much less potent than some organic irritants (see below). Therefore, except in fires fuelled by especially halogen-rich compounds (e.g. PVC cable fires), the effects are likely to be dominated by the organic irritants.

### 6.5.2 Irritant organic compounds

Pyrolysis or incomplete combustion of organic compounds leads to a wide variety of organic substances many of which are irritant. Fingerprints of a large number of these chemicals are given in ISO/IEC (1989) which shows that, of the three stages of fire discussed including growth, steady state and decay, the highest concentrations of volatile organic compounds are produced at steady state. This applies to both natural materials and synthetic materials. The most important of the organic irritants are formaldehyde, unsaturated aldehydes (especially acrolein ) and isocyanates.

Acrolein, which is formed from the smouldering of all cellulosics (Hartzell, 1996), as well as from synthetic materials especially at medium temperatures (400-700° C), is the most irritant of the organic compounds which occurs commonly in fire atmospheres (ISO/IEC, 1989). Of the organic irritants only acrolein has received significant attention in combustion toxicology (Hartzell ,1996) and it is possible that work on the others would give useful information regarding products which may be responsible for the range of irritancy experienced in fire atmospheres.

### 6.6 Solid and liquid particulates

It appears that the greatest hazard from the particulates in fire atmospheres is their effect in reducing visibility and thereby hampering escape from fires.

The short-term toxic effects from exposure to fire particulates are related to their irritative action on the eyes and respiratory system and it is suggested that there may be other less well-defined longer-term effects eg Purser 1996, Levin 1987b, Hill 1996 (see also Annexe 5, Section 4.6)

### 6.7 Oxides of nitrogen ( $NO_X$)

$NO_2$ in fire atmospheres is derived from nitrogen-containing fuels and from the high temperature oxidation of atmospheric nitrogen. Nitric oxide (NO) is the initial product and this is rapidly converted in the atmosphere to nitrogen dioxide ($NO_2$) which is the more acutely lethal, its effects being primarily due to pulmonary irritancy (Hartzell, 1996). However, $NO_2$ in fire atmospheres is of prime importance because of its influence on the toxicity of other gases (Levin et al, 1987a; see also Annex 5).

The toxicology of $NO_X$ has been widely reviewed because of its occurrence in atmospheric pollution (e.g. WHO, 1977; UK DoH, 1995a. It may aggravate the symptoms in asthmatic people (UK DoH, 1995b) and may therefore have an impact on the ability of asthmatics to escape from fire.

### 6.8 Products of extreme or unusual toxicity

There have been a small number of documented cases of products with extreme or unusal toxicity (see Annexe 5), but in general these are rare. Indeed, some workers (e.g. Levin, 1987b; Babrauskas et al, 1988; ISO/IEC, 1989) have looked for but failed to find evidence of extreme toxicity in atmospheres from experimental and real fires involving a wide range of materials.

Despite this, future fire atmosphere toxicity testing is unlikely to utilise animal exposures. Hence the comparison route with chemical assay fractional effective dose (FED) methods may no longer be available to detect the presence of unusually toxic compounds. This will require that alternative approaches to the detection of unusually toxic compounds should be developed.

## 6.9 Carcinogens

The most commonly found carcinogens in fire atmospheres are the polyaromatic hydrocarbons (PAHs) (e.g. Spindler, 1997). Besides these Morse et al (1991) list six known carcinogens, acrylonitrile, arsenic, benzene, benzopyrene, chromium (presumably hexavalent chromium) and vinyl chloride, which have been found in samples taken from 24 fires. However, the finding of known carcinogens does not necessarily indicate that there is significant excess risk compared with the risk from exposure to urban air or ordinary diets.

Some authorities (e.g. USEPA) calculate carcinogenic risk from lifetime exposure to carcinogens and it is sometimes assumed that significant carcinogenic risk is only associated with massive or repeated exposure. On this basis the carcinogenic risk from exposure to fire atmospheres would be judged to be negligible except, possibly for personnel such as firefighters who have repeated exposures. On the other hand some theories of carcinogenesis (eg the one-hit theory) assume that even a brief single exposure, particularly to genotoxic carcinogens, involves some risk. We are not aware of definitive evidence for either viewpoint.

We have not found any long term experimental animal studies which might give an indication of the carcinogenic risk of exposure to fire atmospheres. Neither have we found any relevant epidemiological studies, although Morse et al (1991) state that there is an increased frequency of the brain tumour glioblastoma in firefighters.

## 6.10 Dioxins

### 6.10.1 General.

Dioxin is the general name given to a large group of polyhalogenated dibenzodioxins and dibenzofurans. They are formed in practically all high temperature processes involving organic materials and chlorine or bromine. The toxicology of dioxins is reviewed in Annexe 5 and in the following references: IEH (1997), MAFF (1992), Fries and Paustenak (1990), IARC (1977, 1997).

The detail about dioxins in this report reflects the public concern over these compounds rather than the indications of actual risk in the context of fires and flame retardants.

Dioxins produce a range of toxicological effects in experimental animals, often at very low exposure levels. However, evidence linking these effects with human toxicological end-points is far from conclusive and the only well-documented human effects are chloroacne and transient hepatic changes (IEH, 1997). Certain human cancers have been linked with dioxins but this linkage has been disputed. However IARC have stated that mechanistic considerations indicate that one isomer, 2,3,7,8-TCDD presents a slightly increased cancer risk in the most heavily exposed workers (IARC 1997).

### 6.10.2 Dioxins in fire atmospheres

It is to be expected that chlorodioxins would generally be found in and around fires most probably in the soot. However, except in special cases such as in fires involving polychlorinated biphenyls (PCBs) (e.g. Schecter, 1983) we are unable to make even a semi-quantitative estimate of the likely exposures to chlorodioxins.

The low volatility of the dioxins would indicate that inhalation of vapour is probably not the main route of exposure. Other routes of exposure which are hypothetically possible are inhalation of particles with adsorbed dioxins and percutaneous exposure by contact with dioxin-containing soot.

According to Spindler (1997) the production of dioxins in fires - except, possibly in transformer fires -involves a very small increase in cancer risk compared with the risk from polyaromatic hydrocarbons (PAHs). Even in fires involving PCBs such as the Dusseldorf Airport fire in 1996 the carcinogenic risk calculated for lifetime exposure (see Section 6.9 and Annexe 5) was some 500 times higher for the PAHs than for the dioxins produced.

Concern about brominated dioxins has arisen mainly because of the use of brominated flame retardants, although brominated dioxins have been found in vehicle exhausts presumably derived from lead scavengers. It has been confirmed experimentally that when brominated flame retardants such polybrominated diphenylethers (PBDEs) are heated at 510 to 630°C a range of brominated dioxins are formed with yields up to 10%. The isomers of greatest toxicological interest, those with 2,3,7,8-substitution, were not present among the main thermolysis products (Dumler et al, 1989). In an investigation of three fires in private residences, TV cases containing brominated flame retardants produced concentrations of up to 14.9ppm of brominated dioxins in deposits on surfaces around the fires (Zelinski et al , 1993).

With the controversial debate on the human toxicology of dioxins still ongoing, it is not possible to be clear about their potential effects in fire atmospheres. Nevertheless, a better understanding of the type and availability of dioxins formed would provide a good platform from which to assess potential human and environmental toxicology effects of fire, when the wider debate on dioxins is concluded.

## 6.11 Influence of Flame Retardants on the Toxic Risk From Fire Atmospheres.

The main effects of flame retardants are to delay the spread of fire over the burning product and to inhibit the development of the fire (see Annexes 3 and 7). The overall effect in real fires is to generally reduce the heat release rate, reduce the consumption of substrate and consequently to reduce the evolution of toxic gases. In addition flame retardants reduce the exposure of personnel to toxic gases by increasing the time available to escape before flashover or the occurrence of an incapacitating atmosphere (see Section 9.2).

There appear to be a number of special cases - mostly demonstrated in smaller scale test systems - in which the influence of flame retardants is to increase the production of toxic gases (see Annexe 5). This influence has not been demonstrated in room scale tests or in real fires. It is also clear that small and large scale tests on modern commercial flame retardants indicate that they do not produce effluents of extreme or unusual toxicity.

# 7. The Toxicology of Flame Retardants

The number of flame retardants used in consumer products is too large to undertake a general review of the toxicity of each compound in this report. We therefore selected a group of flame retardants for assessment which we consider are representative of the more common types. Our criteria for selection centred on the tonnages used, concern which may have been expressed on their toxicology, the need to consider a balanced group of compounds across several application areas in consumer products and the availability of toxicity information to attempt such an assessment.

The human exposure toxicology of six common flame retardants used in consumer products are reviewed in detail in Annexe 6 in which an assessment of the toxicology of each compound and an associated appraisal of toxic risk is provided. The extent of use and application of these retardants in consumer products can be determined by reference to Annexe 2.

## 7.1 General Considerations

Each toxicology review deals with data from toxicity or epidemiological studies. These studies are on the flame retardants themselves rather than on the consumer products containing them. Hence, the studies will tend to exaggerate the toxic risk for flame retardants in consumer products, especially for those which form part of a polymer matrix or are otherwise tightly bound, because their bioavailability will be limited by the host material.

Each appraisal of toxic risk utilises the corresponding toxicology review in the context of the likely exposure people may have to consumer products containing flame retardants. The exposure may be oral, especially with children, dermal or by inhalation. This last route of exposure has been proposed as a possibility because airborne particles may be produced from consumer products by abrasive wear. However, only a very small proportion of abrasion particles are likely to be small enough to penetrate the lower respiratory tract. Only particles with an aerodynamic diameter of about 10 microns or less will produce respiratory effects. Larger particles tend to be trapped in the upper respiratory tract, transported up the mucociliary escalator and then swallowed or expectorated. Any possible toxic effects will therefore be similar to those from oral ingestion although the quantities involved are likely to be very much smaller. None of the flame retardants under consideration have vapour pressures high enough to be a significant consideration for inhalation toxicity.

It is not possible with the presently available information to make quantitative estimates of the exposures by people using consumer products containing flame retardants. There is limited recent work in this area (e.g. CPSC 1997, 1998b) and there is the need for further work. The limited work available and the application of basic judgement (in the absence of other guidance) suggests that exposures to flame retardants in consumer products are unlikely to be greater than a few µg/kg-bodyweight/day. Therefore we can conclude that at the low levels of exposure envisaged flame retardants of low toxic potency are unlikely to have adverse toxicological effects.

The readers attention is drawn to Annexe 4 which briefly describes the methods of assessing toxicity with their utility and limitations.

## 7.2 Toxicity Risk Appraisals

A fuller discussion on each flame retardant appears in Annexe 6.

**Alumina Trihydrate(ATH):**

Alumina, aluminium hydroxide and aluminium compounds in general have very low levels of toxicity except when there are very high exposure levels or unusual routes of exposure. In view of the lack of reported adverse effects from the very extensive environmental exposure to aluminium compounds, including alumina, it is extremely unlikely that any adverse effects would ensue from the levels of exposure to ATH in the use of consumer products.

**Antimony Trioxide:**

Recent comprehensive genotoxicity studies (Elliott et al 1998) have indicated, contrary to the indications of earlier less well authenticated studies, that antimony trioxide is not a genotoxic carcinogen. Early rat inhalation studies which appeared to indicate some carcinogenic potential involved high levels of particulate dosing and other work shows that the rat may be predisposd to the formation of lung tumors under conditions of particle overload. The recent studies at lower, but still high, dose levels indicate no carcinogenicity. In addition, a study of the epidemiology of workers in an antimony smelting plant indicated an excess of lung cancer. However, the results of this study are questionable as the observed cancers may have been attributable to materials other than antimony trioxide in the plant.

In a similar vein, an expert group in the UK (Limerick, 1998) investigating cot death (sudden infant death syndrome) found no connection with antimony compounds.

Hence, no adverse health effects are expected from antimony trioxide at the levels of exposure expected from consumer products. Indeed, this exposure is probably minor compared with exposure to antimony trioxide from other sources in the domestic and urban environment.

