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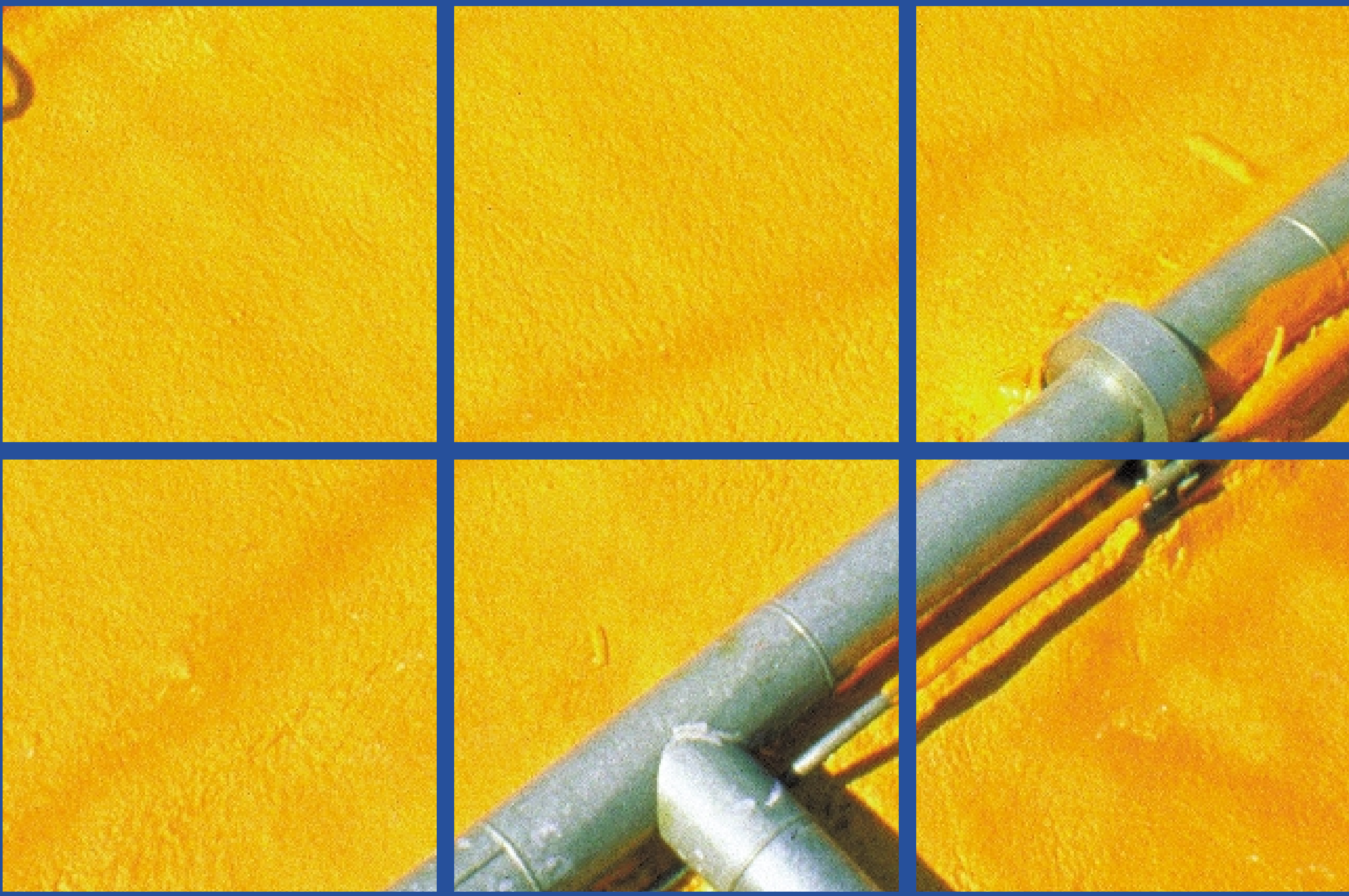
# PERFORMANCE OF POLYURETHANE (PUR) BUILDING PRODUCTS IN FIRES



**SUMMARY**

The performance of rigid polyurethane foam building products in building fire situations has been extensively reviewed. The report describes the typical building applications and the type of polyurethane building products that are currently being used in the European construction market. A review is given of the fire statistics as well as a description of the general fire safety aspects in buildings.

The fire performance of polyurethane foams and of the building products derived therefrom is discussed with respect to the compliance with fire regulations and the performance in end use conditions. Further, the general principles of smoke and toxic hazard together with test methods have been described. In this context, published and unpublished data concerning smoke and toxic gases for rigid polyurethane foams have been compiled.

The aim of the review is to provide the reader with scientific information and background on the general performance of this diverse family of products and to describe the assessment criteria.

Finally, it is an opportunity to show compliance of rigid polyurethane foam building products with small and large-scale test requirements and satisfactory behaviour in end use test conditions.

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## CONTENTS





*Authors : Wittbecker, Daems and Werther.*

*Dr. W. Wittbecker, Bayer AG, Leverkusen, Germany.*
*Dr. D. Daems, Huntsman Polyurethanes, Everberg Belgium.*
*Dr U. Werther, BASF GmbH, Karlsruhe, Germany.*

## GENERAL INTRODUCTION

Rigid polyurethane foams are widely used as an insulation material in a variety of building applications. Since the first oil crisis in the seventies and the resulting increase in energy cost, insulation materials have been gradually applied more and more in buildings. Since then, regulatory requirements and recommendations to achieve a certain k-factor, have come into force in several countries. Logical that nowadays the majority of new buildings have, to some extend, insulation installed.

It is anticipated that the regulatory requirements regarding building energy efficiency will become more stringent in the future, as it is an important remedy to reduce the $CO_2$ emission from fossil fuel combustion. Calculations have shown that 40 per cent of the $CO_2$ emissions are due to the heating and cooling of buildings. Emissions of global warming gasses, of which $CO_2$ is the main one, has to be controlled to comply with the requirements laid down in Kyoto in order to combat global warming. Tighter building insulation regulations and the retrofitting of all European buildings to these standards would produce significant results. Research has shown that the European Union could cut global warming gas emissions sufficiently to meet half of its proposed 2010 target reductions through better insulation in buildings [63].

The insulation capacity of rigid polyurethane is exemplary and extremely competitive [64]. In addition the foams have excellent physical properties like mechanical strength, dimensional stability, water resistance, etc. Also the light weight, quickly to install polyurethane rigid boards like sandwich panels, which can be factory engineered, offer several advantages in comparison to site assembled constructions.

Polyurethane foams are combustible however; their use is controlled by the building regulations and influenced by the applicable insurance requirements. All building products must comply with the fire standards described therein. Many misconceptions have occurred concerning the performance in a fire situation of polyurethane based building products. This scientific review was therefore produced to provide information on the general performance of rigid polyurethane foam in a fire situation and the construction products derived therefrom. It also describes the regulatory and other requirements. Further, safe use is demonstrated in large-scale test investigations and tests in end use conditions.

The first chapter summarises the typical applications for rigid polyurethane foam insulation and shows a great versatility of products and uses. The review then focuses on fire safety objectives and fire statistics. In chapter four the general fire safety aspects and the fire properties of rigid polyurethane foam and building products is described. Finally, chapter five covers smoke and toxic gases, decomposition models and test methods. Several published and unpublished data for polyurethane products are given.

