GFPA	Technical Report	GFPA TR 04-01 March 2020

Guideline
Fire Protection Engineering

published by Jochen Zehfuß

4th revised and supplemented edition March 2020

Technical-Scientific Advisory Board (TAB)
of the German Fire Protection Association (GFPA)
Postfach 4967, D-48338 Münster

Guideline Fire Protection Engineering

Technical Report GFPA TR 04-01
4th revised and supplemented edition March 2020

Publisher: German Fire Protection Association (GFPA)
(Vereinigung zur Förderung des Deutschen Brandschutzes e. V. – vfdb),
Technical-Scientific Advisory Board (TAB), Section 4,
Jochen Zehfuß.

Münster; Braunschweig: vfdb, 2020

457 pages, A4

TABLE OF CONTENTS Page

PRELIMINARY REMARK

The German Fire Protection Association (GFPA) Department 4 "Engineering Methods of Fire Protection" (also known as performance-based design or fire safety engineering) has set itself the goal of accompanying the development of engineering methods of fire protection, preparing them accordingly and making them available to practice in the form of a guideline, which is now available in its 4th edition.

Fire protection as an engineering discipline is comparatively young. Established disciplines in civil engineering, such as steel construction or solid construction, are based on decades or even centuries-old knowledge. The fundamentals have been known for a long time, the models and verification methods are often highly developed and have been standardised for many years. The engineering procedures and models of fire protection are still at an early stage of development. The scientific foundations of fire protection were mainly konset in the 1960s, 1970s and 1980s. In the field of structural fire protection, standardization began with the first generation of Eurocodes at the beginning of the millennium and is only now beginning to be applied to engineering methods for fire and smoke propagation and evacuation analysis. The guide has a pre-normative character right from the start. It is neither a textbook of engineering methods nor does it contain in large parts specific regulations as one would expect from a standard. The prenormative character is expressed in an explanatory presentation of procedures and calculation methods, background information and application examples. The extent of this varies in the individual chapters. In areas for which no German or European standards exist to date, such as in the field of pedestrian flow analysis, specific regulations and verification equations are increasingly included, whereby in areas that are already regulated by standards, such as fire protection verification of the Eurocodes, background information and application examples are provided. A focus of the 4th edition of the guideline "Fire Protection Engineering" is therefore, in addition to the description and evaluation of newly developed approaches and procedures of engineering methods, in particular the standardization and improvement of the quality of proof through appropriate validation and documentation.

The 1st edition of the guideline was published as Technical Report TR 04-01 by the GFPA in May 2006. This was the first time that the basic principles, boundary conditions and application aids of and for engineering processes in fire protection were compiled for Germany. The guideline has subsequently proved to be very useful in the preparation of fire protection reports for unique and complex buildings using engineering methods and was further updated in accordance with the state-of-the-art and published in 2009 in a 2nd edition and in 2013 in a 3rd edition. In 2015, an English version was published for the first time.

The basic concept of the guideline has consisted since the 1st edition and remains practically unchanged in the current 4th edition. The basic idea is that the structure corresponds to the real course of a project processing when applying engineering procedures of fire protection.

The 10 chapters of the guidelines were prepared by 6 working teams (WT) in vfdb Department 4 and discussed and decided upon in the permanent working group (WG) (see Table 1).

Table 1 Tasks of the Department 4 teams

WT	Designation of the working team (leader)	Chapter
1	Fire safety in buildings (Dr. Klinzmann)	1 – 3, 10
2	Fire simulation models (Dr. Riese)	5
3	Fire scenarios and design fires (Dr. Wiese)	4
4	Technical plant fire protection and averting fire protection (Rusch)	7
5	Life safety and escape routes (Dr. Schneider)	8 + 9
6	Structural fire protection (Prof. Zehfuß)	6

A complete list of the members of the Department and external experts who, in various functions, have contributed to the preparation of the individual chapters and to the consultation of the overall work, as well as more detailed information on the organisation of work and the responsibilities for the individual subject areas, can be found on the GFPA homepage at

http://www.vfdb.de/themen/referate/referat-4

or on the homepage of the Institute for Building Materials, Concrete Construction and Fire Safety (iBMB) of the TU Braunschweig at

https://www.tu-braunschweig.de/ibmb

The final editorial work on the guideline for the 4th edition was carried out by iBMB staff according to the specifications of an editorial team consisting of the leaders of the working teams. The final version was approved for publication on the internet by the Technical-Scientific Advisory Board and the Executive Committee of the GFPA at their meetings on February 12, 2020.

We would like to take this opportunity to thank all the members of the Department, but above all the leaders of the working teams, for their great commitment. I would also like to thank the experts of engineering methods, who supplemented the internal considerations of the Department with comments, corrections and suggestions for improvement.

In view of the extremely complex subject matter and the ongoing international discussion and development on some issues, this 4th edition of the guideline will also require further adaptation to newer knowledge and experience gained from its application to date. In the meantime, all users of the guideline are invited to send their comments on the applicability of the guideline to practical problems, errors discovered and open questions to the address given below.

Brunswick, August 2022

Prof. Dr.-Ing. Jochen Zehfuß

Chairman of the GFPA Department 4
and editor of the guideline

Address for comments and suggestions:

Prof. Dr.-Ing. Jochen Zehfuß

Chairman of the GFPA Department 4

Institute for Building Materials, Concrete Construction and Fire Safety

Beethovenstrasse 52

D-38106 Brunswick

Phone 0531/391-5441 - Fax 0531/391-8201

E-Mail j.zehfuss@tu-braunschweig.de

Website: http://www.ibmb.tu-braunschweig.de

1 CONCEPT AND APPLICATION OF THE GUIDELINE

1.1 Concept and structure

For the application of fire safety engineering methods within the framework of the preparation or review of a fire safety concept, this guideline provides assistance for the selection of suitable methods and input data to developed and verified appropriate fire protection solutions. The guideline outlines compactly the suitably validated engineering methods for the fire safety engineering according to the state-of-the-art and provides the required information, data and evaluation criteria.

In accordance with the various tasks, the guideline is intended on the one hand to enable a fire protection engineer as a specialist planner to design a building of a special type and use in a risk-adjusted and economical manner. On the other hand, it is supposed to help the approving authority, the approving fire safety engineer or the fire brigade to validate the layout with the least possible effort or, in the case of deviations from building regulations, to define fire protection requirements for the construction and use of the building in such a way that the protection objectives of fire safety under building regulations are achieved.

Figure 1.1 gives an overview of the field of application of fire safety engineering methods within the scope of the fire safety design of buildings (right part of the figure) compared to the traditional design (i.e. prescripte approach) by compliance with material building regulations (left part of the figure). For the work stage listed in chronological order on the right-hand side of Figure 1.1, the respective chapters of the guideline contain the necessary information on verification methods and input data.

1.2 Basic procedure for use

The guideline is intended in particular for application to buildings of a special type or use (special buildings), where, due to the building concept or for operational reasons, the recognised solutions arising from the building regulations are not to be pursued, but where at least the same safety level of the recognised solutions is to be demonstrated by other means using fire safety engineering methods. The implementation of a specific project is done in several work stages:

- preparation of a qualitative analysis,
- preparation of a quantitative analysis,
- comparison of the results with the requirements,
- presentation and interpretation of the results.

In accordance with the legal requirements of the regional building regulations or the model building regulations, the results determined using fire safety engineering methods to ensure that persons can escape and be rescued from a building. In certain instances, however, they can also provide important information on protection of environment, buildings and other property.

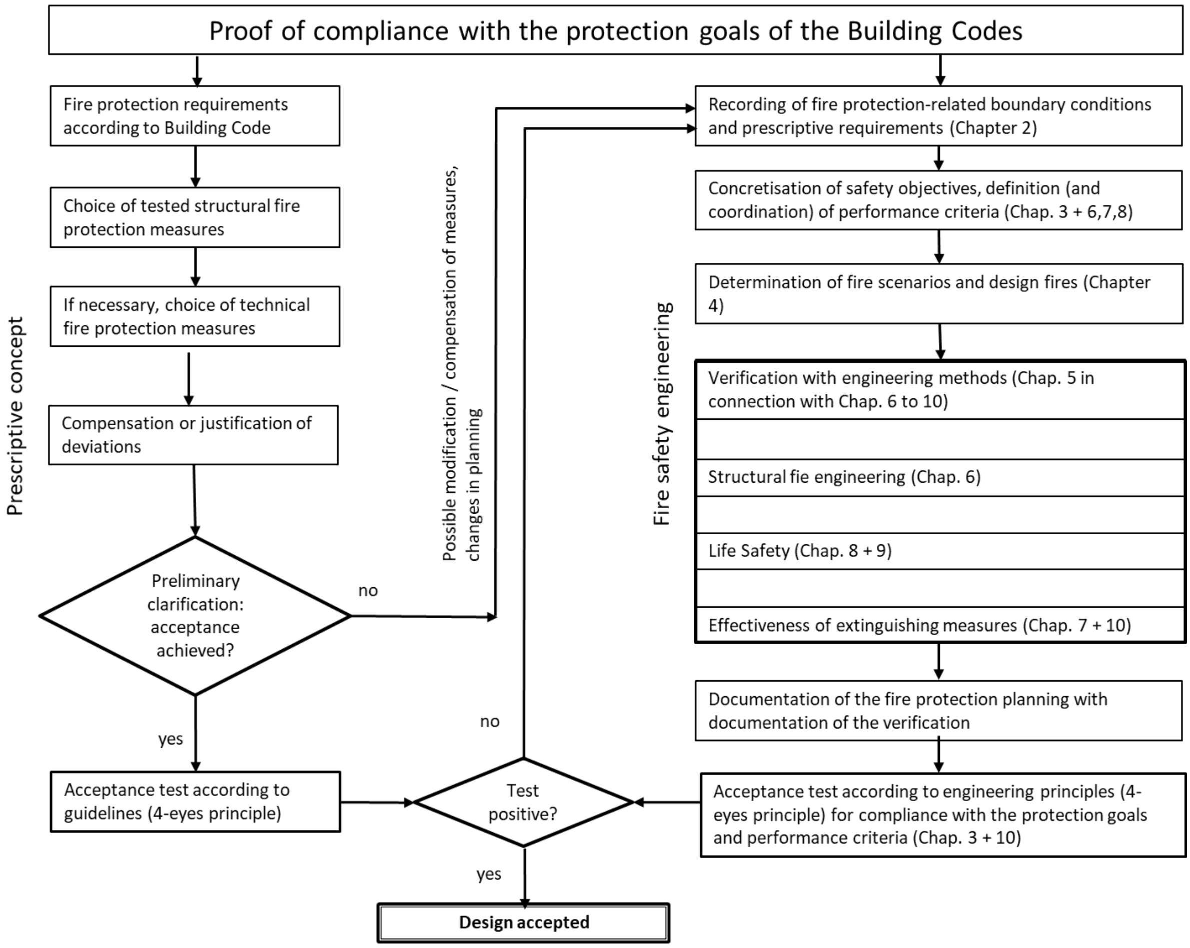


Figure 1.1 Field of application for fire safety engineering methods (right part of figure) compared to the prescriptive approach (left part of figure) in fire safety design

In this guideline, the user can find references and examples for the correct selection of design methods and input data and the interpretation of calculation results. It is assumed, however, that the user has basic knowledge of the fundamentals of fire safety as well as relevant experience in the application of fire safety engineering methods.

1.3 Qualitative analysis

Due to different types of buildings, their use and the uncertain behavior of people, various scenarios can occur. Since it is not possible to make specifications for the required design situation that apply to all buildings, representative fire scenarios must be identified in the first step. This is done by means of a qualitative analysis in which the building owner, planner, fire protection engineer, approving authority or test engineer and fire brigade agree on general and, if necessary, specific protection objectives (e.g., special requirements for the evacuation of the building) and develop fundamental solution options.

In this regard, the technical fire protection constraints of the building and its use should be taken into account and documented in the required level of detail as important input parameters for the subsequent quantitative analysis. These include in particular:

- building concept (building construction and materials, subdivision into fire compartments, layout and separation of escape routes),
- Use of building or compartment (fire loads, users, intended uses and variants),

- infrastructure (plant-related fire protection measures, precautions for fire protection),
- fire scenarios (possible fire locations and ways of fire spread, other boundary conditions of the fire scenario).

Furthermore, it must be checked whether the building is subject to any risks and associated protection objectives that go beyond the requirements of the building regulations. For instance, measures to limit an interruption of operations can be agreed between the builder/operator and the insurance company. More detailed information on this can be found in Chapter 3.

1.4 Quantitative analysis

The protection objectives and selected fire scenarios defined in the qualitative analysis, together with the determined fire protection boundary conditions, now form the basis for quantitative investigations of various sub-problems using fire safety engineering methods. The guideline provides a foundation for the following frequently asked questions:

- Fire scenarios and design fires (Chapter 4),
- Models for fire simulation (Chapter 5),
- Fire protection-related verifications of structural elements and supporting structures (Chapter 6),
- Plant engineering and averting fire protection (Chapter 7),
- Life safety in escape routes (Chapter 8),
- Passenger flow analysis with mathematical verification procedures (Chapter 9),
- Risk methods and safety concept (Chapter 10).

The calculation methods range from simple basic or approximate equations (e.g., plume formulas for locally limited fires or hydraulic approaches to determine the required evacuation time) to complex simulation models (e.g., CFD models for calculating the smoke propagation in buildings or individual models for evacuation simulation). The choice of the appropriate method depends on the required statements and the required level of accuracy. The calculation methods available according to the state-of-the-art are explained for each individual question, preferred areas of application are shown and information on validation, e.g., through relevant fire tests within certain application limits, are provided. The calculation results essential for the user, their vagueness and existing cope for interpretation are explained.

In Annex 2 of the guideline, an example of a building is examined step by step according to the recommended procedure. Various verification methods are compared and differences in the results, which can also occur in other applications, are pointed out and interpreted.

Many parameters are to be investigated time-dependently, i.e., the calculation results for one issue serve as initial variables for an issue that occurs later in the course of the fire (or in the processing). Thereby, mutual dependencies of the physical input and output variables must also be considered in order to ensure a consistent overall evaluation.

The responsibility for selecting an appropriate calculation method and the suitable input data lies with the fire protection engineer. If only incomplete input variables or insufficiently verified verification procedures are available for a specific problem, the fire protection engineer has to either make conservative assumptions on the safe side or take the existing uncertainties into account by means of parameter variations. If in doubt, validation via a real or model experiment may be necessary.

1.5 Check of compliance with relevant requirements

The results of the quantitative analyses (Chapters 5 to 9) for the relevant fire scenarios - (Chapter 4) are to be compared with the fire safety objectives essential for the object and the associated performance criteria (Chapter 3). The defined performance criteria should be adhered to for a risk-appropriate technical fire safety design of the building. If this cannot be achieved in certain cases, either the structural or fire protection boundary conditions can be changed or additional compensatory measures can be provided. In this case, the affected validation stages should be repeated.

To begin with, the fire development and its effects have to be investigated (Chapter 5). As a rule, two cases are to be considered:

- Fire development and fire effects in area of the fire itself as a basis for the thermal load of structural components and the smoke propagation in the room,
- Fire spread beyond the area of the fire as a basis for the thermal load of structural components as well as for the propagation and extraction of smoke into neighbouring areas.

The following parameters play a role, when simulating a fire with a fire model: heat release, thermal radiation, heat transport (convective and conductive), fire propagation, mass loss, ventilation, smoke yield and combustion products (Chapter 4). The parameters can be influenced by the technical and defensive fire protection measures (Chapter 7). Taking these physical quantities into account, the limit conditions assigned to the individual protection objectives can be analyzed. These include, on the one hand, limit states of the load-bearing capacity of structural components and supporting structures in case of fire (Chapter 6) and limit states of life safety (Chapter 8) and safe evacuation on the other hand (Chapter 9).

The guideline will be used primarily for buildings of a special or complex type or use, where the material requirements of the building regulations, which are geared towards "standard buildings", cannot be fulfilled. In addition, the methods are used to define compensatory measures in situations where certain requirements of the codes cannot be fulfilled directly to guarantee the require safety level. This applies to the compensation of deviations in

- structural partitions,
- load-bearing components,
- escape route lengths and widths,
- distance requirements.

1.6 Presentation and interpretation of the results

The presentation of the results should list all assumptions and constraints for better understanding by third parties. In the presentation, the following information in particular is required:

- Goal of the examinations,
- Representation of the building,
- Participants in the development of the qualitative analysis,
- Results of the qualitative analysis, including the protection objectives,
- Performance of the computational investigations with indication of the assumptions used, the validated models or calculation methods used and the associated application limits,
- Comparison of the calculated analysis with the required safety objectives,
- Recommendations for structural fire protection measures,
- Recommendations for technical fire protection measures,
- Recommendations for the organisational fire protection measures during operation of the building, e.g., requirements, operating instructions, management.

When interpreting the results, their uncertainties and ranges should also be taken into account. It should be explained how the influence of uncertain input variables and calculation models and assumptions has been examined and taken into consideration with help of parameter variations or conservative assumptions on the safe side.

2 BUILDING INFORMATION

2.1 General information

Before a fire protection assessment can be carried out for a building in accordance with this guideline, the information and input data required for the safety engineering approaches should be compiled. This relates in particular to:

- the building structure,
- the building content and use,
- the fire protection infrastructure,
- the environmental influences,
- the occupants.

The information consists partly of specific details about the building, such as dimensions, adjacent development and type of use, or of specifications / ideas of the planners, which are recorded in the context of the qualitative analysis, such as subdivision of the building into sections, ventilation, smoke and heat extraction or type of materials used.

2.2 Building structure

The structure of the building should be recognisable from the drawings and other documents of the designer. The following information should be contained, determined or specified:

- exterior dimensions of the building, height and number of floors,
- location of the load-bearing parts of the structure (beams, columns, walls) and required fire resistance,
- subdivision of the building into sections with the required information on the quality of the fire resistance of the walls, ceilings, doors, roofs, and enclosures within them,
- access to the building from the outside and escape routes (necessary stairwells and corridors) inside the building to safe areas (escape route lengths),
- arrangement of stairwells, sluices (vestibules), design of the construction and connection to the use in the individual levels of the building,
- separation of the corridors from the compartments and stairwells, design of the structure, division of the corridors into sections by automatically closing smoke stop doors or gates (limiting the propagation of smoke),
- arrangement and structural design of vertical and horizontal installation and ventilation shafts in the building, including the shut-off devices in the junctions, as well as information on the installation of technical building facilities and the required bulkheading in partition walls and ceilings,
- recording of fire brigade elevators, anterooms and their connections,
- recording the structural design of lowered ceilings and double floors, their separation from neighbouring sections and their subdivision,

- design of the facades and materials used as well as the positioning of windows, doors and gates,
- thermal properties (density, heat conduction and thermal capacity) of the building materials used and their building material classification.

2.3 Building content and use

The recording of the building contents and its type of use is one of the basis for the evaluation of a building, since the use-related fire hazards and the existing fire load influences both the duration and the intensity of a fire in a compartment. Quantitative data from the combustible materials are necessary to be able to calculate the fire effects in the fire compartment and, if necessary, the fire spread beyond the fire compartment. In addition to the ventilation conditions, the type and distribution of the fire load is decisive for the intensity of a fire and the fire load of the construction as well as for the quantity and composition of the smoke gases emitted. These can spread throughout the building and affect people during escape and rescue while making it more difficult for the fire brigade to fight and control the fire. In addition, corrosive smoke gases can cause considerable material damage to sensitive equipment.

Within the framework of the international working group CIB W 14, surveys were conducted on the average fire load densities in buildings with different uses (see Appendix to Chapter 4, Table A 4.1). These fire load densities are given in MJ/m^2. Among other relevant values, they serve as a basis for determining a design fire according to Chapter 4.

In special occupancy buildings, the fire load density can deviate considerably from the statistically determined values. In these cases, an individual survey is necessary, which is carried out directly on site for an existing building and corresponding use. Representative fire loads from buildings and compartments with comparable use can be used for new buildings, which are only in the planning stage. Due to the wide scatter of fire loads, several buildings should be included in the investigations.

2.4 Fire safety infrastructure

The following information is required for the evaluation of the fire protection infrastructure:

- accessibility of the building with fire brigade equipment,
- supply of extinguishing water for the building,
- compartmentation,
- number and location of risers (dry or wet) inside the building and hydrants outside the building,
- areas with automatic fire detectors that respond to smoke, heat or flames and alarm systems that operate acoustically or visually,
- areas with automatic fire extinguishing systems (water extinguishing systems, gas extinguishing systems, etc.)
- areas with automatic systems for natural smoke extraction (vertical or horizontal) or mechanical smoke extraction,

- areas with pressure ventilation such as stairwells, airlocks or fire brigade elevators.

2.5 Environmental influences

The design and dimensioning of natural smoke exhausts can be influenced by surroundings, such as wind effects on the building, temperature differences between inside and outside, snow loads and air movements in the building.

Wind creates an overpressure on the side of the building facing the wind. The wind flows around the building, creating negative pressure or suction on its sides and on the roof opposite the side facing the wind. In the event of fire, smoke vents should only be opened in external walls where wind suction (negative pressure) prevails, and air vents in external walls with wind pressure. This applies in the same manner to suction openings for mechanical smoke extraction.

If it is important for the fire safety design, the temperature spectrum relevant for the building location (summer and winter case) must be considered. The temperatures in the building can vary considerably depending on the location, 20 °C is used as a benchmark. In high rooms such as atria, larger temperature differences can occur from top to bottom when the sun shines. A heated layer of air can form under the roof ceiling, which cannot be penetrated in the event of fire by the rising and cooling smoke gases (see "Inversion weather conditions"). This should be taken into account when planning the natural smoke extraction and the technical building facilities.

Snow loads and ice can impede the functioning of smoke and heat vents in the roof or cause time delays when triggered automatically. The functionality under snow loads is certified for classified devices.

Mechanical ventilation near the ceiling can generate significant air movements, e.g., in large exhibition halls. In case of fire, this can influence the rising smoke gases and lead to uncontrolled smoke propagation. This can lead to time delays in the triggering of smoke detectors. Under such conditions, additional tests should be carried out with the ventilation system switched off in order to estimate the effects on the fire development.

2.6 Occupants

The public law objectives of fire protection focus on ensuring the escape and rescue of persons. For this purpose, information on the expected number of people in the building and their expected behaviour is required. The following criteria are of importance:

- familiarity with the building: People who are in the building on a daily basis and who are familiar with the local conditions and safety requirements will choose the shortest route to safe areas in the event of danger. On the other hand, people who are unfamiliar with the building will generally choose the escape route by which they entered the building.
- awareness: Persons who are permanently working in a building, as well as persons who, for instance, serve as contact persons for other people (information), generally are more aware of changing situations.

- mobility: The walking speed of people escape through doors, corridors and staircases can vary greatly between young people and elderly people. For people with reduced mobility, such as wheelchair users or people with impaired walking ability, additional requirements have to be met when designing escape routes.
- social affiliation: Persons in groups (family or visitor groups) usually stay together and move as a group also to the exit. In a group, a dangerous situation is often recognized earlier, but the speed of escape is usually determined by the slowest person in the group.
- responsibility: Persons in a building who have a certain amount of responsibility influence the behaviour of others. Indications of dangerous situations shorten the time from the fire alarm to the start of the escape movement.
- activity in the building: The time to start the escape movement is longer for persons in resting position (sleeping or resting) than for persons sitting, standing or moving.
- obligation: Persons who have taken on a special task, such as queuing in a queue, eating together in a restaurant, will not leave their seat at short notice if the warnings about the fire are not clear (alarm system or announcement to vacate the building).

In Chapter 8, the behaviour of occupants is recorded and evaluated in more detail. Models for the evacuation of a building are presented in Chapter 9.

3 FIRE SAFTEY OBJECTIVES, FUNCTIONAL REQUIREMENTS AND PERFORMANCE CRITERIA

3.1 General information

Fire safety in buildings - in particular buildings of special type or use - results from the interaction of preventive structural and technical fire protection measures, organisational fire protection measures during operation or use firefighting measures after the occurrence of a fire. Any change in the fire risk, e.g., due to very high fire loads and/or ignition hazards or oversized fire compartments, should be compensated by fire protection measures that take into account the increased hazard in order to achieve adequate fire safety at the previously accustomed safety level. Changes with regard to the fire protection measures that have been customary up to now, e.g., simplifications in structural fire protection measures or savings in the fire brigade's emergency services, will inevitably have an effect on fire safety - but only measurable after statistically evaluable periods of time. Fundamentals and methods for a comprehensive analysis and evaluation of such changes can be found in [3.9]. On this basis, simplified approaches for a risk-oriented specification of the safety requirements for fire protection certificates were derived in the concluding Chapter 10 of this guideline.

The fire safety objectives result on the one hand from public law regulations (such as building law or workplace law) and on the other hand from private law regulations and private interests of the owners or operators of a building.

The achievement of protection objectives under building regulations must be verified within the framework of fire protection certificates or fire protection concepts as required by the building regulations of the federal states or the Model Building Code (MBO) [3.1]. Concrete specifications for the content and structure of fire protection concepts can be found, for example, in the GFPA guideline 01/01 [3.2]. This also addresses calculation methods of fire protection engineering.

In principle, engineering fire protection certificates should always be prepared and documented in connection with a fire protection concept/fire protection certificate (see GFPA guideline 01/01).

The performance of the fire protection measures should correspond to the fire hazards and fire risks of the buildings including their use and the protection objectives. From the point of view of a licensing authority, it is important to know the generally required safety level of fire safety and to be able to correctly assess the safety level that exists and is to be licensed in individual cases.

Fire safety design on the basis of fire safety objectives is not limited to the mathematical determination of the required fire resistance of the building components, as e.g., in [3.3] for a design of industrial buildings, e.g., according to [3.4]. It also concerns the design of smoke extraction systems for securing the escape routes or of automatic or semi-stationary fire extinguishing systems for enabling effective extinguishing measures in connection with an evaluation of the performance of the fire protection measures for the building to be evaluated. In this context, calculation methods of fire safety engineering are increasingly applied, for which assumptions about the fire occurrence and requirements on the performance of fire protection measures are needed. This allows to justify deviating solutions for individual concrete fire protection requirements of the building code or regulation or guideline for special buildings or to provide performance-based methods.

In the following, the question will also be examined to what extent the updating of the technical regulations (DIN, EN standards, other design guidelines for fire protection measures) will introduce new performance classes for fire protection measures which are no longer easily in line with the protection under building regulations.

The frequently observed tendency to explicitly consider all risk-reducing factors in the fire protection concepts can lead to the fact that corresponding assumptions and prerequisites, e.g., with regard to the operational use, safety-relevant requirements and conditions, e.g., the ordering of in-service inspections, have to be ensured. This restricts the freedom of the building owner and the organisational responsibility of the operator of the structural facility increases. Therefore, there are limits to the consideration of risk-reducing factors in actual practice.

3.2 Relationship between fire risks, fire scenarios and safety objectives

Design fire scenarios are characterized, among other things, by the fact that they do not have to cover or include every conceivable or actual fire on the safe side. Instead, they delimit the area to be protected from the area of accepted residual risks. In this regard, fire scenarios in conjunction with design fires are a commitment to a very specific safety level. Each fire scenario describes a situation that is associated with a certain risk.

The risk can be defined as the product of the probability of occurrence and the extent of damage.

$$\text{Risk} = \text{Probability of occurrence} \cdot \text{Extent of damage} \qquad (3.1)$$

Accordingly, risks can be assigned to any number of finely differentiated risk classes, as is shown in Figure 3.1. High and very high risks can thus be justified both by a high probability of occurrence and by a large extent of damage. Depending on the risk class, the fire protection measures required in individual cases or the associated performance requirements can be graded.