**Decabromodiphenyl Ether (DBDPE):**

None of the available data give any indication of toxic risk from the levels of exposure envisaged from the use of DBDPE in consumer products. It is very poorly absorbed from the gastrointestinal tract and its low vapour pressure indicates that inhalation exposure is unlikely to be significant. Its tendency to bioaccumulate is low. It is important that the toxicology of polybromodiphenyl ethers is not confused with that of the polybromobiphenyls. The latter have distinctly different toxicological characteristics.

DBDPE together with its lower brominated congeners, octa- and penta-bromodiphenyl ethers are being assessed as priority substances under the EU Existing Substances Regulations (see Annexe 6c).

### Melamine:

All of the available information indicates that melamine has low acute and chronic toxicity, so no adverse effects are envisaged from the level of exposure expected from the use of melamine as a flame retardant.

A consistent feature of tests on melamine is its rapid removal from the blood and its excretion unchanged in the urine. At very high doses this results in precipitation in the renal tubules and in the bladder with consequent irritation. At the level of exposure expected from the use of melamine as a flame retardant this should not present a significant risk.

It has been shown that the bladder carcinomas produced in male rats at very high doses were almost certainly due to irritation by the precipitates and not to the chemical nature of melamine. The fact that melamine is negative in mutagenicity studies supports the conclusion that it is not a genotoxic carcinogen. IARC has concluded that the evidence of carcinogenicity of melamine in experimental animals was inadequate and, in the absence of human epidemiological data, no evaluation of the carcinogenicity of melamine to humans could be made.

Melamine has been available commercially since the late 1930s (IARC, 1986) and no significant reports of adverse health effects in humans have been found. It may therefore be concluded that for the low levels of exposure expected from the use of melamine as a flame retardant, it can be considered toxicologically safe.

### Tetrabromobisphenol A (TBBA):

No chronic data are available but the subacute studies by oral, dermal and inhalation routes of exposure indicate such low levels of toxicity that it would be surprising if there were appreciable effects from low levels of long-term exposure.

There are no carcinogenicity data but the chemical structure of TBBPA and the absence of mutagenic activity in standard tests indicate that it is not a genotoxic carcinogen. There are no data on possible effects on fertility but TBBPA was negative in tests for teratogenicity.

In spite of the data gaps, the overall conclusions from the available data, and from the probably very low bioavailability of TBBPA in its polymer applications, is that there are most unlikely to be any toxic effects from the use of consumer products containing TBBPA.

Since there is evidence that bisphenol A has weak estrogenic properties it may be advisable to consider investigating the oestrogenic potential of TBBPA.

### Tris-(chloropropyl)-phosphate (TCPP):

None of the available data give any indication that TCPP is likely to cause any toxic risk at the exposure levels envisaged from its use in consumer products. A Russian study with a product referred to as TCPP but of doubtful relevance to commercial TCPP produced an adverse effect on male fertility. Because of the nature of the material under test the Russian study is not an indication of a hazard with commercial TCPP. There were equivocal results in one transformation assay and in an assay of unscheduled DNA synthesis but the negative results in other in vitro tests and in an in vivo test give reassurance that the compound is not significantly genotoxic. No data are available concerning chronic toxicity or carcinogenicity but the results of the subacute and the genotoxicity studies indicate that there would probably not be any adverse effects if these studies were done.

It is important that TCPP and other tris-haloalkyl phosphates are not confused with the flame retardant known as TRIS, i.e. tris-(2,3-dibromopropyl)-phosphate which has been banned in the UK and US and has not been commercially available in Western Europe since 1976.

## 7.3 Conclusions and Issues

Examination of the toxicology of six of the more common flame retardants used in consumer products indicates that in general they do not pose any significant threats to human life and the environment. Moreover any indication of risk from the toxicology of flame retardants themselves in isolation will be exaggerated because of their limited bioavailability when they are incorporated into a polymer matrix.

There is little data available on bioavailability but the US Consumer Product Safety Commission (CPSC 1998b), using solvent extractability from textile furniture covering as the criterion, has concluded that the flame retardants examined have low bioavailability. However, this remains a key issue in determining the degree of possible human and environmental exposure; more published work is required to assess the effectiveness of the containment of flame retardants in polymer matrices where the flame retardant is not covalently bonded to the host matrix.

Caution is therefore required in generalising our conclusions, obtained on a limited number of flame retardants, to all flame retardants. This reflects the fact that data on many flame retardants, in common with most other chemicals on the European existing chemicals list, are incomplete. The corollary is that a number of flame retardants are among some of the most extensively studied chemicals on the existing chemicals list. Despite this, it is important that each flame retardant is considered individually and in the context of its incorporation into consumer products and that its human exposure and environmental life-cycle risks are assessed.

It is important that where potential concerns exist that risk assessments are undertaken in a thorough yet speedy manner to encourage confidence in the regulatory process and industry’s willingness to vigorously manage their obligations.

# 8. Risk Perception and Assessment

When considering the risks related to fire hazards and those associated with flame retardants it is important that we understand the factors that influence our perception of risk in addition to how we actually measure risk. Understanding our everyday experience of risk in its broader sense is also helpful.

As we shall see, the issues surrounding risk assessment and risk perception of flame retardant compounds in consumer products are not significantly different from that of other chemical compounds. The key difference is that when flame retardants are activated they act to potentially reduce or counter fire hazards, so it is important that these risk reduction benefits be considered in relation to the risks presented by fire. At the same time, flame retardants may present additional potential risks from their intervention in the fire process. Enumerating and reconciling this dual influence and considering the resulting balance of risk requires an appreciation of current thinking on risk (this is discussed in greater detail in Annexe 8).

## 8.1 Personal Risk

Risk is associated with any form of existing or potential hazard from any source. For chemicals coming into contact with man or the environment, hazard may be defined as the inherent capability of a chemical or a mixture to cause adverse effects on man or the environment under particular exposure conditions (Van Leeuwen et al 1995). Risk is the chance that something adverse will happen or more precisely the likelihood of a particular undesired event or hazard occurring within a specified set of circumstances or period of time.

Whenever we deliberately do something that involves taking a risk we usually do so because we realise or perceive a benefit that outweighs the risk. We instinctively estimate the risk and take measures to reduce it when we have some degree of control over the risk. In the case of natural risks, such as death caused by lighting or flood, where we have little or no control and where the risks are small (e.g. the chance of any one of us being killed by lighting are 1 in $10^7$) we usually regard such risks as negligible. There is no such thing as a nil or zero risk. Whatever we do and however unlikely or remote an event we constantly face risks.

The statistics of voluntary risk and natural risk appear not to deter us from taking risks. The degree to which we are personally prepared to take risks depends on our awareness of the risks and whether we are more or less a risk-taker or are risk-adverse. For example most people accept air travel but relatively few would consider parachute jumping.

## 8.2 Perception of Risk

Personal judgements and perception of risk connect with the ability of a person to relate to the hazard and to understand the associated risk, or if the hazard is understood the degree of aversion or dread felt by an individual (Fischoff et al, 1987; Slovic, 1987). Personal perception of risk is therefore based on personal views and preferences.

However, as Kasperon et al (1988) have shown, public response to risk may be socially amplified or attenuated according to psychological, social, cultural and institutional processes; this may explain why different cultures and countries respond differently to the same risks. The role of the media cannot be ignored in these processes. Sandman (1996) has discussed many factors that can significantly influence journalists and opinion formers and, by extension, the response of the public. Understanding what underlies peoples judgement of risk is central if progress on the social discussion of risk and the development of policies to manage risk are to succeed (Adams 1996, Gaskell, 1996).

It is however clear that both personal and societal views should, where possible, be based on a reasonable understanding of the facts so that informed choices can be made. In many cases personal choice translates to action (e.g. purchasing decisions) and in some cases this may be translated into legislative or regulatory actions within a society.

## 8.3 Societally Regulated Risks

Risks that are regulated or managed by society as a whole, are generally those that relate to securing general benefits for the majority. For example, the wearing of car seat belts to reduce the risk of death or injury in a road traffic accident or the enforcement of fire safety regulations and codes to reduce the risk of fire or to reduce the risk of death or injury in the event of fire.  Risks may also be regulated to secure benefits for minorities e.g. regulations regarding child safety or care of the elderly and the physically disabled.

When risks are regulated by society, judgements on risk are in the hands of the regulators and cease to be in the control of those who bear the risk.  This can act to transfer risks to some but reduce them for the majority e.g. the siting of a new reservoir or dam to collect water and reduce the risk of flooding downstream also increasing the risks to people living close to the dam. Similarly, the introduction of a flame retarded consumer product affords increased fire protection for all people, and particularly for those more vunerable groups in society, but it may also present possible human and environmental exposure risks.

In this context risk assessment is one of a number of components in the overall political process.  However, policy making must be based on rational and where possible quantitative methods of risk assessment and appropriate risk management methods which can be incorporated into an informed decision-making process.

## 8.4 Precautionary Principle

This principle has underpinned traditional actions in Europe on environmental issues. The precautionary principle asserts that where there are significant, or even suspected, risks of damage to humans or the environment, precautionary action to limit the use of potentially dangerous materials or the spread of dangerous pollutants should be taken, even where scientific knowledge is not conclusive, if the balance of likely costs and benefits justifies it.

It is clear that some people and organisations adopt the precautionary approach but either ignore or fail to quantify the balance of likely costs and benefits that justify the limited use or banning of a substance. Quantifying the balance of likely costs and benefits is an essential step in any approach to risk management.

The precautionary principle is also generally applied to single issues ignoring the fact that actions to reduce a particular risk may increase other kinds of risk. This is well illustrated in the case of flame retardants where application of the precautionary principle to protect people from the risk of contact with flame retardants is likely to produce a much larger risk from the effects of fire.

Quantified cost-benefit assessments have not been produced historically for fire and flame retardant measures. Recently this has been partially redressed through some of the pre-regulation work of the US CPSC in examining the potential economic impact and benefits arising from the possible introduction of upholstery fire regulations in the US (CPSC 1998b). Also, an estimate of the potential life saving, injury reduction and economic benefits of the UK upholstered furniture fire regulations is currently being produced as part of a DTI assessment of the benefits of the UK regulations.

## 8.5 Tolerability of Risk

Since there is no absolute definition of acceptable or tolerable risk, we have to consider all risks in relation to other risks and the benefits the risk confers. Ultimately, what constitutes an acceptable risk is a societal and most commonly a governmental policy decision - in the case of flame retardants few people will have an understanding of flame retardant use in consumer products and be able to make judgements on risk, but society would expect government to be in a position to do this. In this respect, examination of some other risk concepts is helpful.

The concept of acceptable and tolerable risks has been used in connection with the siting of nuclear power stations in the British Isles (Health and Safety Executive, 1988, 1992) and where appropriate the HSE applies them to other occupational risks of death (HSE 1992, and private communication). More recently it has been debated in the context of consumer safety where expanding responsibilities and limited resources compel policy makers to prioritise risk reduction measures and to decide what safety standards are appropriate.

The essential principles of ALARP (as low as reasonably practical) assert that above a certain level, a risk is regarded as intolerable, it cannot be justified on any grounds and is forbidden whatever the benefit may be. In the case of individual risk of occupational death, HSEs upper limit is 1 in $10^3$ pa for workers and 1 in $10^4$ pa for workers and the public affected by the work activity. Below this level, an activity and associated risk may be allowed against a background where the higher or more unacceptable the risk, then proportionately more resource will be required to reduce that risk. At the lower end of the risk spectrum, further risk reduction may be impractical or its cost may be grossly disproportionate to the improvement gained. HSE consider a broadly acceptable risk of death in the general population to be 1 in $10^6$ pa.

Adoption of maximum tolerable occupational risk in one area does not mean that the same level of acceptance can apply to all situations. It is important to consider the population size in any consideration of so-called tolerable or acceptable risks and to differentiate between individual risk and population risk (Graham and Wiener, 1995; Goldstein 1989). For example, if 1,000 people in a defined population each face an incremental lifetime cancer risk of 1 in $10^6$, the population risk of 0.001 cancer cases seems negligible; however, if a population of 20,000,000 people are exposed to the same individual risk the resulting population risk of 20 cancer cases may be perceived differently. It is also important to identify the size of exposed populations to avoid the trap of transferring a small individual risk from a small to a large population.