*source : EPIC*

## TYPICAL APPLICATIONS OF PUR RIGID FOAM INSULATION

Rigid polyurethane foam is a thermosetting plastic expanded to form a predominately low-density cellular structure. As a thermoset, polyurethane foam has a number of benefits:

- It is not fusible
- It is largely resistant to chemicals and solvents
- It has a high softening temperature and hence good heat resistance

Rigid polyurethane foam is an exceptional thermal insulating material, also noted for its suitable physical properties such as mechanical and compressive strength [41], dimensional stability [62] and water resistance. The production method and the raw material formulation can be varied to produce foams that are cost effective and tailored to suit individual applications.

Polyurethane is a generic term, which covers a whole range of different formulations. The principle linkages formed during polymerisation is the urethane bond, but other linkages as isocyanurate, urea and others may be introduced to a varying degree. Isocyanurate modified polyurethane foams, for example, show a better heat resistance, lower volatiles production and better char formation than standard polyurethane. They are referred to as PIR foams in this text.

Rigid polyurethane foam complies with the majority of structural, economic and statutory requirements made on insulation systems in the building industry. For the architect and the client polyurethane insulation offers numerous benefits:

- Extra space due to thinner insulation: with pitched roofs, the second layer, required by other types of insulation, is unnecessary, and with flat roofs and floors the reduced height of the structure is an advantage
- Increased scope for design because walls can be made thinner
- Savings in heating energy improve the quality of the environment
- Greater comfort and a better interior climate in buildings
- Avoidance of cold bridges


*Fig.1. Examples of the relative thicknesses of alternative building materials needed to match the thermal conductivity properties of rigid PU foam at 50mm.*

Polyurethane foam's ability to adhere to other building materials, facings or coatings, also opens the door to a broad spectrum of applications ranging from insulating boards for roofs, walls, floors and ceilings to self-supporting metal-faced sandwich panels.

The light weight of polyurethane rigid foam board also provides an incentive for innovative lightweight construction techniques due to its ability - especially in the form of sandwich panels - to bridge wide spans.

## INSULATION FOR ROOFS

### Pitched roofs

In many countries, living space and energy have become such precious and rare commodities nowadays that few building owners or householders can afford a poorly insulated pitched roof which prevents the loft space beneath from being put to efficient use. Pitched roofs today, whether in new housing or old properties being renovated, are expected to meet all the normal demands made on a building in terms of structural integrity, economy and comfort.

Insulating boards made from rigid polyurethane foam give top-quality performance on pitched roofs. When laid under the rafters, polyurethane insulation takes up far less space than any other insulant, thanks to its effectiveness in thin layers.

Systems with integrated battens, tight-sealing tongue-and-groove joints and overlapping foil or special profiles to carry away water are perfect for installation on top of conventional rafters. If self-supporting wood-faced polyurethane foam panels are used, the complex rafter structure can be dispensed with altogether. The panels are then laid directly on top of the purlins, giving an architecturally perfect finish to the interior of the roof space.

*Pitched roof insulation.*

### Flat roofs

Flat roof insulation has to satisfy particularly stringent demands. Solid flat roofs, for example, must always be insulated on the top. The insulating material, therefore, needs to combine a high degree of insulating efficiency with a level of heat resistance and dimensional stability sufficient to withstand the temperatures generated by solar radiation, which can be as high as 80°C or more. This is where rigid polyurethane foam, with its high long-term heat resistance, comes into its own. It can even withstand short-term temperatures of up to +250°C, enabling it to be laid using hot bitumen.

The compressive strength of polyurethane flat roof insulating boards makes them suitable as a substrate not only for gravel fill layers, but also for tiles and roof gardens, terraces, roofing decks capable of withstanding wheeled traffic and parking decks.

With rigid polyurethane foam products, the compressive strength can be tailored exactly to individual loading requirements. Compressive stress values of 1.0 $N/mm^2$ can be achieved with no sacrifice of thermal conductivity. With terraces, the low thickness of polyurethane foam insulation is a particular structural advantage.

## INSULATION FOR WALLS, FLOORS AND CEILINGS

### Insulation of external walls

In order to maintain a correct energy balance, an efficient form of insulation for the external walls of a building is essential. Insulating the entire outside wall surface with rigid polyurethane foam saves a great deal of energy.

When combined with a suitable form of external cladding, polyurethane foam ensures long-lasting protection against weathering, and eliminates cold bridging at ceilings and lintel beams. This system is suitable for many different types of wall construction.

### Cavity wall insulation

*Cavity wall insulation.*

Rigid polyurethane foam core insulation - with no air space between the outer masonry leaf and the insulation - is widely used in new housing. It enables walls to be kept thin, thereby offering greater architectural freedom. Rigid polyurethane foam is an easy-to-install system, which ensures optimum thermal insulation and a high level of energy savings. The inner leaf of the wall is protected against thermal stress and moisture penetration.

### Insulation of floors and ceilings

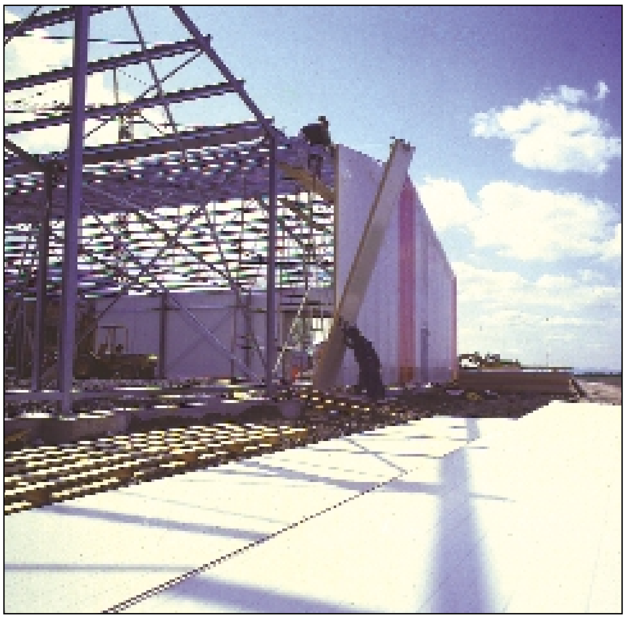
Rigid polyurethane foam satisfies the requirements of the fuel and power conservation regulations for buildings with minimal thickness. This means that efficient floor insulation can be produced with exceptionally thin layers of foam. Additionally, the compressive strength of polyurethane foam boards, their excellent insulation performance and ability to withstand foot traffic are also crucial benefits.

Continuous manufacture allows the production of large-format insulating boards (e.g. in lengths of up to 4 metres for suspended ceilings in animal houses), bringing substantial savings in time, labour and costs.

## METAL-FACED SANDWICH PANELS

Metal-faced polyurethane sandwich panels are the system of choice today for large industrial buildings, refrigerated and other warehouses, office blocks, exhibition halls, fair pavilions, schools and sports halls.

Prefabricated sandwich wall and lightweight roofing consist of metal facings bonded tightly together by a core of rigid polyurethane foam. The aluminium or steel facings themselves are surface coated and can be manufactured either flat or with profiles of various depths. Polyurethane sandwich panels come complete with specially formed tongue-and-groove joints ensuring a perfect fit and maximum integrity. Assembly is fast, easy and cost effective.



*Construction of industrial building using steel faced panels.*

During the expansion process, rigid polyurethane foam passes through a tacky phase, which enables it to form a strong bond with the facings. The resultant sandwich panel has a load-bearing capability, which is many times greater than that achieved by adding together the load-bearing capacities of the individual layers. As a result, these thin, relatively lightweight sandwich panels can safely bridge wide spans. For example, a panel just 100mm thick can easily bridge a clear span of some 6 metres.