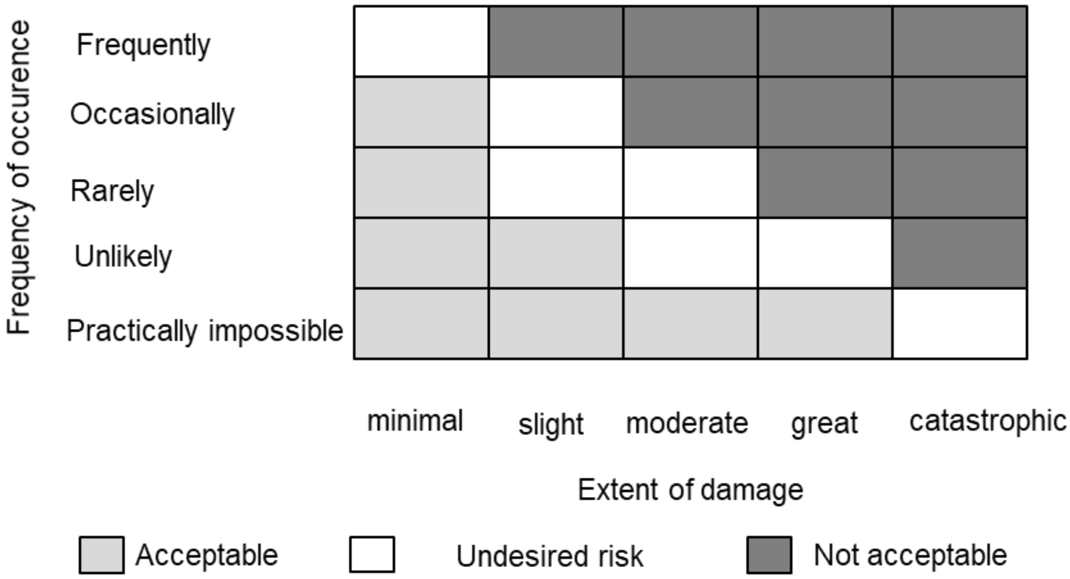


Figure 3.1 Example for the definition of risk classes (according to DIN EN 18009-1:2016-09)

The transfer of the general safety philosophy of the regional building regulations to the required fire safety in special risk situations of special buildings is complex and often a discretionary decision. In principle, it must be proven that the fire risks existing in each individual case are covered by the specially chosen and assessed fire protection measures so that the "general requirements" of the regional building regulations (LBO) are satisfied in the same manner. This is stated, for instance, in § 3 Paragraph 1 MBO [3.1]:

> *"Physical structures shall be so arranged, constructed, modified and maintained as not to endanger public safety and order, in particular life, health and the natural resources, taking into account the basic requirements for construction works set out in Annex I to Regulation (EU) No 305/2011. This also applies to the removal of installations and to changes in their use".*

In addition, Section 85a (1) and (2) MBO [3.1] stipulates the following:

> *("1") The requirements according to § 3 may be concretized by Technical Building Regulations. The Technical Building Regulations shall be observed. Deviations from the planning, dimensioning and execution regulations contained in the Technical Building Regulations may be made if the requirements are met to the same extent by another solution and a deviation is not excluded in the Technical Building Regulations; §§ 16a para. 2, 17 para. 1 and 67 para. 1 remain unaffected.*
>
> *"(2) Concretisations may be made by reference to technical rules and their references or by other means, in particular*
>
> 1. certain buildings or parts thereof,
>
> 2. the planning, dimensioning and execution of structural facilities and their parts,
>
> 3. the performance of construction products in specific construction works or parts thereof [...]. "

In practice, this means that an increased fire risk should be compensated by additional or more effective fire protection measures. On the other hand, it is generally not possible to require that the fire risk must be reduced below the normally accepted residual risk by a bundle of high-quality fire protection measures.

Basically, three classes of events can be distinguished:

- dangerous fire events which must be covered by regulations (events which have to be regulated and to be made safe),
- dangerous fire events that cannot be directly covered by regulations (events of accepted residual risk),
- Events that are classified as non-hazardous although they have certain hazard potentials (uncritical events not worthy of regulation).

The assignment of events to one of these classes is extremely important for the scope of security measures and often leads to controversial discussions in practice. Particularly affected are the requirements for buildings regarding

- Distances from neighbouring borders,
- Location on the property,
- Arrangement and type of components and building materials,
- Fire protection facilities and Fire protection precautions,
- Firing systems, boiler rooms, elevators,
- Escape routes: corridors, stairwells, hallways,
- Permissible number of persons / users,
- Building services: ventilation, pipework,
- Operational / organizational fire protection measures.

With regard to the determination of the relevant fire scenarios, reference is made to Chapter 4 and Section 7 of DIN 18009-1:2016-09.

3.3 Safety objectives

3.3.1 General safety objectives

Fire protection does not end in itself, but serves the protection of interests:

- Life and health of humans and animals
- Protection of material assets (property protection)
- Protection of the environment
  - Air (combustion gases)
  - Water (extinguishing water)
  - Soil (extinguishing water)
  - Flora and fauna
  - Avoidance of fire debris,

- Possibilities of deployment of fire brigades and safety of emergency services

  There are personnel and technical limits to the safe deployment of fire brigades. These limits should be taken into account. Relevant notes are contained in [7.16].

- Risk Management

  The residual risk remaining when building regulations are complied with is usually transferred to the fire insurers within the framework of risk management. In principle, it is possible to make one's own financial provision.

The protection of the above-mentioned safety objectives is essentially formulated in public and private law regulations. In addition, the operators of structural facilities also have protection interests that lie in the business management sphere:

- Protection of goods and resources,
- Limitation of operational disruptions (loss of use and delay in delivery means, among other things, loss of customers),
- Avoidance of
  - criminal and civil liability, especially of executives
  - Environmental problems that create a negative public image
  - Problems with re-erection, since in many cases a permit for operating facilities must be obtained
  - Optimisation of the costs for insurance coverage through preventive measures.
- Maintenance of creditworthiness and insurability.

3.3.2 Safety objectives and their related functional requirements

Since engineering fire safety certificates have become an integral part of the building permit-procedure, the concretization of safety objectives in connection with the definition of fire scenarios, which are to be used as a basis for the assessment and approval of construction projects, has become increasingly important.

Various aspects such as

- Fire protection philosophy and fire protection concepts,
- Protected goods and protection targets,
- Design fire scenarios and design fires,
- Dimensioning and design of fire protection measures, and
- Fire safety level

to be considered holistically in engineering terms. In detail, this involves a large number of individual questions, e.g., the qualitative and quantitative description of fire scenarios in rooms with sprinkler system. Approaches for taking into account the interactions between the various influencing parameters in a holistic fire protection concept can be found in Chapter 7.

Possible fire safety objectives are:

- Integrity of persons,
- Prevention of outbreak of fire,
- Limiting the spread of fire and smoke.

The fire safety objectives can be fulfilled by satisfying the related functional requirements which can include the following:

- Creation of conditions for a (successful) intervention by the fire brigade, verifiable through personnel and technical equipment to ensure an agreed time-period of assistance,
- Load-bearing capacity of the building structure under certain fire exposure over a defined period of time,
- Ensuring the minimum thickness of a low-smoke layer in case of fire over a certain period of time.

The functional requirement describes what is to be (technically) achieved, while the safety objectives describe why something has to be achieved. Under fire protection, a distinction is usually made between personal protection, neighbourhood protection, environmental protection and protection of property. In a first step, the fire safety objectives could be specified in more detail in the Table 3.1. Limiting criteria (relative or absolute) indicate the conditions under which the functional requirement is considered to be fulfilled.

Table 3.1 makes it clear that accepted levels of damage are agreed and that zero risk cannot be aimed for.

Table 3.1 Examples for a concretion of safety objectives [3.8]

Protection of	Functional requirement	Performance criterion
People	Avoidance of personal injury	Type and number of accepted personal injuries per claim
Assets	Limit fires to maximum areas	< 200 m²
Environment	Do not allow irreversible damage to air, water, soil and species (fauna and flora)	Accepted limits for permissible contamination of soil, air and water

A next stage of concretion is shown in the Table 3.2 as an example of the safety objectives under building law.

Table 3.2 Examples for the concretion of safety objectives for personal and property protection under building law

Functional requirement	Concretion by specifying performance criteria to be met
Limiting the spread of fire and smoke	Ensuring a smoke free layer to enable people to escape on their own (depending on the building, for instance, at least 10 minutes or for the proven period of self-rescue)
Rescue of people	Refuge in secured areas until the rescue by the fire brigade (depending on the building, for instance, at least 30 minutes or for the proven period of self-rescue)
Enabling effective firefighting operations inside a building	Stability of the construction of multi-storey buildings (depending on the building, for instance, at least 90 minutes or over the course of a natural fire), smoke and heat extraction over time x with maximum smoke layer thickness y

The risk is effectively minimized, e.g., by supporting self-rescue options or firefighting by the fire brigade, measures that prevent the occurrence of fires as well as the development and spread of fire and smoke are particularly worth considering. These are so-called primary measures (to prevent the development of fire) and secondary measures (limiting the spread and development of a damaging fire). They take effect prior to the structural measures (tertiary measures), which are particularly effective in the full fire phase, when the primary and secondary measures have failed or when the fire develops beyond the primary and secondary phase. The primary and secondary measures thus essentially reduce the probability of dangerous fire events to such an extent that the special risks of the special buildings are sufficiently compensated (but not 100% excluded). Secondary measures include, among other things, measures that are specifically designed to hinder the spread of smoke and that assign the necessary requirements for escape and rescue as well as for effective firefighting to the fire stages Table 3.3.

Table 3.3 Assignment of the protective effects of fire safety measures to the fire stages (see also Figure 3.3)

Initial fire	Growing fire	Fully developed fire	Decaying fire
Operational measures	Organisational arrangements	Organization of the fire brigade	
Combustibility of building materials	Combustibility of building materials; burning behaviour of substances and goods	Fire load density	Disposal
Fire detection and alarm system (BMA / ELA)	Fire detection and alarm system (BMA / ELA)		
Escape routes	Escape and emergency routes	Shelters	
Fire extinguisher	Response time of fire fighters, fire extinguishing system, extinguishing water supply		
Windows / ventilation / mechanical smoke extraction	Smoke extraction systems (natural / mechanical)		
Separation, encapsulation of fire loads	Separation, smoke zones	Separation, fire compartments	
	Stability of individual components	Stability of single structures	Stability of whole building construction
	Reliability of active fire protection measures		

3.4 Further safety objectives

If, in individual cases, the public-law safety objectives are supplemented by private-law objectives, further requirements may be imposed. Typical these could be the self-interests of a plant operator, which should in principle coincide with the interests of property insurers, because the latter are contractually bound to take over certain selected risks of the operator. If private law protection interests determine the measure for the safety assessment, then the public law safety philosophy, which primarily aims the protection of persons and common goods, can be applied as well. In the case of greater risks (product of the probability of occurrence of dangerous fires and the probable maximum damage), this can lead to fire protection concepts that reduce the fire risk even further with more reliable or additional measures.

If the size of an expected total loss is the measure for the safety assessment and if this is fully independent of the primary and secondary protective measures, mainly measures of damage limitation (fire protection partitioning of areas or distance arrangements) are available. The corresponding design fire scenarios and/or design fires then refer to the "controlled combustion" of an area and to the protection of the neighbourhood and, if necessary, the environment. Such scenarios not only form a basis for risk acceptance in insurance-related issues, they must also be considered in terms of building regulations, such as when the fire safety of buildings is to be guaranteed mainly through technical systems. In the unlikely event of a system and concept failure (residual risk), the fire scenario to be expected can usually no longer be controlled with the existing firefighting and structural fire protection measures.

Technical fire protection systems such as smoke extraction systems or sprinkler systems can be designed in such a way that they cover both the fire safety objectives under building regulations and the protection interests of the operator and/or insurer of a building. In this regard, technical rules have been developed which can also be applied to unusual or rare fire scenarios. For fire protection systems, which should also satisfy property protection in addition to the approvement-relevant safety objectives under building law, the requirements resulting from the different safety objectives, special design fire scenarios, performance and acceptance criteria must be viewed, agreed and applied holistically.

While in the private law sector the various protection interests can be covered with various concepts, which are agreed between the insurer and the policy holder and which can have different weighting in terms of protection and financial precautions, in the public law sector there is a binding legal requirement (although not always very clear in detail due to the use of vague legal terms) in the building regulations of the federal states. It is supplemented by the "generally recognized rules of technology" (GRRT), which were developed with the participation of all parties concerned.

3.5 Fulfilment of functional requirements through compliance with performance criteria

3.5.1 Definition of fire safety objectives by technical rules

The legal definition of the safety objectives under building regulations (e.g., in § 14 of the MBO [3.1]) is practically carried out by introducing certain technical rules as technical building regulations to meet the general requirements according to which buildings must be designed in such a way that

- preventing the development of fire and limiting the spread of fire and smoke,
- the rescue of humans and animals in a fire, and
- effective extinguishing work are possible.

In the technical building regulations introduced, e.g., in DIN 4102 [3.5] or DIN EN 13501 [3.7], requirements are specified for achieving the safety objectives mentioned with regard to

- Fire behaviour of building materials,
- Fire resistance of the structural components in terms of integrity and load-bearing capacity, expressed in fire resistance classes,
- Tightness of the closures of openings, and
- Layout of escape routes.

With DIN 4102, DIN EN 1363 and MVV TB [3.9] according to § 85a MBO, the public-law expectations of fire safety are also defined in so far as the test requirements and test fires clearly state the effects and failure criteria. Furthermore, the certification of building materials, structural elements and types of construction also ensures compliance with the underlying safety concept. Additionally, the fire protection measures required for compliance with the safety objectives must meet the requirements of the relevant technical rules and regulations.

To ensure that the technical rules can serve as components of a legal definition of safety objectives of the building regulations they must contain the following elements:

- Defined actions (defined fire scenarios and design fires: e.g., the fire model of a fully-developed fire with an evolvement of room temperature according to the standard temperature-time curve of DIN 4102),
- Defined failure criteria (failure model: e.g., maximum surface temperature or deflection speed of structural components),
- Defined safety concept (e.g., defined exploitation reserves for the "cold" load-bearing capacity in the form of permissible stresses), and
- Defined application rules.

3.5.2 Requirements in the building regulations

Often the building regulations do not contain definitions of the safety objectives in the form of a description of the fire model (design fire scenario and design fire, failure model, safety objectives/ performance requirements) and safety concept (safety coefficient / safety margin), but only material requirements for certain protection measures. The fire safety objectives behind each of these building regulations and special building codes are often not apparent. In any case, in the search for alternative solutions through other measures, there is a large margin of discretion when interpreting these regulations.

With the time data in Figure 3.4, an attempt is made to allocate the chronological sequence of the fire to typical fire safety objectives. This is based on the following thought model: If an unprotected exposure in a "fire-smoke atmosphere" beyond the tolerable limits beyond the duration of the resuscitation limit, the statistical probability of a successful external rescue falls below 50 %. The listed times can merely be rough orientation values. Depending on the object, significantly different values could be decisive. Assessment values for the tolerability limits under different aspects are given in Chapter 8. They are generally used as a basis for assessing the safety of people when using fire simulation models.

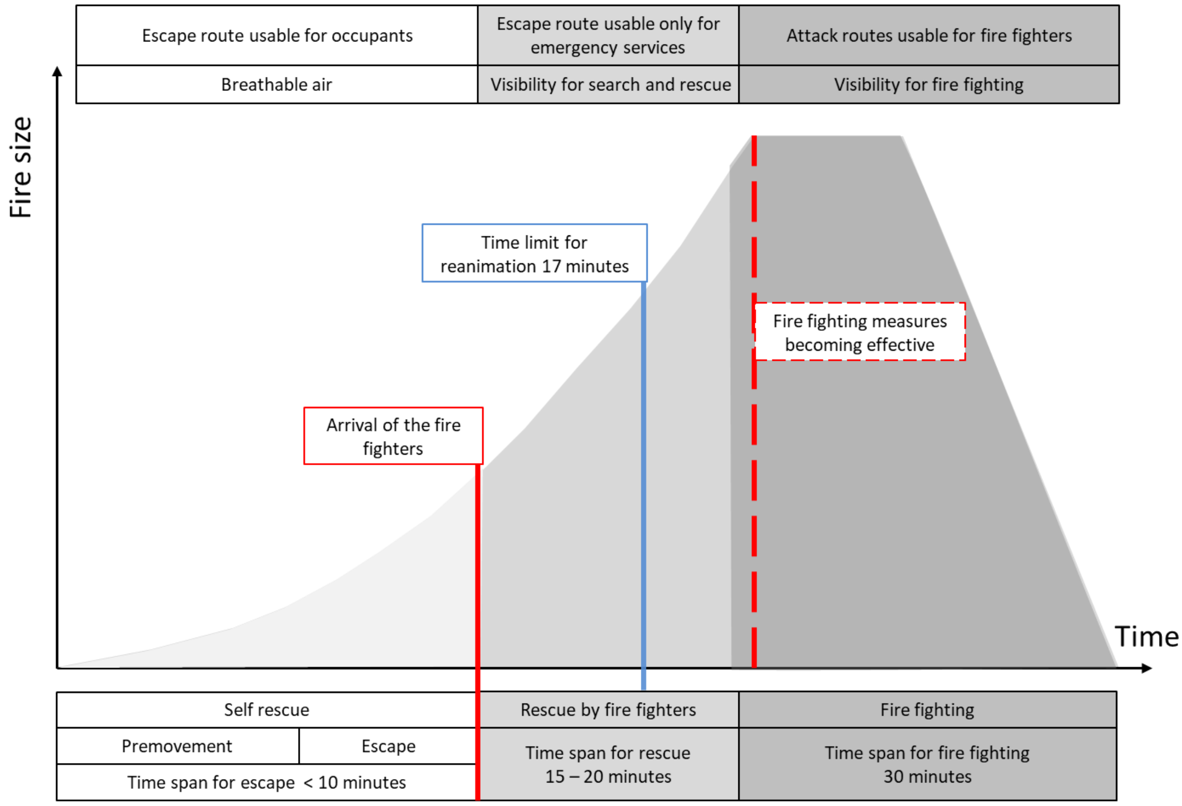


Figure 3.4 Fire phases with assigned main uses of the escape routes and conditions for the usability of the escape routes in case of fire

3.5.3 Linking safety objectives, design and performance criteria

This guideline is intended to offer assistance in the preparation or examination of performance-oriented fire protection concept and in the selection of the corresponding engineering methods and performance criteria. Since the individual safety objectives are not independent of each other and the fire protection measures sometimes affect several fire safety objectives, it is not easy to identify the relevant verification and performance criteria.

Using the example of the public-law safety objectives, the

Table 3.4 therefore attempts to compile the evidence and the performance criteria to be observed in the evidence as clearly as possible in tabular form. This overview aims to make it easier to find the relevant verification and performance criteria in the following chapters of the guideline.

Table 3.4 Relationship between safety objectives, functional requirements, qualitative evidence and performance criteria for quantitative evidence

Safety objective	Functional requirement and qualitative verification	Performance criteria for quantitative verification
Public safety and order Protection of life and health Enabling the rescue of humans and animals	Safe usability of escape routes for a defined period of time through: – Fulfilment of material requirements for the escape routes and/or – Verification of evacuation of the building before the occurrence of critical conditions $t_{Evacuation} < t_{available}$ ⇨ *see Chapter 9*	– Two independent escape routes – Maximum permissible escape route length – Enclosure components with fire resistance – Minimum widths of escape routes and exits – Minimum requirements for building materials - $t_{Evacuation}$ according to calculation by hand or evacuation simulation - $t_{available}$ as default or after fire simulation ⇨ *see Chapter 5*
	Safety of persons under the influence of – Smoke – (respiratory) toxins – High temperatures Verification by means of – Analytic equations – Zone model (smoke, – heat) – CFD Model (all) ⇨ see *Chapter* 5	– Height of smoke-free layer or optical smoke density or visibility – maximum FED value, – maximum gas temperature or maximum heat radiation ⇨ Assessment values see *Chapter* 8
	Stability of the construction and integrity of the escape routes for the duration of self- and third-party rescue. Proof by: - Fulfilment of material requirements for components - Verification using simplified or general calculation methods ⇨ *see Chapter 6*	- Tabular data (technical rules e.g., DIN 4102-4, Eurocodes or proof of usability such as abZ, abP, ETA, hEN) - e.g., critical steel temperature - e.g., load-bearing capacity when exposed to fire

Table 3.4 continued

Safety objective	Functional requirement and qualitative proof	Performance criteria for quantitative detection
Prevent the fire from starting	Restriction of combustible building materials. Verification by: − Proof of usability like [abZ, abP] − Test	− Norm specifications − Testing and authorisation criteria − z. e.g., fire shaft, SBI
Prevent the spread of fire and smoke	Limiting the fire effects to one use − Fulfilment of material requirements for partitioning components Proof of the effects of fire ⇨ *see Chapter 5*	− Test criteria for integrity or smoke denseness − Minimum distance to neighbouring buildings or − Norm requirements for building end walls or fire end walls − e.g., maximum temperature or heat radiation
Enable effective fire fighting	Stability of the construction and integrity of the attack routes for the duration of the extinguishing work: − Fulfilment of material requirements for components − Simplified calculation method. − General calculation methods ⇨ *see chapter 6* Provision of areas for the fire brigade, Proof that the quantity of extinguishing water is sufficient, Verification of firefighting equipment − Self-help systems − Risers − Extinguishing systems − Early fire detection and alarm Provision of adequate visibility through smoke extraction ⇨ *see Chapter 5 + 10*	− Tabular data (technical rules e.g., DIN 4102-4, Eurocodes or proof of usability such as abZ, abP, ETA, hEN) − e.g., critical steel temperature − e.g., load-bearing capacity under fire exposure − Norm requirements − Fire water requirement according to DVGW W405 − e.g., fire extinguisher according to ASR 2.2 − Modified requirements ⇨ *see chapter 7 + 10* − e.g., minimum smoke extraction surfaces − Target values for optical density or visibility ⇨ *Assessment values see Chapter 8*
Public safety and order, protection of natural resources	Prevention of contamination of the environment (air, soil, water) by − Fulfilment of material requirements (e.g., retention of extinguishing water) − Verification of pollutant generation/spread (incident analysis)	− Fire resistance class of the components − Maximum storage quantities − Permissible contaminant concentration ⇨ *Assessment values see Chapter 8*

In principle, instead of an individual proof, standard requirements for a specific fire protection measure according to regional building regulations or special construction can be fulfilled in writing prior to construction. This possibility is listed first in the middle column of the

Table 3.4. This is followed by simplified and general calculation methods, if available. In the right-hand column the performance criteria are listed to be determined in the verifications, which are to be compared with the corresponding upper or lower limit values according to legal building regulations or recognised calculation approaches.

3.6 Notes on the safety level for verifications using the guideline

Fire is an extraordinary situation that occurs with a comparatively low probability within the service life of a building. For an extraordinary design situation, lower safety requirements are usually placed on the design of measures compared to situations of normal operation. In semi-probabilistic safety concepts for the design of load-bearing structures (see [3.9]), the partial safety factors for actions and building resistances applicable for the service load cases are usually reduced to 1.0, so that the relevant influencing variables are always included with their characteristic values, i.e., the nominal values according to the respective load or material standards. In addition, further reductions with combination coefficients are made when combining actions, because the simultaneous occurrence of several independent extraordinary actions in addition to the fire is highly unlikely. As a rule, the expected values are not used as characteristic values, but rather increased or decreased fractiles to be on the safe side.

In accordance with this safety philosophy, which is valid today for all designs in civil engineering, the following concept is pursued within the framework of this guideline:

- The design fire scenarios and design fires to be specified in Chapter 4 should be on the safe side compared to the expected values and should take random variations and uncertainties into account appropriately.
- For this purpose, the fire load and the heat release rate are usually to be specified as upper fractiles, taking into account their scattering. Based on DIN EN 1991-1-2/NA [3.5], this guideline assumes 90 % percentiles (in the international references 80 % to 95 % percentiles are given). In addition, uncertainties regarding the combustion behavior under the existing boundary conditions (e.g., fire load arrangement, ventilation conditions) shall be taken into account by parameter variations.
- When determining the effects of fire according to Chapter 5, it is assumed that the fire models described there accurately reflect the physical and thermodynamic conditions on average within their application limits; they must be validated for the application.
- The standard fire curve in connection with the fire resistance duration required by building regulations can serve as a standard of comparison for the conservative approach to the fire exposure to be determined by calculation as a nominal fire load for verifying the fire behaviour of building components. It covers the effects of different natural fire developments in buildings of normal type or use predominantly on the safe side.
- The verifications of structural elements and supporting structures according to Chapter 6 must always be based on the safety concept oriented to the above-mentioned safety philosophy in accordance with the fire protection parts of the Eurocodes and the associated National Annexes.

- It is assumed that the models for life safety in escapes routes (Chapter 8) and pedestrian dynamics (Chapter 9) on average lead to realistic results in case they are applied accurately. Furthermore, it is assumed that design values for the corresponding performance criteria (see Table 3.5 and Table 3.6) contain sufficient safety margins.
- Differentiated safety requirements for special fire risks can be justified on a case-by-case basis using the information and methods in Chapter 10. If necessary, Chapter 10 can also be used to provide quantitative verification of the safety level achieved for an existing fire protection layout that may not comply with the specifications and, if necessary, to correct it by optimised measures.

3.7 Literature

[3.1] Musterbauordnung – MBO – Fassung November 2002.

[3.2] vfdb-Richtlinie 01-01 „Brandschutzkonzept“, Ausgabe April 2008.

[3.3] DIN 18230-1: Baulicher Brandschutz im Industriebau – Rechnerisch erforderliche Feuerwiderstandsdauer, Ausgabe September 2010.

[3.4] Muster-Industriebaurichtlinie – M IndBauRL, Mai 2019.

[3.5] DIN EN 1991-1-2/NA:2015-09 – Nationaler Anhang – National festgelegte Parameter – Eurocode 1: Einwirkungen auf Tragwerke – Teil 1-2: Allgemeine Einwirkungen – Brandeinwirkungen auf Tragwerke.

[3.6] DIN 4102. Brandverhalten von Baustoffen und Bauteilen.

[3.7] DIN EN 13501. Klassifizierung von Bauprodukten und Bauarten zu ihrem Brandverhalten.

[3.8] ISO 16733-1:2015: Fire Safety Engineering: Design Fire Scenarios and Design Fires, September 2015.

[3.9] *DEHNE, M.:* Probabilistisches Sicherheitskonzept für die brandschutztechnische Bemessung. Institut für Baustoffe, Massivbau und Brandschutz, iBMB, TU Braunschweig, Heft 169 (2003).

[3.10] DIN EN 1991-1-2:2010-12 – Eurocode 1: Einwirkungen auf Tragwerke – Teil 1-2: Allgemeine Einwirkungen – Brandeinwirkungen auf Tragwerk.

[3.11] MVV TB: Muster-Verwaltungsvorschrift Technische Baubestimmungen. Ausgabe August 2017.

[3.12] ISO/WD TS 16733- Fire safety engineering- Selection of design fires- Part 2: Design fires, 2019.

4 FIRE SCENARIOS AND DESIGN FIRES

4.1 Introduction

Depending on local and temporal conditions, there exists a wide range of possible fire developments in building structures. A variety of fire scenarios are conceivable for a single room, functional units or fire compartments. This results from a number of influencing factors such as cause of a fire, place of fire origin, special fire hazards and other possible fire-influencing factors. Therefore, so-called design fire scenarios should be defined for a specific building. According to DIN 18009-1 [4.1] design fire scenarios describe all essential parameters that can influence the course of the fire and safety-relevant events.

These include, in particular, the interaction of fire protection measures, the influence of persons (e.g. operational arrangements, fire extinguishing by employees) and the effect of technical installations. Aspects of the type of use and, if applicable, of external climatic conditions are also taken into account [4.1].

In order to provide a load-bearing proof, the course of fire should be qualitatively described using relevant design fire scenarios, and should be also quantified with the aid of design fires. The objective of scenario definition and scenario concretization is to define the "fire load case" for the individual case by means of design fire scenarios in such a way that the resulting fire courses, which are defined as design fires, are only exceeded with very low probability in an actual fire case.