Where risks give rise to significant societal concerns it is possible that an individual risk of 1 in $10^6$ pa may not be considered acceptable, particularly if the risk leads to a significant number of fatalities in a single incident or where persistence of a risk leads to significant cumulative fatalities. Other situations could relate to society demanding a higher standard of protection for vunerable groups such as children and the disabled. Clearly, society and government will decide what is and is not an acceptable or tolerable risk and in the case of fire risks and countervailing flame retardant exposure risks, both of which affect the whole of society, policy decisions will be required to achieve a suitable balance point of acceptability. Comparison of these risks with others is then a legitimate area to consider.

## 8.6 Comparison of Risk

How do so-called tolerable risks for an individual informed worker and member of the public compare with other risks faced by members of the public in their day to day activities including the risks posed by fire? Some comparisons are shown in Table 6 for risks of death as an annual experience, for risks associated with major events, and for risks of death as a consequence of activity. These should be compared with those risks that are normally considered negligible such as being killed by lightning, 1 in $10^7$ pa.

Most people are not deterred from having gas central heating or cooking in their home despite a risk of death from a gas explosion being 2 in $10^6$ pa. They will also voluntarily accept childbirth or drive a car with a risk of death of 1 in $10^4$ pa.

On the other hand, fire risks are involuntary and are relatively high in comparison with other experiences (e.g. 68,376 reported dwelling fires reported in the UK in 1995) and the risk of death due to fire is moderate (8 per 1000 serious fire experiences). However, despite the overall risks appearing in the broadly tolerable band (typically, risk of death due to fire is 1 in$10^5$ pa), everyone would agree that risk reduction measures in this area is necessary and worthwhile if the risks can be brought as low as reasonably practical for loss of life, injury and economic losses.

**Table 6** Risks of death due to fire in comparison with other risk measures

**Risks of Death Expressed as Annual Experiences**
(based on UK experience)

| Cause of Death | Annual Incidence (per million per year) |
|---|---|
| Entire population (all causes) | 10816 |
| Dying from Cancer (average over UK population) | 2708 |
| Death due to violent causes (all accidents and violence) | 327 |
| Death by road accidents | 63 |
| Death due to fires (1995) | 14 |
| Death by gas incidents (fire, explosion, CO poisoning) | 1.8 |
| Death by lighting | 0.1 |

*Sources:UK Annual Abstracts of Statistics (1996), Health and Safety Statistics (1996), UK Fire Statistics (1995)*

**Major Events Occurring or Estimated Per Year**

| Event | Risk per annum | Basis |
|---|---|---|
| Fires killing ~5000 people per annum in Europe and ~5,900 in the United States | 1 | Worldwide fire statistics [1] |
| Fires killing ~800 per annum in UK | 1 | UK fire statistics (1995)[2] |
| A single fire killing 10 or more people | 1 | Experience |
| A railway accident killing or seriously injuring 100 or more people | 1 in 15 or 20 | Experience (last 40 years) |
| An aircraft accident killing 500 people | 1 in 1000 | Limited worldwide experience |

*Sources:*

*1. Lloyds List 2 August 1995, Insurance Day Issue No. 044, page 3.*

*2. Summary of Fire Statistics, UK 1995, Home Office Statistical Bulletin.*

*Rest: UK Health and Safety Executive report on The tolerability of risk from nuclear power stations, 1988*

**Some Risks of Death Expressed as a Consequence of Activity/Involvement**

| Activity | Risk |
|---|---|
| Pregnancy and associated conditions | 76 per million live birth experiences (UK 1985) |
| Surgical anaesthesia | 40 per million experiences (UK 1970 1973) |
| Vaccination | 1 per million cases (UK 1967 1976) |
| Rock climbing | 4 per ten thousand participant hours (UK 1961) |
| Fire in a dwelling | 8 per thousand fire experiences * |

*Sources: Transport and Pregnancy Risks: Annual Abstract of Statistics HMSO 1987*

*Medical and Sports Risks: Report of the Royal Society Study Group on Risk Assessment, London, 1983*

**Summary of UK Fire Statistics, UK 1997, Home Office Statistical Bulletin, November 1998 (gives 549 deaths in 68,376 dwelling fires in 1995)*

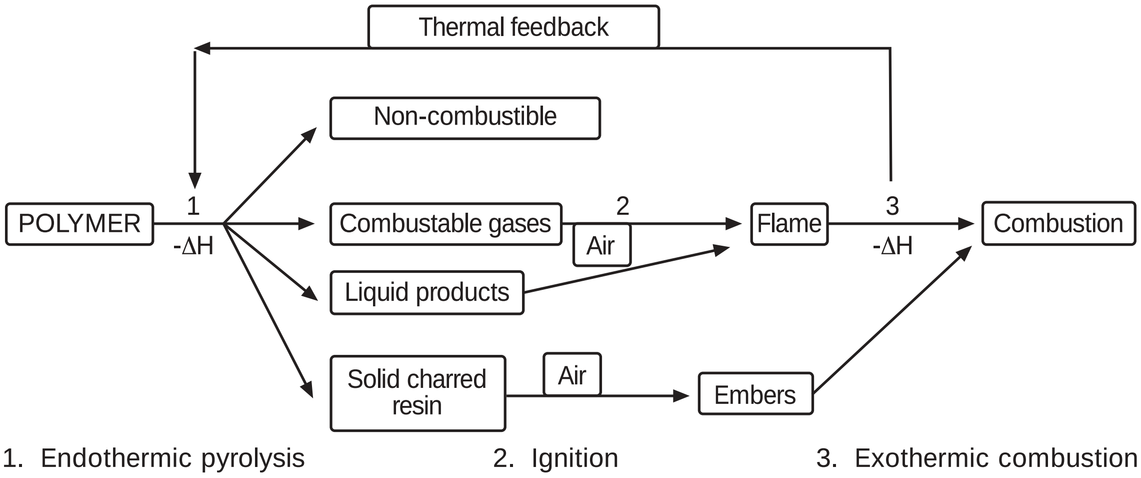
## 9 The Role of Flame Retardants in Reducing Fire Hazards and Risk

Flame retardants act to reduce fire hazard and risk in consumer products by interfering with the combustion behaviour of polymeric materials that make up these products. This section focuses on the essential mechanisms of flame retardant action in polymers and discusses how this reduces fire hazard arising from materials and consumer products involved in fire.

### 9.1 Mechanisms of Flame Retardant Action

To understand the principal mechanisms by which flame retardants operate, it is necessary to first appreciate the complex mechanism of the combustion process itself. This is illustrated in a very simple way in Figure 3, which is itself a much simplified representation of the true picture (Troitzsch, 1990). In the first stage, a source of energy (radiative, convective or conductive heat) causes thermal degradation (pyrolysis) of the polymer resulting in breakage of covalent bonds and formation of a range of intermediate products. The precise degradation mechanism also depends on the nature of the atmosphere and environment in which the polymer substrate degrades. Under reduced oxygen conditions the pyrolysis is endothermic but in the presence of oxygen oxidative pyrolysis occurs which is generally exothermic.

Figure 3 Polymer combustion process



The initial pyrolysis products consist of a complex mixture of combustible and non-combustible gases, liquids which may subsequently volatilise and solid carbonaceous chars, together with highly reactive species such as free radicals. The free radicals formed at different stages of the combustion process play a key role in determining the course of this process, the rate and magnitude of heat release and the consequential rate of flame spread.

When the initial combustible products in an admixture with atmospheric oxygen reach the lower ignition limit, they ignite producing the flame. These reactions with oxygen are generally exothermic. The energy released by these processes can initiate further thermal degradation reactions promulgating the fuel source to sustain combustion, thus leading to flame spread. The reactions which take place in the flame are radical chain branching reactions which lead to the production of highly energetic hydrogen and hydroxyl radicals (H• and •OH respectively) which propagate the overall combustion process.

Flame retardants can act by one or more mechanisms (Troitzsch, 1990; Cullis and Hirschler 1981; Mark et al, 1988) and they may be effective at different stages in the combustion process. The main criterion is that they must inhibit or suppress the combustion process in such a way as to reduce the overall heat release and flame spread of the material. By reference to Figure 3, it can be seen that flame retardancy routes can include any or all combinations of the following:

(a) Provision of a protective coating which acts as a thermal insulator protecting the substrate from thermal degradation. These are physical barrier systems generally comprising the so-called intumescent coatings

(b) Interference with the degradation processes of the solid phase material, thus inhibiting the formation of combustible gases and promoting solid phase reactions such as carbonisation. This is the mechanism of action of flame retardants operating in the condensed phase which reduces or limits the amount of fuel available to the fire.

(c) Interference with the vapour phase chemistry of the combustion process. This can occur in a variety of different ways and is the basis of the large group of so-called vapour phase active flame retardants which act to reduce heat release from the combustion process.

The mode of action of individual categories of flame retardants is discussed in relation to these mechanisms in Annexe 3 and the reader is referred to this for greater detail.

## 9.2 Flame Retardant Action in Reducing in Fire Hazard

Recently Buszard (1996, 1998) summarised in a very simple and hypothetical way the role of flame retardants in reducing hazards during the growth phase of fire. He posed a comparison of two hypothetical materials, one (A) having smoke production and toxic potencies half that of the other material (B) but with a flame spread factor twice that of a second material. By allowing both materials to burn radially for a fixed time he demonstrated the clear benefit of the lower flame spread material (B) in that it produced half the overall hazard of the theoretically cleaner burning material (A) because the latter consumed 4 times the mass. Thus in principle the use of flame retardants to reduce flame spread would also be expected to reduce toxic hazard and risk.

Whilst care is required in extending this very idealised argument to real situations - because in practice surface coverage alone is not a good measure of the mass of fuel consumed - the example serves the useful purpose of emphasizing the importance of hazard and risk assessment measures rather than toxic potency measures when comparing the fire performance of materials.

Babrauskas (1994) and Hirschler (1994) had earlier reached the same conclusion by comparing data drawn from a variety of work on heat release, toxic potency and smoke production across a wide range of materials, both natural and synthetic. In confirming the importance of controlling the fire dynamics in order to control the hazards, they concluded:

1. the effects of heat release rate on creating lethal occupant conditions are preponderant; other factors are at best contributory
2. the maximum toxic potency of a very wide range of natural and synthetic materials is at most 3 times greater than the least toxic and at the upper end is limited by the CO yield. Fire toxicity research indicates that toxic potency values can only be distinguished in practice when they are at least a factor of 3 apart
3. under post flashover conditions, the toxic potency of all tested products to date is indistinguishable
4. heat release rate (HRR) comparisons of product performance suggest that the best performing items produce around 25 to 31 kW (say 30 kW) whilst the worst performing produce around 3000 kW, a range of 100:1

and in relation to the role of flame retardants,

5. heat release rates can be reduced by factors of 10 or more by the use of flame retardants

The opportunities for hazard intervention in real fires therefore focuses on:

- reducing the seriousness of the incident by suppressing or delaying ignition
- reducing the overall hazard by avoiding or delaying flashover, through reductions in heat release rate and flame spread.

It is in these two areas that flame retardants contribute most in modifying fire characteristics to reduce overall hazard and risk.

As already discussed, fire statistics show that the majority of fire deaths are associated with products which create a fire scenario capable of spreading the fire beyond the room of origin (mainly US experience) or lead to a toxicologically untenable position for an occupant in the room of origin (UK and US experience). Further, most of the more serious fire sources involve consumer products where flame retardants could, in principle, have an impact on resultant fire hazards and risks. As we shall see below and in Section 11, both experimental work and analysis of fire statistics suggests that significant life saving benefits can be achieved if flame retardants are used in high risk consumer products.

For polymers in general the most marked influence of flame retardants is at the early well-ventilated stage of a fire when non-flame retarded polymers tend to burn cleanly producing relatively low toxicity effluents. Flame retarded polymers, on the other hand, tend to flame intermittently, if at all, and may produce higher relative yields of smoke, CO, HCN and irritants (Purser, 1995) than their non-flame retarded counterparts. However, whilst the toxic potencies may appear to be higher, the actual toxicological hazard is related to the amount of substrate consumed and allowance has to be made for the influence of flame retardants reducing substrate consumption.