Advantages of rigid polyurethane foam sandwich panels in factory and industrial buildings are:

- Optimum thermal insulation values and no thermal bridges
- Lightweight for easy assembly on various supporting structures
- Quick and simple jointing, even under bad weather conditions
- No restrictions on architectural freedom
- Wall panel systems are ideal for both low- and high-rise buildings
- Easy to dismantle and reassemble

*Building sandwich panels.*

## FIRE SAFETY OBJECTIVES

A fire safety assessment begins by identifying fire safety objective(s) and acceptable levels of safety. Specifications of the product and the end use conditions are required for the fire safety performance determined.

Test methods are used to determine whether the objectives will be met. For the fire hazard assessment procedure to be valid, it is necessary that the characteristic fire test responses used produce valid estimates of success or failure in achievement of the fire safety objectives, given by the specified fire scenario(s).

The primary fire safety objective is to ensure that the time required to evacuate the fire compartment is less than the time for the fire to create untenable conditions in the compartment. The evacuation time includes the time required for the occupants to reach a safe location. Tenability is assessed on the basis of fire effects on the occupants, including both direct effects, such as heat, toxic gases or oxygen deprivation and indirect effects, such as reduced visibility due to smoke obscuration.

A secondary fire safety objective is to prevent flashover inside the works. Additional fire safety objectives, intended to prevent serious injury for fire fighters, shall be considered

Whether the assessment focuses on a material, product or system is determined by an investigation of the risk:

- Is the product likely to be the source of ignition?
- Is the product likely to be the secondary ignited item?
- Is the product a potential significant fuel source even if not being the first or secondary ignited item?
- What is the potential avenue to contribute to the risk (and hazard)?
- How close are occupants and/or critical equipment to the origin of a fire?

In fire safety engineering guidelines the above decision route may be followed. In international standards this product related safety assessment strategy is only partly taken into account. Fire tests vary considerably and focus on different simulated risk situations – walls, roofs etc. This may lead to different classifications depending on the test procedure and end-use conditions e.g. for composite elements although the material composition is chemically identical. Several classification systems require different levels of performance for composite elements: one for the foam itself and a second one for the end-use product.

source : EPIC (57)

*The fire rated (PIR) panel wall claddings remained intact in this major fire even though the internal structure had totally collapsed.*

## STATISTICS

Fire statistics are an important tool to obtain information on frequency of certain fire types, causes, the ignition source and the extent of the fire. They can give correlations between the type of fire, the type of the building, peoples' practices and casualty rate. Historically, UK and US are the countries with the most detailed fire statistics.

Safety measures can be deduced from a statistical analysis of fires. When carrying out probability tests, fire safety engineers will consider the likelihood of a fire occurring within a specific type of a building, based on statistical data from buildings of similar type and occupancy. Where no fire data is available for a particular building, the figures shown in Table 1 may be used.



An important cause for fires is arson and can be as high as 70 per cent in schools. Malicious ignition is the lowest in dwellings and is about 20 per cent. Table 2 indicates the causes of all accidental fires in the UK statistics for 1995 [1]. In dwellings by far the most frequent cause is misuse of cooking appliances; whereas other factors play a more significant role in other buildings such as faulty appliances. Eighty-eight per cent of the fires are confined to the room in which the item first ignited and the consequences are rather minor.

*Table 1. Overall probability of fire starting in various types of occupancy.*

| Occupancy | Fire starts per occupancy (starts/year) | Probability of fire start |
|---|---|---|
| **Dwellings** | 0.0030 | Low |
| **Offices** | 0.0062 | |
| **Storage** | 0.013 | Medium |
| **Assembly** (non-residential) | 0.020 | |
| **School** | 0.044 | |
| **Assembly** (entertainment) | 0.12 | High |
| **Hospital** | 0.30 | |

*Table 2. Fires in dwellings and other buildings by cause, Home Office statistics 1995, UK.*

| Cause of accidental fires | Dwellings | Other buildings |
|---|---|---|
| Misuse of equipment | 26,400 | 5,200 |
| Faulty appliances and leads | 7,500 | 5,700 |
| Careless handling of fire or hot substances | 5,700 | 3,400 |
| Placing articles too close to heat | 3,900 | 2,000 |
| **Total** | **51,500** | **24,700** |

Although the probability of fire starting in a dwelling is very low, the majority of fire deaths occur in dwellings. It is generally accepted that the most common cause of death in a fire is to be overcome by smoke and gases. This is confirmed by UK and US data. In the US, however, 66 per cent to 75 per cent of deaths are caused this way, compared with 40 per cent in the UK [2,3].

The prevalence of greater compartmentation and use of closed doors in European home design, so that fires are more likely to stay small, may be the reason why fire conditions differ between US and Europe. It is when the fire extends beyond the room of origin that the majority of fire deaths occur. The dominant factor in cause of death is the period after flashover, when large amounts of smoke and gas containing carbon monoxide are produced.

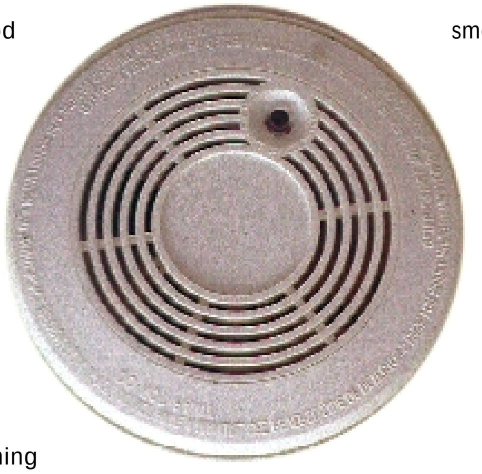
For assessing potency values, such as smoke toxicity and heat release, there is a need to differentiate gases produced under different fire situations, taking into account, for example, smouldering, flaming and ventilation conditions [4]. The hazard of reduced visibility caused by smoke should also be assessed according to the material and to the environmental conditions.

There are significant differences in the use of smoke detectors amongst the various countries in Europe, from as low as a few per cent in the south e.g. France, to as high as 90 per cent in the north e.g. Sweden [56]. A mandatory requirement across Europe would decrease the number of large fires significantly [5,36]. For example, in the period from 1988 to 1995, the use of smoke alarms in dwellings in UK rose from 15 per cent to over 70 per cent. In the same period the number of fires discovered by smoke detectors rose from two to 10 per cent.

In summary the advantages of smoke detectors in dwellings are:

- More rapid discovery after ignition
- Lower casualty rates
- Less damage as fires are more often confined to the item first ignited

Logically, the shorter the interval between ignition and discovery, the faster escape and the earlier intervention is possible. This explains why the death rates for fires in dwellings, discovered by smoke alarms, are lower and the extent of the fire smaller.



*Smoke detector.*

source : *Benelux Press*

## FIRE SCENARIOS

Fires can develop in numerous ways, dependent on factors such as enclosure type and size, ventilation conditions, heat and smoke movement. Eight different fire scenarios have been identified in an EU pre-normative research programme which was finalised in 1995 [6]: a small and large room, a vertical and horizontal cavity, a facade, a corridor, a staircase and a roof.

In Figure 2, a schematic diagram is plotted of a fire from before ignition to the completion of combustion in an enclosure with sufficiently high fire load to create flashover. A number of fire parameters influence the development of a fire. Fire parameters between the pre-flashover and the post-flashover condition are distinctly different. In the pre-flashover phase, reaction to fire characteristics of products are important, while in the post-flashover phase, resistance to fire parameters of complete assemblies apply. Fire building regulations make a distinction between these two conditions. Smoke and toxic gases are secondary parameters and are dependent on the fire phase. They are described in detail in a separate chapter. Table 3 summarises the important fire parameters associated with reaction and resistance to fire.