When assessing the fire effects of design fire scenarios and when using fire simulations, the effects of a fire specified in advance as the source term are usually calculated rather than the combustion. In the run-up to the fire simulations, the fire scenarios to be investigated should be quantified as design fire with regard to heat and smoke release. The design fire thus derived then serves as the necessary input for fire simulations. This chapter deals with methods of theoretical derivation of design fires which serve in particular to determine the time course of the heat release rate (fire course curve). Information on the release of fire effluents, e.g. on smoke yields, is given in Chapter 8 of this guide.

The specifications in this chapter are intended to ensure that the relevant calculation assumptions regarding the fire occurrence are determined according to uniform criteria and are thus subject to a smaller scatter range.

The aim of the definition of design fire scenarios and design fires is to enable calculations to be made on the safe side. The calculation assumptions should cover all probable fires. The "degree of coverage" of all possible fire events depends in particular on the specification of the protection objectives. So-called "worst case" cases, on the other hand, whose boundary conditions are extremely unlikely, do not usually have to be taken into account (see Chapter 3 of the guide). The design is usually based on "worst credible" scenarios (in the following, decisive scenarios) and assumptions whose boundary conditions can occur with sufficient probability even during the entire lifetime of the building.

Of the multitude of conceivable fire scenarios, only a few should be identified or redesigned in order to limit the required computer-aided parameter studies that lead to sufficiently safe fire protection reports for the respective fire protection problems (design fire scenarios). Certain key events (such as the opening of doors and windows or the start of extinguishing measures) can be specified either directly as variables depending on the duration of the fire or indirectly in dependence on other (calculated) parameters (such as room temperature) and used as boundary and initial conditions.

For the various design fire scenarios, quantified fire courses must be defined as design fires. For this purpose, the corresponding physical parameters must be quantified. The data material in this chapter serves as the basis for the object-specific concretization of the fires to be applied by the expert.

Since these parameters have been implemented differently in the available calculation models, the required data in practical use may have to be adapted to the calculation software used (see Chapter 5).

As the fire is always determined by a number of influencing factors, in particular by the flammable materials, the type and intensity of ignition, the room configuration and ventilation, it is practically impossible to make an "exact" prediction of the fire development. Nevertheless, sufficiently qualified fire characteristics can be specified for the assessment of fire safety in buildings and for the dimensioning of certain fire protection systems. These characteristics can be analysed with the methods of fire protection engineering within the scope of parameter studies and can be used as a basis for the calculations. Reference values for the derivation of object-specific design fires are compiled in the Appendix to Chapter 4.

To interpret the results of engineering investigations in regard to achieve the protection objectives, it is of crucial importance that the specifications made for the design fire scenarios and the design fires for the subsequent building use must be ensured as authorised limits. For this reason, the corresponding assumptions must also be determined sufficiently conservatively with regard to changes over time.

Annex 1 of the Guide explains the terms used in this chapter as well as the symbols and units used.

4.2 Design fire scenarios

4.2.1 General information

The relevant design fire scenarios are developed and described with a view to the attainability of the specified protection objectives (see Chapter 3). Priority will be given initially to a systematic identification of fire hazards with subsequent risk assessment (see Chapter 10). The latter evaluates the likelihood of occurrence of dangerous scenarios (the possibility of activating the fire hazard) combined with the expected consequences of events (assumed extent of damage in relation to the protection objective). Within the framework of the definition of design fire scenarios, aspects directly related to the flammable substances are of increased importance in this risk assessment. These aspects include questions such as:

- Which flammable substances are to be expected within a given room and how are they arranged or stored there?
- How easily can these combustible materials be ignited and how do these materials tend to sustain combustion in the assumed arrangement?
- Which ignition sources or activation energy can affect these substances during the period under consideration?
- Which fire effluents and what combustion heat can be released by these substances?

In practice, it is usually assumed that the probability of a fire occurring is the same at all locations in a room because the risk parameters cannot be permanently determined for specific locations. For special investigations, the parameters of use (such as the arrangement of flammable substances or of possible ignition sources) can be determined and the source of the fire can be located in the given room. In the further course of a fire, all flammable substances may be involved. In individual cases, it may be necessary to consider whether the fire can spread between flammable substances and areas free of fire loads. The time period from ignition to the beginning of fire propagation is usually neglected in fire scenarios (see Figure 4.1).

In addition to the assumed material characteristics, the combustion conditions and extinguishing measures in particular determine the fire development to a large extent. Combustion conditions refer in particular to the available atmospheric oxygen in the combustion zone. In terms of extinguishing measures, the activation time in relation to the scale of fire and fire propagation speed is taken into account as well as the assumed effectiveness in influencing the fire.

Other plant-related fire protection measures such as automatic fire detection systems and alarm systems in particular do not directly influence the fire occurrence. However, they may affect the activation time of manual extinguishing measures and thus indirectly affect the fire. The main value of these fire protection measures assumed in fire protection planning lies in life safety and is addressed in Chapters 8 and 9 of this guide.

From the different possible fire scenarios influenced by structural, plant-related and organisational boundary conditions and measures, the relevant scenarios with regard to validate a protection objective shall be selected. In this context, the probability of occurrence of a scenario (e.g. with/without sprinkler system) plays an important role, but also the potential damage. For the structural fire design of load-bearing components, it will be initially assumed that all extinguishing measures by persons on site, the fire brigade or extinguishing systems will fail (fully developed fire). Within DIN 18230-1 and DIN EN 1991-1-2/NA [4.21] however, probabilistically derived safety concepts have been implemented which enables the fire protection infrastructure to be taken into account when determining the design fires.

For verifications of life safety, the design fire scenarios are used as "normal case" under consideration of the physical effect of the planned / existing active and passive fire protection measures.

In addition, also sufficiently probable “failure scenarios” shall be deterministically analysed, in which individual or several of the planned fire protection measures fail or do not function as intended. These (additional) investigations highlight that the failure of individual fire protection measures only have a slight influence on the “normal case conditions”, or rather what certain fire protection measures contribute to achieve the protection objectives.

With these "failure scenarios", the dependence of the proven solution on individual fire protection measures can be assessed, which may lead to special requirements on their reliability - or even to redundant measures. Findings about these rare events can also be evaluated by applying corresponding "weaker" performance criteria (as then permissible limit states). For example, to assess the usability of escape routes, assessment values for the "normal case" - according to Chapter 7.6 of this guideline - are established, which are the most conservative approach, that the limit states are linked to an "obstruction of escape". For the "failure scenarios", "weaker" limit states may be used which characterise an "obstruction of escape". See also Chapter 8 - in particular Chapter 10.5 (Note: A normatively defined safety concept such as for structural fire design is not yet available; however, this methodology is also suitable, developed and tested on examples for determining safety factors for typical ASET/RSET considerations [4.53],[4.54]).

A scenario in which all or a majority of the planned fire protection measures fail or in which essential assumptions of the design are not applicable is basically a "worst-case assumption" which is not relevant - i.e. not decisive - for the design due to the extremely low probability of occurrence. If, however, all or many of the planned fire protection measures are technically interrelated in such a way that the failure of one component of the safety concept (e.g. the power supply) leads to the failure of many measures, then these cases are also decisive and have to be considered [4.57].

The specification of the design fire scenarios result in design fires which are the basis for the calculated fire simulations. In the process of calculating, conditions can occur that deviate from the basic assumptions of the design fire scenarios. Therefore, the calculation assumptions of the design fire scenarios must be checked using the calculation results. If necessary, modifications to the design fire scenario and new calculations may be necessary.

Example: The design fire scenario specifies a certain type of fire propagation. Due to the temperature in the hot gas layer, the heat radiation from above causes objects, which are located at a greater distance from the actual fire, to ignite. In this case, the type of fire propagation must be changed (e.g. faster fire propagation) and, from this point on, the corresponding simulation must be recalculated with modified conditions.

It is likely that cross winds will impact building openings. Inside buildings, the wind effects can influence the flow field and the spread of fire effluents. This effect is particularly noticeable in buildings with free openings in facades or free openings in roof surfaces, and during fires and fire phases with low heat release, which occur in the initial phase of a fire scenario. This apllies in particular to fire sources that are located near building openings and whose plumes are in the direct influence of the incoming air. In scenarios with large heat release rates (e.g. for structural design of components), these influences are insignificant and can usually be neglected [4.1].

The wind has only a minor influence on the development of the source term and can therefore usually be neglected for the source term.

4.2.2 Principles for identification of the relevant design fire scenarios

In order to identify the relevant design fire scenarios from the multitude of conceivable and possible fire scenarios, appropriate guidance is given in the following by limiting the number of fire scenarios which have to be examined with computational parameter studies.

Automatic fire detection systems (not sprinkler systems), alarm systems, information systems or smoke and heat exhaust ventilation systems are of great importance for the dynamic course of a fire scenario, but do not normally influence the determination of the design fire until the moment when active firefighting measures are taken by emergency services. However, these measures and technical installations are essential for the evaluation of the fire consequences (available escape time) and the determination of the required escape time by a person flow analysis as described in Chapter 8 and 9particular, the system for determining reaction times (time span between the outbreak of fire and the beginning of the actual escape movement) described in Chapter 9.3 explicitly refers to the alarm system and the fire protection management, which may also include an information system.

The following influencing factors shall be taken into account as a minimum when identifying the relevant design fire scenarios:

a) Unchangeable parameters from the object
    - Fire compartment geometry.

b) Variable parameters
    - Type (fire load, combustible materials), size and location of the source of the fire,

- Ignition sources / ignition initials as well as type and storage of the substances / objects that caught fire first for the consideration of "local fire scenarios,
- Fire phases (fire emergence/pre-burning phase, fire spread phase, locally limited fully developed fire, fully developed fire in the fire room),
- Ventilation and opening conditions,
- Trigger conditions of active (plant-related) measures.

c) Special cases (to be considered only in exceptional cases)

- special events / rare and exceptional events (e.g. : Arson with multiple sources of fire and fire accelerant),
- Scenarios in which planned fire protection measures do not work or do not work as intended.

Depending on the concretion of the protection objective and the accepted extent of damage, different and appropriate design fire scenarios shall be applied. For initial orientation, the following assignment of essential scenario characteristics to the protection objective can be used:

- Personal protection aspects of the users:

  Phase of the pre-burning time is usually neglected and is then part of the safety concept / additional safety reserve, which is not quantified by fire simulations over time. The essential requirements for personal safety are evaluated in connection with the fire propagation phase.

- Rescue by fire and rescue services:

  The requirement and the extent of external rescue measures as well as the concretization of the protection objective are defined in the fire protection concept under consideration of object-specific criteria. Direct reference is to be made to this. Scenarios of fire propagation in the vicinity of the persons to be rescued, but also full fire scenarios in other parts of the building can be considered.

- Enabling effective firefighting by the fire brigade:

  In principle, fire protection concepts start from the internal attack of the fire brigade when evaluating the effectiveness of manual extinguishing measures. The maximum size of fires that can still be controlled by the fire brigade depends on the efficiency of the fire brigade. In principle, the stability of the main structure of the building parts required for firefighting should be ensured for a firefighting attack (see stability).

- Stability and integrity in case of fire:

  Advanced and fully developed fires, which generally appear as full fires in "small" spaces and as local fires in "large" spaces.

- Asset protection:

  The concretion of the protection objectives depends strongly on the individual case. It is not possible to give any general indications in this respect.

In preparation for a mathematical fire simulation, the design fire scenarios to be considered can be determined by a systematic evaluation of the "variable parameters". First of all, possible / conceivable fire scenarios are compiled on the basis of identified fire hazards and then evaluated with regard to their assumed probability of occurrence and the resulting expected, protection objective related damage (both usually: expert judgement). For this purpose, the following aspects are usually to be evaluated for each fire scenario:

1) Select the location of the source of the fire

- The room or place in a room is selected where a fire can break out, which can have large or dangerous effects.
- As a rule, several fire sources are possible and equally probable in one room. Then one of them is determined which covers the other fire locations. If this is not possible, several fire sources must be considered. So-called authoritative scenarios are chosen.

2) Describe fire load and fire origin

- The fire load involved in the fire with a high probability is described (type, location and storage, quantity, risk of fire spreading).
- The origin of the fire (initial release of heat at the beginning of the fire spread phase) and, if necessary, the objects set on fire first are determined.
- For the design fire, the data result in particular in the heat release rate and the fire propagation velocity.

3) Describe the ventilation conditions of the fire compartment

- Openings of the fire compartment (such as windows, doors, SHEVS, etc.) are described with regard to their opening areas or their performance criteria (mass flow), their arrangement in the building and including their opening conditions.

4) Type of fire

- The fire phase primarily relevant for the objective of the investigations is named and it is provisionally[1] determined whether it is a fire load-controlled fire (sufficient combustion air available) or a ventilation-controlled fire.

5) Influence of the system technology on the course of the fire and the fire scenario

- If plant-technical measures are taken into account (e.g. automatic fire extinguishing systems such as sprinklers), a limitation of the "undisturbed" fire propagation is possible. For this purpose, criteria for the activation of this system technology shall be specified and their expected effects on the fire event shall be described.
- The approach of plant-engineering measures in the determination of design fire scenarios and a limitation of the fire progress curves caused by this should be evaluated under consideration of the failure probabilities of the plant-engineering

[1]This specification is checked during the fire simulations and, if necessary, adapted and modified to the ventilation conditions that have changed in the course of the event.

systems (see Chapter 10). The expected effectiveness of all safety measures is generally assumed[2].

6) Firefighting by the fire brigade

- The consideration of the firefighting measures of the fire brigade (effectiveness of fire fighting) on the course of the fire and the intervention of the fire brigade in the design fire scenario has to be coordinated with the responsible fire protection authority in each individual case.
- As a rule, firefighting operations cannot be defined in concrete terms in a time regime, since the decisions of the operational command must be based on the actual local situation and the actually available forces and resources. This cannot be determined with the necessary reliability for a time regime. Often, however, planning principles for firefighting operations can be used for an engineering evaluation and for involving the fire brigade in fire simulations (see Chapter 7).

7) Estimation of the expected damage

- The expected fire consequences / damage patterns of the fire scenario shall be described and evaluated.
- Overall evaluation and selection of the design fire scenario.
- From the fire scenarios considered, one or, if necessary, several design fire scenarios/design fire scenarios are selected. These should cover all relevant fire scenarios on the safe side.
- The criterion for selection is the expected extent of damage over the life of the building. This involves - mentally - multiplying the probabilities of occurrence of the events by the expected extent of damage. This is usually done on the basis of available expert knowledge / estimates ("expert judgement"), although systematic risk assessment procedures can also be used (see Chapter 10).

4.2.3 Design fire scenarios for the usability of escape routes

The safety of persons is initially determined by the conditions during the fire spread phase. This is based on the assumption that the persons are able to rescue themselves via the designated escape routes.

During the period relevant for the assessment, fire spread and evacuation take place simultaneously. The aim is to check the criteria for the proof of personal safety (see Chapter 3 and Chapter 8).

For the assessment of personal safety, several scenarios usually have to be examined. Both under-ventilated fires with a low heat release rate and sufficiently ventilated fires with a high heat release rate should be considered as ventilation conditions.

[2]The consideration of the failure of safety devices is subject of the safety concept and the risk analysis. This results in other scenarios that are also relevant and calculable for certain issues (safety concept, risk analysis).

4.2.4 Design fire scenarios for external rescue by the fire brigade

External rescue by the fire brigade is only a plannable event for buildings with a "low fire risk" for their users. A typical example is the evacuation of apartments or hotel rooms that are not directly affected via smoky corridors or ladders with the support of the fire brigade.

In principle, this external rescue process can only be conceptually provided for in fire protection planning as a measure for those parts of the building which are not directly affected by the fire themselves, i.e. for units of use and parts of the building in which the source of the fire is not located.

For the implementation of external rescue measures, boundary conditions are required which can be checked with engineering methods. For the usability of corridors, for example, the fire resistance of the corridor walls and their ceilings (suspended ceilings) or the flammability of their building materials are essential. For the usability of instructable areas, the possible escape of fire and smoke from building openings in nearby facade areas must be evaluated.

The design fire scenarios suitable for this purpose should be based on a full fire or on a fire event in an "other" unit of use (or storey, fire compartment) that could already have developed over a longer period of time (possibly to a full-developed fire).

4.2.5 Design fire scenarios for firefighting by the fire brigade

In principle, effective extinguishing measures of the fire brigade require sufficient conditions for an internal attack. Whether an internal attack can still be carried out successfully depends, among other things, on the accessibility of the source of the fire and its expansion, speed of propagation and the rate of heat release at the time of arrival at the fire site. Due to the performance limits of the fire brigade, automatic fire extinguishing systems are often used to support or enable effective extinguishing measures and/or structural partitions are arranged.

For a realistic estimation of whether these fire brigade deployment limits are exceeded by a real fire, it is necessary to examine corresponding fire scenarios more in detail.

The "worst-credible scenario" must be defined for this purpose in areas where high fire loads are present. When evaluating possible fire sources, the flammability of the combustible materials as well as their combustion behavior and the expected rate of fire propagation shall also be taken into account.

4.2.6 Design fire scenarios for the component or structure design

Components with stability requirements should be able to resist the fire attack for a reasonable period of time and remain stable in the event of a fire. Room-enclosing building components should prevent the spread of fire and not expose any openings or heat them so strongly that ignition temperatures for flammable substances occur on the side facing away from the fire. First of all, the components for which a fire protection design is required are determined. For these, in addition to the temperature load, the static load (load utilization for load-bearing components, static system with boundary conditions) should also be taken into account (engineering task on the specific object).

For the assessment of the load-bearing and deformation behaviour of building components, fire scenarios are considered in which the fire has already developed strongly - usually into a fully-developed fire. The fire impact is composed of the radiation components of the flames and the temperature of the hot gases on the component. Scenarios with strongly developed fires are relevant for assessment over the duration until complete burnout or until an event specified in the protection objective definition is reached.

As a rule, fully-developed fires or locally limited fires are investigated which affect all fire loads in the immediate vicinity of the components to be evaluated.

For components in the ceiling area, such as beams, the hot gas temperature is usually relevant for design. In larger rooms (> 400 m²) the local stress in the plume area must be taken into account. For columns, the plume temperature or flame temperature in the area of the source of the fire is decisive in the initial phase of the fire. In larger rooms (> 400 m²), the hot gas temperature is decisive for the design of columns and girders as soon as the fire load in the area of the columns has burned away.

In the case of very large and/or high rooms - such as in large industrial halls and atria - the average hot gas temperature in the ceiling area is not relevant for the design of the stability and the space closure of the components in the area close to the fire. Local temperatures and radiation effects (e.g. from a plume calculation or CFD simulation) should be used for this purpose.

Ventilation conditions are a major factor influencing the temperatures in the fire compartment. For the determination of the relevant ventilation conditions, all windows and doors of the fire compartment are to be considered as possible openings of the fire compartment, whereby the opening conditions are to be determined or varied in such a way that the maximum fire impact on the construction components is achieved.

Only openings that lead directly outdoors should be charged as ventilation openings. Doors should be considered as ventilation openings if it is ensured that they lead to the outside or to a room with sufficient air supply.

The fire-induced failure of window surfaces can have a considerable influence on the ventilation control and the resulting design fire.

The time of failure of a glazing depends, among other things, on temperature differences, stresses within the glass, width and height of the pane, degree of perfection of the production (micro-cracks), type of frame, storage and thickness of the pane, number of panes (single or multiple glazing) and thermal stress (shock or uniform). Furthermore, a breakage of the pane does not mean that it is completely available as a ventilation opening. Since an estimation of the fire-related failure of window surfaces, e.g. based on temperature, is only possible to a limited extent, a conservative and protection objective-oriented assumption of the release of ventilation openings seems appropriate.

Various ventilation conditions can be relevant when determining the effects of natural fire on supporting structures. For example, for exposed steel girders, the level of the maximum temperature is primarily decisive (fire load controlled fire), whereas for clad steel and reinforced concrete structures the duration of the fire exposure is relevant (ventilation controlled fire). Therefore, it may be necessary to investigate a variation of the ventilation conditions within the scope of a parameter study. Usually, the opening area in the transition between ventilation-controlled and fire load-controlled fire provides the most conservative results for the design of structural elements.

From fire tests, e.g. [4.3], [4.5] reference values for fire room temperatures near the glazing can be roughly derived from engineering practice, at which glazing fails in such a way that chargeable ventilation openings are released. The order of magnitude of such destructive room temperatures results approximately as follows:

- Single glazing (3 mm) 300°C to 360°C
- Single glazing (4 - 6 mm) 450°C

- Double glazing 600°C
- Double glazing; PVC frame 550°C (after 30 minutes exposure)
- Double glazing: wooden frame 550°C (after 60 minutes exposure)
- Triple glazing, wooden frame 730°C (after 30 minutes exposure)

The results show that with modern construction methods, it cannot be assumed that window surfaces will be available early on for smoke and heat dissipation.

The extent to which firefighting can be taken into account when determining the design scenario is a question of the safety concept (see Chapter 10). Triggering times of system-related measures and intervention times of the fire brigade shall be determined in accordance with Chapter 10.

4.2.7 Fire scenarios for property protection risk assessment

Within the framework of a hazard analysis with subsequent risk assessment, the protection objectives for the protection of property are assessed according to the typical fire events that pose a particular risk. In particular, the following types of damage can be considered:

- Damage to equipment, means of production or of materials or products through direct exposure to smoke, for example through contamination or through corrosion damage,
- Damage to equipment, means of production or of materials or products due to direct thermal fire effects,
- Damage to equipment essential to operation (bottleneck),
- Damage caused by failure or considerable repair work on parts of buildings,
- Damage due to a fire-related interruption of operations,
- Damage to equipment, means of production or of materials or products caused by extensive or very intensive firefighting measures, for example by the extinguishing water,
- Damage due to loss of image of the company.

The fire scenarios are based on the main risks identified, for example

- Fire developments with considerable smoke development at an early stage,
- Fire developments with high fire propagation speed and heat release rate,
- Fire developments with a high heat release rate in the vicinity of goods to be protected,
- Fire developments that can lead to failure or significant damage to large parts of the building,
- Local fires with the potential for disproportionate damage or fire consequences.

If necessary, the analysis of the scenarios already provides information at the stage of a qualitative assessment as to whether the expected fire effects require special protective measures to achieve the protection objective. Based on the expected fire effects, decisions on additional or special fire protection measures can be further secured by numerical investigations.

4.2.8 Special questions

4.2.8.1 Local fires (limiting the spread of fire)

The spread of fire can be effectively limited by the following measures:

- Effective extinguishing works are successful and prevent a further spread of fire.
- An example of such a procedure are the design fires for the design of natural and mechanical smoke ventilation systems in DIN 18232.
- Automatic extinguishing systems can be considered in the same way. DIN 18232 assumes a maximum fire area of 20 m² as an example.
- Walls or fixtures prevent a direct fire spread beyond them (at least for a certain period of time).
- An example of this is a wall, that was build without requirements for a fire resistance class (e.g. sheet metal wall as smoke protection). A further spread of fire beyond this obstacle can only occur if, for example, a temperature is reached at the back of the wall which can lead to an ignition of the combustible materials behind it.
- Between flammable materials, fire load-free strips (free strips) are arranged with a width that prevents the fire from spreading any further (see e.g. DIN 18 230-1; Appendix A - in conjunction with other measures).
- A critical heat flux density (for spontaneous ignition) or a critical temperature increase (ignition temperature) on the substances is used as a criterion for demonstrating that ignition of fire loads beyond the free strips does not occur.

The same conditions and models as for fires without limitation of fire spread shall apply to the occurrence of fire and its propagation on the partial area.

4.2.8.2 Consideration of wind and air flows in fire simulations

The relevance of considering wind influences in superposition with the exceptional fire effect can be tested with the methods of Chapter 10.

The decision on the consideration of the wind influence must be made in individual cases with the parties involved in the project.

The following cases may be considered for this purpose:

- Deflection of the flame outside of buildings due to the influence of cross winds, e.g. when assessing combustible facades or when dimensioning building components in front of the facade,
- Disturbande of the smoke gas stratification and smoke removal, e.g. in case of evidence to enable the rescue of persons and/or effective extinguishing work.

For the removal of smoke from rooms and in particular for the formation of stable smoke layers wind currents can be

- essential, for example, for wind-dependent smoke extraction concepts such as a wind-exposed position of natural air intake and/or smoke extraction openings (e.g. openings in side walls),

- of secondary importance for wind-independent concepts with mechanical smoke extraction measures and appropriate air supply.

The following points should be observed when considering wind currents:

- Investigation especially for the local main wind direction,
- Comparison of the results with simulations without wind influence,
- The determination of the wind effects (wind direction, wind force) should be derived from corresponding local wind measurements. Since both the design fire and a specific wind event are rather rare random variables, their occurrence probabilities must be taken into account for the simultaneous occurrence of both events. Since the design fire is already determined "conservatively", particularly large and correspondingly rare wind load cases are rather not safety-relevant for the protection goals of smoke removal.

4.3 Design fires

4.3.1 The fire course and principles of its modelling

4.3.1.1 General information

In addition to the qualitative description of the fire scenarios and the fire sources, a quantitative specification of the fire development is necessary. It describes the essential fire parameters in their development over time. The different fire development stages of a "naturally" developing fire (without external effects by extinguishing measures) are shown in the Figure 4.1.

The design fire is usually a theoretical - but certainly possible - fire course, which covers a large number of conceivable fire developments on the safe side. The design fire need not necessarily cover all conceivable and possible fire events on the "safe side". It should, however, cover the risks resulting from the fires in their entirety with sufficient certainty. Within the scope of the "fire simulation", it is checked whether the specifications defined in the design fire are physically possible; if necessary, the specifications are then replaced by realistic values (and documented).

When developing fire protection concepts, it is assumed that[3] the fire only starts at one point in the building. Fire transmission to other objects should be taken into account.

[3] Special case of arson: see "Design fire scenarios for asset protection tasks”

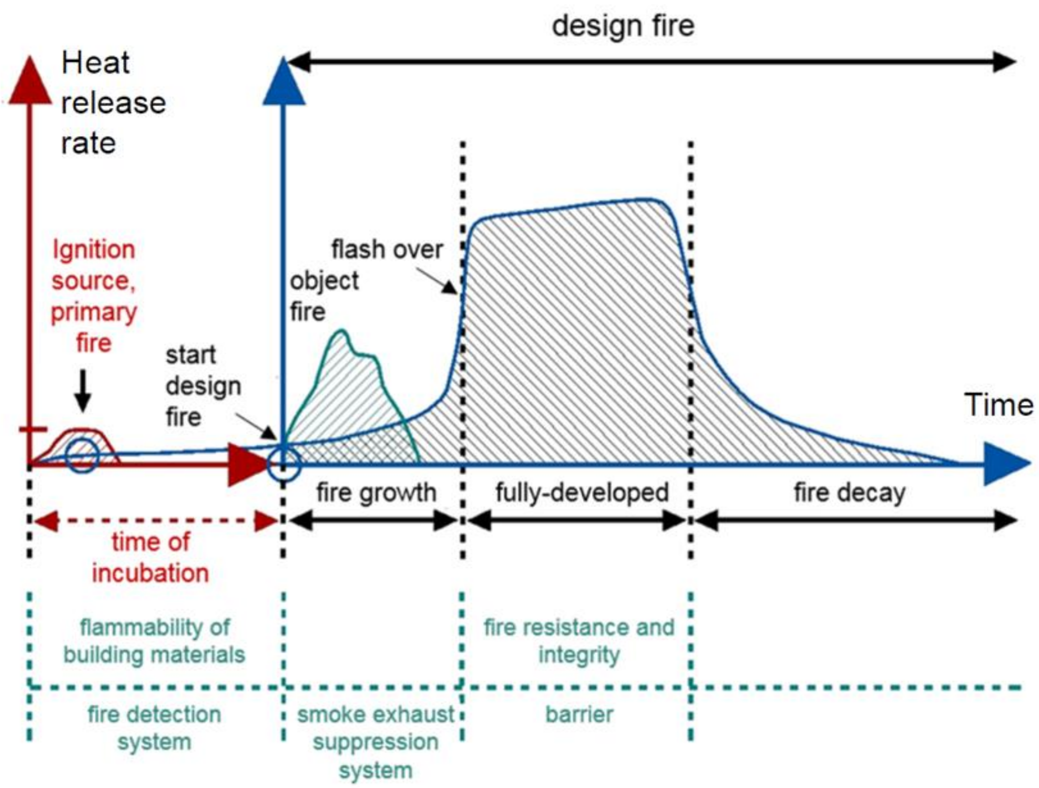


Figure 4.1 Fire development phases during "natural fire" (Schematic diagram of the heat release rate)

The time courses for the heat release rate and for the release of combustion products are also called "source terms".