Babrauskas et al (1988) compared five consumer products, and the materials they were made of, with and without flame retardants (for details see Annexe 7). Conclusions from the smaller scale tests were:

- in four out of five product categories the FR products had reduced burning rates. The exception was electrical cables
- none of the products gave smoke of extreme or unusual toxicity although, in the cases of the flame retarded TV cabinet, insulated wire and circuit board, unidentified agents made a small contribution to the specimens toxicity
- smoke from flame retarded and non-retarded products was of similar toxic potency and comparable with smoke from materials commonly found in buildings.

In contrast more significant conclusions came from the room/corridor tests on all of the consumer products:

- the time to untenability (i.e. time to flashover or to the occurrence of an incapacitating atmosphere) was more than 15 times greater for flame retarded than for non-retarded products
- the amount of material consumed in the fire was twice as much in the non-retarded tests as in the flame retarded tests
- the amount of heat released was 4 times as much in the non-retarded tests as in the flame retarded tests
- the quantity of toxic gases in CO equivalents was 3 times as much in the non-retarded tests as in the flame retarded
- smoke production was not significantly different in both sets of tests.

In contrast, Purser (1990) in a review study, considered the influence of flame retardants on flexible polyurethane foams. He concluded that, whereas flame retardants confer great benefit in making flaming ignition less likely and in slowing the rate of fire growth, they have less benefit if fires become established. He further suggested that the most likely adverse effect of flame retardants would be to delay the onset of flaming and reduce combustion intensity during early flaming, thereby decreasing combustion efficiency and increasing yields of CO, HCN and other pyrolysis products. Purser cites evidence from bench-scale and chair-scale studies indicating that flame retardants may have adverse effects if a period of smouldering precedes flaming combustion. However, care is required in the interpretation of these observations because it is important to account for the total mass consumed and how effective the delay in ignition would be in facilitating escape and reducing the overall risk.

The overall conclusion of the survey by Purser (1990) was that there may be a safety gain in the use of flame retardants in reducing the incidence of fires but, once smouldering or flaming begins, the hazard is scenario-dependent and there may be a disadvantage in using flame retardants. If fires reach flashover, flexible polyurethane foams give high yields of CO, HCN and organic irritants and any influence of flame retardants during this stage of the fire is likely to be insignificant.

A study has been carried out on the effects of flame retardants on the fire effluents from 44 different textile substrates (Wright 1997) using the tube furnace method of DIN53436 and chemical analysis based FED calculations to assess toxic potency.

Flame retardants had the effect of reducing the proportion of the substrate consumed under non flaming conditions at the test temperatures used (400°C and 700°C). The effect of the flame retardants was to reduce the yields of the organic irritants, acrolein and formaldehyde, at both test temperatures under non flaming conditions. Wright concluded that differences in toxic potency caused by flame retardants under non flaming conditions are not great enough to outweigh the advantage of reducing the rate of growth of fires.

These examples serve to illustrate that flame retardants are usually most efffective in the early and developmental stages of fire when they can confer a net reduction in overall fire hazards. Further, benefits in fire risk reduction are to be expected through avoidance or delay in ignition and the reduction in heat release rate during the growth phase of fires

## 10 Flame Retardant Use in Consumer Products

With concern being expressed over the potential risks associated with human exposure to flame retardants it is useful to understand the extent to which they are used in general and in consumer products in particular, within Europe.

The flame retardant chemicals market in Europe is estimated to be around 200,000 tonnes per annum and worth over £500m per annum in 1995 and growing at between 3% and 6% per annum. In contrast, it is conservatively estimated that only around 17,000 tonnes are used in consumer products each year. According to a recent market report on the European Flame Retardant Chemicals Industry 1996 (IAL Consultants, 1997):

- Organobromine compounds constitute the largest value business in Europe with an estimated volume of 64,000 tonnes and a value of £174m
- Germany is the largest country market
- PVC is the largest end-use materials sector in Europe
- Alumina trihydrate (at 120,000 tonnes/£60m per annum) and other inorganics are the fastest growing flame retardant sectors
- Polypropylenes are the fastest growing end-use materials sector for flame retardants

Understanding commercial flame retardant usage in consumer products is a non-trivial task as there are a wide range of flame retardant compounds on the market (in 1996 the European Flame Retardants Association listed 425) and commercial confidentiality restricts information on the markets they service and the tonnages actually in use. Gaining access to this information in the open literature is not really possible and it is necessary to use alternative sources including industry interviews to piece together an overall picture.

In Annexe 2 we present detailed information drawn from several independent technical and market reports, including among others an Environmental Health Criteria report (EHC, 1997) and a recent market report (IAL,1997), to build a comprehensive picture of flame retardant use generally in Western Europe. We have also used recent work undertaken by the DTI on flame retardant use in consumer products. This work utilised consumer product information, technical and market reports and industry interviews to obtain an indicative view of this market. These results are summarised in Table 7.

**Table 7** UK and European Use of flame retardants by consumer product type

| Upholstered furniture | Main FR used | UK (tonnes) | Rest of Europe (tonnes) | Europe Total (tonnes) |
|---|---|---|---|---|
| Textiles | Brominated FRs typically DBDPEs/HBCD + antimony trioxide | 1500<br>600 | 0 | 1500<br>600 |
| | Phosphorus based FRs, eg Proban, Pyrovatex | 300 | 0 | 300 |
| Fillings (foam) | Melamine +<br>TCPP | 5000<br>2500 | 0 | 5000<br>2500 |
| **Total furniture** | | **9900** | **0** | **9900** |

| Televisions | Main FR used | UK (tonnes) | Rest of Europe (tonnes) | Europe Total (tonnes) |
|---|---|---|---|---|
| Backcasings | Mainly brominated (eg DBDPEs, TBBPA), + antimony trioxide, Others phosphate esters, triphenyl phosphates, chlorinated phosphates, melamine cyanide800 | 300+<br>100<br>100 | 2100+<br>700<br>700 | 2400<br>800<br>800 |
| Printed circuit boards | Brominated FRs, eg TBBPA + antimony trioxide,<br>also halogen free phosphorous based FRs, red phosphorus, chlorinated FRs, magnesium or aluminium hydroxide | 50<br>10<br>5 | 350<br>70<br>15 | 400<br>80<br>20 |
| **Total TV** | | **565** | **3935** | **4500** |

| Business machines in the home | Main FR used | UK (tonnes) | Rest of Europe (tonnes) | Europe Total (tonnes) |
|---|---|---|---|---|
| PC monitor casings, internal components<br>PCs, printers, fax machines, copiers | Brominated, eg TBBPA, + antimony trioxide<br>Phosphate esters, aromatic phosphorus based FRs | 85+<br>15<br><25<br><25 | 460+<br>90<br><50<br><50 | 545+<br>105<br><75<br><75 |

| Other consumer Electrical/electronic products | Main FR used | UK (tonnes) | Rest of Europe (tonnes) | Europe Total (tonnes) |
|---|---|---|---|---|
| vacuum cleaners, coffee machines, printed circuit boards, plugs, sockets | Mainly brominated FRs, typically FF680, TBBPA + Antimony trioxide<br>Others phosphate esters, aromatic phosphorus based FRs, red phosphorus, chlorinated FRs, magnesium or aluminium hydroxide | 85+<br>15<br><15 | 460+<br>90<br><75 | 545+<br>105<br><100 |

| DIY products | Main FR used | UK (tonnes) | Rest of Europe (tonnes) | Europe Total (tonnes) |
|---|---|---|---|---|
| PU foams/sealants. Some used in insulation and DIY electrical products | Organic phosphates<br>Brominated FRs also mentioned | <40<br><25 | >210<br>>125 | 250<br>150 |

| Automotive | Main FR used | UK (tonnes) | Rest of Europe (tonnes) | Europe Total (tonnes) |
|---|---|---|---|---|
| seating, headrests, door panels | TCPP, chlorinated phosphates also developments in other non brominated/ non chlorinated phosphates | 0 | 500 | 500 |

| Childrens nightwear | Main FR used | UK (tonnes) | Rest of Europe (tonnes) | Europe Total (tonnes) |
|---|---|---|---|---|
| Girls nightdresses | Phosphorus based FRs, with typical tradenames: Aflammit KWB, Proban, Amgard TFR1, Pyrovatex | 125 | 0 | 125 |

| Yoys/nursery | Main FR used | UK (tonnes) | Rest of Europe (tonnes) | Europe Total (tonnes) |
|---|---|---|---|---|
| Wendy houses | Phosphate esters<br>+ antimony trioxide | 20<br>5 | 0<br>0 | 20<br>5 |

| | | | | |
|---|---|---|---|---|
| **Total use of FRs** | | **10,920** | **6130** | **17,050** |

One problem that was highlighted in this work was that producers of flame retardants rarely know where the chemical is going. Hence the tonnage estimates are best estimates based on pulling together the views of respondents across the market as a whole.

In the consumer product market suppliers of flame retardants have seen a global rise in the use of flame retardants with a greater increase in brominated flame retardants as these are considered the most effective. In general a compounder or injection moulder will try to avoid using a flame retardant as it changes the properties of the plastic and can make it more difficult and more expensive to satisfy all product requirements. Therefore flame retardants tend to be used only where there are legislative requirements, (e.g. UK upholstered furniture regulations), or where component performance standards have to be met, (e.g. television back casings, low fire hazard cables) where flame retardants may be used to meet these requirements.

# 11 Flame Retardants in the Context of the Risks of Existing and New Chemicals

When considering flame retardants we cannot divorce our consideration of these compounds from the attention paid to other chemical substances and the regulations and controls that affect all chemicals both existing and new.

## 11.1 General Observations

Our perception of the risks associated with flame retardants and our actual approach to risk assessment of these compounds in their unactivated state should, in principle, be no different from that of other chemical compounds. The key difference is that when flame retardants are activated by fires they act to potentially reduce or counter fire hazards and risks but at the same time they may present additional risks to human health and to the environment and from their potential contribution to, or change of, the fire atmosphere. As already stated, it is important that these risks be considered in relation to the risks presented by fire and enumerating and reconciling these relative risks is at the heart of the problem.

The International Programme on Chemical Safety (IPCS) is leading the harmonisation effort with regard to toxic risks for human health (and the environment) and the OECD is leading the effort with respect to environmental risk assessment. Both are long term activities that recognise the enormity of the task.

In Annexe 8 it is argued that risks associated with new and existing synthetic chemicals, including flame retardants, should not be differentiated from those presented by natural products. What may differ are the methods of management, control and regulation. Moreover, the risks associated with synthetic chemicals should not be considered in isolation but compared with those presented by all compounds that can come into contact with humans or the environment; flame retardants are no exception.

## 11.2 Progress in the Risk Assessment of Chemicals

Since 1993 in the European Union, new chemicals that are not listed on the European Inventory of Existing Chemicals (EINECS) are regulated and cannot be introduced without prior notification; this requires extensive testing. However, existing chemicals, which are already on the list, did not and do not currently require testing.

The objective of the existing chemicals regulations is to gather all available information on chemical substances produced in quantities greater than 10 tonnes/year in order to evaluate and control any risks in relation to human health and the environment. When new concerns arise on existing chemicals, they may be prioritised for review according to the same criteria that are adopted for new chemicals. This has occurred for several flame retardants that are currently undergoing priority chemical review.

Generally, it is recognised that risk assessment should be fully integrated for all chemical substances, in that both human health and environmental exposure and effects should be considered together. Rigorous risk assessment, prioritisation, estimation and management methods for chemical substances are in their infancy and progress with the methods being adopted in the European Union has recently been reviewed at a meeting under the auspices of the European Environmental Research Organisation (EERO). This review (Van Leeuwen et al, 1996) concluded that whilst prioritisation methods appear acceptable, improvements are necessary for:

(i) the estimation of consumer and occupational exposure

(ii) the derivation, use and transparency of assessment factors for substances based on their mode of toxic action

(iii) environmental exposure models, their validation and their relation with monitoring data

Also a key action was to:

(iv) develop tools including voluntary agreements to speed up the slow chemical-by-chemical approach to risk assessment and management.