*Table 3. Fire parameters related to classification and testing.*

| | | |
|---|---|---|
| **Developing fire** | Reaction to fire | Ignability<br>Heat release<br>Flame spread |
| **Fully developed fire** | Resistance to fire | Loadbearing<br>Insulation and<br>Integrity capacity |

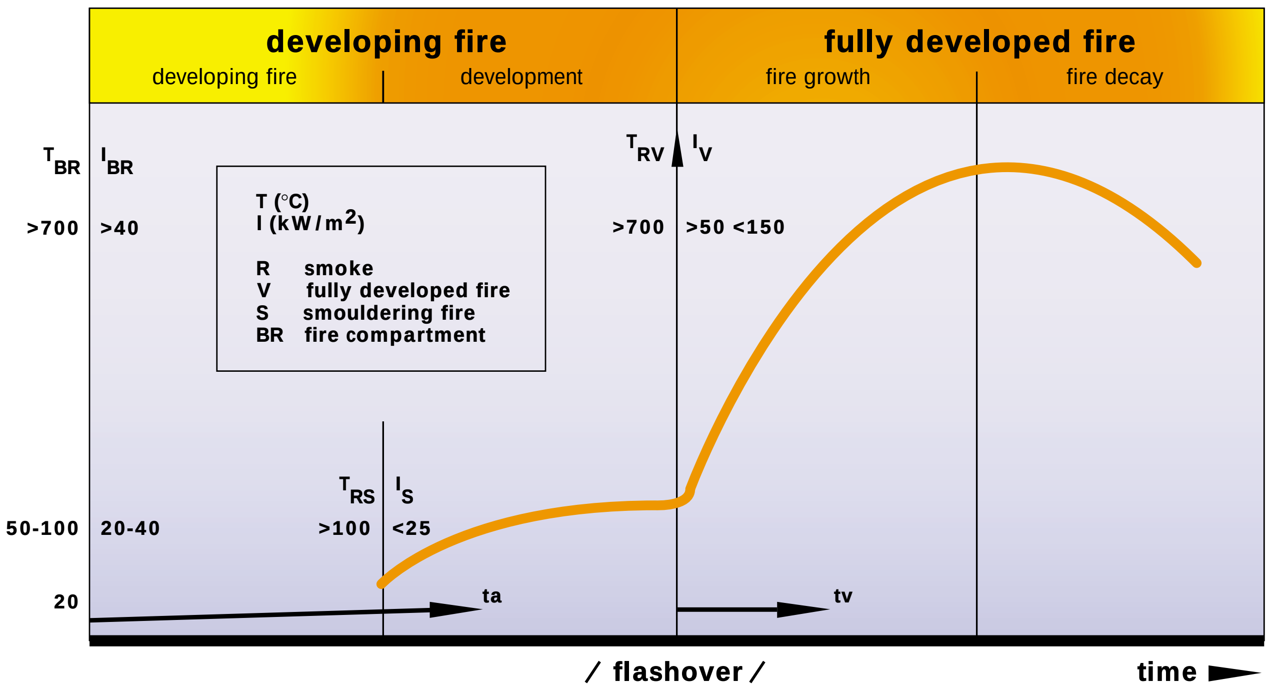



*Fig.2. Development of fires in enclosures*

A further description of several fire parameters follows:

- The typical ignition source is small (i.e. candles, matches, and hot electrical wires).

- External irradiance is zero for the first ignited item. $O_2$ content of air is almost 21%. The relevant risk for further assessing the fire is extensive flame spread. It can be expected that people in the room of origin either extinguish the fire, escape or are easily rescued.

- Self-sustained smouldering may be propagated inside structural elements. The material decomposes at a nearly constant temperature. In the case of an oxidation smouldering process, smouldering of wall and ceiling linings (or any other material in the vicinity) may also be initiated by an external source such as other materials burning in the same room. Cellulosic materials have been shown to create smoke visibility hazards by decomposing at comparatively low irradiance levels, as reported in [7].

- Combustible materials placed in the vicinity of an ignited item are heated by convection and irradiance. Oxygen content in the fire compartment begins to decrease. After a certain period, flashover may occur if temperature exceeds 500°C and irradiance is about 25 $kW/m^2$.

The development of a fire depends on the size and on the ventilation conditions in the room of fire origin: Various scenarios for the development of a fire are mentioned in the following examples [48]:

- In small rooms the amount of oxygen is normally not sufficient for complete combustion. In large rooms oxygen is not restricted in the developing stage of a fire.

*Table 4. Definition of room size.*

| | | |
|---|---|---|
| **1** | Small rooms | $A < 25m^2$ and $h < 4m$ |
| **2** | Medium rooms | $25m^2 \leq A < 100m^2$ and $h < 6m$ |
| **3** | Large rooms | $100m^2 \leq A < 400m^2$ and $h < 12m$ |
| **4** | Ultra large rooms | $A \leq 400m^2$ and $h < 12m$ |
| **5** | Special room sizes | not defined |

**Length/Width ratio of rooms 1-4 should be less than 1/3**

- In some applications, such as classrooms, the type of combustible material is more or less precisely defined, i.e. one chair and one table for each child. Ignited by burning waste paper baskets, moderate flame spread can be expected.

- In rooms containing a suspended ceiling, smouldering fire may occur in the ceiling cavity, typically caused by electrical failure. Fire conditions are defined by an oxidative non-flaming combustion. As long as the ceiling membrane remains intact, the room below will hardly be effected. Due to restricted oxygen, smouldering may, however, be sustained for a long period.

- In shops, department stores, warehouses etc. special fire load conditions may cause accelerated flashover. The $CO_2/CO$ ratio decreases rapidly to below 10. When doors and windows are closed, combustion will be incomplete. Openings will improve ventilation and thereby increase the fire intensity.

- In large and ultra large rooms, i.e. theatres, open plan offices, warehouses, supermarkets, sports halls etc., the fire compartments are freely ventilated for long periods of time. Contrary to the situation in small rooms, there are few interrelated effects and development of fire is directly dependent on the successive combustion of the burning items.

- In areas where flammable liquids are stored, small ignition sources cause accelerated development of fire, resulting in immediate flashover. Flashover causes the $CO_2$/CO ratio to drop instantaneously.

Heat release may be expressed as the hydrocarbon curve. Relatively high ventilation is necessary for such a temperature development, $CO_2$/CO ratio are about 100, low ventilation is likely to lead to lower temperature in the range of 600°C to 900°C.

Toxic and corrosive effects, light obscuration and temperature increase by fire gases are dependent on the quantity of material burning. The highest possible rate of smoke generation must therefore be standardised in relation to the burning surface area.

The following should be assessed, if practicable, during the phases of an incipient fire:

- Possible contribution of the various factors to surface flame propagation
- Burning rate of any material which contributes to inward spreading of the fire; this will depend on the effectiveness of protective covers
- Material-specific smoke data as functions of the fire durations

With regard to the post-flashover phases of an advanced fire, the problems of smoke movement must be considered according to the amount of smoke produced per unit time.

As smoke data gained under the different test conditions will depend mainly on the area burning, smoke potency data comparisons should be based on volume instead of weight.

## BURNING CHARACTERISTICS OF PUR RIGID FOAM

As all organic materials, polyurethane foam is combustible. When exposed to heat or ignition sources, polyurethane rigid foams start to decompose at temperatures of T≥250°C. There is no melting in general and burning droplets are not formed during the whole fire. There is no smouldering behaviour as seen e.g. for cork or for some high density mineral insulation materials.

Ignitable decomposition products in practice are generated at temperatures of 300°C - 320°C. Ignition properties of materials are e.g. determined by the Setchkin apparatus (ASTM-D 1929). Table 5 shows self ignition and flash ignition temperatures according to this method. For determining flash ignition temperatures a pilot flame is used.