The design fire begins with the formation of a stable flame. During the installation/discharge of the design fire, the phenomena and developments of the fire should be analysed in advance. Influence on the course of the fire:

- the type of ignition (initial, material),
- flammable substances, type and distribution,
- characteristic material data on combustion behaviour, smoke potentials, packing density, utilisation,
- fire load,
- possible fire surface or fire spread,
- room geometry including openings,
- ventilation openings, opening effect possibly staggered over time,
- flashover conditions,
- heat-specific parameters of the components,
- combustion processes outside the room (flames outside in front of the openings), which must be taken into account in the heat balance for the fire compartment,
- total releasable energy.

The "design fire" represents the time-dependent release rate of heat and of fire products. Important parameters that can be used to describe the design fire are summarised in Table A4.1 of the appendix in Chapter 4.

In the case of ventilation-controlled fires, the rate of release of fire products in particular can change considerably compared to a fire load-controlled fire (see Chapter 8). For heat release rates given by the source term, the fire regime should be controlled continuously during the calculations or separately after the calculations, taking into account the global or local oxygen supply.

The proportions of fire products in the combustion (g/g or vol. %/g) are treated as "substance-specific characteristic values", whereby, as a rule, only a dependence on the fire regime[4] is taken into account. Under this model assumption, the heat release rate is used to directly infer the release rate of the fire products, taking into account the specifications regarding the type of fire loads via the averaged calorific value.

Thus, the heat release rate (HRR-) in connection with the type of fire loads can be used as a central source of information. From the heat release rate, the formation of further fire products including smoke particles can then usually be deduced.

4.3.1.2 Heat release rate

The heat release rate can be set in different ways, for example

(a) by experiments (similar fire load under similar room and ventilation conditions),

(b) by calculations,

- Reproduction of fire development and propagation with the aid of a propagation and combustion model (conditionally possible),
- Calculation of the fire development (fire spread and fire leaps) by calculating heating, pyrolysis and ignition of further fire loads, starting from a small primary fire source (still in development, not yet secured for broad applications),

(c) by agreement on the basis of damage assessments or other findings,

- Use of ready-made design fire curves mentioned in the literature for special cases (e.g. burning sofa) - Caution: Consider comparability of boundary conditions,

d) through normative specifications and technical regulations,

- Design according to simplified theoretical approaches using characteristic values from the literature (e.g. q, H_i, $\dot{m}$, v_{aus}) - if sufficient data material is available, it is recommended to use different approaches for the calculation.

4.3.1.3 Design fires based on project-specific fire tests

Fire tests under realistic boundary conditions with regard to the fuels, the room configuration and the ventilation conditions can be metrologically recorded in such a way that the input parameters and input data for fire simulations can be realistically described and specified for the individual case to be evaluated.

For the use of published measured values from fire tests, knowledge of the exact test boundary conditions, in particular the arrangement of combustible materials and ventilation conditions, is of particular importance. Since, as a rule, the boundary conditions of the tests are either not

[4] fire load controlled or ventilation controlled fire

completely known or deviate from the object to be evaluated, an engineering-appropriate transfer of the published numerical material to the object-specific boundary conditions is generally required.

Findings regarding the burning of individual objects under excess air conditions can be mathematically combined to form spreading fire patterns as long as fire load-controlled fire conditions (excess air) are given.

4.3.1.4 Design fires by direct specification of fire actions

Important is the selection of the decisive fire parameters and the fire development phases to be investigated. For this purpose, all parties involved in the construction should reach an agreement.

In fire protection practice, however, certain fire parameters are often used directly as direct design fire specifications - for example the temperature development in the fire room (e.g. the standard nominal fire curve) for the design of structural fire protection measures. Suitable sources for corresponding specifications in these cases are, for example, the test fires of standard test procedures.

4.3.1.5 Fires of individual objects

A typical application for fire simulations is the analysis of fires of individual objects.

In general, the fire behaviour of objects to be evaluated cannot be derived theoretically. If necessary, it should be determined experimentally. It is important, among other things, to realistically represent both the objects themselves and the conditions of the fire room (ventilation and size) in the test setup. Likewise, the type of ignition / fire development (ignition initial) is of great importance for the experimental course of the fire event.

When using published fire curves, the experimental boundary conditions should be compared with the application case.

4.3.1.6 Normally regulated ignition initial

The heat release rate and the resulting fire effect of an ignition initial on "existing fire loads" is decisive for whether a local fire develops and how quickly it develops into an independently spreading fire in the fire formation phase. Consideration of the local fire development is important if details of the fire course are important.

The experimental findings on the fire behaviour of articles have been determined for specific ignition initials and do not apply to all ignition initials. For example, the fire behaviour of furniture differs significantly if high heat release rate initials are used instead of low heat release rate initials.

The ignition initial is usually understood as an "alien body" and establishes the connection between the ignition source and the user-specific fire loads. The Table 4.1 shows a selection of normatively regulated ignition initials with the time-dependent heat release rate.

Table 4.1 Selection of normatively regulated ignition initials

Initial ignition	Heat release rate Time - reference	Source
Small open flame	0.05 to 0.5 kW for 30 s	UL 94
Newsprint / waste	7 kW for 3 minutes	DIN EN 45545-1 Appendix A / UIC 564-2 (paper pad)
Single burning object, e.g. waste paper basket	30 kW for 20 minutes	DIN EN 13823 (SBI)
Luggage / baggage	75 kW for 2 minutes and 150 kW for another 8 minutes	DIN EN 45545-1 Appendix A
	120 kW up to the 5th minute and 150 kW up to the 8th minute	TRStrab fire protection
Wooden crib (200 kg spruce wood, floor space approx. 1.2 m²)	up to 3,000 kW according to [4.8].	MVV TB Annex 5 Base fire test method

4.3.2 Approaches for design fires

4.3.2.1 t² model for the fire development phase

The t²-model is mainly used for the calculation of the temporal heat release with low determination of the fire conditions with normative approaches and is widely used in the international field.

If no reliable information on the combustion properties (combustion velocity) of the fire loads is available, general assumptions must be made on the safe side. As the calculations are usually to be valid for a wider range of possible uses and fire loads, this is a frequently used procedure.

The following approach has been adopted in international standardization (see Figure 4.2, Table 4.2 and Table 4.3):

- Different fire developments are classified, for example: slow, medium, fast and very fast.
- The characteristic fire developments are necessarily idealised values, but are based on scientific research using tests and the evaluation of real damage fires. They were established with regard to personal protection in the USA (see NFPA 92B [4.14]).
- The fire development is described with a t^2 approach:

$$\dot{Q} = \alpha \cdot t^2 \tag{4.1}$$

$$\dot{Q} = \dot{Q}_S + \dot{Q}_0 \cdot \left(\frac{t}{t_\alpha}\right)^2 \qquad (4.2)$$

with

$\dot{Q}$ Heat release rate [kW],

$\dot{Q}_S$ Heat release rate [kW] at the time t_0, when the initial fire changes from an object fire to a fire spreading over the object (start of design fire, see Figure 4.1)

$\dot{Q}_0$ = 1000 kW

α Fire development factor [kW/s²]

t Fire duration without consideration of the ignition phase / smouldering fire phase [s]

t_α characteristic fire development time; the numerical value corresponds to the fire duration in [s] until a heat release rate of 1 MW is reached

The curve determined with the t² function is left when a flashover occurs and the fire progress curve rises up to the maximum value according to equation (4.19).

The fire course curve will be controlled by the existing fire load (see Chapter 4.3.3.4).

The fire courses determined in this way are each characterised by a constant area-specific heat release rate [kW/m²] related to a circular fire area. The radius of the circle increases linearly with time. A sufficient air supply is a prerequisite for the application of the following tables. Therefore, when used for ventilation-controlled room fires, this equation is only valid until the flashover is initiated.

For local fires in large halls, the increase curve of the heat release rate ends when the maximum heat release in relation to this limited fire area is reached.

This parameter α indicates the increase in the heat release rate. A corresponding representation of the fire development for characteristic values of the control variable for the heat release rate is given in the Figure 4.2. An assignment of the stepped fire development to t_α or α can be found in Table 4.2 or Table 4.3.

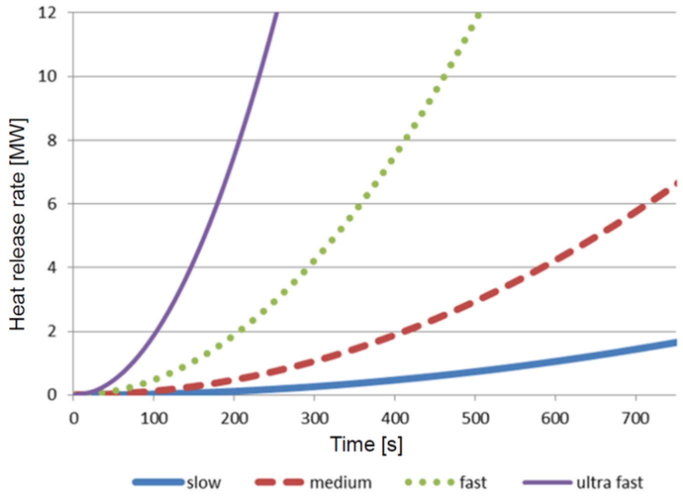


Figure 4.2 Fire development until a maximum heat release rate

The table appendix [5] contains recommendations for the classification of different uses and values for certain combustible materials.

The tests in original scale for the classification of units of use resulted in maximum values for the fire performance before a different decay of the fire. The formula therefore only gives a usable approximation of the course of the fire until this maximum value is reached.

In the calculations of the heat release rate according to the t^2 relationship or via the area-related heat release rate, the burn-up of the combustible materials is not directly included in the calculations. Therefore, additional numerical values for the smoke potentials and the oxygen demand of the combustible materials should be provided as input values for the fire simulation models to determine the current fire regime or if the smoke control is the target of the calculation (see Chapter 8).

Table 4.2 Assignment of fire development to different types of use and substance groups

Fire development	Type of use [4.8]	Substance groups [4.10], [4.11]
Slow	Picture gallery	Tightly packed wood products
Moderate	Apartment, office, hotel (reception, rooms), any use without easily combustible materials [4.5]	Cotton / polyester spring mattress, solid wooden furniture (e.g. desk), individual pieces of furniture with small amounts of plastic
Fast	Shop	(High) stacked wooden pallets, filled mailbags, cartons on pallets, some upholstered furniture, plastic foam
Very fast	Industrial warehouse, production hall	(Fast-burning) upholstered furniture, high stacked plastics, thin wooden furniture (e.g. wardrobe), light curtains, pool fire

Table 4.3 Standard values for α (Drysdale [4.12]) and t_α (NFPA 92 B [4.14])

Fire development	Parameter α [kW/s²]	$t\alpha$ [s] Fire duration until $\dot{Q}$ = 1 MW is reached *)
Slow	0,002931	600
Moderate	0,011720	300
Fast	0,046890	150
Very fast	0,187600	75

*) The values for the fire development factors α were determined and standardised for a heat release rate of 1000 BTU/s. The following conversion applies:
1 BTU (British Thermal Unit) ≈ 1055.056 J; 1 BTU/s ≈ 1055.056 W.

[5] The table values are to be understood as guide values and not as normative specifications.

4.3.2.2 Geometric dispersion model for the fire development phase

The t² model described above assumes a circular fire spread with the ignition point in the middle of the room. With the geometric propagation model, the real fire development can be depicted for the case that, based on the selected scenario, the ignition point is not in the middle of the room but at a different location. In addition, a more realistic representation of the development of the fire can be achieved by taking into account the geometric propagation when modelling the fire area in simulation models, since local fire effects are better taken into account.

In a first step, the geometric propagation model is used to determine the development of the fire area as a function of time and then the fire course curve using the area-related heat release rate.

The fire area or fire progress curve determined in this way is limited by the geometric boundary conditions of the fire room and the fire loads and, if necessary, by operational and plant-related fire protection measures.

Orientational values for the fire propagation speed v_{aus} can be found in the appendix. Further information on the fire propagation velocity can be found in [4.13], [4.24] and [4.26].

Another possibility to determine the fire propagation velocity v_{aus} is the conversion of the t² model into the geometric model:

$$v_{aus} = \frac{r}{t} = \frac{\sqrt{Q_0}}{t_\alpha \sqrt{\pi \cdot RHR_f}} \tag{4.3}$$

with

v_{aus} constant fire propagation speed in m/min

r radial fire propagation [m]

RHR_f surface-specific heat release rate [MW/m²]

t time [min]

In the geometric fire model, the local burn-out can be considered in the manner of a simplified "traveling fires". This assumes that the fire spreads over the area, and the fire area is divided into sub-areas. Using the area-specific heat release rate and the calorific value of the fire loads, it is possible to calculate when the fire load in the corresponding partial area has been consumed.

4.3.2.3 Description of the phase of a fully developed fire

Design fires for the description of the phase of a fully developed fire are mainly required for the design of the structural components of buildings, which should retain their stability even if extinguishing measures are unsuccessful. When determining the heat release rate, the fire regime should be taken into account.

Two fundamentally different fire regimes can be distinguished:

a) By limiting activatable fire loads, the fire performance is limited even if all combustible materials are involved in the fire (fire load controlled fire).

b) Due to a lack of combustion air, even if all combustible materials are involved in the fire, the total fire performance is limited depending on the available air supply (ventilation-controlled fire).

The maximum heat release rate can be determined as the smaller of the two maximum values of the ventilation-controlled or fire load-controlled fire [4.15], since the maximum action in the fire space is determined by the dominant fire regime:

$$\dot{Q}_{max} = \mathrm{MIN}\left\{\dot{Q}_{max,v}\,;\dot{Q}_{max,f}\right\} \quad \text{in kW} \tag{4.4}$$

With the help of equations (4.4) it can thus be determined whether the fire is ventilation-controlled or fire load-controlled.

Figure 4.3 shows the temporal course of the heat release rate and the converted fire load for a fire load-controlled and a ventilation-controlled fire under different ventilation and otherwise identical conditions.

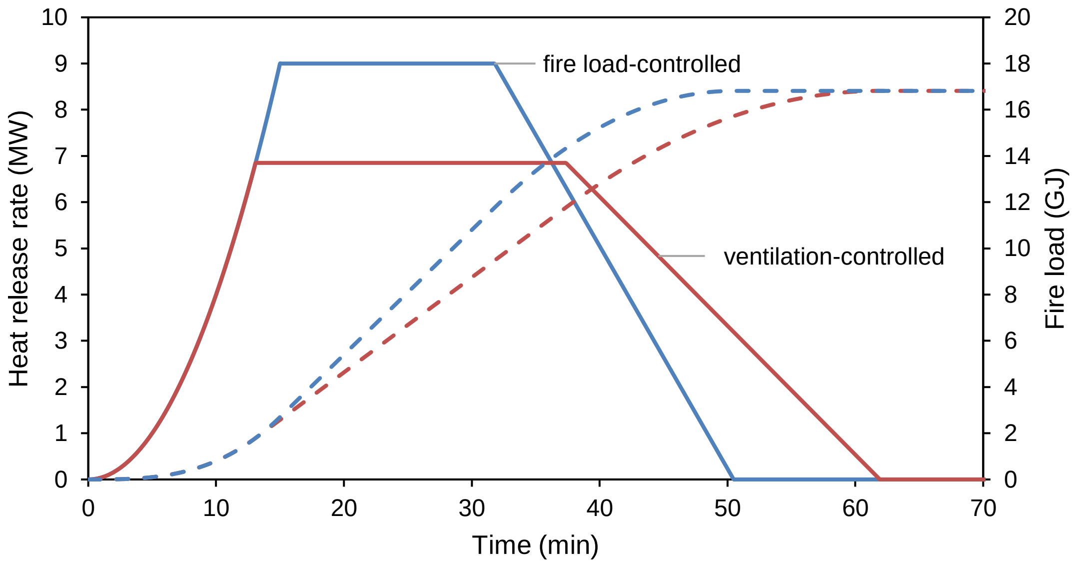


Figure 4.3 Representation of the temporal course of the heat release rate and the converted fire load for a fire load-controlled and a ventilation-controlled fire under different ventilation and otherwise identical conditions

For the description of the temporal course of the heat release rate, a distinction is made in the following between the fire regimes already introduced.

Fire load controlled fire

In a fire load controlled fire, heat release is limited by the burning surface of the fire loads. According to [4.21] the heat release rate is calculated as

$$\dot{Q}(t) = \dot{m}'' \cdot A_F(t) \cdot \chi \cdot H_i \quad \text{in MW} \tag{4.5}$$

with

$\dot{m}''$ area-specific burnup rate in kg/(m^{2}s),

$A_F(t)$ Fire area (increasing with fire duration) in m^2,

T Time in h,

χ Combustion effectiveness [-],

H_i Calorific value of combustible substances in MJ/kg.

In accordance with DIN EN 1991-1-2 [4.21] simplified value of 0.8 is given for solid fire loads χ, 0.9 for liquid fire loads χ and 1.0 for gaseous fire loads χ.

In [4.21] the correlation is proposed for determining the heat release rate in office and residential premises:

$$\dot{Q}_{max;f} = 0{,}25 \cdot A_{Fire} \quad \text{in MW} \tag{4.6}$$

This equation was verified by means of real fire tests. It can be applied to fire areas of up to 400 m².

Ventilation controlled fire

Ventilation-controlled fire is a type of combustion in which there is not enough combustion air available in the room in question, measured in terms of the fire materials present. Combustion in the room is thus limited by the gas components flowing in and out through the openings.

While in the fire load controlled case the burning rate is the limiting factor of heat release, in the ventilation controlled case it is the air or oxygen inflow. Analogous to the combustion efficiency χ in the fire load controlled case, in the ventilation controlled case the oxygen demand and the degree of oxygen utilization are also χ_{O_2} considered.

Simplified, the maximum heat release rate $\dot{Q}_{max,v}$ in a ventilation-controlled room fire can be described as the product of the oxygen mass flow $\dot{m}_{O_2}$ or the supply air mass flow $\dot{m}_L$ and the respective heat release per converted mass of oxygen E_{O_2} or fresh air as E_L follows [4.12],[4.15]

$$\dot{Q}_{max,v} = \dot{m}_{O_2} \cdot E_{O_2} \cdot \chi_{O_2} = \dot{m}_L \cdot E_L \cdot \chi_{O_2} \quad \text{in MW} \tag{4.7}$$

During the combustion of organic fire loads, an almost constant heat release per mass unit of consumed oxygen takes place. An average value of E_{O2} = 13.1 MJ/kg_{O2} or E_L = 0.231 · E_{O2} = 3.03 MJ/kg_L was determined for this heat release [4.17].

The aforementioned value E_L related to air consumption can also be replaced by the fire load related calorific value H_i in conjunction with the stoichiometric air requirement r:

$$\dot{Q}_{max,v} = \dot{m}_L \cdot \chi_{O_2} \cdot \frac{H_i}{r} \quad \text{in MW} \tag{4.8}$$

with

$\dot{m}_L$ Supply air mass flow rate in kg/s

H_i calorific value of combustible materials in MJ/$kg_{fire\ load}$

χ_{O_2} Oxygen utilization factor [-]

r Stoichiometric air requirement in [kg_{air} / kg_{fuel}].

There is a mathematical relationship between the calorific value of organic fire loads and the stoichiometric air demand. In evaluation of the values documented in [4.5] for various representative fire loads, this relationship is linear and amounts to

$$r \approx 0{,}33 \cdot H_i = \frac{1}{E_L} \cdot H_i \quad \text{in } kg_{air}/kg_{fuel} \tag{4.9}$$

This correlation (see Figure 4.4) applies to both complete and incomplete combustion [4.16].

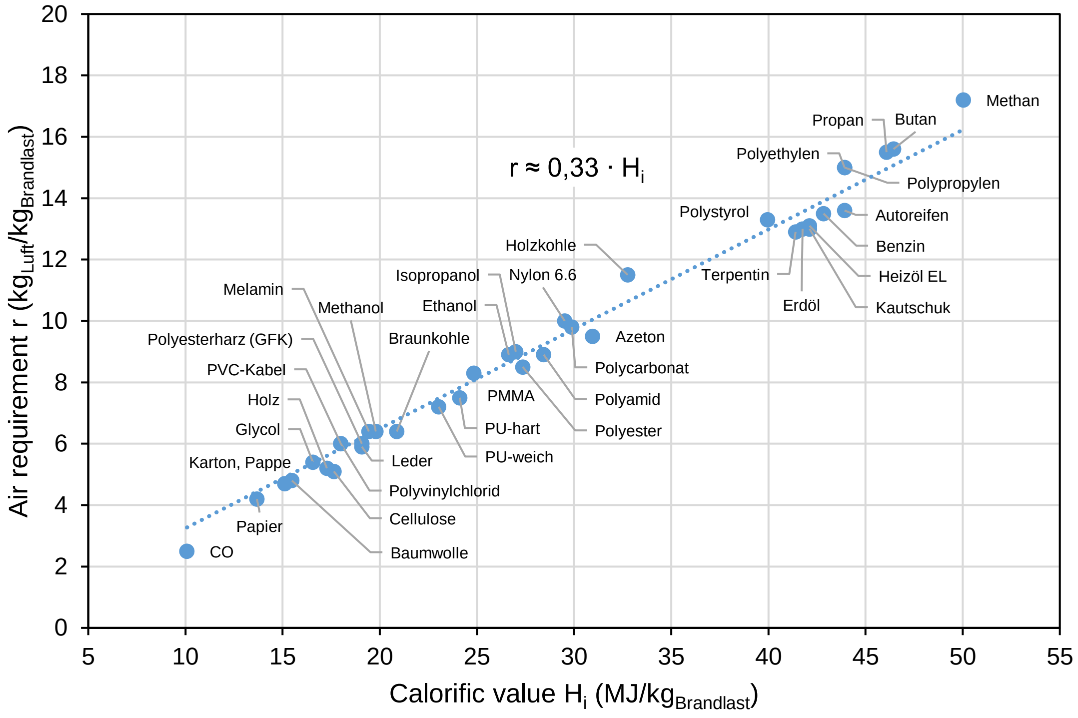


Figure 4.4 Relationship between air demand and heating value, compiled according to [4.5]

The supply air mass flow $\dot{m}_L$ required to dissipate the maximum heat release rate $\dot{Q}_{max,v}$ can be reduced for fires in rooms with exclusively

a) mechanical ventilation can be estimated from the supply air mass flow of the forced ventilation,

b) natural vertical openings in walls can be estimated using the Kawagoe equation (4.10) [4.21]. The area of ventilation openings and the clear height of openings in a room limit the supply air mass flow.

The supply air mass flow rate $\dot{m}_L$ is calculated according to [4.22] as

$$\dot{m}_L = 0{,}52 \cdot A_W \cdot \sqrt{h_W} \quad \text{in kg/s} \tag{4.10}$$

By inserting (4.9) and (4.10) in (4.8) you can write in general terms:

$$\dot{Q}_{max,v} = 1{,}57 \cdot \chi_{O_2} \cdot A_W \cdot \sqrt{h_W} \quad \text{in MW} \tag{4.12}$$

In [4.19] a vertical temperature distribution in the area of the supply air surfaces between 900°C and 1,000°C was measured for room fires in the full fire phase. Even at these temperatures, not all the oxygen is consumed by the combustion. The oxygen index indicates the oxygen volume fraction at which extinguishing occurs. This oxygen index depends on the fuel and the temperature (Figure 4.5).

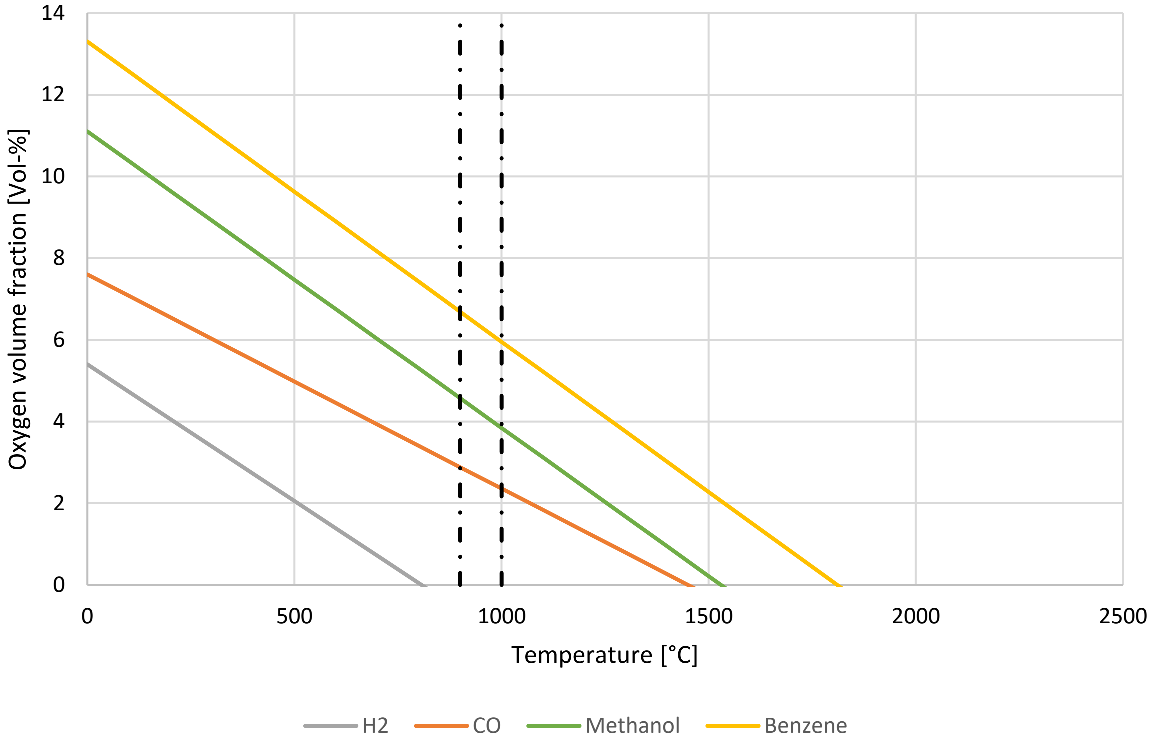


Figure 4.5 Maintenance of combustion as a function of temperature and oxygen volume fraction according to [4.20]

No combustion takes place below the boundary lines shown in the Figure 4.5. For the temperature range between 900°C and 1,000°C occurring in the full combustion phase, the oxygen content is between 2.35 % and 6.89 % by volume. Based on an oxygen content of 21 vol.% in the supply air mass flow, the maximum oxygen utilization rate for these fuels is between 0.68 and 0.89.

If an oxygen utilization factor of 0.8 is assumed, the following relationship results

$$\dot{Q}_{max,v} = 1{,}26 \cdot A_W \cdot \sqrt{h_W} \quad \text{in MW} \tag{4.13}$$

for equation (4.11).

The pre-factor in equation (4.12) lies in this order of magnitude between the factor 1.21 according to [4.21] equation (AA.1) and 1.38 according to [4.21] equation (BB.6). In [4.22], these approaches are assumed for rooms up to 400 m²; for larger rooms, the assumptions for calculating the heat release rate are on the safe side.

In the case of several vertical openings i, the height of the opening areas h_w is determined by the ratio of the sum of the height of the openings $h_{w,i}$ multiplied by the related opening areas $A_{w,i}$ to the total existing opening area $A_{w,ges}$

$$h_w = \sum \frac{h_{w,i} \cdot A_{w,i}}{A_{w,ges}} \quad \text{in metres} \tag{4.14}$$

The empirical approach to the supply air mass flow (equation (4.10)) can also be derived from the Bernoulli equation for stationary flows [4.12] and includes fundamental simplifications (e.g.

constant fire room temperature), which neglect the fire dynamics within the fire room in order to derive an analytical solution.