It is likely to take a number of years to achieve these improvements for all chemicals including flame retardants.

In the meantime, new chemicals with potential sales or supply above 10 kg in Europe have to be notified and are required to satisfy a limited number of chemical safety criteria before they can be placed on the market. Similar requirements exist in North America, Japan and a number of other countries

The cost of research and testing to gain approval is extremely high, so manufacturers are unlikely to embark on approval unless they have confidence in the chemical safety and environmental acceptability of their products. These costs will also commercially mitigate against new flame retardants coming on to the market; to quote Clous (1998), *“although the market requests more environmentally friendly flame retardants the barriers to successfully introduce such products is considerable ... ... ... . to do this at the same costs as the old established products is even more difficult if not impossible”*.

# 12 Risk-Benefit Assessment of Flame Retardants

In common with other groups of chemical compounds there is an incomplete understanding of the potential hazards and risks associated with many flame retardants. In spite of this, our common experience does not indicate any practical risk from human exposure to flame retardants in consumer products. It is apparent that there is public exaggeration of the risks of supposed exposure from these chemicals (see Annexe 8). On the other hand, there is an incomplete understanding of the benefits flame retardants confer in terms of lives saved, non-fatal casualties avoided and reduction in adverse health effects resulting from human exposure to fire. Similarly, there is a paucity of data on the economic benefits associated with reduced property loss and other consequential losses due to fire.

So, both sides of the risk-benefit equation have not been fully enumerated and have been poorly communicated historically. Indeed, flame retardants have also become entrenched in the chemical paranoia or chemophobia that characterises many people’s response to synthetic chemicals, particularly those associated with halogen and phosphorus containing substances and others with exotic-sounding chemical names. Continuing reference by the media and some pressure groups to the flame retardant TRIS - tris-(2,3-dibromopropyl) phosphate - which has been banned in the UK and US and has not been commercially available in Western Europe since 1976 - aggravates public chemophobia and continues to influence some regulatory authorities in their judgement concerning flame retardants in general.

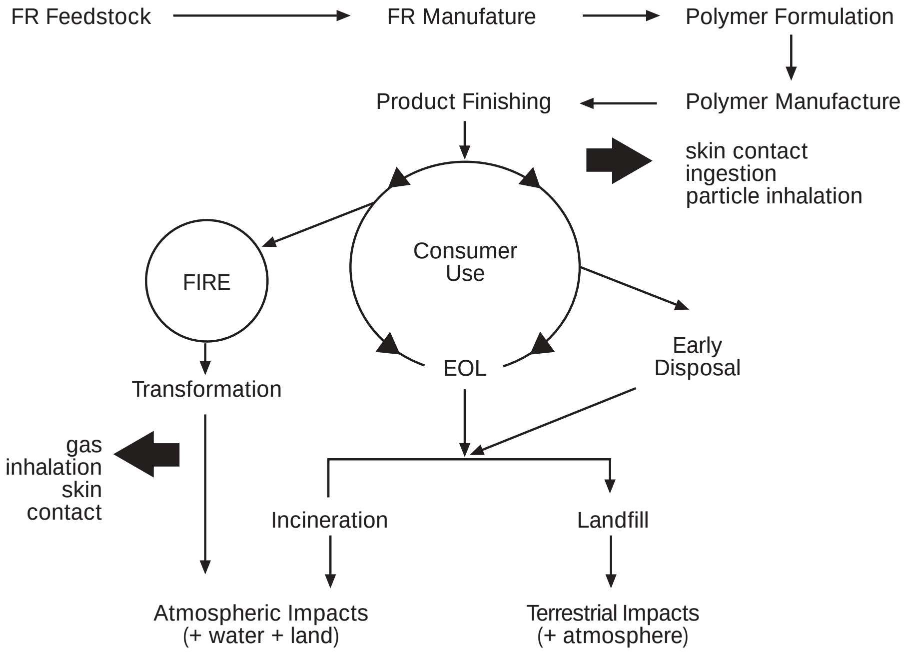
Flame retardants are part of the existing and new substances regulations and their risks are now being assessed and managed according to the principles and methods being established for other chemicals. Such action has already seen the brominated flame retardant industry enter into a voluntary agreement with OECD to undertake several specified measures to give improved assurance on human toxicology and environmental safety (OECD, 1995).

Life saving and cost-benefit assessments have recently been considered by the US CPSC in examining the potential economic impact and benefits arising from the possible introduction of upholstery fire regulations in the US (CPSC 1997). Also, an assessment of the life and injury savings and potential economic benefits arising from the introduction of the UK upholstered furniture fire regulations is currently being produced as part of a DTI assessment of the general benefits of the UK regulations. This work demonstrates that significant life saving benefits exist; this should form part of more detailed life-cycle benefit studies in the future.

## 12.1 Life-Cycle Risk Assessment

Despite these advances the authors are unaware of any published comprehensive life-cycle risk-benefit studies on flame retardants. However, this is not surprising as such studies are rare for any compound. Nevertheless, the need to develop such a perspective is important as we see society moving slowly yet progressively from linear consumer economics toward more sustainable closed-loop and recycling economies. It is clear that the risk assessment exercises would be different for these two cases when account is taken of the cumulative effect of risks associated with repeated recovery and recycling and the change in human and environmental exposure.

Figure 4 Linear economy life-cycle for a flame retarded polymer consumer product.



A schematic of a linear economy life-cycle model (with no recycling) for flame retarded consumer products is shown in Figure 4. Life-cycle toxicological hazard and risk assessments require that the human exposure and environmental impacts at all points in the life-cycle be assessed. Such cradle to grave analysis would also differentiate between the occurrence of a fire event and its associated human and environmental impacts and the usual end of life (EOL) impacts arising from either disposal by incineration or landfill.

It is appropriate to focus on the prime area of benefit associated with flame retardants in their role as a fire hazard counter-measure during consumer use. As an alternative to full life-cycle assessment, it is reasonable to focus on the consumer-use region of the products life-cycle. Indeed, at any point in time this part of the life-cycle is essentially equivalent in both the linear and closed-loop recycling representations and a balance-of-risk approach can be applied.

Significant work has also been done on understanding the mode of action of flame retardants in a wide variety of materials and on comparative ad-hoc fire tests in which flame retarded products have been compared with their non-retarded counterparts. However, few studies have been performed on quantifying the action of flame retardants in reducing overall fire hazard and risk; to the authors knowledge only two studies to date have attempted to quantify the life safety benefits of flame retardants.

## 12.2 Television Fires

Television fire trends historically in the UK, Europe and US clearly demonstrate significant improvements in fire safety performance as a result of the introduction of regulatory directives and voluntary action on the part of industry to improve consumer product fire performance.

In the US this arose from the 1973 ruling of the US Consumer Product Safety Commission (CPSC) which required that all television fires be contained within the cabinet. Virtually all of the televisions sold in the US adhere to the voluntary fire standards established by the manufacturers in association with Underwriters Laboratories. As a result of this action CPSC estimates that from 1983 to 1991, the number of residential fires due to televisions fell by 73% from 4,500 to 1,200 which is twice the rate of decrease in fire incidents over the same period.

Studies commissioned by the UK Department of Trade and Industry Consumer Safety Unit indicate a similar trend with essentially the same percentage changes in the UK and Europe, in this case due to the introduction of European Community Directive 73/23/EEC. In the UK, reported TV fires peaked at 2,356 in 1974 and this reduced to around 430 fires per annum between 1989 and 1994, a reduction of 79%.

These improvements were obtained as a result of improved electrical component design and the use of flame retarded circuit boards, components and cabinet panels. Whilst a substantial benefit can be claimed for the action of flame retardants, we are not aware of any attempts in Europe to quantify the life-saving and other benefits of these intervention measures. This example provides an opportunity to assess these benefits critically and we recommend that such an assessment be performed.

This recommendation is made against a background where a new fire performance standard for television backcasings and backplates has been introduced by the International Electrotechnical Commission (IEC 60065). It is also disturbing to see that the introduction of non-legislative/non-regulatory Ecolabels in Germany, requiring the removal of halogenated flame retardants and plastics, has led to a reduction in the fire safety of TVs in Germany and Europe. If the Ecolabel trend continues this could have a significant negative impact on television fire safety standards (Troitzsch, 1998) and the authors would expect this to impact on European fire lethality statistics.

## 12.3 BFRIP Life-Safety Benefit Study

This study sponsored by the Brominated Flame Retardant Industry Panel (BFRIP, 1997b) sought to identify, and where possible quantify, the life safety benefits of brominated flame retardants (BFRs) using US fire experience data from the National Fire Protection Association (NFPA). Consideration of the US fire statistics, from 1983 to date, highlighted a number of key hazards where flame retardants could have an impact; these are summarised below:

1. Fire deaths occur almost exclusively in buildings and most in residential settings, homes, hotels and health care facilities.
2. Fires are common (with up to 90% not reported) but proportionately fatal fires are rare.
3. The 10% of reported fires in the US amounts to 600,000 serious fires annually with over 4,000 deaths 6.7 deaths per 1000 fires in 1991 (compared with 7.9 per 1000 in 1994).
4. Fire hazard from fires which spread beyond the room of origin are from 3 to 10 times more deadly than those that do not

The BFRIP study (discussed in Annexe 7) utilised the US residential fire statistics presented in Section 3.4 and Table 5. It focused on four product classes in which brominated flame retardants are commonly used, including: television appliances, wire and cable insulation, curtains and draperies, and upholstered furniture.

Two statistical analysis approaches were used; a retrospective analysis for televisions, curtains and drapes and wire and cable insulation, and a prospective analysis for upholstered furniture in which the source of ignition (cigarette or open flame) and flame retardant intervention options were also considered. In both cases attempts were made to identify upper and lower bounds on the inferred or prospective number of lives saved and these were compared with the maximum potential savings of life. Some of the key results are summarised in Table 8.

Table 8 Estimates of annual lives saved from retrospective or prospective analysis of US fire statistics.

Retrospective Estimates of Annual Lives Saved

| BFR Retarded Product | Total from Direct Ignition | Total from Secondary Involvement | Total Estimated Life Saving | Maximum Potential Saving |
|---|---|---|---|---|
| Television sets/appliances | 90 | 100 | 190 | 510 |
| Electrical Insulation | >80 | ~0 | >80 | >80 |
| Draperies | >10 | ~0 | >10 | >10 |
| Upholstery Fabric (back-coating) | 10 | >0 | 10 | 10 |
| **Totals** | **>190** | **>100** | **>290** | **>610** |

Prospective Estimates for Upholstered Furniture

| BFR Treatment | Total Estimated Life Saving | Maximum Potential Saving |
|---|---|---|
| Back-coating of Fabric | 144 | 160 |
| Flame Retarded Cushioning | 216 | 216 |

This study concluded that within US experience the total life loss reduction associated with the use of flame retardants in the product areas considered, is estimated at 290 deaths avoided per year and it could be as high as twice that number. For upholstered furniture another 140-220 fire deaths per year were identified as avoidable if non-cellulosic upholstered furniture fabric were back-coated with a flame retardant latex.

By summing the number of fires in Table 5 for these higher risk product areas, we estimate approximately 500 and at most around 800 avoided deaths for a total of 55,873 fires. This equates to an effective risk reduction of 9 - 14 avoided deaths per 1000 fires for these higher risk products. This may be compared with specific risks of death due to different items first ignited in Table 5; these currently fall in the range 0.5 to 86 deaths per 1000 fires for the products considered. Broader comparisons may be made with the overall 1986 - 1990 statistics of 8.6 deaths per 1000 fires, for fires confined to the room of origin, and 27 per 1000 for fires which spread beyond the room of origin.