*Table 5. Ignition temperatures of materials. A range is given for versatile product families.*

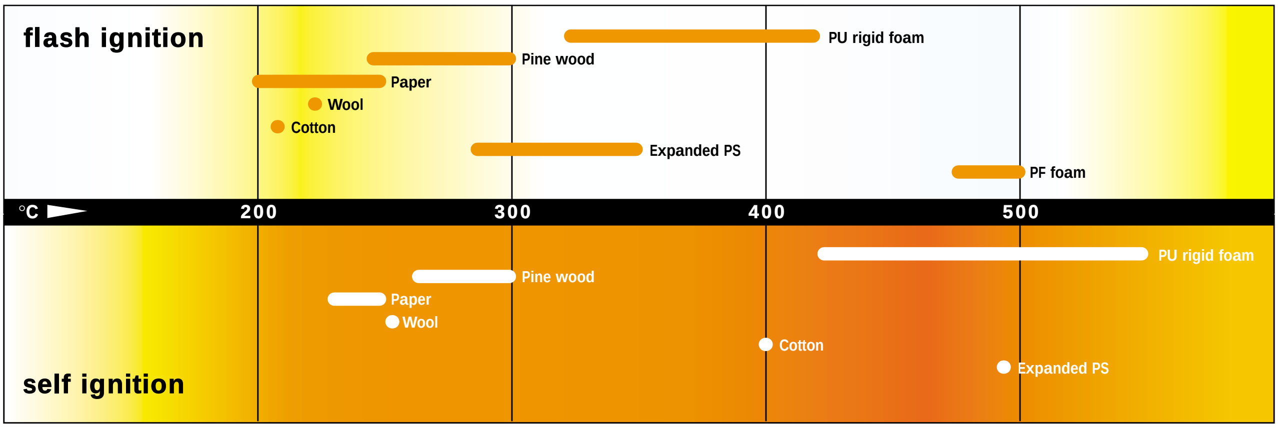


*Table 6. Materials and ignition time in cone calorimeter tests [48]*

| Sample | Joint | | Edge Protection | | Time to ignition | $CO_2$/CO |
|---|---|---|---|---|---|---|
| | Without | With | Without | With | $t_{ign}$ (s) | Ratio |
| 1. PUR/steel sandwich panel | ● | | | ● | 104 | 11 |
| 2. PUR/steel sandwich panel | | ● | | ● | 46 | 11 |
| Uncovered foam | ● | | ● | | 2 | 5 |

During construction works, the risk of ignition occurs where protective layers have not yet been installed. This risk is shown in Table 6. The end use conditions of the products are normally different. (see section 1).

Another property concerning fire hazard are the heat release characteristics. Table 7 is showing typical values determined for various products in a cone calorimeter.

*Table 7. Heat release rate of uncovered PUR foam and sandwich panels [48], see table 6 for specimen details.*

| Samples | Av. value | | Av. integral | | |
|---|---|---|---|---|---|
| | $\dot{q}''$ max (kW/m$^2$) | *t* max (s) | $\dot{q}''_{60s}$ (kW/m$^2$) | $\dot{q}''_{180s}$ (kW/m$^2$) | $\dot{q}''_{300s}$ (kW/m$^2$) |
| 1. PUR/steel sandwich panel | 80 | 131 | 35 | 11 | 0 |
| 2. PUR/steel sandwich panel | 305 | 65 | 154 | 76 | 50 |
| Uncovered PUR - foam | 153 | 11 | 122 | 0 | 0 |

The net calorific values of PUR foams are H=27 MJ/kg or 6,7 kWh/kg. Taking into account the various densities of the products in Table 8, comparisons can be established for a construction board of 1m$^2$, 1cm thick or a 1cm thick layer in the case of asphalt.

*Table 8. Net calorific values for different materials.*

| Material | Density | Calorific value |
|---|---|---|
| Wood, pine | r = 500 kg/m$^3$ | 80 MJ |
| Wood, oak | r = 700 | 120 |
| PUR | r = 30 | 8 |
| PUR | r = 40 | 11 |
| PF | r = 35 | 9 |
| EPS | r = 16 | 7 |
| Asphalt | r = 1200 | 480 |

If we consider, for example [42], a typical industry hall, with a floor area of 1000m$^2$ and a height of 8m (thickness of the insulating layer in the walls and roof is 10cm), a sandwich panel envelope with a density of 40kg/m$^3$, the weight of the foam is calculated to be around 8 tonnes. Assuming that about 30 per cent - according to German standard DIN 18230 - of the material contributes the fire load qr = 8000* 0,3* 6,7 / 1000 = 16 kWh/m$^2$ = 57,6 MJ/m$^2$.

The insulation capacity of the insulating foam is lost, however, when the building content is in the further developed fire stage. By the decomposition process the insulating performance decreases and wall and the roof release heat from the fire compartment. This leads to a longer resistance time of other load bearing constructional elements. This effect may be larger than purely compensating the additional fire load.

For the industrial applications the Swiss “Schweizerische Ingenieur und Architektenverein” in document no.81 for example gives recommendations (Table 9) for the fire load to be assumed as an average.

*Table 9. Typical fire loads*

| Type of building | Calorific value MJ/m² |
|---|---|
| Offices | 800 |
| Furniture shop | 500 |
| Restaurants | 500 |
| Automotive stores | 300 |
| Library | 2000 |

## FIRE PERFORMANCE OF PUR BUILDING PRODUCTS

Although polyurethane foams are combustible, its fire properties can be modified to suit a variety of building applications. The desired fire performance can be obtained in different ways : via proper choice of formulation, the use of additives and the physical design of the building structure. For example, insulation foams are generally installed such that they are not directly exposed to heat and flames and are protected by a facing.

A product can be used in building and construction if it complies with the regulatory requirements. Ignitability, flame spread and heat release are currently assessed for regulatory purposes in Europe via small scale reaction to fire test methods which differ from country to country. Dependent on the test method, the relevant importance of the fire parameters being assessed is different. The tests are performed either on the material or on a small or intermediate size composite. In Germany, all foam materials for construction must have a minimum performance of B2 according to DIN 4102 part 1. Other countries, such as France, Spain, UK or Benelux, do not require such minimum performance levels, as long as the building element meets the fire requirement specified in the building regulation.

EU member countries are currently in the process of changing to a harmonised European reaction-to-fire classification system. This system is planned to be ready for implemention by the end of the century. Building products will then be classified in classes from A1, A2, B to F. The main test methods for polyurethane building products will be the single burning item (SBI) and the “Kleinbrenner” test. This classification system will allow the products to be tested in end use conditions. The performance of polyurethane products in the new classification system needs to be established.

*Table 10. Simplified representation of the Euro classification system.*

| Fire situation | Euroclasses | Methods |
|---|---|---|
| Fully developed fire in a room | A1 | Bomb calorimeter and furnace test + list of non-combustible products |
| | A2 | Bomb calorimeter and /or furnace test +SBI |
| | B | SBI + Kleinbrennen (30 s) |
| Single burning item in a room | C | SBI + Kleinbrenner (30 s) |
| | D | SBI + Kleinbrenner (30 s) |
| Small fire attack on a limited area | E | Kleinbrenner (15 s) |
| | F | No performance determined |

Taking the regulations into account, the polyurethane material can be formulated to comply with the German requirement for materials, namely DIN 4102 B2 by the simple use of additives. This means that small ignition sources, such as candles and matches, will not lead to sustained ignition of the foam, but will char in the area of direct impingement.

The performance of polyurethane materials can further be enhanced by careful formulation of the main stream components. Chemically the polymer structure can be modified to limit the amount of volatile decomposition products formed at 320°C during fire exposure.