When using fire simulation softwares, it is advisable to base the model calculation on the ventilation conditions as time-dependent calculation variables / boundary conditions. It should be taken into account that the ventilation conditions change depending on time, since windows are opened, for example, to control smoke extraction measures. For this purpose, the higher value of the heat release rate according to the equation (4.4) should be used which is available at the beginning of the fire. In this case the fire load controlled case is used to specify the heat release rate and the actual heat release rate is determined by oxygen control of the combustion model. In this way, the course of the fire is taken into account, which is conservative for the hot design.

4.3.3 Normatively regulated design fires

4.3.3.1 General information

In the following subchapters, various normatively defined design fires are listed. For some of these design fires - which are defined by the specification of mean fire room temperature/time curves - the temperature developments are shown graphically in Figure 4.4.

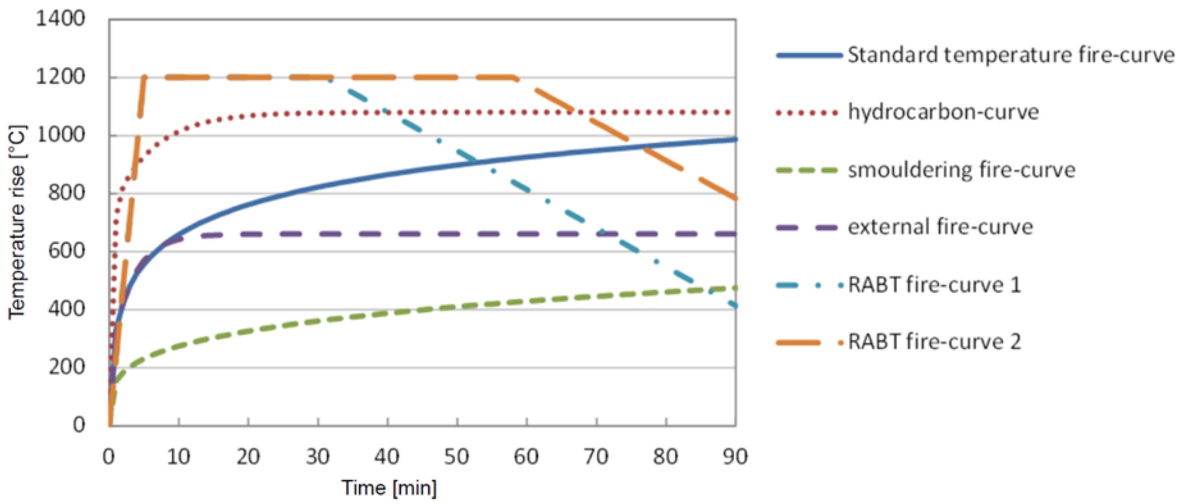


Figure 4.6 Design fire curves in comparison; representation of the temperature increase in the fire compartment

The following symbols are used for the equations (4.14) to. (4.17)

T	burning space temperature [K]
T_0	Temperature of the test specimens at the start of the test [K]
t	Time [min]

4.3.3.2 Design fires according to the smouldering fire curve

The so-called smouldering fire curve is used for the fire propagation phase of a natural fire with a small increase in the heat release rate. The development of the fire room temperature is defined by the following formula:

$$T - T_0 = 154 \cdot (t)^{0,25} \quad \text{in K} \tag{4.15}$$

4.3.3.3 Design fires for the full fire phase

Normatively defined design fires are required in order to dimension in particular measures of plant-related fire protection and components without having to evaluate special object-specific fire scenarios with the methods of fire protection engineering. The plant-engineering measures must develop their effect in the phase of fire development (especially fire detection elements) and fire propagation (especially for fire fighting), i.e. before the full fire phase has occurred.

Standard nominal fire curve

The standard nominal fire curve - ETK - according to DIN 4102-2 (or DIN EN 1991-1-2 or ISO 834) is directly used as a fire-room temperature curve for component design.

It is defined by the following formula:

$$T - T_0 = 345 \cdot \lg(8 \cdot t + 1) \quad \text{in K} \tag{4.16}$$

External fire curve

According to DIN EN 1991-1-2, the external fire curve can be used for the design of structural elements located outside the fire compartment within the respective national application areas.

The development of the fire room temperature is defined by the following formula:

$$T - T_0 = 660 \cdot \left(1 - 0{,}687 \cdot e^{(-0{,}32 \cdot t)} - 0{,}313 \cdot e^{(-3{,}8 \cdot t)}\right) \quad \text{in K} \tag{4.17}$$

Hydrocarbon fire curve

Fires of hydrocarbons can reach significantly higher temperatures in a shorter time in a full fire situation than the ETK indicates. In such cases the harmonised hydrocarbon fire curve can be used. The development of the increase in fire room temperature is defined in DIN EN 1991-1-2 by the following formula:

$$T - T_0 = 1080 \cdot \left[1 - 0{,}325 \cdot e^{(-0{,}167 \cdot t)} - 0{,}675 \cdot e^{(-2{,}5 \cdot t)}\right] \quad \text{in K} \tag{4.18}$$

RABT curve (tunnel fire curve)

The RABT curve is used for the design of components in tunnels. A temperature rise in the fire chamber to 1200°C within 5 minutes is assumed.

The beginning of the linear fall of the curve occurs after 30 minutes (Figure 4.4).

4.3.3.4 Simplified natural fire model for component design

The combustion proceeds according to fire phases and can be roughly divided into the fire development or propagation phase (up to t_1), the full combustion phase (t_1 to t_2) and the decay phase (t_2 to t_3). For mathematical fire simulations as a basis for the component design, a schematic diagram of the heat release rate is generally used as shown in Figure 4.5. Where:

$\dot{Q}_s$ Heat release rate at time t_0, at which the initial fire changes into a spreading fire (start of design fire, see Figure 4.1)

$\dot{Q}_o$ = 1000 kW

t_g characteristic fire development time in s; the numerical value corresponds to the fire duration until a heat release rate of 1 MW is reached

$\dot{Q}_{max,v}$ maximum heat release rate of the ventilation-controlled fire

$\dot{Q}_{max,f}$ maximum heat release rate of the fuel-controlled fire

Q_1-Q_3 Energy of the fire load that is converted in the individual fire phases

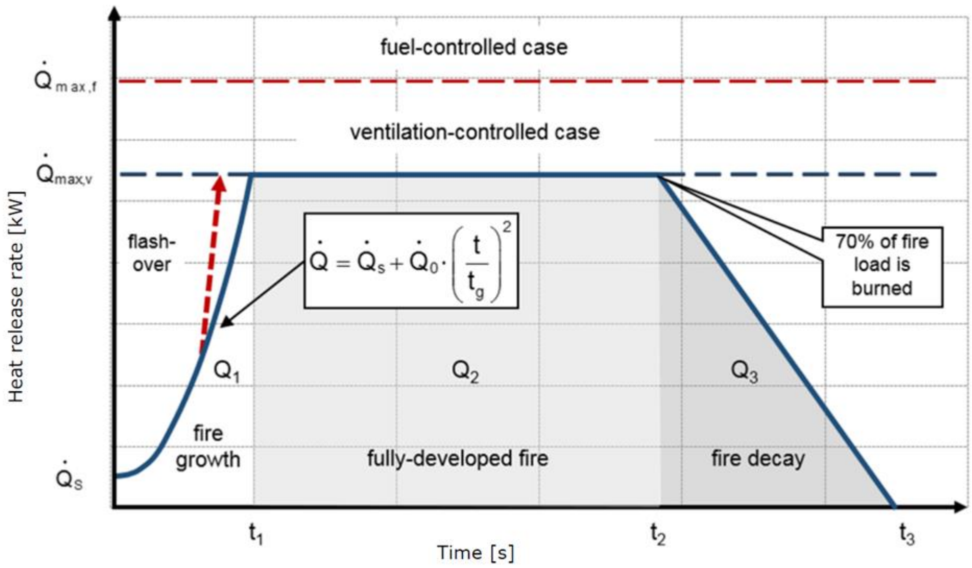


Figure 4.7 Schematized fire course for a "natural fire" with the fire phases: Fire growth, full-developed fire and fire decay

Using the simplified natural fire model for the fully developed fire phase according to [4.21] the temperature-time curve can be calculated for rooms up to 400 m² with a height of up to 5 m, vertical opening areas of 12.5 % to 50 % of the room floor area and fire load densities of 100 MJ/m² to 1300 MJ/m². For larger and/or higher rooms, the calculated temperatures are increasingly on the safe side.

The maximum heat release rate for ventilation/fuel-controlled fires of any use can be determined according to Chapter 4.3.2.4.

Figure 4.6 shows the standardized fire curve according to [4.21] with the characteristic times and the assigned temperatures in the fire room. It is important that the heat release and the fire compartment temperature show characteristic events at the same time.

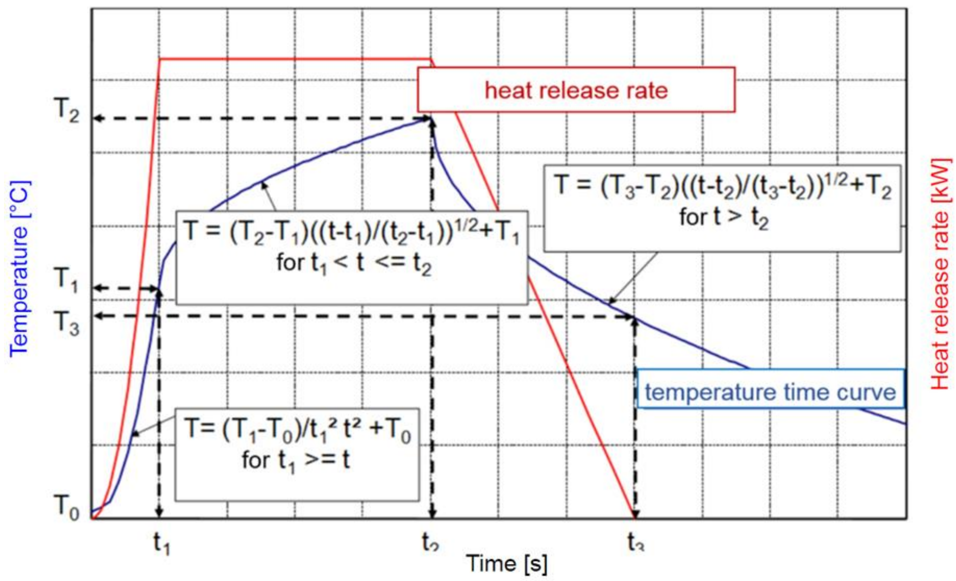


Figure 4.8 Heat release rate and temperature-time curve according to the simplified natural fire model [4.21]

The point in time of a flashover $t_{1,fo}$, if any, at which the heat release rate suddenly rises to its maximum can be determined using equation (4.19):

$$t_{1,fo} = \sqrt{t_g^2 \cdot \dot{Q}_{fo}} \quad \text{in s} \tag{4.19}$$

where $\dot{Q}_{fo}$ in [MW] can be determined according to the method of Thomas [4.24] (see Chapter 4.3.4).

Decay phase

The decay phase of an "undisturbed" fire usually begins after approx. 70% of the total energy that can be released on the fire surface has been converted. Then the heat release rate drops until the fire load is used up. In a simplified way, the waste can be linearly calculated.

4.3.4 Flashover

The fire can suddenly change from the fire propagation phase to the full fire phase if the so-called "flashover criteria" are fulfilled.

The flashover occurs in a room when a small localized fire spreads in such a way that all exposed combustible surfaces are included in the burnup. The spread occurs in a relatively short time.

Above the localised fire, unburned pyrolysis gases accumulate and spread in the area close to the ceiling. If the ignitable concentration and the ignition temperature are exceeded, these gases are ignited over a large area of the room depending on the oxygen content in the hot gas. Hot gases interspersed with flames are produced, whose radiant effect ignites the combustible surfaces below.

The flashover is connected to the entry of the following parameters. The most important Flashover criteria are

- Heat release rate,
- the flame radiation and/or the heat radiation from the hot gas layer

It can be assumed that a flashover occurs in rooms if the temperature of the hot gas layer exceeds values between 450 °C and 600 °C.

According to THOMAS and WALTON [4.24] (also included in the National Annex to DIN EN 1991-1-2) a flashover occurs when a certain heat release rate is exceeded:

$$\dot{Q}_{fo} = 7{,}8 \cdot A_T + 378 \cdot A_w \cdot \sqrt{h_w} \quad \text{in kW} \tag{4.20}$$

with

A_T Interior surfaces of the room total in m²

A_W opening area in m²

h_W averaged clear height of the openings in m

This formula is only valid for fire rooms without openings in the roof or ceiling area and for fire rooms with a maximum floor area of 400 m².

Figure 4.7 shows the course of the heat release rate considering a sudden increase of the heat release rate at the time of the flashover. As a result of the flashover the full firing phase is initiated, in which the maximum heat release rate is reached.

An abrupt increase in the heat release rate, as for example also provided for in DIN EN 1991-1-2/NA, is a conservative assumption. Especially in large rooms, a delayed increase of the heat release rate due to the flashover can be assumed. Alternative approaches to determine the delayed increase of the heat release rate following the flashover are contained in [4.25]

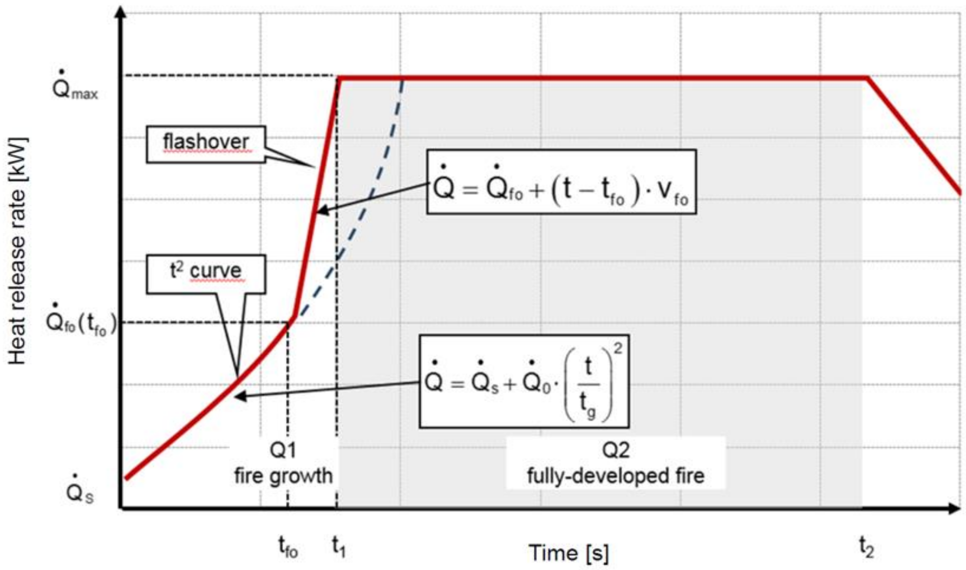


Figure 4.9 Fire course for a "natural fire" considering a flashover in the fire phase Fire propagation

4.3.5 Object specific design fires for small fire objects

If the fire behaviour of an individual object itself is important as a basis for the assessment of fire safety in buildings, suitable experimental investigations are required in which the essential fire parameters heat release and smoke release are reproducibly recorded. The time course of the fire is measured and can be used as a basis for the mathematical investigations (e.g. seating group or reception desk in an entrance hall). In general, these tests can be carried out with an unobstructed air supply, provided that in reality the air requirement for combustion is small compared to the existing room size of the fire room.

The measured values of these "individual tests" can also be combined with each other for special tests in such a way that they reflect a possible course of the developing fire event in a room during the fire phase of "fire spread" (see [4.25]). Reference values can be obtained from the technical literature. Some examples are compiled in the appendix to this Chapter 4.

4.3.6 Influence of extinguishing processes on the course of the fire

The influence of extinguishing processes on the pyrolysis rate, combustion efficiency and development of fire products is usually limited to the reduction of the combustion rate. The effect on the development of fire products is calculated from this.

In many cases, the influence of active fire protection measures on fire development can also be estimated in advance and specified for further investigations. For example, it can be assumed that the heat release in a sprinkler-protected room is limited. Depending on the time of activation and the assessable effectiveness of the extinguishing measure, different fire developments can occur (Figure 4.8).

As a rule, the extinguishing effect of firefighting by the fire brigade must not be used as the basis for a fire simulation within the framework of fire protection concepts, because

- compliance with the auxiliary deadline to be assumed cannot be guaranteed,
- the start of the extinguishing measures after arrival at the scene can be considerably delayed by other tasks of the fire brigade (e.g. rescuing people, safety measures).

If, in individual cases, the extinguishing effectiveness of the fire brigade is to be taken into account, the requirements must be agreed in advance with the responsible authority. The effectiveness can then be estimated using the simplified extinguishing model proposed in Chapter 7.6.1.4 of the Guidelines. This model compares the undisturbed spread of the fire area A_F up to the beginning of the extinguishing measures (activation time t_{act}) with the fire area $A_{extinguishing,max}$.

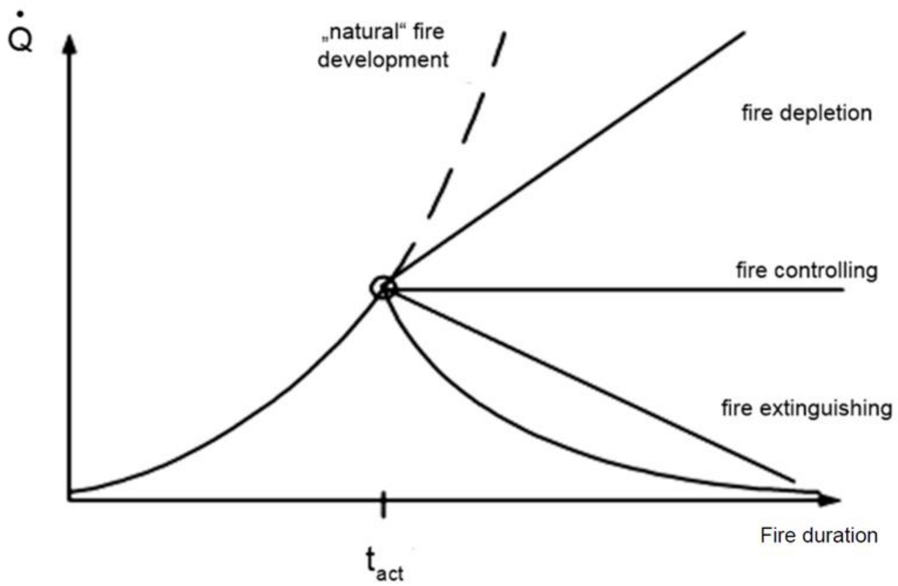


Figure 4.10 Model characteristics for the influence of extinguishing measures on the development of a design fire

For the reduction of the heat release rate of a fire source through the effect of a sprinkler system with a certain water load w after activation of the sprinklers at the time t_{act} an approach developed in the USA [4.28], [4.31] can be used, which is also described in chapter 7 of the guide.

4.3.7 Display of the design fires in program codes

The presented methods for the determination of design fires for different fire scenarios or fire phases aim at $\dot{Q}(t)$ describing the fire development in the form of a stationary or time-dependent heat release rate.

For simple fire models or calculation methods, in which the source of the fire is regarded as a point source in a highly simplified manner, the specification of $\dot{Q}(t)$ - typically often in the form of the normative $\alpha \cdot t^2$ design fire is sufficient. However, in many modelling approaches, especially in CFD simulation of smoke and heat propagation, the expansion as well as form and location of the source of the fire play an important role. In addition, the extent, area, shape (round or rectangular) or position (free or in a corner) of the fire source are often used as parameters in empirical approaches (e.g. plume models) (see Chapter 5 including chapter appendix).

The expansion and shape of the fire source are usually dynamically changing variables which in reality usually also depend to a greater or lesser extent on the development of the environmental conditions through feedback mechanisms. The dependence of the heat release rate of a pool fire on the heat radiation on the pool surface and thus on the fire room temperature is an example of a strong feedback mechanism.

If design fires are used in fire modelling, these dependencies on external influencing variables are normally already taken into account when selecting the design fire, e.g. by selecting a sufficiently high (area-specific) fire performance or by taking into account a correspondingly fast fire spread.

Therefore, it is usually not necessary to deal with a direct reaction of the environmental conditions to the fire intensity. An exception is the transition from fire load controlled to ventilation controlled burn-up, which is explicitly considered in many models by balancing the supply and exhaust air mass flows or by calculating the local oxygen concentration. However, in the case of geometric fire propagation models, the geometrical parameters of the fire that change over time must be determined. This requires different input variables depending on the simulation model.

The location of the source of the fire within the spatial structures has an important influence on the occurrence of the fire, especially the relative position to ventilation openings. This effect can only be considered in detail in three-dimensional room fire models (CFD simulations or suitably designed physical models).

Further explanations of the representation of the design fires are discussed in more detail in Chapter 5 connection with the individual mathematical models.

4.4 Literature

[4.1] DIN 18009-1: 2016-09. Brandschutzingenieurwesen – Grundsätze und Regeln für die Anwendung. Berlin: Beuth Verlag, September 2016.

[4.2] *ZEHFUSS, J.:* Festlegung von Bemessungs-Brandszenarien und Bemessungsbränden – geeignete Vorgehensweisen für ingenieurtechnische Verfahren. vfdb-Zeitschrift 3/2019, S.159-167.

[4.3] DIN EN 1991-1-2:2010-12, Eurocode 1 - Einwirkungen auf Tragwerke; Teil 1-2: Allgemeine Einwirkungen, Brandeinwirkungen auf Tragwerke.

[4.4] *BABRAUSKAS; V.:* Glass breakage in fire, Fire Science and Technology Inc., https://www.researchgate.net/publication/267852703_Glass_breakage_in_fires

[4.5] *KUNKELMANN, J.:* Feuerwehreinsatzpraktische Problemstellungen bei der Brandbekämpfung in Gebäude moderner Bauweise, Teil 2, Brandschutzforschung der Länder der Bundesrepublik Deutschland, Karlsruher Institut für Technologie (KIT), Forschungsstelle Brandschutztechnik, Forschungsbericht 164, Februar 2013.

[4.6] *SCHNEIDER, U.:* Grundlagen der Ingenieurmethoden im Baulichen Brandschutz. 3. Auflage, Werner Verlag, Düsseldorf, 2004. ISBN 3-8041-4189-7

[4.7] *BUKOWSKI, R. W.:* How to Evaluate Alternative Designs Based on Fire Modelling. NFPA Journal, March / April 1995, NFPA, Quincy MA (USA).

[4.8] *KOTTHOFF, I.; WILK, E.; REDMER, T.; WAGNER, S.:* Originalbrandversuche zur Darstellung der Brandentwicklung in Räumen und zur Brandbelastung der Fassade, MFPA Leipzig / Brandschutz Consult Leipzig / Landeskriminalamt Sachsen, 1997 – 2011.

[4.9] BSI DD 240:Part1:1997 Fire Safety Engineering in Buildings. Guide to the application of fire safety engineering principles und Part 2:1997 Fire Safety Engineering in Buildings. Commentary on the equations given in Part 1.

[4.10] Fire Code Reform Centre Limited, Fire Engineering Guidelines, Sydney, New South Wales, Australia, 1997.

[4.11] *BUCHANAN, A. H.* (Hrsg.): Fire Engineering Design Guide, Second Edition, Centre of Advanced Engineering, Christchurch, New Zealand, 2001.

[4.12] Autorenkollegium, Brandschutz - Formeln und Tabellen, Staatsverlag der DDR, Berlin, 1979.

[4.13] *DRYSDALE, D.:* An Introduction to Fire Dynamics. Third Edition, Wiley-Interscience, New York, 2011.

[4.14] NFPA 92 B: Guide for Smoke Management. NFPA, Quincy, MA (USA), 2000.

[4.15] *HOSSER, D.; ZEHFUSS, J.:* Theoretische und experimentelle Untersuchungen zum erforderlichen Brandschutz bei mehrgeschossigen Gebäuden in Stahlbauweise. Forschungsvorhaben S 503 im Auftrag der Stiftung Industrieforschung Köln. Abschlussbericht, Braunschweig, Institut für Baustoffe, Massivbau und Brandschutz, 2002.

[4.16] *FORELL, B.; PARK, J.; BIRN, T.:* Bedeutung der Sauerstoffausnutzung bei Vollbränden, Symposium Heißbemessung, 12.09.2017, Braunschweig, 2017.

[4.17] *OSBURG, M.; WILK, E.; GERUSCHKAT, F. J.:* Differenzierung des Brandverlaufs bei Raumbränden, Eine experimentell gestützte Untersuchung zur Ventilationssteuerung des Brandverlaufs bei Raumbränden, Symposium Heißbemessung, 24.09.2019, Braunschweig, 2019.

[4.18] *HUGGET, C.:* Estimation of Rate of Heat Release by Means of Oxygen Consumption Measurements, Fire and Materials, 1980, Bd. 4, S. 61-65.

[4.19] *BABRAUSKAS, W.; WILLIAMSON, R.B.:* Post flashover compartment fires: basis of a theoretical model, Fire and Materials, 2, p.39-53, 1978.

[4.20] *BEYLER, C.:* Flammability Limits of Premixed and Diffusion Flames in SFPE, fifth edition, 2016.

[4.21] *ZEHFUSS, J.:* Bemessung von Tragsystemen mehrgeschossiger Gebäude in Stahlbauweise für realistische Brandbeanspruchung. Dissertation Technische Universität Braunschweig, Fachbereich Bauingenieurwesen, 2004.

[4.22] DIN EN 1991-1-2/NA:2015-09, Nationaler Anhang – National festgelegte Parameter – Eurocode 1, Einwirkungen auf Tragwerke – Teil 1-2/NA: Allgemeine Einwirkungen – Brandeinwirkungen auf Tragwerke.

[4.23] *KAWAGOE, K.:* Fire Behaviour in rooms, Report Nr. 27, Tokyo: Building Research Institute, 1958.

[4.24] *WALTON, W. D.; THOMAS, P. H.:* Estimating Temperatures in Compartment Fires. In: DiNenno, P. J. et al. (Hrsg.). The SFPE Handbook of Fire Protection Engineering. Fourth Edition, Quincy, Massachusetts (USA), S. 3-204 – 3-221. 2008.

[4.25] *WILK, E. ET AL.:* Der Brand in Räumen – Auswertung von Originalbrandversuchen im Vergleich mit analytischen Rechenverfahren, ab vfdb-Zeitschrift 4/2012.

[4.26] Internetzugang des NIST der U.S.A, http://fire.nist.gov/fire/fires.

[4.27] VDI-Wärmeatlas: Berechnungsblätter für den Wärmeübergang, Hrsg.: Verein Deutscher Ingenieure, VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen (GVC), 10., überarbeitete Auflage, Springer, Berlin, 2006.

[4.28] *BASCHKIRZEW, M. P.:* Aufgaben zur Wärmeübertragung, Staatsverlag der DDR, Berlin 1979.

[4.29] *MADRZYKOWSKI, D.; VETTORI, R.:* A Sprinkler Fire Suppression Algorithm for the GSA Engineering Fire Assessment System. NISTIR 4833, U.S. Department of Commerce, 1992, USA.

[4.30] Draft British Standard Code of Practice for Application of Fire Safety Engineering Principles to Fire Safety in Buildings Document 94 / 340340 DC, 3 June 1994, BSI, London (GB).

[4.31] *EVANS, D.:* Sprinkler Fire Suppression Algorithm for Hazard. NISTIR 5254, 1993, U.S. Department of Commerce, Technology Administration, USA.

[4.32] The SFPE Handbook of Fire Protection Engineering. Fourth Edition, Quincy, Massachusetts (USA), 2008.

[4.33] *ALPERT, R. L.:* Ceiling jet flows.

[4.34] *BABRAUSKAS, V.:* Heat Release Rates.