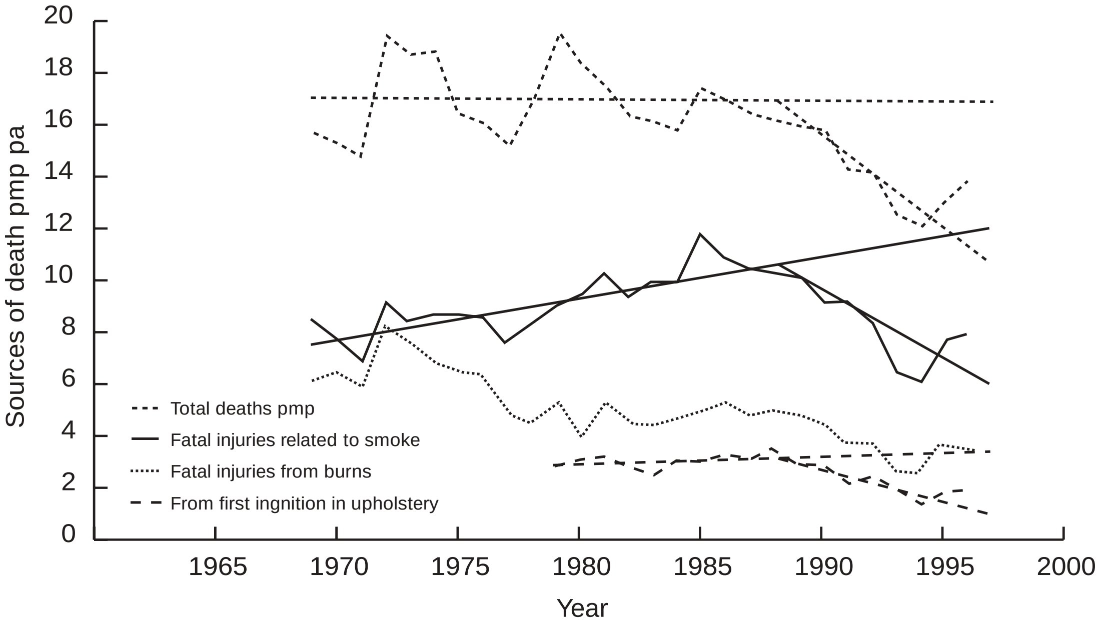
This analysis suggests that significant fire lethality risk reduction benefits can be ascribed to the influence of flame retardants on the fire performance of high risk consumer products. Critically, we could question the precise size of the risk reduction and examine what fraction of the benefit could be ascribed to factors other than flame retardants. The US CPSC has also examined the BFRIP report and whilst they disagree with several aspects of the approach and methodology, they do agree with the general conclusions; they also obtained similar savings projections for furniture but by a different route (CPSC, private communication). So, despite a number of obvious limitations in the existing analysis, the primary intervention or risk reduction benefit of flame retardants is clear.

### 12.4 Study on the Benefits of the UK Upholstered Furniture Fire Regulations

This study, being carried out by the Polymer Research Centre of the University of Surrey (Emsley and Stevens, to be published) has critically examined the current and future prospective life-saving, injury-reduction and economic benefits of the UK upholstered furniture fire regulations (HMG, 1988). This report is to be published early in 1999. We show here some of the more important preliminary findings concerning life-saving benefits.

Using data from the last 30 years of UK Home Office Fire Statistics reports and UK demographic data, the change in the number of deaths per million of the population (pmp) due to fires in dwellings can be determined before and after the introduction of the regulations. This is shown for a variety of metrics in figure 5.

Figure 5 Pre- and post 1988 UK trends in fatal fire injuries.

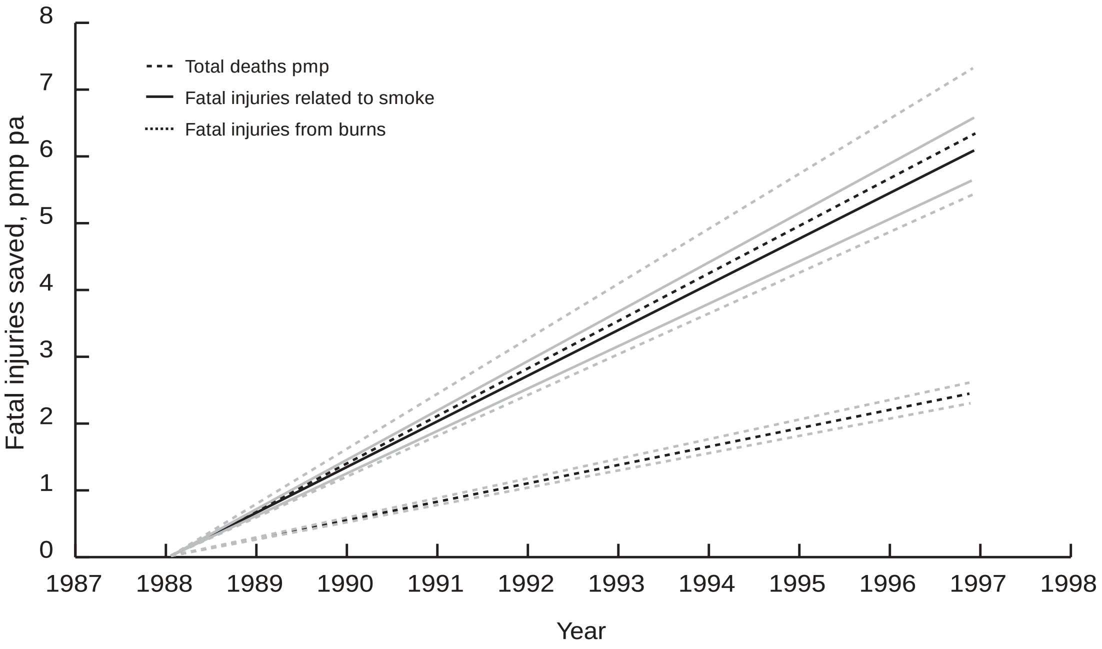


Interestingly, these plots show that the inexorable pre-1988 rise in the number of fatal injuries resulting from smoke inhalation is being balanced by a progressive reduction in fatal injuries due to burns. Post-1988 the reduction in the number of deaths connected with upholstery as the first item ignited, and from fatal injuries arising from smoke inhalation, lead to clear reduction in the overall total incidence of death due to fires in dwellings. We have chosen 1988 as the intercept point for the pre and post regulation trends because this fits the data better than any other intercept.

The life saving benefits can be determined by comparing the pre- and post-1988 projections where the intercept has been chosen to give a zero difference in 1988. These data are also corrected for the effect of smoke alarms which only play a small role in achieving life-saving benefits in the UK (see Annexe 1, Section 7). The projected savings are shown in figure 6 below.

This indicates that in 1997 a life-saving benefit of around 6 lives pmp per annum was achieved (ie 354 lives in 1997) and that in the 10 years since the introduction of the regulations there has been an overall average saving of 32 lives pmp (ie the total cumulative lives saved from 1988 could be as many as 1860). These figures relate to the involvement of all consumer products covered by the regulations and are fully reconciled. In the case of upholstered furniture as the first item ignited the corresponding benefits obtained from provisional statistics are about 2.4 lives pmp per annum in 1997 (ie 142 lives in 1997) and around 12 lives pmp (ie the total cumulative lives saved from 1988 could be as many as 710) since the introduction of the regulations.

**Figure 6** Post 1998 fatal injury savings; fine dotted lines are the 95% confidence limits.



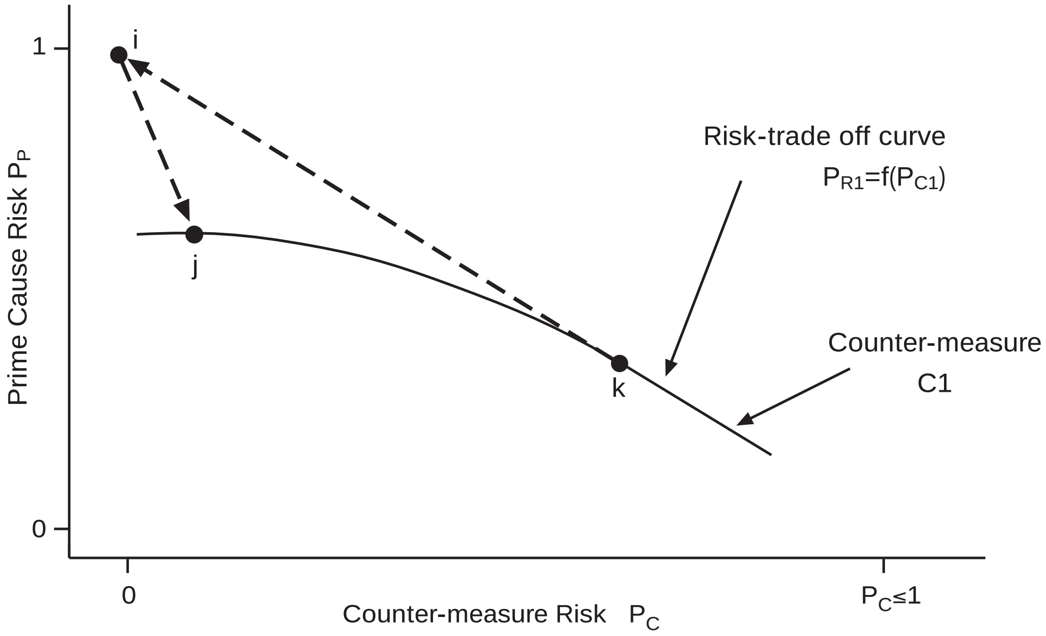
Potential approaches to considering balance-of-risk and risk-trading are discussed in Annexe 9. A simple method for a balance of risk assessment is also discussed which is applied here to flame retardants in fires.

### 13.1 Framework for Risk Tradeoff Analysis

The concept of risk-trading is illustrated in Figure 7. The approach is to reduce the impact of a prime cause risk by the use of a counter-measure which has its own countervailing risk. If the reduction in the prime cause risk is large enough and the countervailing risks are small enough then we may gain an overall risk-reduction benefit.

In Figure 7 we consider one particular counter-measure C1 which can achieve a range of reductions in the prime cause risk for increasing levels of counter-measure risk. The risk-tradeoff curve defines the risk-trading relationship (or operational range). We could elect to move from our original position i where no interventions apply (e.g. unrestrained fire) to either point j or k for the counter-measure C1 (e.g. flame retardant with level of fire restraint increasing with increasing concentration). We can then assess the level of risk-reduction benefits (for the same risk end-point) i.e. $P_{Pi}$-$P_{Cj}$ compared with $P_{Pi}$ -$P_{Ck}$ and seek the best possible level of risk reduction. This can be repeated for a number of potential counter-measures.

Figure 7 Risk-reduction through risk-trading schematic.



A structured approach to risk tradeoff (or so-called risk-risk) analysis would contain the following essential steps:

(i) characterisation of the prime cause risk

(ii) identification and characterisation of the tradeoffs that might result from an intervention or counter-measure

(iii) weigh the comparative importance of the target (or prime-cause) risks and countervailing risks using the same risk metric

(iv) analyse overall risk reduction options and identify so-called risk-superior opportunities (i.e. having significant overall risk reduction benefits)

(v) assess the net benefits and costs of alternative risk reduction strategies, consider other relevant factors, then select the most appropriate counter-measure.

It is important in this approach to assess the impact of a counter-measure on the target or prime cause risk and to assess the size and significance of any associated countervailing risks. For example, the need to account for short and long term benefits alongside the side effects of a drug with those of alternative therapies e.g. the value of child immunisation programmes in eliminating potentially lethal epidemics versus the finite but small risks of disabling side effects. Similarly, the need to consider short and long term human and environmental toxicity hazards and risks arising from flame retardant use with those related to exposure to unrestrained fires.

Risk tradeoffs may also involve seeking risk-superior moves, as discussed in Annexe 9. These, could be achieved by the use of one or more intervention measures; for example, a combination of flame retardants acting synergistically, or the combination of design change with flame retardancy, as shown in the work of the CBUF group on upholstered furniture fire performance (see Annexe 7).

The final choice of counter-measure may involve weighing up and assessing a number of hard and soft factors such as net cost benefit, significant life saving benefit versus long term side effects, public opinion, availability of alternative counter-measures etc. Such choices can be based on quantitative and qualitative information and may require the assistance of multi-attribute decision support techniques.