A well-known example is PIR foam. Instead a protective char is produced. As a result heat and smoke emissions are significantly reduced.

In practice, polyurethane foams are hardly used as such but are essentially laminates with a foam core and one or two facings. Appropriate facings can enhance the performance of the products to comply with more demanding standards. Table 11 illustrates the effect of facings on the flame spread measured according to BS 476 part 7.

*Table 11. Surface spread of flame results according to BS 476 part 7 on PUR and PIR foam with different facings.*

| Facing | Classification for foam type | |
|---|---|---|
| | PUR | PIR |
| None | class 1-3 | class 1 |
| PE-coated paper | class 3 | class 3 |
| Al Foil (1) | class 3 | class 1 |
| Al Foil (2) | class 1 | class 1 |
| Pre-painted steel | class 1 | class 1 |
| Plasterboard | class 1 | class 1 |

*LPS 1181 configuration, observation and recording.*

source : EPIC (57)

For end use applications, insurance companies like Factory Mutual (FM) and Loss Prevention Council (LPC) have introduced additional performance standards to the regulatory requirements. These large-scale tests also address reaction-to-fire parameters but are usually more onerous than the regulatory tests. Polyurethane products and constructions derived therefrom have achieved approval in different applications. One example is the performance of PUR steel-faced composite panels in the LPS 1181 or the FM 4880 standard [57].

*Test building according to LPS 1181 configuration.*

source : EPIC (57)

In 1992, ISOPA has funded a series of large fire tests at the "Materialforschungs ud Prufungsanstalt fur Bauwesen" in Leipzig on metal faced rigid polyurethane foam composite panels. This project followed the EU fire research guidelines and demonstrated:

- The fire performance of the panel is independent of the blowing agent used in the B2 foam
- The thermal attack of ignition sources up to a room flash over will lead to a very limited flame spread on the facade.

The corner tests involved an 80m$^2$ facade, 10m high and a 40kg wooden crib to simulate the window flame effect encountered in facade fires. These results indicate a satisfactory performance on ignitability and flame spread in a large-scale test [8].

In addition, ISOPA has conducted large-scale tests on steel deck roofing [9]. The results of these tests show that the contribution of the insulation to the heat release was not a dominant factor. Further, the type of insulation did not have a significant impact on fire spread on the roof. It could be concluded that conventional types of lightweight steel deck roofing did not constitute a special fire risk provided installation work is properly carried out [9]. Results from other large-scale tests confirming these conclusions are also reported in [18,19,40].

Traditionally, polyurethane foam products have been used in applications where fire resistance was not required. Behind a masonry wall, this would not pose particular problems, however, for lightweight insulated partitions, there was a general belief that a fire insulation resistance time of 30 minutes would not be possible. Nowadays, it has been shown that some assemblies, for example sandwich panels, can achieve 30 minute insulation resistance times and longer.


source : ISOPA (9)

*Contribution to lateral spread-corner position of ignition source.*

## SMOKE AND TOXIC GASES

Historically, building regulations have focused on fire testing and classification. A few countries have regulations for smoke hazard, but the tests used have limited relevance. Smoke is a consequence of fire, it is a potency value for which it is difficult to determine the hazard.

The main issue related to smoke hazard is the length of time required to evacuate the fire compartment before the visibility - or the concentration of toxic products - reaches untenable conditions. In the case of a material-focused assessment, it is not only necessary to consider which type of gases or smoke density can be released, but also over which period of time. It is also essential to consider whether the product is likely to ignite, whether there is a smouldering or open flaming situation, what influence is caused by factors such as the fire condition, room situation and burning rate of the product.

In the past, a number of small-scale test methods have been used to produce data on the toxicity of combustion from materials. Unfortunately, however, all the small-scale potency tests currently available are limited because of their inability to replicate the dynamics of fire growth which determine the time/concentration profiles of the effluent in full-scale fires. This is a crucial limitation because the effects of combustion emissions are now known to depend much more on the rates and conditions of combustion, than on the chemistry of the burning materials [4]. The only way that the performance of a material can be assessed realistically is, therefore:

a) to measure the toxic potency of a material in order to assess the contribution it will give in a certain fire condition, and;
b) to check how different fire conditions will contribute to the fire hazard by a combination of tests and modelling predictions so that a realistic assessment of the overall contribution of a product to the developing hazard in a fire is achieved.

Approaches have been made to predict effects of smoke in fires [43,61]. Whilst the levels of protection have solely engineering solutions, this approach is more applicable to ensuring a safe escape of occupants. These approaches provide calculation procedures for the life-threatening components and include fire effluent toxicity, heat and visual obscuration due to smoke.

### DECOMPOSITION MODELS

Smoke performance - optical density, toxic potency etc. - of materials are almost exclusively determined in small and intermediate scale tests. The fire model chosen for decomposing materials or products must permit a comprehensive simulation of the different fire situations.

For years, fire performance test procedures for building products have been used to measure potency values and classify building products [20], [21], [22]. For example, work at the TNO laboratories in the Netherlands has revealed weaknesses in fire performance laboratory tests linked to specific fire scenarios [23].

source : Bayer

*SBI text and data recording.*

The addition of separate smoke-performance determination methods to the standard methods of testing would seem logical, but many parameters have yet to be resolved.

Generally, smoke properties can be measured by both static and dynamic methods. The static method determines the smoke properties in a given volume, whilst the dynamic system measures the values continuously.

The most widely-known static method is the NBS chamber method [25], developed by the former National Bureau of Standards and used in the aircraft industry [26,27] even though the SAFER (Special Aviation Fire and Explosion Reduction) Advisory Committee [28] regarded its results as inappropriate.

Another static method is the dual chamber box, which provides variation of the radiation intensity, thus giving different measurements. The method failed sufficient support in ISO for development into an international standard. Nevertheless, the dual chamber box is a mandatory method in the Netherlands.

According to DIN 53436/37, the tube system is an authentic dynamic method [30]. A given weight, volume or surface area is decomposed at the specified test intervals, so that a roughly constant fire gas stream of unchanging composition is generated throughout the test. With the DIN tube system, the time-temperature relationship can be simulated for different fire scenarios, as described elsewhere [30,31].

The cone calorimeter method - another dynamic method - seems to neglect some well-known basic principles. Smouldering conditions, which sometimes play the dominant role as far as the smoke production is concerned, are completely disregarded. In the case of the pool fire configuration, the influence of the ventilation, which is demonstrated by the measurements in other decomposition procedures, is also lost.