[4.35] *FLEMING, R.:* Automatic Sprinkler System Calculations.

[4.36] *PURSER, D. A.:* Toxicity Assessment of Combustion Products.

[4.37] NFPA 92 B: Guide for Smoke Management Systems in Malls, Atria and Large Areas. NFPA, 1995, Quincy MA (USA).

[4.38] *REICHEL, V.:* Brandschutzanforderungen an Baukonstruktionen, Staatsverlag der DDR – 1979.

[4.39] NFPA 204 M: Guide for Smoke and Heat Venting. NFPA, 2007, Quincy, MA (USA).

[4.40] *WALTON, W.; BUDNICK, E.:* Quick Response Sprinkler in Office Configurations: Fire Test Results. NBSIR 88-3695, U.S. Department of Commerce, 1988, USA.

[4.41] *MADRZYKOWSKI, D.:* Office work station heat release study: Full scale vs. bench scale. Interflam ‘96 – Conference Proceedings. 7th International Fire Science and Engineering Conference, Interscience Communications, 1996, London (GB).

[4.42] *LOUGHEED, G. D.* ET AL.: Full-Scale Fire Tests and the Development of Design Criteria for Sprinkler Protection of Mobile Shelving Units. Fire Technology, First Quarter 1994, NFPA, Quincy, MA (USA).

[4.43] *WALTON, W. D.:* Quick Response Sprinklers in Chemical Laboratories: Fire Test Results. NISTIR 89-4200, U.S. Department of Commerce, 1989, USA.

[4.44] *HÄGGLUND, B.; WICKSTRÖM, U.:* Smoke Control in Hospitals – A Numerical Study. Fire Safety Journal Vol. 16 No. 1, 1990, Elsevier Science, Barking, Essex (GB).

[4.45] Brandrisikobewertung, Berechnungsverfahren, SIA 81, Schweizerischer Ingenieur- und Architektenverein, 1984.

[4.46] Beuth-Kommentare: Baulicher Brandschutz im Industriebau – Kommentar zu DIN 18230. 3te Auflage, Beuth-Verlag, 2003.

[4.47] *STEINERT, C.:* Feuerübersprung und Abbrandverhalten von Personenkraftwagen - Teil 1, Materialforschungs- und Prüfungsanstalt für das Bauwesen Leipzig e.V., 1998, Fraunhofer IRB Verlag, Heft T 2876, Stuttgart, 1999, ISBN 3-8167-5446-5. - Teil 2, Materialforschungs- und Prüfungsanstalt für das Bauwesen Leipzig e.V., 1999, Fraunhofer IRB Verlag, Heft T 2934, Stuttgart, 2000, ISBN 3-8167-5774-X.

[4.48] *PREISS, H.; WILK, E.; WESKAMP, F.; BÖHME, K.:* Datenbank zur Erfassung von Brandkenndaten im Ergebnis von Branduntersuchungen und Experimenten sowie Angaben zu Stoffkennwerten. Feuerwehr Leipzig / Institut für Baustoffe - begonnen: 1987 (bürointernes Arbeitsmaterial - nicht veröffentlicht).

[4.49] *SCHNEIDER, U.:* Grundlagen von Brandszenarien für den Brandschutzentwurf. vfdb-Zeitschrift 3 / 1995.

[4.50] *STEINBACH, K.; PLESS, G.:* Zum Brandverhalten zündfähiger Stoffe. Mitteilungen aus dem Institut der Feuerwehr vom 17.7.1989.

[4.51] *SCHULZE, G.; SCHLIEMANN, H.:* Einsatz von Luftschaum bei der Bekämpfung von Bränden kritischer Brandmedien. Zeitschrift Unser Brandschutz – wiss.-tech. Beilage 7/1972.

[4.52] *PLESS, G.; STEINBACH, K.:* Brandverhalten von Feststoffen. Institut der Feuerwehr Heyrothsberge – MdI-Information 1/1982.

[4.53] *KOTTHOFF, I.:* Erarbeitung realer Prüfbedingungen für die Durchführung von Original-Brandprüfungen an B1-Fassadenelementen und eines Verfahrens zur Berechnung von Brandverläufen an Fassaden, Forschungsbericht Nr. BI5-8001-96-18, MFPA Leipzig, 2000.

[4.54] *ALBRECHT, C.:* A risk-informed and performance-based life safety concept in case of fire. Dissertation, Technische Universität Braunschweig, 2012.

[4.55] *KONG, D.; LU, S.; FRANTZICH, H.; LO, S. M.* 2013. A method for linking safety factor to the target probability of failure in fire safety engineering, Journal of Civil Engineering and Management 19 (Supplement 1): S. 212–S221.

[4.56] http://dx.doi.org/10.3846/13923730.2013.802718

[4.57] *FORELL, B:* Zur Notwendigkeit von Ausfallbetrachtungen bei ingenieurgemäßen Brandschutznachweisen. In: Tagungsband der 64. Jahresfachtagung der vfdb, Bremen, 21.-24.Mai 2017, 2017.

ANNEX TO CHAPTER 4

A4.1 Preliminary remark

The information in the tables of this chapter appendix has been selected to give the user an indication of the quantities to be expected in relation to the individual parameters. Only data from reliable sources that are suitable for practical application have been used.

Nevertheless, the user should always evaluate the table values critically in relation to the source term to be set by him and thus check the suitability of the table value.

Depending on the information available for the specific use-related design fire, the above-mentioned substance data are included individually or in combination in the creation of the (design) fire scenario. Material properties can be taken from DIN 18230-3 [4.5] or the SFPE Handbook [4.32]. The use of data from literature sources (generally available technical literature) or simplified generalised approaches is possible, provided that their applicability to the concrete fire scenario at hand can be proven.

In this appendix (appendix of tables[6]) information on uses, objects and stored goods have been selected, which frequently occur in the context of the preparation of fire protection concepts. When selecting these data, particular attention was paid to data that correspond to the experimental experience of the authors of this chapter. Literature data that represent extreme values were not cited[7]. Further literature references follow. When using literature data, it should be noted that the boundary conditions must always be compared with the concrete application case.

A4.2 Guidance values for the determination of design fires

Table A4.1 Characteristic values for uses for estimating and developing the source terms

Material or use	Notes / Conditions	Fire load [MJ/m²]	Calorific value[8] [MJ/kg]	[9]Fire development time t_α [s]	$\dot{q}$ = f(A)[10] [kW/m²]	Source
Living space		780 / 1085	19,5	300	250 310	[4.21] [4.8]
Office space	with large equipment or upholstered furniture	420 / 584	18,7	300	250 270	[4.21] [4.8]
Office space	functional, without upholstered furniture	320 - 500	17,9	600	240	[4.8]

[6] The table values are to be understood as guide values and not as normative specifications.
[7] e.g. the burning of an empty wardrobe with more than 6 MW/m² can probably be considered exotic, because in reality no empty wardrobe is the subject of the evaluation and one has to take into account that the fire of an entire living space may yield only 5 MW.
[8] related to mixed fire loads that are present in most cases; this term is used in all shall be commonly understood as a mixture of fuels according to their respective uses;
[9] Control quantity t_α according to DIN EN 1991-1-2, appendix E.4, (t_α corresponds to tg)
[10]all values without sprinkler protection

Material or use	Notes / Conditions	Fire load [MJ/m²]	Calorific value[8] [MJ/kg]	[9]Fire development time t_α [s]	$\dot{q}$ = f(A)[10] [kW/m²]	Source
Hospital room	2 beds	230 / 320	18,6	300	250 160	[4.21] [4.8]
Hotel room	2 beds, furniture chipboard	310 / 431 430 / ---	19,5 [4.8]	300 [4.30]	250 [4.37]	[4.21] [4.38]
School: Classroom	Furniture made of wood, seats made of moulded plywood	285 / 397	18,2	300	150	[4.21]
Lecture room	Molded plywood seats, clothing, bags	140 / ---	25,0	1.200	130	[4.8]
Entrance hall	Reception counter, few furniture with little upholstery	150 - 400	19,2	450	240	[4.8]
Shopping Centre		600 / 835		150	250 380	[4.21] [4.8]
Theatre (cinema) / auditorium	upholstered seating	300 / 417		150 450	250 500	[4.21] [4.8]
Transport (public sector)		100 / 139		600	250	[4.21]
Library	with metal shelves	1.500 / 2.087	18,4	450[11]	200 - 500	[4.24]
Drugstore	small amounts of flammable liquids	760 / --- 1000 / ---	28 - 32	200	300	[4.8] [4.11]
Restaurant	light upholstered seats, wooden tables	600 - 700	18 - 25	200 - 300	280	[4.27]

[11] values were corrected or supplemented, as the information given in DIN EN 1991-1-2 does not correspond to the measurements from fire tests; see [4.24]

Material or use	Notes / Conditions	Fire load [MJ/m²]	Calorific value[8] [MJ/kg]	[9]Fire development time t_α [s]	$\dot{q}$ = f(A)[10] [kW/m²]	Source
Restaurant	Upholstered chairs, wooden tables, seating groups, textiles for living areas	1.100 / ---	17 - 20	200	330 - 620	[4.8]
Cloakroom	approx. 12 m²	720 / ---	21	180 - 250	430	[4.8]
little kiosk	approx. 15 m²	650 / ---	22,5	200 - 300	285	[4.8]
Sales booth	2 x 2 m	--- / ---	19,5	300	400	[4.25]

Explanation:

Fire load: First number corresponds to the mean value; second number corresponds to the 90 % quantile (in the EC data [4.21] according to a Gumbel distribution).

Fire development: Control variable t_α according to DIN EN 1991-1-2, Annex E.4 These values, if not given in the literature, were determined using the curve for the heat release rate according to [4.8].

Sprinkler protection: Since the data on the heat release rate under sprinkler protection is very scattered and the associated boundary conditions are not explained in detail in the literature, the fire performance under sprinkler protection should be determined according to Chapter 7.3.3.

Table A4.2 Information on fire development for selected types of storage taking into account the storage height (from tests on a scale of 1:1 according to the sources given)

Goods	Type of storage arrangement	Storage height [m]	Fire growth	Max. specific heat release rate [kW/m²]
Wooden pallets (dimensions: 1.2 x 1.2 x 0.14 m; degree of humidity: 6.0 - 12.0 %) [4.37]	stacked / block storage	0,5	moderate - fast	1.249
Wooden pallets (dimensions: 1.2 x 1.2 x 0.14 m; degree of humidity: 6.0 - 12.0 %) [4.37]	stacked / block storage	1,5	fast	3.746
Wooden pallets (dimensions: 1.2 x 1.2 x 0.14 m; degree of humidity: 6.0 - 12.0 %) [4.37]	stacked / block storage	3,0	fast	6.810
Wooden pallets (dimensions: 1.2 x 1.2 x 0.14 m; degree of humidity: 6.0 - 12.0 %) [4.37]	stacked / block storage	4,9	fast	10.215
Wooden pallets (degree of humidity: 6.0 - 12.0 %) [4.38]	stacked	0,46		1.420 *
Wooden pallets (degree of humidity: 6.0 - 12.0 %) [4.38]	stacked	1,52		4.000 *
Wooden pallets (degree of humidity: 6.0 - 12.0 %) [4.38]	stacked	3,05		6.800 *
Wooden pallets (degree of humidity: 6.0 - 12.0 %) [4.38]	stacked	4,88		10.200 *
Filled mail bags [4.38]	stored	1,52		400 *
Cartons (compartmented) [4.38]	stacked	4,5		1.700 *
PE letter trays filled [4.38]	stacked on a cart	1,5		8.500 *

Goods	Type of storage arrangement	Storage height [m]	Fire growth	Max. specific heat release rate [kW/m²]
PE waste drums in cardboard boxes [4.38]	stacked	4,5		2.000 *
PE-fibreglass shower partitions in cardboard boxes [4.38]	stacked	4,6		1.400 *
FRP bottles packed in cardboard boxes [4.38]	stacked	4,6		3.400 /6 .200 *
PE bottles in cardboard boxes [4.38]	stacked	4,5		2.000 *
PU rigid foam insulation panels [4.38]	stacked	4,6		1.900 *
PU rigid foam Insulation plates [4.1]	stacked /block storage	4,6	very rapidly	1.929,5
FRP vessels packed in cardboard boxes [4.38]	stacked	4,6		14.200 *
PS tubes nested inside each other in cardboard boxes [4.38]	stacked	4,2		5.400 *
PS toy parts in cartons [4.38]	stacked	4,5		2.000 *
PS rigid foam insulation panels [4.38]	stacked	4,2		3.300 *
FRP tubes packed in cardboard boxes [4.38]	stacked	4,6		4.400 *
PP and PE film rolls [4.38]	stacked	4,1		6.200 *
PE bottles in divided cartons [4.37]	Shelves	4,6	very fast	6.242,5
PE bottles in divided cartons [4.37]	stacked / block storage	4,6	very fast	1.929,5
PS cups in divided cartons [4.37]	stacked /block storage	4,6	very fast	13.620,0
PS rigid foam insulation plates [4.37]	stacked /block storage	4,3	very fast	3.291,5

Goods	Type of storage arrangement	Storage height [m]	Fire growth	Max. specific heat release rate [kW/m²]
PVC bottles in divided cartons [4.37]	stacked /block storage	4,6	very fast	3.405,0
PP buckets in divided cartons [4.37]	stacked /block storage	4,6	very fast	4.426,5
PP or PE film rolls [4.37]	stacked/block storage	4,3	very fast	3.972,5
Methyl alcohol [4.38]				600 *
Gasoline [4.37]				2.500 *
Kerosene/petroleum [4.37]				1.700 *
Heavy fuel oil, No. 2 [4.37]				1.700 *
PE: polyethylene, PU: polyurethane; PS: polystyrene; PP: polypropylene; PET: polyethylene terephthalate; HDPE: high-density polyethylene; FRP/GFK: glass fibre reinforced polyester Note: The fire development grows with increasing storage height * Heat release rate per m2 of floor area of the entire combustible material involved; based on negligible radiative feedback from the environment and 100% combustion efficiency.				

Table A4.3 Heat release rate of stored goods at different storage heights

Product	Storage type/storage height [m]	Heat release rate [kW]
Wood or PMMA [4.38]	vertical / 0,61 m	100 per m width
	vertical / 1,83 m	240 per m width
	vertical / 2,44 m	620 per m width
	vertical / 3,66 m	1,000 per m width
	upper side of horizontal surface	720 per m² surface area
Polystyrene (solid) [4.38]	vertical / 0,61 m	220 per m width
	vertical / 1,83 m	450 per m width
	vertical / 2,44 m	1.400 per m width
	vertical / 3,66 m	2,400 per m width
	horizontal	1,400 per m² of floor space
Polypropylene (solid) [4.38]	vertical / 0,61 m	220 per m width
	vertical / 1,83 m	350 per m width
	vertical / 2,44 m	970 per m width
	vertical / 3,66 m	1.600 per m width
	horizontal	800 per m² Surface area

Table A4.4 Information on fire objects with low heat release (low-energy fires)

Object	Heat release rate [kW]	time interval [s]	Source
Copy machines	600 - 800	2.500 - 2.800	[4.25]
Recycle Bin	30 - 45	180 - 450	[4.8]
PC screen	45	900 - 1.500	[4.8]
Travel bag	55 - 100	150 - 300	[4.8]
Desk chair[12]	65	200 - 450	[4.8]
PUR soft foam mattress German-made	190	60 - 850	[4.8]
Spring mattress U.S.-made	700	220 - 350	[4.25]

[12] partly burning with very strong smoke development

Table A4.5 Quality of descriptions of the design fires (exemplary)

Realistic reference	Available information	Method	Instructions for use
very high	Room configuration, flammable substances in the bearing arrangement to be assessed, ventilation conditions, ignition source	object-specific, reproducible fire tests with risk-appropriate test set-up and usable measurement results	directly usable numerical data is available
high	Material data of the fire loads in the bearing arrangement to be evaluated Arrangement of the fire loads in the room	Calculation of the temporal heat release	can be used in the context of parameter studies
medium	Assumptions on fire development for the category	Calculation of the temporal heat release	can be used in the context of parameter studies, under more stringent calculation assumptions or safety considerations
low	Flat-rate information on the type of use of the room with typical fire loads	Calculation of the temporal heat release	can be used in the context of parameter studies, use estimated values that are on the safe side

Table A4.6 Examples from the literature for fire development and heat release for different partial uses based on fire tests

Use	Speed of fire development	max. achieved combustion capacity [MW]
PC workstation; solid furniture (chipboard); free combustion [4.40]	slow	1,8
PC workstation; solid furniture (chipboard); test in a room with ISO 9705 dimensions [4.40]	slow	2,5
PC workstation in an open-plan office; solid furniture (chipboard) and flammable screens divided [4.28], [4.41]	fast	6,8
Office; paper - documentation on metal shelves; free burning [4.40]	up to 200 s - medium and after 200 s - fast	1,6
Office unit; solid furniture (chipboard); test in a room with ISO 9705 dimensions [4.40]	slow	2,25
Miscellaneous office equipment (workplace equipment); free incineration [4.28]	slow on average	-
Mobile metal shelves with archive documents [4.42]	fast	-
Car in a public parking garage [4.46]	slow	2,0 to 5,5
Chemical laboratory [4.24]	very fast	2,0
Various exhibitions [4.37]	slow	-
Normal bed in a Swedish hospital [4.44]	slow	0,3

Table A4.7 Information on fire loads for different uses

Use	Average fire load q (MJ/m²)	Source	Note
Storage room for office and commercial buildings	500	[4.45]	
Car paint shop	500	[4.45]	
Car repair workshop	300	[4.45]	[4.45] Table 10-2, 90% fractile value: 338 MJ/m²
Building materials warehouse	270[13]	[4.45]	Specification in [4.32]: 800 MJ/m³ [4.45] Table 10-2, 90% fractile value: 266 MJ/m²
Data processing, computer centre	400	[4.45]	
laboratory, chemistry	500	[4.45]	
Kindergarten/nursery school	300	[4.45]	
Furniture factory	550	[4.45]	
Apartment basement	900	[4.45]	

13 The value refers to an assumed storage room height of 3 m

Table A4.8 Information on mass burning rate

Examples of mass burnup velocity v_{ab}	v_{ab} [kg/m² min]	Calorific value H_i [kJ/kg]	Source
Office space with upholstered furniture or large appliances as well as living rooms and bedrooms Fire propagation phase Full fire phase	 0,32 - 0,53 0,87	19020 Room sizes up to 40 m²	[4.8]
Office space, simply furnished Fire propagation phase Full fire phase	 0,25 - 0,40 0,80	17300 Room sizes up to 40 m²	[4.8]
Hospital room Fire propagation phase Full fire	 0,21 - 0,38 0,52	18860	[4.8]
Salesroom Fire propagation phase Full fire	 0,31 - 0,84 1,02	22000	[4.8]
Corrugated cardboard boxes, folded and	0,38 - 0,5	15120	[4.47]
stored with flammable contents	1,9 – 2,1	15120	[4.48]
Books on wooden shelves Furniture in rooms in full fire	0,33 1,2	17300 31300	[4.12] [4.49]
Stack of tyres on full fire	3,4	31300	[4.49]
Rubber products 85% value	0,7	31300	[4.50][4.48]
Rubber as profiles and sealing strips	1,24	39200	[4.8]
Foam mattresses	0,62	19100	[4.8]
Polystyrene parts, hard	0,68	39600	[4.51]
Polystyrene foam in stacks, small quantities Fully developed fire, stacks >10 m³	0,4 – 0,7 1,9 – 2,4	39600	[4.48][4.8]

The values for the fire propagation and mass burning velocity apply to room fires only until the flashover enters the room and to local fires until they burn on the given area for storage goods with a maximum height of 1.5 m or furniture up to 1.8 m high.

Table A4.9 Normative information on the calculated fire propagation rate

"classified", normalized fire propagation velocity	v_{aus} [m / min]	Source
slow fire development DIN 18232	0,15	DIN 18232 Part 2 and 5
average fire development DIN 18232	0,25	
fast fire development DIN 18232	0,45	
DIN 18230-1	1,0	[4.5]
DIN EN 1991-1-2, Annex E slow fire development	0,2 - 0,3	[4.5][4.52]
DIN EN 1991-1-2, Annex E Average fire development	0,35 - 0,48	
DIN EN 1991-1-2, Annex E Rapid fire development	0,7 - 1,2	
DIN EN 1991-1-2, Annex E very rapid fire development	1,8 - 3,0	[4.5]
DIN EN 1991-1-2, Annex E Flashover	4,8 - 7,2	[4.5]

5 MODELS FOR FIRE SIMULATION

5.1 General information

5.1.1 Overview

Chapter 5, "Models for fire simulation", is made up of six sub-chapters.

Chapter 5.1 defines the main objectives of fire modelling.

Based on this, Chapter 5.2 presents the fundamentals of fire modelling and describes the different types of models.

Chapter 5.3 describes the mathematical models in more detail and refers to further literature.

Chapter 5.4 addresses with the validation and verification of mathematical models and indicates the basis of the difference between computational and experimental results and how evaluation of a model can be carried out in practice.

Chapter 5.5 describes the application of models, including documentation requirements.

Finally, Chapter 5.6 discusses the influence of selected numerical and physical boundary conditions on the fire models' computational results.

5.1.2 Objective of the fire modelling

The use of fire simulation models has achieved a high priority in the context of fire protection engineering. They are used in particular for the design of fire protection requirements, especially in the following general objectives:

- Calculation of local and global temperatures to assess the behaviour of structural elements, building materials and the risk to people.
- Description of smoke spread and design of smoke extraction measures.

For the verification of these fire protection issues, the models should cover a variety of different phenomena and describe the following details of fire processes:

- combustion processes,
- heat release rate and fire propagation across combustible objects,
- heat transport by convection, radiation and conduction,
- smoke gas volume and composition,
- development of smoke gas layers,
- soot concentration or visibility within smoke gases,
- smoke spread to other areas and
- temperature development at relevant points.

From this list, it is clear that fire modelling is based on the fundamental laws of chemistry and physics (including thermodynamics. Beyond the practical applications (e.g. structural building design and smoke designing extraction measures), fire simulation models can also be used to study the interaction of various processes. An example of this is the consequence of changes in temperature or ventilation boundary conditions on the development of a fire.

In practice, this results in very different problems for which different models are available. These models differ in their structure, the degree of simplifications or assumptions and, within similarly structured models, they also differ in their program codes. This chapter aims to describe the key principles, classify the models according to their structure, and provide instructions for their application.

5.2 Fundamentals of fire modelling

5.2.1 General information

A model in a scientific sense is generally understood as an object representing an original (physical model) to solve tasks that cannot be carried out on the original itself or are too expensive. For the issues discussed here, these are the physical or mathematical reproduction of reality employing mathematical equations or replicas on a reduced scale. The models provide these purposes,

- to obtain new information about the original,
- to uncover or explain relations,
- to indicate characteristics of the original that are not accessible or measurable on it,
- to optimize the original,
- to verify hypotheses,
- to verify the use of subsystems, and
- to provide the bases for planning.

Fire phenomena can also be represented with the help of physical or mathematical models. The models generated based on existing laws of nature, in which specific assumptions, approximations or simplifications are involved.

In the following, the basics of fire will be explained. Based on that, fundamental specifications and model assumptions of the fire simulation models are described. The basic properties of mathematical and physical models are presented in Chapters 5.2.4 and 5.2.5.

5.2.2 Fundamentals of fire

To understand fire models, the description of the essential physical processes in fire phenomena is a fundamental step. Therefore, a short overview of the phenomena is given below.

The primary prerequisite for fire development can be shown through the fire square (Figure 5.1). Combustible material and oxygen in the correct mixing ratio and initial energy lead to a self-sustaining chemical chain reaction to maintain the combustion reaction between the combustible material and oxygen. Combustion generally takes place in a mixture of gaseous substances.

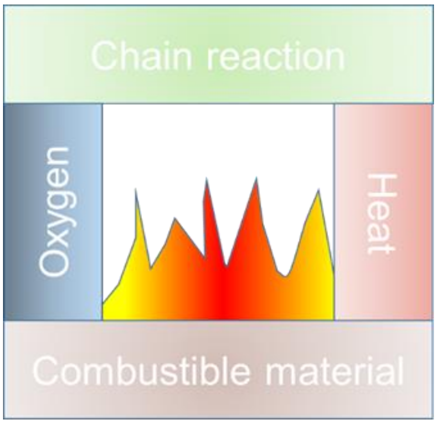


Figure 5.1: Fire square

In combustion reactions, as they are considered in fire protection engineering, the fuel is not in gaseous form at the beginning of the combustion reaction. To achieve the necessary mixing ratio between oxygen and combustible material, liquid and solid substances must first be converted into gaseous fuels.

In the case of liquid substances, this is done by evaporation. Evaporation is an endothermic reaction, i.e. additional energy is required to convert liquids into a gaseous state. This energy is called the latent heat of evaporation and is a physical material property. The evaporation process depends not only on the temperature but also on the partial vapour pressure and can be described by the Clausius-Clapeyron law:

$$\ln(p_v) = -\frac{L_v}{RT} + C \tag{5.1}$$

with:

p_V = partial vapour pressure

L_V = temperature independent evaporation enthalpy [J/kg]

R = general gas constant [J/(kg·K)]

T = Temperature [K]

C = material-dependent constant

In addition to evaporation, where the phase change does not accompany any chemical changes in the initial materials, materials can also decompose to other substances under thermal influence. During these decomposition processes, known as pyrolysis, gaseous substances can be released in addition to liquid and solid ones. In fire protection engineering, pyrolysis of solid materials (e.g. wood) is of particular importance.

The pyrolysis of solids corresponds in most cases to an endothermic process that can be controlled by several chemical reactions. This approach can be described by the Arrhenius law, in which the temperature dependence of the relative decomposition rate of a substance is described by a simple relationship:

$$\dot{m}'' = \rho_s \cdot A \cdot Y_O^m Y_S^n e^{-E/(R \cdot T)} \tag{5.2}$$

with

$R =$ universal gas constant [J/(mol K)], = 8,314 J/(mol K)

$T =$ surface temperature of substance $[K]$
$E =$ activation energy [J/mol]
$A =$ pre-exponential factor [m/s]
$\rho_s =$ density of substance [kg/m³]

Y_O and Y_S represent the mass fractions of oxygen and fuel involved in decomposition, and m and n are constants. For some substances, there is a dependence of the decomposition on the oxygen concentration; for some, there is not. In these cases, m = 0. From a thermal point of view, the decomposition of a (heterogeneous) substance often takes place within several temperature bands (decomposition stages) so that the equation (5.2) may be run through several times and in parallel depending on the composition of the substance. For the respective characteristic decomposition temperatures, corresponding activation energies E and pre-exponential factors A must then be known. Methods for deriving these quantities exist, for example, based on thermogravimetric analysis (DIN 51006).

A fire will generally not extinguish as long as sufficient fuel and atmospheric oxygen are available and adequate energy is returned to the fuel surface to produce further gaseous fuel. Besides, if there is still unused fuel with sufficient oxygen supply, the fire will continue to grow until it is limited by the fire load arrangement or external intervention.

Flame and plume formation is linked to the combustion process. The plume (smoke gas column) is formed by the rising hot gases with the solid and liquid components that accompany it, and the mass flow increases as it mixes in ambient air. This admixture results from an impulse transfer in the transverse direction, which carries ambient air to the edge of the flow in the so-called boundary layer. It is based on the viscosity of the medium (gas). Due to the turbulent flow and diffusion, the ambient air mixes with the flame's fuel gases. This enables combustion, which releases the heat energy. The gases absorb a large proportion of the generated heat within the combustion zones. Thereby the temperature of the gases and the particles they contain will increase. This leads to the already described buoyancy of the gases and particles and their mixture. Since the rising flow continues above the flame (plume), the plume mass flow is constantly increased by the admixture of ambient air. Since combustion no longer takes place above the flame, the plume's temperature decreases with height when the ambient temperatures prevail over the plume. This is a consequence of energy conservation.