Further work is required to develop risk-benefit and risk tradeoff analysis for consumer products involved in fire, and for fires in general, where account is taken of all potential risks within a life-cycle risk assessment framework. We recommend that this is pursued to enable the most beneficial and cost effective strategies to be identified.

## 13.2 Balance of Risk Assessment for Flame Retardants

In the absence of a developed approach to risk tradeoff analysis for fires, we attempt a preliminary and simplistic balance of risk assessment for flame retardants which could set the scene for more detailed analysis in the future. This exercise also serves to illustrate some of the more important issues and where refinement is likely to be needed in a more considered analysis.

This approach recognises that the risk of a fire event (the prime-cause risk) can be reduced (or balanced) by the acceptance of an intervention or counter-measure risk, in this case the use of a flame retardant. At the most fundamental level the methodology requires that the risks being compared relate to the same end-point. Suitable risk end-points for fire events could be (i) death, (ii) short-term injury, (iii) long-term injury, and (iv) the risk of experiencing a particular monetary loss.

The size of the benefit conferred by the flame retardant will be directly related to the reduction in risk due to an unrestrained fire plus any additional risk (related to the same risk measure) arising from the flame retardant itself. For a particular event, the risk reduction benefit is:

P(risk reduction benefit) = P(unrestrained fire risk) - [P(restrained fire risk) + P (flame retardant risk)]

Where the Ps are total risk probabilities, summed over all contributing risk probabilities, for a particular common end-point. If the risk reduction probability is positive a net benefit results; if it is negative, no benefit exists and the use of the flame retardant should be discontinued.

In applying this approach to fires involving consumer products in dwellings, we could consider three risk measures, (i) the risk of death, (ii) the risk of acute short-term injury and, (iii) chronic long-term injury or disability. These three risk measures enable a more complete assessment of the potential short term impacts of fire and of flame retardants with longer term impacts. The latter may arise from, on the one hand, post fire trauma and sequelae effects, and on the other hand, long term exposure to flame retarded products.

In suggesting this approach we recognise that definitive data are not currently available to fully quantify each risk assessment approach. However, going through the exercise illustrates the potential value of this approach and what information we will need in the future to better quantify the risk-reduction benefits of any fire intervention or counter-measures.

### (i) Risk of Death

We have seen that the risk of death due to fires in domestic dwellings can be measured in a variety of ways. We can adopt a number of appropriate measures for input into the balance of risk equation; using UK dwelling fire statistics we can identify the following risks:

(a) 8 fatalities per 1000 reported fires (compared with around 40 per 1000 for higher risk upholstery and covers)

(b) 0.7 fatalities per 1000 household fire events

(c) 9.4 fire fatalities per $10^6$ of the population per annum

However, for high risk consumer products, such as upholstered furniture, we have seen from US statistics that the risk of death can be as high as 86 fatalities per 1000 serious fires when the fire spreads beyond the room of origin; in the UK it is 40 fatalities per 1000 serious fires for the same product (but where part of the population of upholstered furniture meets UK fire performance standards).

The reduction in risk associated with the use of flame retardants is not known precisely. However we can make some estimates based on results reviewed in this report:

1. BIFRIP report suggested risk reductions of 9 - 14 per 1000 fires p.a. on an average of 27 per 1000 fires (for fires that spread beyond the room of origin) in the US, a reduction of around 30 - 50%.
2. UK upholstered furniture fire regulations, gross risk reduction of 6 per $10^6$ of the population p.a.
3. Television fire fatality reductions (peak to plateau without account of growth in total numbers) 70 - 80%, from UK, European and US experience.
4. NBS fire retardant study (Babrauskas 1988):
    - toxic gases reduction x3, could translate to a 67% risk reduction or better based on risk being directly proportional to toxic hazard
    - material consumption reduction x2, could conservatively translate to a 50% risk reduction based on toxic hazard being directly proportional to mass loss
    - heat release rate reduction, x4, could translate to 75% risk reduction if risk is directly related to HRR (this is very conservative)
    - escape time improvement, x15, could translate to 93% risk reduction or better assuming that risk reduction is inversely proportional to escape time; however, this is conservative as the number of casualties increases exponentially with time taken to evacuate (Phillips, 1995).

These potential risk reductions conservatively span the range 30 to over 90% for products that could be considered high risk. It may be different for lower risk products. This serves to illustrate that we need to further partition risk reduction benefits according to product type and according to individual flame retardant systems.

In the case of upholstered furniture in the UK it has been demonstrated that the reductions in risk of death are significant. In 1997 these can be equated to 1 in $4.2 \times 10^5$ p.a. risk reduction for furniture as the item first ignited and 1 in $1.6 \times 10^5$ p.a. for overall risk reduction in dwellings. These equate to risk reductions in relation to pre-1988 trends of 35% and 67% respectively with the prospect of further significant reductions as more post-1988 furniture replaces older furniture in the UK economy (as discussed in the DTI report to be published).

In practice it is now possible to estimate the risks and risk reduction potential associated with a change in heat release rate, toxic gas emissions levels (or mass loss) and delayed ignition time by using one of a number of risk assessment programmes that exist (see Annexe 8 and Phillips 1995). In principle this would enable us to integrate this form of risk assessment into fire safety engineering.

What is the size of the associated counter-risk due to flame retardants in comparison with the above levels of risk reduction? The answer is we dont know precisely. However, our assessments of the toxicology of the flame retardants considered in this report suggest that the population exposure risks are negligible (less than 1 in $10^7$ per annum). Indeed, we are not aware of any deaths occurring as a result of exposure to flame retarded products. If this is correct, the lethality risk reduction benefits are significant and are sustained in the face of the counter-measure risks; i.e. the population lethality benefit risk to adverse risk ratio is greater than 100:1.

However, caution is required in applying this result to all flame retarded products. The context and performance of each product must be considered separately and alternative counter-measures examined that may have very low intrinsic risk, for example the use of non-combustible products or design changes that could confer equivalent fire performance. We need to institute methodologies and produce the data that will enable this exercise to be carried out with appropriate levels of certainty.

### (ii) Risk of Short Term Injury

We can adopt a number of appropriate measures based upon UK dwelling fire statistics:

(d) 191 injuries per 1000 reported fires (compared with 413 per 1000 for higher risk upholstery and covers)

(e) 16 injuries per 1000 household fires

(f) 225 fire injuries per $10^6$ of the population per annum

We can use the same reasoning as in the risk of death case to show that the estimated risk reduction levels for short term injury may be in the range 30% to 90%, or greater, for higher risk products. This leads to a greater degree of overall risk reduction than in the case of death because of the higher risks of injury from fire; the range is 68 to 203 injuries per $10^6$ of the population per annum.

What is the size of the associated counter-risk due to flame retardants in which the injuries are comparable to those of non-fatal fire injuries? Again we cannot answer this precisely but we are unaware of any evidence to suggest that this is likely to be any higher than 1 in $10^6$ per annum. Clearly, the risk reduction benefits are significant for this risk measure and are sustained in the face of counter-measure risks due to flame retardants. The corresponding population risk ratio is probably in excess of 100:1 to 200:1.

### (iii) Risk of Long Term Effects.

It is not possible to assess this area because we have no statistics on the long term human health impacts of fire and of exposure to flame retarded consumer products. However, we noted in Section 6, that there are a number of possible longer term risks arising from exposure to fire atmospheres which may cause health impairment or death (e.g. long term sequelae arising from CO exposure, exposure to known carcinogens in smoke etc).

We would expect flame retardants to reduce these risks using similar reasoning to that above. However, in this case it is difficult to know what the likely counter measure risks will be for the same risk end-point. Our toxicity assessment suggests the risks may be small but in the absence of reliable exposure data we cannot be sure.

It is however likely that the population risks due to long term effects are very small in relation to the overall risks and the risk reduction benefits that apply to lethality and short term injury may also apply to long term effects. If this is true the fire risk reduction benefits for the flame retardants discussed in this report could be said to significantly outweigh any of the countervailing risks. However, our level of confidence is constrained by incomplete information on the long term human exposure toxicology and environmental impact of flame retarded products and the lack of any life-cycle risk assessment experience in this field. We recommend that these areas continue to receive attention as part of the ongoing programme on assessing existing substances in Europe and where possible this be accelerated for the more commonly used flame retardants in consumer products.

## 14 Conclusions and Way Forward

The principal conclusions and way forward are given in the Executive Summary at the start of the report. We present the full set of main points and conclusions below in the order in which they occur in the report.

### 14.1 Main Points and Conclusions

1. Whilst there have been some improvements in fire statistics, the UK, Europe and most advanced nations continue to experience serious fire losses, particularly in dwellings and the home environment. With an estimated 748,000 home fires in England and Wales in 1995 of which around 12 -19% were serious enough for the fire brigade to be called. This leads to a risk of death in fire of 8 per 1000 reported dwelling fires in comparison with an annual population risk of death due to fire of 14 per million.
2. In the UK the major cause of fire death is gas and smoke inhalation, with around 40% of fatalities being attributed to people being overcome by gas and smoke alone and up to a further 20% attributed to burns and gas and smoke inhalation. These causes are driven by the occurrence of life threatening fires and steps to reduce the incidence and rate of development of such fires could have a major impact on other fire losses in society.
3. The risks of death or injury for consumer product related fires is highest for upholstery and covers.These account for around 40 deaths per 1000 product fires and 413 non-fatal injuries per 1000 product fires in the UK, in contrast to up to 86 deaths per 1000 upholstery fires in the United States. Other higher risk sources and products include space heating, textiles and furnishings and historically televisions.
4. The impact of fire across society is not equal. Poorer social groupings have a risk of experiencing fire in the home which is 3 times higher than the best performers and 2.5 times the overall average (i.e. 4.1 per 100 households per year). In general the poorer social groupings are less able, and in some cases, less willing to take steps to mitigate the potential for fire and to protect against it. It is also true that those households in financial difficulty have the highest risks.
5. Smoke detectors and alarms are potentially beneficial as a counter-measure to reduce fire risk, with a risk of death of about 4 per 1000 fires detected by alarms, compared with 9 deaths per 1000 for fires not detected by alarms. However, in 1995 only 11% of dwelling fires were detected by smoke alarms despite a 1997 MORI poll survey showing that 79% of households owned an alarm and 73% of households had them installed. However, 66% of fitted alarms do not respond to fires for various reasons. Hence the clear potential benefits of smoke detectors and alarms as an active fire-risk reduction measure could be

jeopardised in the UK if the low numbers of fully functioning alarm installations in dwellings continues. The same may be true for other European Union member states.

6. It is now generally accepted that the wide range of fire hazards and risks, and particularly those due to fire atmospheres, are directly related to the rate of fire development as reflected in the rate of heat release and the rate of flame spread. In case of toxic hazard the toxicity of fire atmospheres is a function of the rate of production of a small number of key fire gases as well as their concentration and their toxic potency. It is clear that the hazards are greatest in well developed fires and the risks relate to the time of exposure to the fire atmosphere. It follows that the major hazards of a fire are directly related to the fact that a fire exists, rather than what materials are actually involved in the fire. Though complex cocktails of combustion gases can contribute to the overall hazard and act to impede escape, it is widely acknowledged that carbon monoxide is by far the most frequent cause of death in fire.
7. When considering the population as a whole, simple hazard criteria for acute exposure to fire gases and other fire hazards are inappropriate. It is more acceptable to consider a distribution of susceptibility and hazard.
8. In addition to acute exposure toxicity effects in fire, evidence suggests there may be longer term effects from exposure to fire atmospheres that are currently incompletely understood. In particular, despite the existence of a sizeable medical literature on the toxicity of carbon monoxide and evidence of possible long term effects of acute exposure, the occurrence and nature of these effects are not well understood. Similar lack of understanding exists for the long term impacts of hydrogen cyanide in fires. This is a major area of potential concern for all surviving victims of serious fires.
9. Carbon dioxide is the most prolific product of fires and by itself has low acute toxicity. Nevertheless, $CO_2$ can produce adverse psychological effects including panic in susceptible people. It would appear that the toxicology of $CO_2$ may be more complicated than its action as a simple asphyxiant and respiratory stimulant. Similarly, the scientific literature is unclear on whether or not any longer term effects of exposure to fire atmospheres might also relate to their particle content.
10. A further review of the possible effects of air pollutants in the UK has indicated that whilst oxides of nitrogen and other irritant pollutants do not initiate asthma, they may aggravate symptoms in asthmatic people. Irritant gases are common in fires and they could have an impact on the ability of asthmatics to escape from fire. The increasing number of asthmatics in the population, particularly children, could lead to additional population fire risks.