*Table 12. International standardised decomposition models .*

| **Test (Standard)**<br>***S*** - static<br>***D*** - dynamic | **Thermal Impact** | **Sample Dimensions** (mm) | **Sample Volume** ($cm^3$) | **Test Duration** (min) |
|---|---|---|---|---|
| NBS-chamber ***S***<br>ASTM E662 | 25 kW/m2<br>with and without<br>pilot flame | 76 - 76<br>≤ 25 | 144 | 6<br>20 |
| NBS modified ***S***<br>ISO 5657 | 25 kW/m2<br>with and without<br>pilot flame | 76 - 76<br>≤ 25 | 144 | 20 |
| XP2 chamber ***S***<br>ON B3800<br>ASTM-D<br>2843 | Burner | 30 - 30<br>4<br>60 - 60<br>25 | 3,6<br>90 | ≤ 15 |
| GOST ***S***<br>12.1044.89 | Radiant panel<br>400°C - 700°C | 40 - 40<br>≤ 10 | 16 | |
| IEC TC 89 ***S***<br>cable test | Fuel ignition<br>source | 300<br>300 - 2- 25<br>2 - 400 - 4<br>00 - 25<br>1000 - 50<br>0 - 2 - 4 | 225/1<br>80 | 2 |
| ISO Smoke ***S***<br>BOX<br>ISO 5924 | 10 $kW/m^2$<br>50 $kW/m^2$ | 165<br>- 165 -<br><70 | <190<br>6 | 20 |
| DIN 53436 ***D*** | 100°C - 900°C | 270 - 5<br>- 2 | 2,7 | 20 |
| NF-16-101 ***D*** | 100°C - 900°C | 270 - 5<br>- 2 | 2,7 | 10 -15 |
| DIN 54837 ***D*** | Burner | 500 -<br>190 - d | 190 | 5 |
| Brandschacht ***D***<br>DIN 4102 | Burner | 4 -<br>(1000 - 1<br>90 - 80) | 60800 | 10 |
| ORE 14 ***S*** | Radiant panel<br>/Burner | $50cm^2$ -<br>2mm | 10 | 5 |
| DIN 4102 ***D***<br>T14 | Radiant panel<br>and flame | 1050 -<br>230 - d | | 12...30 |
| Cone - ***D***<br>calorimeter<br>ISO/DIS 5660 | Radiant panel | 100 -<br>100 -<br>≤ 50 | 500 | 60 |

In [32,33] static and dynamic systems were compared using a scaled-down room-corridor assembly. They noted a significant discrepancy because dynamic measurement in the plume strongly underestimates the "static" measurements. Freely ventilated methods, such as the cone calorimeter, may provide incorrect data for cellulose-based materials. Wood and viscose provide smoke data levels up to 10 times higher under realistic smoke-gathering conditions.

Information concerning the oxygen deficiency during the test run and the $CO_2/CO$ ratio within the decomposition models provide a comparison of the test conditions with real life fire situations. The chosen decomposition model (Table 12) must be able to simulate the real fire scenarios to be assessed.

Details of the main smoke tests are given by Troitzsch [24]. These tests are relevant to very specific test conditions only.

## OPTICAL PROPERTIES OF SMOKE

The reduction of visibility depends primarily on the quantity of smoke produced by the burning materials [10-13], though other effects must also be taken into account. Whilst dry wood-wool burns without generating visibility-reducing smoke if sufficient air is available, the same material can cause an increased smoke hazard e.g if its moisture content is high enough.

The extinction value may also be governed by the optical properties of the particulates as well as by their size and number. In [10] it was found that the particulate size increases with increasing heat radiation. For example, in comparison with polyurethane, wood produces unfavourable smoke densities at lower levels of irradiance [39]. Another fact to consider is that the absorbent effect is dominant in the case of black smoke, whereas there is a major reflection component in the case of white smoke.

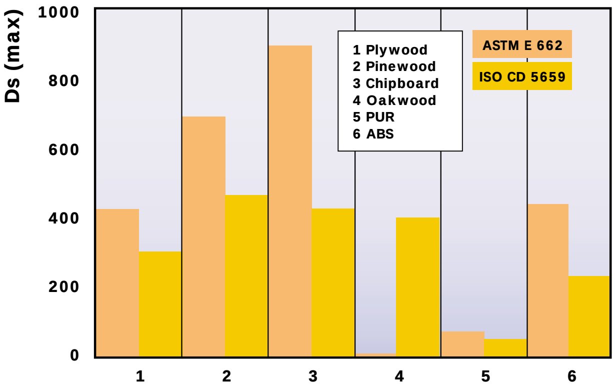
Several methods for evaluating smoke producing potential have been investigated in the past. Most methods use an optical system incorporating an electric light bulb and receiver whose sensitivity (380-780 NM) is similar to that of the human eye [14,15]. Several recently developed methods, including the cone calorimeter method, use a low powered laser [16,17].

Various attempts have been made to assess smoke hazard, e.g. in [49], where the relationship between visibility and optical density D was one of the focal points. According to Jin [49], the product of visibility and optical density D for reflective signs is constant; this was confirmed by Silversides [11].

Smoke density values are dependent on heat flux [34] and the surface area of the sample exposed. Many investigations have shown that widely scattered smoke density values may be obtained for the same material if these and other parameters, such as ventilation and the orientation of the specimen, are varied.

In S.D. Christian [35], compared various methods and revealed the effects of the test procedure on results. This includes effects of thermal barriers and such weak spots as joints and overlaps. According to H.L. Malhotra [15], the decomposing area should be at least 200 $cm^2$. Table 13 illustrates the possible variation of smoke potency data under changing conditions of decomposition.

*Table 13. Optical density of polyurethane in comparison to other products, in two different, but similar decomposition models [39].*




The risk of reduced visibility in fires has to be related to the various scenarios. In the case of a smouldering fire, for example, the risk can be reduced significantly by early warning systems. In the developing stage of a fire, the threat of reduced visibility will depend on the propagation of the fire. As long as the material in question is resistant to the simulated ignition sources, the limited amount of material combusted will not cause a significant reduction of visibility. If a fire is spreading, a rough calculation can be made by estimating the smoke produced by the burning area. The smoke potency data must be related to the threatened ambience and burning time.

As far as the flash-over situation is concerned, the total burning area - wall, ceiling and floor coverings and the surface of the contents of the fire area - have to be taken into consideration. If flash-over occurs, a relevant reduction of the smoke hazard cannot be achieved by altering the material-specific optical density levels, but only by fire prevention measures related to the formation and movement of smoke.



## TOXIC POTENCY OF MATERIALS AND TOXIC HAZARD OF FIRE SITUATIONS

A toxic potency is the exposure dose of toxic products caused by thermal decomposition of a given material, required to produce a given toxic effect, e.g. incapacitation. One way in which toxic potency data can be used is to express them in terms of LC50 values, the exposure dose calculated to produce lethality in 50 per cent of exposed test animals within a specified exposure time of usually 30 minutes [43].

In the past, toxic potency values have been evaluated in laboratory small-scale tests (Table 14). With well-known smouldering and/or flaming conditions, materials have been burned in a temperature range of 400°C - 600°C and the decomposition products passed a chamber of exposition with animals. To validate small-scale laboratory tests, full-scale investigations are requested but are rare. A clear identification of the fire situation simulated in the decomposition model is, therefore, essential.

The method and apparatus used according to DIN 53436 [30] is very suitable for this purpose since ventilation and temperature - two of the three most important parameters - can be accurately installed. Only the pressure, the third parameter - which changes constantly during the fire - is out of control. Up to now, it is not possible to simulate the pressure influence correctly in small-scale laboratory tests. Other decomposition apparatus are not as suitable as the DIN tube, since ventilation effects cannot be taken into consideration.

Today, the use of animal tests to evaluate toxic potency values, has decreased to a minimum. The evidence gathered in many experiments allows test results to be combined with mathematical calculation systems, calibrated in an animal test, so that toxic potency of products can be accurately assessed. The mathematical prediction is based on analytical elucidation of the main toxic smoke components: CO, $CO_2$; $SO_2$, HCN, NOx, $NH_3$ and depleted $O_2$ content of the fire atmosphere.

*Table 14. Toxic potency values (LC50) in different decomposition methods [48].*

| Decomposition model | Toxicity ($g/m^3$) | | |
|---|---|---|---|
| | Wood | Wool | PUR |
| DIN 53436 | 25 | 7 | 7 |
| Potts-Pott | 19 | 15 | 11 |
| U-Pitt | 106 | | 13 |
| US-Radiant | 60 | | |
| GUS-IMO | 15 | | 13 |

Available test results [38, 58, 59] have demonstrated nogeneral differences between plastics and natural products (Table 15), but differences between wood and wool and/or differences between polystyrene, polyamide and polyvinylchloride for instance. The smoke of all materials tested has been in the same range, including nitrogen-containing materials. The influence of the temperature (fig. 4 and 5) and ventilation is approximately in the same range, like the influence of the different materials involved.