If the buoyancy is sufficiently high, the hot gases rise in a vertical direction until they hit the ceiling. This is only prevented if the buoyancy is very weak concerning the temperature gradients or air flows. However, with increasing fire performance, a plume flow usually forms up to the ceiling. At this point, the smoke gases can only spread in a horizontal direction. This flow's driving force, known as the ceiling jet, is still buoyancy (density difference to the ambient air). As this flow is also turbulent, vortices are produced, which have a vertical component in addition to the horizontal component. With sufficient density difference and undisturbed dispersion, a smoke gas layer forms below the ceiling. This smoke gas layer continues to grow as long as the fire does not extinguish or smoke is removed. This smoke-layer releases convective and radiative heat to the ceilings, walls and other objects. When the smoke gases reach an opening, the outflowing smoke gases transfer heat to the outside of the room.

As the temperature rises, the thermal radiation increases, which not only affects the enclosure surrounded by the smoke gas layer but also all objects below the smoke gas layer. This thermal radiation not only has a significant effect on the burning rate of the objects but can also ignite other combustible objects (flashover). Therefore, the heat radiation also directly impacts the spread of fire on the relevant objects. On the other hand, the smoke layer also receives heat radiation from the flame, just like the surrounding components. This energy balance determines the temperature of the smoke gases.

The smoke gas volume grows until new openings are created or they reach an opening. The pressure increases and the smoke gas volume forms a smoke layer under the ceiling. Overpressures are obtained in the upper part of the room and under pressure in the room's lower part. It is separated by a level where the internal pressure is equal to the external pressure. This so-called neutral plane is an idealization because it is not necessarily exactly flat. The neutral plane does not match with the smoke layer height necessarily. Below this neutral plane, fresh ambient air flows in through the opening, which is required for combustion. If this inflow is not sufficient for combustion, it is known as ventilation-controlled combustion, in which the composition of the burned materials changes. Depending on the openings' position and arrangement, the incoming supply air can influence the smoke gas flow in the same way as the plume.

5.2.3 Model assumptions and simplifications

Basic specifications must be made for all models. In addition to the initial conditions (temperature, pressure, etc.) and the boundary conditions such as heat sources (fire, supply air, heating, etc.) and sinks (smoke and heat exhaust, cooling, etc.), these include the building geometry, walls, opening areas and the material data of the boundaries and their representation in the model. Since complex geometries cannot always be represented entirely identically to the original, the geometry's essential elements must be assessed and recorded by the user. For this work step, it is necessary to know the respective model's physical basics to decide on the essential features.

The models can differ considerably concerning the scope of the input data. In the zone model, attention must be on the reasonable simplification of the complex geometries and the openings' position. In contrast, the other models may require a more significant amount of preliminary considerations. In the Computational Fluid Dynamics (CFD) models, for example, specific definitions of mathematical boundary conditions regarding speed, pressure and thermal boundary conditions are the matter. In the case of the physical models, the focus is on the most realistic as possible replication. However, the difficulty here is to conduct similarity between model and original.

The most important input is the fire development and related material data. Concerning the fire development, modelling of the evaporation and pyrolysis processes, which are based on fundamental material properties, is limited to a narrow scope of application. The modelling of these processes currently plays a role in science and is of limited application for general predictions. Practical application also faces the problem that knowledge about the composition and arrangement of substances at a specific point in time is usually not available. Therefore, a different approach to the problem has been adopted by assuming specific fire patterns based on experiments or using phenomenological approaches (see Chapter 4 "Fire scenarios"), which cover particular areas of application. Based on the existing application, typical fire loads are assumed. A quantity of combustible material (burn rate or heat release rate) converted into thermal energy per unit of time is as-signed. Thus, it is not the fire phenomenon that is calculated but the consequences of the pre-defined amount of energy and mass introduced into the calculation area.

Investigating the spread of a fire over several objects is required more detailed information, which, for example, influences the heat transfer or ignition.

For modelling of the combustion, if it should be considered in the individual model, one is faced with the problem in practical application that the combustion reactions taking place in the real fire case are not known in advance. In the case of mixed fire loads, which are typical for fire protection engineering problems, several hundreds of reactions can occur simultaneously and cannot be calculated meaningfully. Instead, a reaction is calculated as a proxy and experimentally determined values for the released soot and carbon monoxide (CO) are taken into account.

For the fire development, it must be determined if sufficient oxygen is available for complete combustion of the material. If sufficient oxygen is available, depending on the combustible material's properties, combustion is more or less complete and the fire is controlled by the amount of availabe combustible material, so called fuel-controlled fire. If there is a lack of oxygen, on the other hand, a ventilation-controlled fire occurs. This leads to incomplete combustion, in which, among other things, large quantities of CO and gaseous, unburned carbon hydroxides enter the smoke gases. Soot and ashes are also produced, depending on the type of combustible material. The further material data regarding the formation of combustion products depends on the ventilation. All related input data, such as the soot yields, carbon monoxide, carbon dioxide, combustion efficiency, calorific value and radiation fraction, must be changed or conservatively selected depending on the boundary conditions.

In addition to these frequently used model assumptions and simplifications, there are further model assumptions and simplifications, depending on the selected model, which influences the calculation result. In determining models and sub-models, it is essential to check the influence of model parameters on the calculation result. It should be represented by a widely used model assumption from the CFD models.

To reduce the calculation effort, the assumption can be made for fires that their flow velocities are significantly lower than the speed of sound ("low Mach number assumption"). This assumption is proven in the case of fire, but the calculation of fast combustion processes (deflagrations or detonations) is not possible.

5.2.4 Mathematical models

Mathematical models consist of a system of equations, which describe the occurring phenomena using the relevant parameters. The systems of equations are the mathematical form of the laws of nature. In most cases, these equations' structure is already so complex that they can only be solved numerically.

Mathematical fire models can be further divided into deterministic and probabilistic models. Deterministic models describe the fire growth and the fire development for a particular initial situation, specified by the user in the form of boundary and initial conditions, which determine the system's temporal development under consideration. They consist of a set of mathematical algorithms which describe the physical laws and related dependencies. The deterministic models can vary widely in their complexity.

The probabilistic models describe fires as a series of events and simulate fire growth on the basis of probabilities that certain events will occur and transition probabilities between certain conditions. However, the difficulty with this type of model comes when determining the appropriate probabilities from statistical evaluations or reliability analyses of observations or test results. They are not relevant to the aims laid out above and are therefore not addressed below.

Three groups of mathematical deterministic fire simulation models can be distinguished:

- Empirically proven approaches,
- Zone models, and
- CFD models.

The empirical approaches are methods that are obtained based on experiments concerning a specific problem. Examples are the description of flame heights, heat radiation and smoke gas flows as a function of fire intensity, the geometrical conditions and the initial and boundary conditions. The empirical model approaches are for special problems, which are themselves part of more complex calculation methods.

Zone and CFD models differ in that the CFD models are generally based on fundamental equations. In contrast, the zone models contain simplified systems of equations developed from the fundamental laws with empirical approaches' aid. This results in a different mathematical structure and, consequently, other solution methods. These differences are also responsible for applying specific problems and the level of detail of the respective models.

5.2.5 Experimental models

The experimental model describes a real situation, taking into account scaling and similarity laws (e.g. reproduction on a reduced scale). A well-known example from the research field of fluid mechanics is wind tunnel experiments where the Reynolds number is used as a scaling law. In fire research, however, a whole series of similarity laws must be observed. It means that the model is only consistent for a certain partial aspect, and other aspects are only approximately fulfilled.

The "hot smoke tests" carried out with increasing numbers can also be classified as an experimental model. Although real geometries are taken into account, the heat released is scaled-down compared to an actual fire event. As a result, during the evaluation of such tests, the similarity laws must be observed, and the test result cannot be directly transferred to a design situation.

In Annex A5.2, the "Experimental Models" are examined in more detail.

5.3 Description of the mathematical models

5.3.1 General Information

Mathematical models describe the processes taking place in the event of fire using mathematical equations. Every form of modelling of fire processes is based on the fundamental laws which result from the conservation laws for mass, momentum and energy. However, these equations are so complicated for the problems arising in fire processes that a solution employing simple mathematical operations is impossible. Three approaches are available for the solution, namely

- numerical solution of the fundamental equations,
- simplification of the equations and

- derivation of equations from observations of fire tests in simplified form.

The first approach leads to the CFD models and the second approach to the zone models, in which the conservation of momentum in the general form is no longer considered.

5.3.2 Empirical correlation

Simple empirical equations (correlations derived from experiments) as a tool for modern fire protection engineering generated by the result of a large number of detailed investigations on the fire events, which aim to describe the processes as quantitative as possible. The descriptions as simplified approaches are derived from the fundamental equations by experimentally determined indefinite constants and parameters. These approaches can be used to calculate the plume mass flow at a certain level or to determine the plume temperature. The summary of these simple equations often allows a sufficient understanding of the processes without solving a complex system of equations, e.g. the manual calculations for smoke extraction, according to Yamana and Tanaka [5.1] or more advanced calculation methods proposed by the Fire Research Station [5.2]. Besides, they provide useful basics and complementaries for zone modelling. As mentioned in the beginning, many such results exist with updated complementaries, but their presentation is not the aim of this chapter. The simple analytical approaches presented in Appendix A5.1 are those which are of particular importance in practical applications. They essentially deal with the conditions arising above a fire source concerning combustion, smoke gas production and temperature development which are part of the theoretical and experimental considerations on forming the plume forms above a fire surface or fire source. This plume is formed due to the heat released during the combustion process. This leads to an up-ward convection flow via a local temperature increase after exceeding a specific minimum value. In addition to the combustion zone (flame area), it also includes the part of the upward flow above it. The relationships described are the subject of many articles and are, for example, summarized in [5.3], [5.4], [5.5] The processes prevailing in this flow path determine the smoke gas production and temperature development. These submodels for describing fire effects, which are important for the application, are the subject of the explanations summarized in Appendix A5.1. During the application of these approaches, their range of validity and the error limits should be taken into account.

5.3.3 Post-flashover model

5.3.3.1 General information

The one-zone model, which is better known as the full fire model or post-flashover model in the English literature, was the beginning of theoretical fire research. The fundamental prerequisite for applying a one-zone or full-fire model is a temperature within the fire zone that is as uniform as possible. This approximately fulfils the full fire (post-flashover) phase.

According to practical experience in fully developed fires in small rooms, it is assumed that the room is evenly filled with hot gases: the entire room is considered as one zone (control volume) in which homogeneous conditions (e.g. temperature, gas composition) prevail. The main assumptions can be summarized as follows:

- Combustion gases and the flames in the fire zone are well mixed so that an uniform temperature is achieved.
- Emissivity of the smoke gases and the flames is equal and constant during the course of the fire.

- Inner walls are grey bodies with constant emissivity.
- In addition to radiative heat exchange between gas and wall, there is also a convective exchange.
- The outside of the enclosure is cooled by convective heat exchange.

The physical variables necessary for the mathematical description are summarized below; instead of the internal energy, the enthalpy can also be used as a characterising variable:

T	Temperature of the gas mixture (smoke gases) in the smoke,
m	Mass of the smoke gas inside the room,
V	Volume of the room (constant),
E	Internal energy of the smoke gas in the room,
ρ	The density of the gas mixture,
c_V	Heat capacity at constant volume
R	General gas constant,
p	Pressure in the room and
Z_n	Position of the neutral plane.

Besides, the mass exchange between the room and the environment is considered. As the position of the neutral plane is defined by equal pressure between inside and outside, air can enter below this plane (min) and exit above (mout) it. This mass exchange is also associated with an energy exchange (Qc), which is increased by¬ additional energy losses due to radiation (QR). The physical quantities describing the system are summarized in the middle of Figure 1.2 and are considered constant over the entire room. They can be supplemented by additional variables such as oxygen concentration. The law of conservation of energy and the law of conservation of mass are available for the calculation of the¬ mentioned physical quantities, which are completed by the following relations between the variables:

$$\rho = \frac{m}{V} \text{ Density,} \tag{5.3}$$

$$E = c_V \cdot m \cdot T \text{ Internal energy at constant volume,} \tag{5.4}$$

$$p = \rho \cdot R \cdot T \text{ Equation of ideal gases law} \tag{5.5}$$

The temperature and the mass of the gas mixture are calculated step by step from the above conservation equations. Additional equations is necessary to describe the energy loss to the walls (convective and radiative) and the exchange of mass and energy with the environment. This additional equations¬ are called submodels. These submodels also result from simplified considerations and are valid independent of the general model assumptions; they are partly empirically based. Typical submodels for post-flashover models include:

- description of the energy released during a fire
- mass exchange with the environment
- energy dissipation on the surrounding walls

Although the pressure is assumed to be approximately constant, small pressure differences over the room are responsible for the exchange of masses between the room and its surroundings. This mass exchange is calculated based on the Bernoulli equation.

To calculate the energy loss over the room's surface, the heat flux density must be calculated as a summation (convective and radiative). Here a balance of all zones that absorb or release heat is created. The description of heat transport through the wall is done by solving the one-dimensional heat conduction equation. The heat loss through the openings is taken into account via the outgoing mass flows (convective) and via the radiation with considering the opening area.

To have a deeper understanding of the calculation methods in fire protection, it is useful to become familiar with the basics of the thermodynamic calculations for simple geometries. The single-room model presented here is in a way the original cell of the multi-zone or multi-room models. In the following, the energy balance and the mass balance for a post-flashover fire in a room are established and described. It is assumed that the room with an opening is connected to the environment and that the room temperature is homogeneous.

5.3.3.2 Energy balance and mass balance equation

As mentioned above, the general concept is to determine the gas temperature from the energy balance. Figure 5.2 illustrates this energy balance.

The inner enclosing area is defined as Aj, and the window area is Aw. It is assumed that the heat losses in the wall and ceiling can be described by the one-dimensional transient heat conduction equation.

For the energy balance, these assumptions are based on the first law of thermodynamics:

$$\dot{h}_c - \left(\dot{h}_l + \dot{h}_o + \dot{h}_w + \dot{h}_g + \dot{h}_s\right) = 0 \tag{5.6}$$

The following energy terms are included:

- $\dot{h}_c$ energy released per unit time due to combustion and fireside effects in the fire compartment
- $\dot{h}_l$ outflowing energy of the gases (convection energy) per unit time due to the gas exchange (convection through openings)
- $\dot{h}_o$ energy extracted by the window radiation per unit time
- $\dot{h}_w$ energy transferred to the enclosure components (wall, ceilings) per unit time by convection and radiation
- $\dot{h}_g$ energy of the gases stored in the enclosure per unit time, which determines the fire temperature
- $\dot{h}_s$ other energy components loss per unit time (e.g. energy stored by components)

The equation of the mass balance in the fire compartment is given by

$$\dot{m}_g - \left(\dot{m}_l + \dot{R}\right) = 0 \tag{5.7}$$

This includes the temporal changes of the following mass fractions:

$\dot{m}_g$ mass of gas flow out of the enclosure per unit time

$\dot{m}_l$ mass of air flow into the enclosure per unit time

$\dot{R}$ mass of fuel per unit time, causing heat release

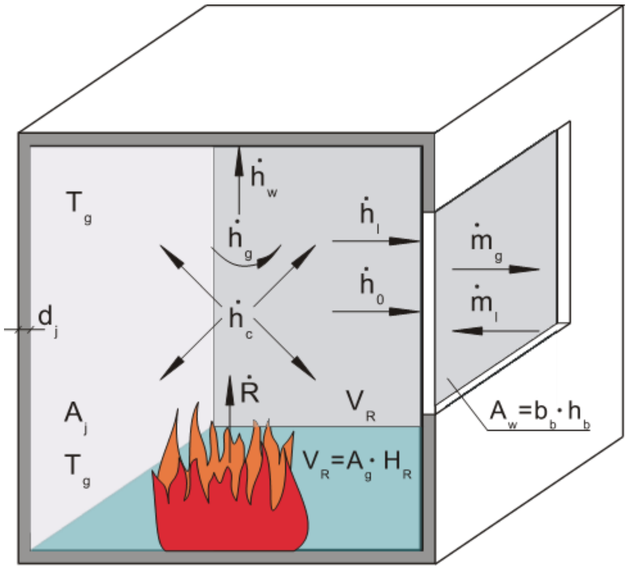


Figure 5.2 Geometry, heat and mass flow of the heat balance model [5.37]

It should be noted that this model does not cover the case of combustion outside the room (flame spread from the opening), nor does it determine the flame temperature itself.

Each of the quantities mentioned above in the energy balance must be calculated by suitable sub-models. This can be a single equation or a set of equations. From this brief characterization, it is already clear that the post-flashover fire models exclude all elements of the fire development phase. Therefore, they are only suitable for tasks which concern the complete fire phase. Caution is required in extrapolating the calculation results to large rooms and in fire scenarios (e.g. with low fire load), which do not allow uniform heating of the space.

5.3.4 Zone models

With increasing knowledge in fire research, the post-flashover models' limitations were recognized, and the multi-zone models' development was initiated. The zone models' basis is the separation between a warmer layer of smoke and an underlying colder layer of air, which is smoke-free or low smoke. These conditions are mainly found in fires' pre-flashover phase with a limited flame spread compared to the fire zone. As a consequence of this division into zones, it is necessary to make an appropriate division of the physical quantities described, i.e., differentiate between the temperature of the smoke gas layer and the air layer. From this, the number of variables increases significantly. Besides, the exchange of mass becomes more complex, as different flows can now occur. This is a consequence of the fact that the neutral plane's position (z_n) does not have to coincide with the position of the smoke gas layer (z_s). Furthermore, the exchange of mass and energy between the layers must be described. This makes both of the equations more complex, and submodels are required.

At this point, it should be noted that the determined zone is not used uniformly. It refers to the areas mentioned above. However, other relevant areas such as walls, ceilings and additional flammable objects are often considered as separate zones.

The applied basic equations consist of the conservation laws for mass and energy, applied to the zones, respectively. The theoretical basis can now be formulated as follows. The gas in each layer is defined by mass, internal energy, temperature, density and volume. The mass flow and the energy flow to both layers are calculated based on the existing submodels.

The multi-zone modelling is mainly based on the following assumptions (see Figure 5.3):

- In the fire compartment, two different gas layers are formed, the upper hot smoke gas layer (g) and the lower relatively clean and cool air layer (l).
- The layers are separated by an imaginary horizontal interface (thermal boundary lay-er), which in principle acts as a barrier against mass exchange (apart from the plume mass flow and special effects).
- Each layer has a uniform average temperature.
- The fluids within the zones are assumed to stay without movement (except plume, ceiling jet and ventilation openings), and the pressure is a function of height and time.

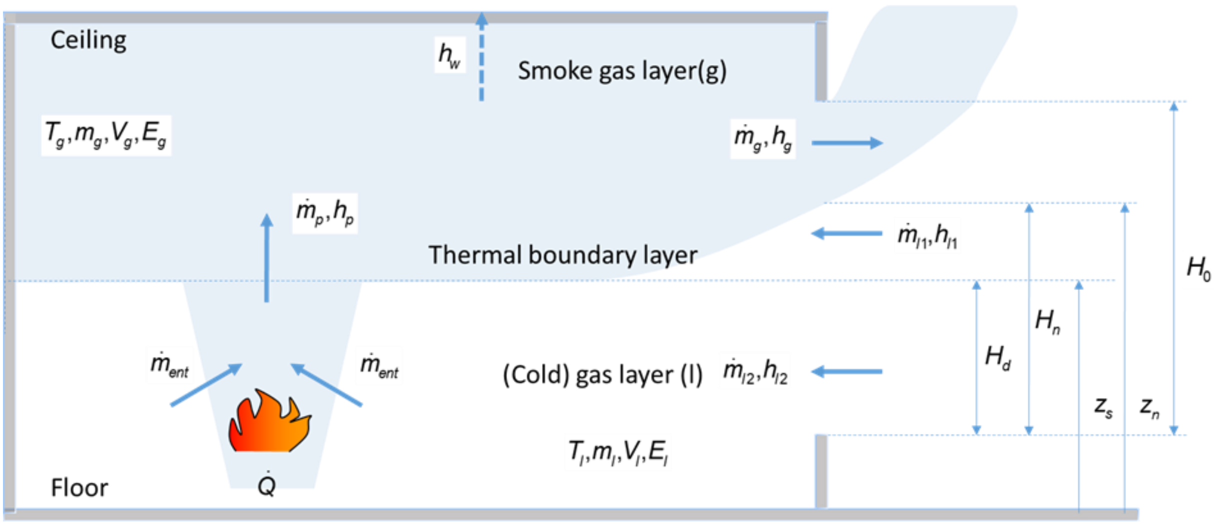


Figure 5.3: Geometry, heat and mass flows multi-zone model

The extensions compared to the full fire model, which appear relatively minor at first glance, nevertheless allow a more realistic description of the conditions before the flashover. This includes the smoke gas stratification, the radiation exchange between different areas in the fire development stage, the recirculation of smoke gases into the cooler air layer, etc.. The distinction of at least two zones leads to a larger number of areas with different temperature and emissivity. The radiation exchange calculation between flames, walls, and objects contributes significantly to the multi-zone models' higher level of detail.

The following relationships exist between the variables or thermodynamic quantities:

$$\begin{aligned}
&\rho_i = \frac{m_i}{V_i} \\
&E_i = c_V \cdot m_i \cdot T_i \\
&p = R \cdot \rho_i \cdot T_i \\
&V = V_s + V_l
\end{aligned} \tag{5.8}$$

with

V_s	Volume of the smoke gas layer
V_l	Volume of the air layer
E_i	Internal energy at constant volume
p	Pressure

The above conservation equations, together with the relations of the physical variables among them, lead to a set of coupled differential equations that are solved numerically. As already described, both the number and the required submodels' complexity is greater than the full-fire models.

As with the post-flashover models, the heat release rate can be specified as a time-dependent curve. However, the flame or plume is treated in a more differentiated way, since here there is a source of radiation, its energy does not flow just to one volume but two layers. Furthermore, other compounds, besides oxygen, are described. For example, these are the gaseous components released during combustion, such as CO_2, CO and HCN or the soot particles responsible for the opacity of the smoke gas. An additional conservation law (species conservation) and the specification of experimentally determined yields from different fuels (yields) are necessary to balance these products. This is the simplest version of a combustion model. Some zone models can also predict the heat release or the combustion rate depending on the conditions inside the fire zone. However, it is necessary to point out that this is only possible for a few pure fuels and elementary fuel geometries.

An essential submodel is a plume mass flow (see above), which describes how much mass and energy (convectively) is added to the smoke gas layer. Several different model approaches are described in the literature, but some are modified in the zone models by additional considerations. In general, the approaches used within the models are not entirely identical to the original data.

The pressure curve concerning the room height is necessary to determine the exchange mass flows.

Due to the different layers and the neutral plane's position, the description of the mass exchange with the environment is more complicated than in the full fire model. The basis is the Bernoulli equation, but case distinctions have to be made concerning the neutral plane's position. Depending on its position in relation to the smoke gas layer, the mass flows are assigned.

In the case of openings in ceilings or floors, the flow behaviour at small pressure differences must also be taken into account; for this reason, submodels differ for openings in vertical components.

The energy losses are balanced according to the same principles as in the post-flashover model, but the conditions are also more complicated due to the different layers. In addition to considering the exchange of radiation between the existing time-dependent layers, the different ambient temperatures of the enclosure components located in the respective layers must also be considered. Furthermore, the proportion of the flame radiation is considered.

The one-dimensional heat conduction equation can describe the heat transport through the enclosure components.

The submodels mentioned so far are necessary components of zone models. Moreover, additional calculations can or must be carried out to determine the local temperatures.

These include plume temperatures, i.e. the temperature values above the flames and temperature values in the ceiling jet (see above). These approaches can be used to calculate component temperatures or to describe the triggering behaviour of sprinklers. By balancing combustion products, it is possible to calculate average concentration values, which can be used for further evaluations (e.g. detection range within the smoke gases, see Chapter 8) Furthermore, most models have approaches to defining mechanical ventilation.

In addition to the aforementioned submodels, there is a range of modelling approaches for the description of flow phenomena. Examples of this are flow patterns which contribute to the mixture between the smoke gas layer and the air layer. However, the relationships available to date for describing these secondary flows are not fully accepted or not verified with sufficient certainty and for this reason they are generally not used.

Further details of the submodels and their mathematical representation cannot be discussed here. For an introduction to the basics of the zone models, please refer to the literature [5.1], [5.2], [5.3], [5.4], [5.5], [5.6].

According to the introduction of multi-zone models, calculation of the mass and energy exchange between several rooms with different ventilation openings is possible, and the demands on the numerical methods also increased. In numerical simulation involving several rooms, not only the computing time increases but also there is a possibility that the algorithms do not converge. Therefore, numerical methods have been improved in recent years.

Multi-zone models are internationally recognized as a tool for evaluation of the smoke gas layer under different ventilation conditions and fire development [5.1], [5.2], [5.3], [5.4], [5.5], [5.6], [5.8]. This is critical in assessing firefighters' ability to escape and rescue people from the fire room and fight the fire. In addition to the average smoke gas temperature, fire products' mass fractions can also be estimated. For this purpose, however, the formation rates should be known.

5.3.4.1 Multi-room multi-zone models

The coupling between the individual rooms (segments) is effected by the fact that the outflows of mass and energy from the coupled rooms are returned to the balance as inflows to the rooms. The connection between the fire-smoke layers and the cold air layers is established via mixing flows and thus via the plume's balance.

A mass and energy balance is available for each layer. The resulting system of equations can be solved with suitable numerical methods. The calculation of unknowns starts from an initial value (old state) and changes until all equations' requirements are met with a certain accuracy.

Rooms in the calculation program can be defined as:

- Fire or smoke sections,

- individual structurally designed rooms, and
- Hall areas or rooms with subdivisions by fixtures or partial partitions.

5.3.4.2 General assessment of zone models

In principle, new findings can be transferred relatively easy into zone models; the decisive factor here is how the underlying physics can be introduced into the model equations appropriately. Although many approaches exist, phenomena such as mixing processes, flames from windows, transient corridor flows or flows in shafts cannot yet be described adequately. This restricts the use of zone models in these specific areas. It depends on the possibility of using trend analysis.

Zone models certainly be used successfully for large rooms such as atriums. However, it can be assumed that the application does not make sense up to arbitrarily large rooms, since the basic requirement of two stable layers is generally no longer given. As experiments in large rooms of up to 3,600 m² show, stable layering can indeed form here, but experiments with even more extensive areas are not yet available. For areas of the size as mentioned earlier, however, it should be ensured that the distance between the smoke gas boundary and the air inlet openings is sufficiently large since the layering stability decreases by the reduction of smoke gas temperature. Until more precise boundaries are available, the requirements of DIN 18232-2 can be used as a guide.

5.3.5 CFD models

CFD models ("Computational Fluid Dynamics") can be used for solving problems from the field of fluid dynamics numerically. In a more specific view, a CFD model is a computer program, which regarding its physical submodels and the numerical solution algorithm, is capable of adequately describing the phenomena of smoke and heat propagation in a fire event. The use of CFD models is not necessarily limited to fires in buildings or similar enclosed areas. Preferably, this method can also simulate outdoor fires or the propagation of fire gases from a building into the environment.

This model is based on a fundamental approach, which considers the basics physical laws of fluid dynamic and thermodynamics. Thus, the influence of empirical model parameters, determined by adaptation to experimental data, is kept as small as possible.

Based on the generally valid physical principles of conservation of mass, energy and momentum, corresponding conservation equations are derived in fluid dynamics. This describes the temporal and three-dimensional change of elementary quantities such as pressure, considering effective parameters such as viscosity and thermal conductivity of the smoke-air mixture. In detail, this results in equations for the total density and individual components of the gas mixture, the flow velocity, the pressure and the temperature.

Overviews of computer programs for the simulation of fire zones, including CFD models, with detailed information on the physical and mathematical background and with practical application examples, can be found, e.g. in [5.5], [5.22], [5.24], [5.25], [5.26], [5.27], [5.28].

To calculate the buoyancy-controlled flows, numerically, space and time should be first discretized in the model, and the boundary conditions must be defined. To limit the computational effort or make fire introduced flows computable, submodels must also take turbulence effects into account. Furthermore, submodels are needed to take into account the combustion source terms. These are in particular:

- combustion,
- radiation,
- smoke production and
- pyrolysis.