11. Dioxins are known to be produced in fires from materials that contain chlorine and bromine. However, there is no information on the bioavailability of dioxins from fires and in particular from carrier smoke particles (solid and liquid) which may hypothetically be transported from fire atmospheres to the lungs. There is also the possibility of dioxins being absorbed through soot contact with the skin. With the controversial debate on the human toxicology of dioxins still ongoing it is not possible to be clear about their potential effects in fire atmospheres. Nevertheless, a better understanding of the type and availability of dioxins formed in fires would provide a good platform from which to assess potential human and environmental toxicology effects; this could be undertaken when the wider debate on dioxins is concluded.
12. There is no absolute definition of acceptable or tolerable risk; we have to consider all risks in relation to others and the potential benefits that may arise from intervention measures which themselves have associated risks. Fire risks are relatively high in comparison with other common risks, but the risk of death due to fire is moderate in relation to other major causes of death. Nevertheless, risk reduction measures are necessary and worthwhile if the risks relating to loss of life, injury and economic losses can be brought as low as reasonably practical. Fire risk reductions are possible, particularly for higher risk consumer products. This has been shown by actions which have made furniture and televisions safer as a result of using flame retardants.
13. In considering the role of intervention measures that may reduce fire hazards and risks, it is important to recognise that the counter-measure may have a risk associated with its use and for consumer products the population as a whole may be exposed to these risks. Flame retardants present such counter-measure risks in relation to human exposure and environmental impacts but the size of these risks is not well quantified for all products.
14. The opportunities for hazard and risk reduction in real fires focus on, (i) reducing the seriousness of the incident by suppressing or delaying ignition, (ii) avoiding or delaying flashover, through reductions in heat release rate and flame spread. Fire performance testing and analysis of fire statistics indicates that significant lives can be saved and other benefits can be achieved if flame retardants are used, particularly in high risk consumer products.
15. Flame retardants act by making flaming ignition less likely and by limiting the rate of fire growth. They have less benefit when fires become well established. There is therefore a safety gain in the use of flame retardants in reducing the incidence and rate of development of fires. Once smouldering or flaming begins, the hazard is related to the detailed characteristics of the fire and there may be some circumstances where flame retardants do not confer positive benefits. A number of examples illustrate that whilst there may be some

negative aspects of using certain flame retardants, in the early and developmental stages of fire they generally bring about a net reduction in overall fire hazards.

16. Significant work has been done on understanding the mode of action of flame retardants in a wide variety of materials and on comparative ad-hoc fire testing in which flame retarded products have been compared with their non-retarded counterparts. However, few studies have been performed on quantifying the action of flame retardants in reducing overall fire hazard and risk and only two studies to date has attempted to quantify the life-safety benefits of flame retardants. This is a major weakness in the published work on flame retardants. Further work is required to quantify the benefits, to ensure that existing approaches are effective and to identify best possible and cost effective solutions.

17. Examination of the toxicology of a number of the more common flame retardants used in consumer products indicates that most do not pose any significant threats to human life and the environment and that the associated risks are very small in comparison with the risks of death arising from unrestrained fire processes. Nevertheless, caution is required in generalising this conclusion to all flame retardants because the human and environmental toxicology of flame retardants, in common with other chemicals, is incomplete.

    Also, it is not possible with presently available information to make quantitative estimates of exposure by people using consumer products containing flame retardants. This remains a key issue in determining the degree of possible human and environmental risk; more published work is required to demonstrate the effectiveness of the containment of flame retardants in polymer matrices where the flame retardant is not covalently bonded to the host matrix.

    The limited data available suggests that exposures to flame retardants in consumer products are unlikely to be greater than a few µg/kg of bodyweight/day. We can therefore only draw firm conclusions on human safety risks when the toxic potency of the flame retardants is so low that it is unlikely to have adverse effects at the levels of exposure currently envisaged.

18. Recent comprehensive genotoxicity studies indicated that, contrary to the indications of earlier less well authenticated studies, antimony trioxide is not a genotoxic carcinogen. In addition, a study of the epidemiology of workers in an antimony smelting plant which indicated an excess of lung cancer is questionable as the observed cancers may have been attributable to materials other than antimony trioxide in the plant.

    Our overall conclusion, and that of other recent investigators, is that antimony trioxide is not a genotoxic carcinogen. The carcinogenic effects observed in early rat studies was probably a rat-specific particle overload effect which is not relevant to humans especially at the levels of exposure anticipated from the use of antimony trioxide in consumer products. This exposure is probably minor compared with exposure to antimony trioxide from other sources in the domestic and urban environment.

19. No comprehensive life-cycle risk-benefit studies on flame retardants have been performed to date. However, an opportunity exists to develop appropriate methodologies for these, in parallel with the life-cycle risk assessment approaches that are being developed for new and existing chemicals in Europe.

20. For flame retardants the risk-benefit equation has not been fully enumerated and it has been poorly communicated to date. There is also an incomplete understanding of all the hazards and risks associated with human exposure to fire and of the benefits flame retardants produce in terms of lives saved, avoided non-fatal casualties and reduction in adverse health effects resulting from exposure to fire. The potential economic benefits associated with flame retardant reduction of property fire losses and other consequential losses due to fire are also poorly understood.

21. Flame retardants are part of the existing and new substances regulations in Europe and their risks are now being assessed and managed according to the principles and methods being established for other chemicals. Approximately 425 flame retardants are marketed in Europe and only a small number, among them deca-, octa- and penta-bromodiphenyl ethers, have been placed on the priority chemicals list for assessment according to the criteria applied to new substances. However, it is important to appreciate that of the 200,000 tonnes of flame retardants in use in Western Europe annually, only 17,000 tonnes are estimated to be present in consumer products. In turn, flame retardants constitute only a small fraction of the approximately 100,000 chemicals that are classed as existing substances in Europe, which in turn is relatively small in comparison with the 5 million chemicals that are considered to exist globally.

22. It is also necessary to appreciate that the risks associated with new and existing synthetic chemicals, should not be differentiated from those presented by natural products. What may differ are the methods of management, control and regulation. Moreover, the risks associated with synthetic chemicals should not be considered in isolation but compared with those presented by all compounds that can come into contact with humans or the environment; flame retardants are no exception.

23. Also, any risks need to be considered in the context of other risks that people face and the benefits conferred by taking those risks. Indeed it is the overall balance of risk to consumers which is more important than the individual risk that may be posed by a flame retardant.

24. Fire performance testing and the analysis of fire statistics show that there are significant benefits to be gained from using flame retardants particularly in higher fire risk consumer products. Such analysis suggests that the risk of death or injury from a fire involving consumer products, such as upholstered furniture, can be reduced by 30% to 90% or more.

25. The lack of a complete understanding of the risks of flame retardants and the absence of comprehensive life-cycle studies should not detract from sustaining the potential life saving benefits of flame retardants in the face of inappropriate application of the precautionary principle. In turn, any compelling evidence or legitimate doubts over the efficacy of particular flame retardants should be examined vigorously.

## 14.2 Way Forward

1. It is imperative that the UK, and other countries facing the challenge of serious domestic fires, take all reasonable and cost effective steps to reduce the impact of fire with appropriate counter-measures that present low risks to human safety and the environment. Fire risk reduction strategies for higher risk consumer products need to be pursued and the improvements made in some products, particularly television sets, need to be sustained.

2. In an effort to assist the protection of more vunerable groups, regulatory policies must recognise that poorer social groupings and those in financial difficulty experience a higher risk of fire in the home. Improvement may be achieved by active measures (e.g. smoke alarms with campaigns to ensure they are operating correctly in the home - and sprinkler systems) and also by permanent passive measures (e.g. design-for-fire and flame retardants).

3. When considering the effect of fire-hazard counter-measures on the population, regulatory policy development should acknowledge differences in the susceptibility and response of individuals to fire hazards and that of the most susceptible groups in particular.

4. Despite the existence of a sizeable medical literature on the toxicity of carbon monoxide and evidence of possible long term effects of acute exposure, the occurrence and nature of these effects are not well understood. Similar lack of understanding exists for the long term impacts of hydrogen cyanide in fires. It is also apparent that the toxicology of $CO_2$ may be more complicated than its action as a simple asphyxiant and respiratory stimulant. These are major areas of potential concern for all surviving victims of serious fires and further in-depth investigations should be pursued. The potential for particles causing synergistic effects with other products, particularly carcinogens and dioxins also warrants further examination.

5. The increasing number of asthmatics in the population, particularly children, could lead to additional population fire risks arising from irritant gas exposure; further work is needed to understand the potential size of this problem.
6. There is no information on the bioavailability of dioxins from fires. There is a hypothetical possibility of bioavailability from carrier smoke particles (solid and liquid) transported from fire atmospheres to the lungs and the possibility of percutaneous uptake through contact with soot should be considered. With the controversial debate on the human toxicology of dioxins still ongoing it is not possible to be clear about their potential effects in fire atmospheres. Nevertheless, a better understanding of the type and availability of dioxins formed in fires should be sought to assess any potential human and environmental toxicological effects; this should be undertaken when the wider debate on dioxins is concluded.
7. Few studies have been performed on quantifying the action of flame retardants in reducing overall fire hazard and risk and only two studies to date have attempted to quantify the life-safety benefits of flame retardants. Further work should focus on enumerating the human safety benefits to ensure that existing and new approaches to flame retardancy produce the greatest benefits and are cost effective.
8. Risk assessments of flame retardants should be considered in the context of their incorporation into consumer products and human exposure and environmental life-cycle risks should be assessed. An opportunity exists to develop appropriate assessment methodologies in parallel with the life-cycle risk assessment approaches being developed for new and existing chemicals in Europe; this should be pursued vigorously.

   However, it is not possible with the presently available information to make quantitative estimates of exposure by people using consumer products containing flame retardants. There is limited data available so there is a need for further laboratory and field work in this area.
9. It is important to consider ways in which significant risk reduction moves could be made in relation to fire hazards through new and improved flame retardants and other non-retardant solutions. Assessing potential moves can be done at an elementary level initially and subsequently refined with life-cycle risk assessment methods. It is imperative that we pursue developments which maximise the risk-benefit equation for individual consumer products. This requires that we seek practical methods which can be commonly accepted to carry out an assessment of the balance of risks and benefits now and to investigate the most effective risk-trading opportunities for the future.

10. There is a need to institute methodologies and produce data that will enable toxic hazard and risk assessment to be carried out with appropriate levels of certainty. We also need to ensure that we can apportion risk reduction benefits according to product type and to individual flame retardant systems with appropriate account of other contributing risk reduction measures such as smoke detectors and alarms.
11. It is not possible currently to complete the risk-balance equation for long term health effects arising from exposure to fire and exposure to consumer products containing flame retardants. We recommend that this area receive attention and is supported by the ongoing programme on assessing existing substances in Europe. Where possible the activity should be accelerated for the more commonly used flame retardants in consumer products.
12. Potential approaches to risk assessment of consumer products involved in fire, and for fires in general, is required within a life-cycle risk assessment framework. We recommend that this be pursued to enable the most beneficial and cost effective strategies to be identified.
13. In principle it should be possible to estimate the fire-risks and risk-reduction potential from measured reductions in heat release rate, toxic gas emissions (or mass loss) and delayed ignition time, by using one of a number of fire risk models that currently exist. This would enable risk-reduction assessment of flame retarded products based on their measured fire performance. It would also provide an opportunity to integrate this form of risk assessment into fire safety engineering practice, allowing flame retarded product performance to impact on design for fire in domestic, building and public environments. We recommend that this opportunity be explored.

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**Annexe 10**