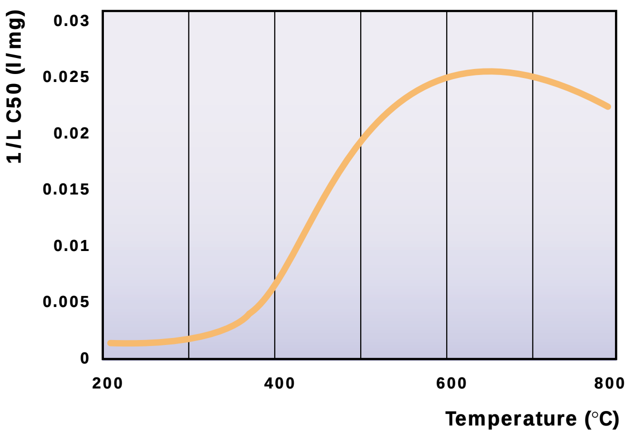
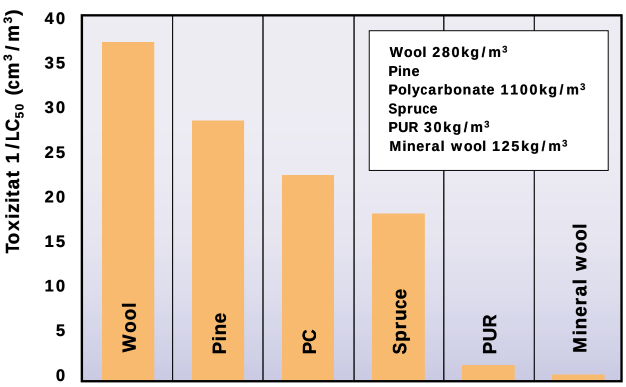



*Fig.3. Toxic potency of a rigid polyurethane product depending on temperature [38].*

Depending on the fire conditions, a certain synergistic mixture of CO, $CO_2$, HCN and NOx ($N_2O$, $NO_2$ etc.) is formed in the fire emissions, which affect life, together with a decreased level of oxygen. HCN and NOx may arise from the oxidation of nitrogen from nitrogen-containing materials such as wool, leather, polyamide or polyurethane foam [47]. As with the other tested gases in binary gas mixture studies, the addition of CO and/or $CO_2$ increased the toxicity of $NO_2$, whereas an antagonistic effect existed in the case of $NO_2$ and HCN. Results of the tertiary mixtures $NO_2$, $CO_2$ and HCN - which are much more realistic than a binary gas mixture in case of a fire - indicate that $CO_2$ does not cause a synergistic toxicological effect as reported with binary gas mixtures. Some animals survived exposure to combined levels of HCN, $NO_2$ and $CO_2$, which would be equivalent to 4,7 - 5,5 times the combined lethal concentrations of the gases.

*Table 15. Toxic potency of various materials [38].*




In [60], however, 4000 different experiments with various materials as well as different fire conditions are described. In 92 per cent of the cases lethality was caused by CO - two per cent by HCl and two per cent by unknown effects. Only in four per cent of all cases, was a combined effect of HCN and CO recognised as the main contribution of HCN to animal totality. This does not correspond to the large amount of nitrogen containing materials tested. It can be stated, therefore, that the overall toxicity of fire emissions caused by nitrogen-containing materials, such as polyurethane foams, is not automatically increased; and is in the same range of toxicity caused by non nitrogen-containing materials under comparable test conditions.

## YIELD OF DIOXINS AND FURANS IN FIRES

In practically all fires involving natural products or plastics, a variety of residual products - commonly known as dioxins and furans to which the group of polyhalogenated dibenzodioxins and furans belong - are generated as well as the overall known smoke components [42, 50].

During a fully-developed fire, elevated temperatures are reached which favour the generation of dioxins, if halogens - suitable carbon containing molecules and/or traces of special heavy metals - are available. Natural products, including so-called halogen free products, fulfil these conditions as they normally contain halogenated compounds due to (technical) pollution. In every fire, therefore, the yield of dioxins and furans has to be expected on a sub-ppm-level.

In addition, dioxins and furans are generated in every controlled combustion process, and they are present in the environment. The catastrophic fire case has to be related in comparison to this background. To be complete, the biological availability of dioxins bonded to soot in fires is very poor [51].

Fire residues normally contain dioxins. Their hazard potential cannot be evaluated on a general basis. The group of dioxins and furans contain around 210 different chlorinated compounds and a similar number of bromine derivatives. Analytical data can only be the basis for a risk assessment if the type of dioxins and the concentration found in the residues are known. Approximately 25 chlorinated and brominated dioxins and furans have been identified as toxicologically relevant; special regulatory measures exist in some countries for these types of dioxins. 2.3.7.8 TetraChlorDibenzoDioxin (TCDD) is the reference substance. With the help of internationally agreed toxicological equivalence factors and assumptions related to the factors, all the toxicologically relevant dioxins and furans can be assessed relative to TCDD.

In polyurethane fires, quantities of brominated or chlorinated dioxins/furans must not be expected to exceed an equivalent sum of 2 µg/kg TCDD, which is the concentration limit e.g. in the German Gefahrstoff VO; this was confirmed by tests under controlled laboratory conditions. Tests have been performed at an industrial scale and in an independent laboratory. The tested polyurethane rigid foams contained halogenated and halogen-free flame retardants. The blowing agent used in earlier investigations was CFC11. In recent tests, HCFC has also been used [46].

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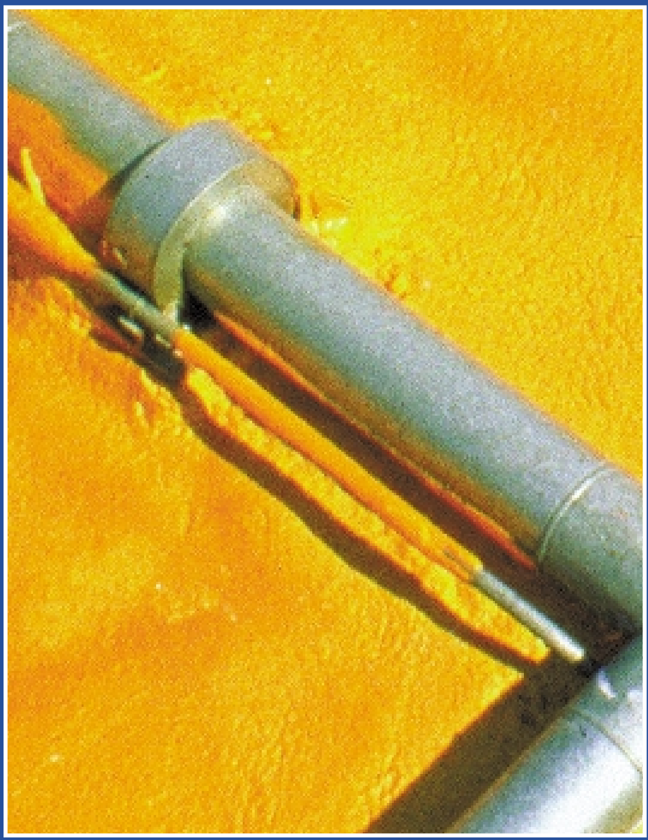

European Isocyanate
Isopa
Producers Association

**ISOPA**
Avenue E. van Nieuwenhuyse 4, Box 9
Brussels B-1160, Belgium
Tel: +32 2 676 74 75
Fax: +32 2 676 74 79

E mail: main@isopa.org
www.isopa.org