In the following, the modelling steps and submodels for the application of CFD models are fundamentally considered. Further explanations can be found in [5.90] and [5.92].

5.3.5.1 Spatial and temporal discretization

Since the local conservation equations cannot be solved analytically in all practical interest cases, they are solved numerically. For this purpose, a three-dimensional grid is constructed, which covers the desired area. This area usually consists of the building or the fire or smoke section to be investigated and, if necessary, areas outside the building in order to adequately capture the supply air or hot smoke gases exchange through openings. The computational grids typically consist of a hundred thousand up to millions of cells called control volumes. The cells' size is variable in most calculation methods so that the mesh can be optimally adapted to the geometry conditions and the problem definition. Often rectangular meshes (Cartesian co-ordinate system with the horizontal coordinates x and y and the vertical coordinate z) are used.

The structure is determined by the boundary conditions and the introduction of specified areas by computational meshes, representing either 3-dimensionally extended objects or areas inaccessible to the gas flow. They influence the solution of the conservation equations by the corresponding boundary conditions.

The time variable is also discretized. This means that the system changes are calculated after a small time step (typical fractions of seconds).

Figure 5.4 schematically represents - the buoyant convection flow - of the physical processes between the mesh cells, described by the fundamental conservation equations. This model approach is therefore suitable for detailed mathematical proofs as well as for determining the reason for fire [5.29].

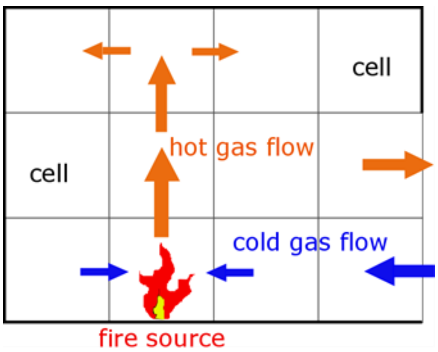


Figure 5.4 Schematic (two-dimensional) representation of the physical processes taking place between the cells of computing grids for exchanging energy, mass and momentum

The hot gases generated in the fire source area rise upwards under the influence of the buoyancy force, whereby ambient air is mixed in. In this way, the plume is formed without additional assumptions or the introduction of further submodels for the modelling. The plume structure is determined by the fire source's power, structural boundary conditions, and the interactions with room or ventilation flows. If the plume reaches the ceiling area, a radial gas flow spreads out (ceiling jet). However, if the temperature is insufficient to create a plume reaching the ceiling, the model approach can be used with similar functionality. Other effects such as the sinking of the cooling gases at the enclosure walls and the formation of air vortices and smoke rolls are also consistently obtained by solving the local conservation equations.

5.3.5.2 Boundary Conditions

In addition to the specification of suitable initial conditions, the conservation equation's solution requires the definition of boundary conditions for the variables, either by explicit solvers or by applying physical models that are compatible with the local field model approach.

In the case of solid boundaries (enclosure components, objects or blocked areas of the mesh), special attention should be paid to appropriate analysis of the heat transfer. Explicit temperature boundary conditions can be used under certain conditions. These include the so-called adiabatic boundary condition, in which the temperature at the edge corresponds to the adjacent inner mesh cells and the isothermal boundary conditions. The temperature at the edge is kept at a fixed value. Interpolation can also be performed between these two boundary conditions. However, considerably more meaningful results are obtained if the temperature boundary condition is based on the heat transfer calculation by convection and radiation by solving the associated time-dependent heat conduction equation (Fourier equation).

The mass flow at solid interfaces is zero. If necessary, appropriate boundary layers should be modelled for considering the viscosity.

Free edge surfaces represent artificial boundaries of the simulation area, where the local pressure and temperature values, flow velocities, substance concentrations, and, if necessary, other flow dynamic variables are defined. A distinction must be made between free boundary conditions in the true sense and boundary conditions for forced ventilation. In the latter case, either the mass flow rates or the volume flow rates are explicitly known as a function of time, and the local velocity can be calculated from them.

Usually, the free boundary conditions describe a closure of the simulation area at some distance from the structure under investigation, which represents a transition to the other environment which is no longer covered by the computational grids. The ambient area related to the flow conditions around the structure is directly included in the simulation. Suppose the distance to the actual fire event is large enough. In that case, the flow velocity at the boundary surfaces changes insignificantly so that a gradient of velocity from zero at the free boundary surface can be given in a good approximation. Figure 5.5 illustrates this with an example that shows the flow processes calculated with a field model in a fire zone with open doors to the surroundings. A longitudinal section through the three-dimensional scenario is shown at the door's height in the fire zone.

In general, free boundary conditions can be defined by specifying suitable velocity or pressure of boundaries (e.g., considering the influence of wind). The validity range of such specifications must always be carefully controlled since boundary conditions can significantly influence the simulation results.

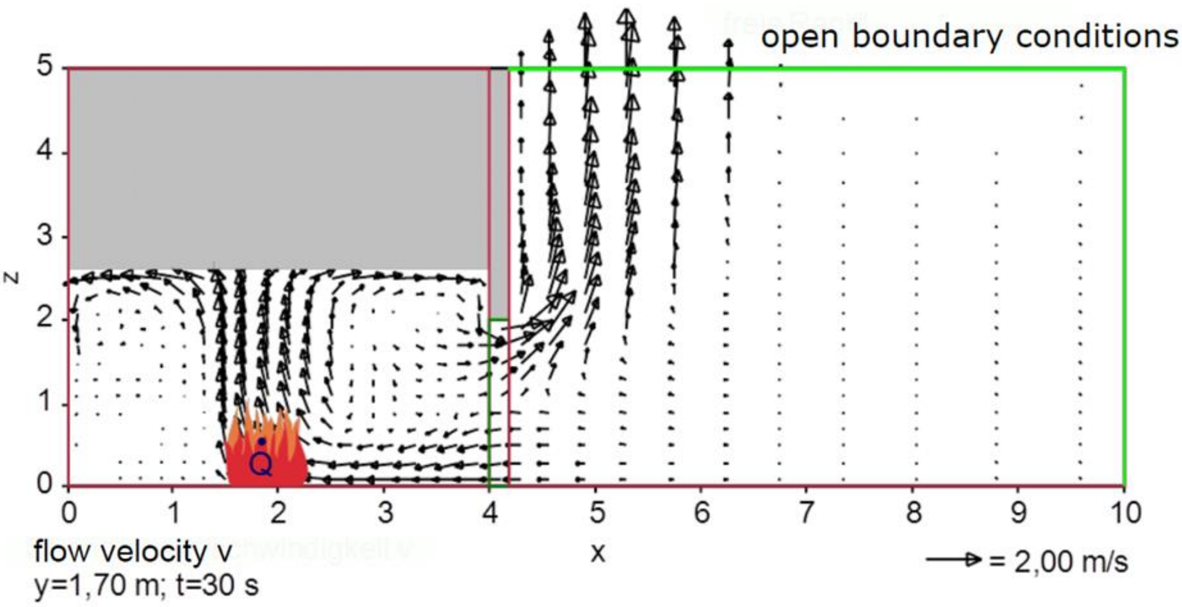


Figure 1.5 Schematic example of a structural opening within the calculation grids (CFD simulation with a field model). A longitudinal section through the three-dimensional scenario is shown at the height of the door in the fire zone

5.3.5.3 Turbulence modelling

With increasing Reynolds number - a dimensionless number characterizing the ratio of inertial to viscous forces - flow changes from laminar to turbulent. This turbulent flow is characteristically unsteady, irregular and generally three-dimensional. A special feature is the occurrence of vortices with sizes that can vary over a wide range and the conversion of energy into heat by viscous friction. The conservation equations apply equally to both laminar and turbulent flow, so in principle, there is no need to use additional turbulence modelling methods. However, the size of the representable vortices is limited in practice by the resolution of the computational mesh. Various methods (turbulence models) have been developed to consider the effects of such vortices that cannot be directly resolved.

No turbulence model is used for the "Direct Numerical Simulation" (DNS). Therefore, the smallest vortices still have to be resolved, which forces a very fine mesh structure. Since this exceeds the available computing power capacity or leads to extremely long computing times, this approach is attempted to be implemented approximately with larger mesh sizes.

The k-ε turbulence model describes turbulence effects by two additional variables in the conservation equations by solving averaged flow equations according to the mean values of the flow variables. Further common two-equation models are, for example, the k-ω turbulence model or the k-ω-SST turbulence model. Such statistical models solve a special form of the fluid mechanical conservation equations, the so-called Reynolds Averaged Navier Stokes equations (RANS).

In the "Large Eddy Simulation" (LES), the vortices relevant for smoke and heat propagation are directly resolved (as in DNS), and the small-scale structures, for which the grid is too coarse, are appropriately modelled (fine structure model). Since experimental findings show that in the case of fire modelling, the vortices, which are important with regard to their energy content, have a spatial extension that corresponds to the local plume size [5.30], [5.31], these methods can also be used for larger spaces with the possible grid resolutions for the computing power, - as assumed here - the combustion process itself is not modelled.

A relatively new possibility for turbulence modelling is the "Detached Eddy Simulation". This is a combination of the RANS approach in the boundary area of walls and ceilings and a LES approach in areas further away from the boundary area.

5.3.5.4 Combustion modelling

With the three-dimensional CFD modelling, a further aspect should be considered in addition to the (area-specific) heat release rate and the fire area (fire propagation rate): The heat release takes place in a finite volume, which must be determined in a suitable form. There are three fundamentally different approaches

- Volume sources,
- Thermal jets, and
- Combustion modelling.

For the simulation of fires in which the heat release rate is specified as a function of time, the volume sources and combustion modelling provide similar results.

Volume sources

For Volume sources, so much energy is released per unit time in a certain volume range that the (convective) heat release rate (total heat release rate minus radiative heat release) specified by the design fire is achieved - usually for an exact point in time (i.e. in each time step of the CFD simulation) or at least on average for small time intervals. In the simplest case, the volume results from an area of constant height above the fire surface, whereby the current height may change over time (e.g. depending on the heat release rate). It is important to ensure that the size of the volume and heat release - i.e. the energy density per unit of time - is physically consistent. Otherwise, there is a risk that the temperature in the area of the fire source with flame temperatures in the range of about 800 °C - 1300 °C will be significantly exceded or not reached. A typical energy density per time unit within the combustion zone (1.2 - 1.8 MW/m³) can be used to determine the required height of the volume source or to calculate automatically within the fire module of a CFD program for each time step. The convective heat as well as the combustion products determined by mass loss rate are released uniformly in all mesh cells of the volume source and are spatially distributed by the buoyant convection flow, whereby the plume structure dependent on the respective geometry and the ventilation conditions develops without the necessity of further (empirically derived) approaches or specifications.

Thermal jets

With thermal jets, a hot gas (normally air) with a certain volume flow or mass flow is added near to the fire source. In order to determine the parameter of thermal and geometric jets according to the desired heat release rate or, an empirical model (plume model) should be used, which is usually not compatible with the fundamental approach of CFD modelling. Thermal jets are therefore more often used with physical models; they are not typical for calculations with fire simulation models.

Combustion modelling

In addition to the simplified approaches described above, it is also possible to model the combustion reaction itself. An advantage of combustion modelling is that the occurrence of under-ventilated fire conditions can be taken into account. Only as much heat is released in the fire room as is possible on the basis of the combustion reaction and the oxygen concentration. This may result in deviations between the calculated heat release rate and the underlying specified heat release rate of the design fire.

In combustion modelling, a fundamental distinction should be made between the following approaches:

- the approach of an infinitely fast reaction rate and
- the approach of finite reaction rates.

The infinitely fast reaction rate is based on the simplified assumption that the fuel reacts immediately with the oxygen in the ambient air. The energy released by combustion is thus dependent on the mixture of fuel and oxygen. The rate of combustion can then be described by the change over time of the concentration of fuel and oxygen within the control volume:

$$v = -\frac{dF}{dt} = -\frac{dO}{dt} = k \cdot F \cdot O \tag{5.9}$$

The factors and describe the mass fraction of the fuel and oxygen in the control volume. For an infinite reaction rate, the reaction rate is constant (k=1). The approach of an infinitely fast reaction rate can be applied with a good approximation to problems in fire protection engineering since the combustion is controlled by mixing fuel and oxygen to an ignitable mixture, i.e. the actual combustion reaction proceeds significantly faster than mixing fuel and oxygen. In low-energy fires with low heat release and low temperatures, e.g. smouldering fires, the mixing of fuel and oxygen is faster than the actual combustion reaction. In this case, the approach of an infinitely fast reaction rate leads to a very high heat release.

In the finite reaction rate approach, the combustion reaction is not only dependent on the concentration of fuel and oxygen but also on the prevailing temperature. The reaction rate constant or reaction rate can then be described as an Arrhenius function (see pyrolysis reaction (5.2)):

$$k = A \cdot e^{\frac{-E_a}{RT}} \cdot F^a \cdot O^b \tag{5.10}$$

with

A	Pre-exponential factor [-]
T	Temperature [K]
E_a	Activation energy [J/mol]
R	Universal gas constant [8.314 J/(K·mol)]

The exponents a and b are material-dependent characteristic values and can be determined experimentally. Due to the temperature dependence, it is necessary to represent the temperature calculation as accurate as possible, resulting in a very low spatial discretization.

As shown in the equation (5.9) and equation (5.10), the concentration of fuel and oxygen is required for modelling combustion. Therefore, in the modelling of the flow field, not only the mass transport equation for the entire cell but also the mass transports of the individual species of fuel, oxygen and reaction products should be calculated.

Within a control volume of 5 cm x 5 cm x 5 cm, fuel, oxygen and reaction products can be present both in mixed and unmixed form. Therefore, probability density functions are used for the distribution of them.

Using an infinitely fast reaction rate, the combustion can be modelled directly with the Burke-Schumann model ("mixed-is-burnt") (see Figure 5.6). The reaction products are determined from the averaged mixing ratio within the control volume.

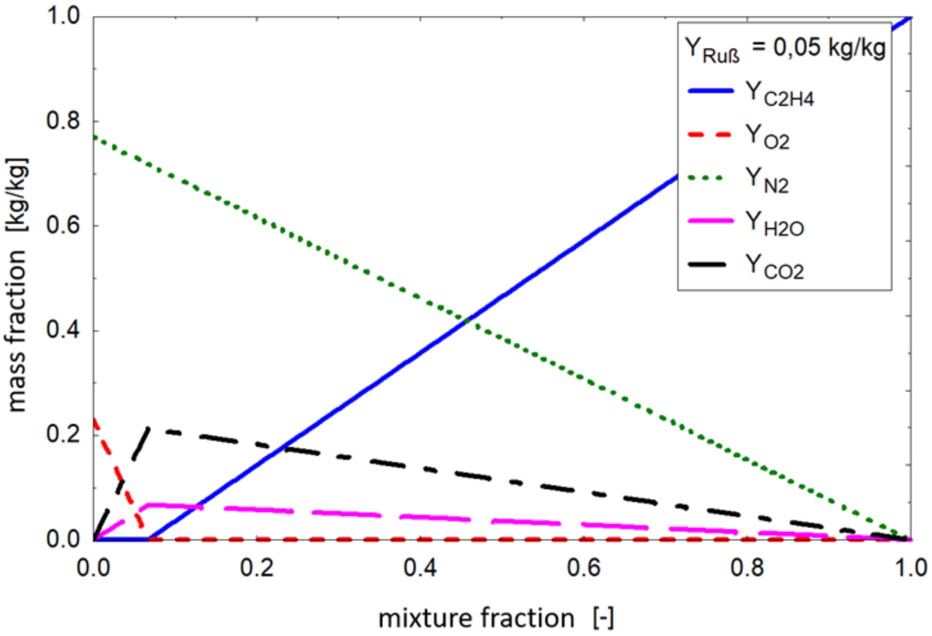


Figure 5.6 Mass fractions (mass proportion) for fuel Y_{C2H4}, oxygen Y_{O2}, (inert fraction) nitrogen YN2 and reaction products Y_{H2O} and Y_{CO2} as a function of the mixture fraction Z for infinitely rapid combustion using ethene as an example

From the average of mixing ratio, it can be seen that the combustion reaction can be better represented with a fine three-dimensional discretization.

When a finite reaction rate is used, it should be distinguished that the mixing time scale t_t is decisive for the combustion reaction:

- the reaction time,
- mixing time due to molecular diffusion,
- mixing time due to buoyancy controlled flows,
- mixing time due to subgrid turbulence, or
- mixture due to large scale turbulence.

One combustion model that takes this into account is the eddy dissipation model. In this model, the burning rate in unit of mass per time and volume is calculated with:

$$\dot{m}'''_{Burn} = -C_R \cdot \bar{\rho} \cdot \frac{1}{t_t} \cdot \min\left(\tilde{F}; \frac{\tilde{O}}{s}; \frac{\tilde{P}}{1+s}\right) \quad [kg/(sm^3)] \tag{5.11}$$

with

C_R	Model parameters dependent on mixing time, kinetic viscosity and turbulent kinetic energy
$\bar{\rho}$	Density
t_t	Mixing time
$\tilde{F}$	Average mass fraction of the fuel
$\tilde{O}$	Average mass fraction of oxygen
$\tilde{P}$	Averaged mass of the reaction products
s	Stoichiometric coefficient

The eddy dissipation model can also be used for combustion modelling with an infinitely fast reaction rate. In this case, the time scale for the reaction time is not taken into account. There is the advantage that the turbulence model is applied for mixing within the control volume, which has a positive effect on the required spatial discretization.

5.3.5.5 Radiation modelling

In addition to heat transfer by convection, which can be calculated by solving the conservation equations, heat transfer by radiation is an essential factor in the modelling of fires. The radiant power of a blackbody is determined using the Stefan-Boltzmann law:

$$P = \sigma \cdot A \cdot \Delta T^4 \tag{5.12}$$

with

σ	Stefan-Boltzmann constant [W/(m²K⁴)]
A	Radiating surface area [m²]
ΔT	Temperature difference [K]

As can (5.12) be seen from the equation, the heat flow transferred by radiation is proportional to the temperature difference of the fourth power, which is why with rising temperatures in the fire zone, radiation has an increasing influence on the heat transfer to adjacent components.

With regard to heat transfer by radiation, it should be noted that the radiation in the fire compartment is emitted and absorbed by the surfaces and, in addition, it is emitted, absorbed and scattered within the room by the predominant gas mixture (oxygen, nitrogen, fuel, combustion products etc.). The heat transfer by radiation can be described by the radiative transfer equation:

$$s \cdot \nabla I_\lambda(x,s) = \underbrace{-\kappa(x,\lambda)\, I_\lambda(x,s)}_{\text{absorption loss}} - \underbrace{\sigma_s(x,\lambda)\, I_\lambda(x,s)}_{\text{scatter loss}} + \underbrace{B(x,\lambda)}_{\text{radiation source term}} + \underbrace{\frac{\sigma_s(x,\lambda)}{4\pi}\int_{4\pi} \Phi(s',s)\, I_\lambda(x,s')\, ds'}_{\text{incident scatterd radiation}} \tag{5.13}$$

with

I_λ	Radiation intensity

$\kappa(x,\lambda)$ Absorption coefficient

$\sigma_s(x,\lambda)$ Scatter coefficient

$B(x,\lambda)$ Radiation source term

Since the radiative transfer equation depends on both the wavelength of the radiation and the direction of the intensity vector s, it cannot be solved for the application of fires simulation with a reasonable computational effort. Therefore, the radiative transfer equation is simplified by different assumptions for the composition of the gas mixture and for the considered spectrum. These assumptions include:

- assumption of a grey gas (grey gas model),
- narrow-band models and
- wide band models.

In order to solve the radiative transfer equation, the calculation area should first be spatially dis-cretised by subdivision using solid angles. For the numerical solution of the radiative transfer equation, a number of methods are available. Basically, one has to distinguish between:

- Static methods,
- Zone methods and
- Differential methods.

An overview of the different methods can be found in [5.92] and [5.93]. Some of the better-known methods are:

- Monte Carlo method,
- Discrete transfer method,
- Finite volume method and
- The P-1 radiation model.

5.4 Validation and verification of mathematical models

5.4.1 General information

Due to the importance of the applied verification methods (manual calculations, computer simulations, experimental models), quality control is essential. Besides a plausibility examination of the respective results, the evaluation (validation) of the methods used is also necessary. These evaluations are best carried out with experiments of various types and sizes. Verifications of analytical solutions are important in the development of a procedure or model in order to demonstrate the fundamental agreement with physics. Such considerations have already been made in other field and are also valid for simulation methods in fire protection [5.88], [5.89]. The evaluation of the programs is carried out methodically in three steps, which are described herein in more detail according to the information of [5.88].

- model qualification,

- model verification and
- model validation.

A model is qualified if the phenomena necessary for the description of the real problem are sufficiently considered in the model. This means nothing else than the quantity, which is used as a result, should also be calculated by the model in a suitable form and in a comprehensible manner. The qualification for practical questions includes two assumptions, that the physical and mathematical foundations of the model are sufficiently documented and that the user is able to decide whether the represented model characteristics are sufficient to answer the respective question.

According to the conceptual basis, model verification can only be limited to processes that can be examined relatively accurate. It therefore includes comparisons with exact solutions for specific boundary conditions or qualified numerical solutions. Both the mathematical-physical and the numerical methods should be considered in the test. In particular, the interaction of the individual program components is verificated. At this level, the sources of error that can creep into the program should be detected and eliminated. Generally, the verification cannot be performed by the user. It is an advantage if this is carried out by the program developer or by a nationally or internationally organized group of users. Models that have gone through such a process are more trustworthy than other models.

Model validation involves comparison with experimental data and is an ongoing process to ensure that the model is applicable for different problems or to detect errors and weak points in their application. For the application of models, the presented methodology should always be applied, i.e. the user must check whether the available manuals of the respective model contain a sufficient description of the model properties. As already described, it is advantageous if the model is already used by a large group of users and if publications are available in which the above-mentioned topics are addressed.

The basic requirements for a successful validation are the description of the physical and methodical fundamentals of the detection method, an exact documentation and description of the fire tests, as well as a profound knowledge of modelling procedures and experimental measurement techniques. The following methodology should be applied:

- selection and collection of experimental data,
- checking the experimental data for plausibility and completeness,
- modelling of the scenario for the corresponding calculation model,
- execution of simulation calculations,
- comparison of the results of simulation and experiment, and
- evaluation of the comparison in terms of quality and quantity if necessary (numerical deviation).

Often not all the necessary values for a full validation are available. Especially with regard to the source terms, i.e. the mass loss rate, the data are usually not sufficient for a simulation specification. Also, the boundary conditions of the tests often do not allow an absolutely complete modelling. If undefined boundary conditions and source data are available, the modelling of a test can be carried out using a parameter study, whereby the unknown or uncertain boundary conditions must be varied.

The modelling should correspond as far as possible to the real scenario in terms of geometry and dimensions. Special attention should be paid to the location of the fire source, the type of ventilation and the wall construction.

As a rule, the source terms place the greatest demands on the modeller. If only imprecise data on the heat release from the experiments are available (especially in experiments of fires with mixed fire loads), then the experimental data may have to be supplemented by known correlations (e.g. with regard to area-specific heat release rate or mass loss rate).

Any thermodynamic data (e.g. emissivities, heat transfer values) that are fixed in the program or accepted as default values in the data set, should be considered.

The comparison of results and experiment can be preceded by a check for the plausibility of the calculated results, but generally, this step is not necessary because of the direct comparison of the calculated data with the experimental data. The more values can be compared directly, the better the validation can be performed. The following quantities are suitable for comparison if corresponding experimental data are available:

- temperatures,
- smoke gas layer thickness or soot concentration field,
- smoke gas composition,
- mass flows and velocity fields,
- pressure distributions,
- wall temperatures.

Special attention should be paid here to the comparison of the measurement and simulation re-sults (with regard to the geometric position of the measurement point or the calculated value). An example is the comparison of a hot gas temperature in zone models and a measuring point in a test. The calculated hot gas temperature of the zone model corresponds to an average gas layer temperature, while the measurement result reflects a local heat transfer into the temperature sensor by convection and radiation energy at a point in space, depending on the type of sensor. A comparison with the results of a zone model can be difficult if the measured values do not allow the determination of an average temperature value. But even the comparison of calculation results of a field model with those of an experiment requires a certain density of measuring points since any deviations in the numerical value can be caused by spatial or temporal shifts.

The changes in the results should be evaluated over time; i.e., changes over time should be reflected in the changes in individual variables.

If possible, the validation should not be based on the comparison of a single variable (e.g. temperature). The overall system of results from the experiment, and simulation should always be evaluated and considered.

5.4.2 Assessment of the predictability

5.4.2.1 General information

For the validation of models, Peacock et al. [5.77] describe basic techniques for comparing two-time series. These are interpreted as vectors, and the elements of vector analysis, such as norm and inner product, are used to describe the deviation of the time series from each other. These approaches can be found directly in corresponding standards, such as ISO/FDIS 16730 [5.78]. Further international approaches can be found, e.g. in ASTM E1355 [5.79].

5.4.2.2 Characteristic uncertainties

Approaches to evaluating the predictive power of models are made in publications of the US NRC. In [5.82], a procedure for evaluating the predictability is described in the context of the validation of international reference tasks (benchmark exercises) based on the approach of ASTM 1355 [5.79]. The essential approach for evaluability is to contrast uncertainties that arise in the simulation of a quantity with uncertainties that arise in the experimental determination of the quantity. The idea is shown in Figure 5.7.

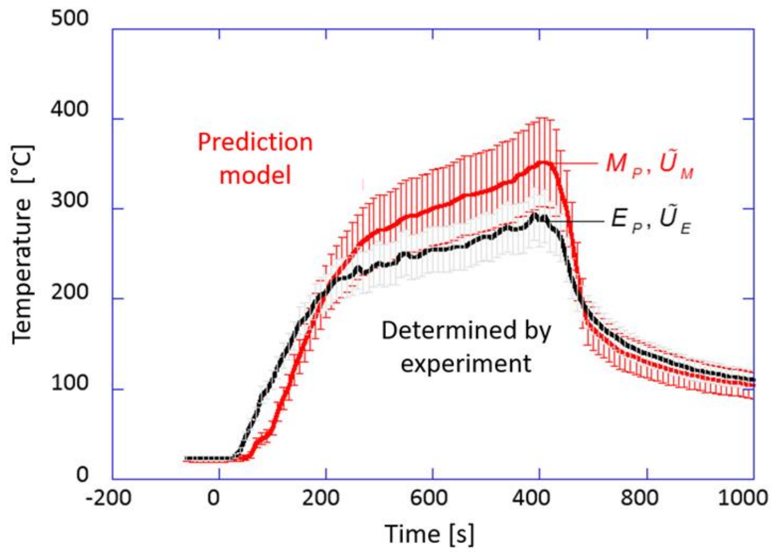


Figure 5.7: Peak values (M_P and E_P) and uncertainties ($\tilde{U}_M$ and $\tilde{U}_E$) for quantities calculated by a model (M) and determined by an experiment (E) [5.82]

Table 5.1 Weighted Combined Expanded Uncertainty, U_{CW}

Measured variable	Number of tests used	U_{CW} (%)
Hot gas layer offset temperature	26	14
Hot gas layer thickness	26	13
Temperature ceiling jet	18	16
Plume temperature	6	14
Gas concentration	16	9
Smoke concentration	15	33

Pressure	15	40 (no mech. ventilation) 80 (mechanical ventilation)
Heat flux density	17	20
Temperature surface	17	14

The uncertainties depend on the model used and the experiment on which it is based so that a generalised representation is not possible. Combined and expanded uncertainties are given by $U_C \approx \left(\tilde{U}_M^2 + \tilde{U}_E^2\right)^{1/2}$. A further step is to combine uncertainties based on several tests. The resulting weighted, combined and expanded uncertainty is the representative uncertainty on which the further evaluation is based. A summary of the values according to the American study [5.82] is given in Table 5.1.

The results of the study on the calculated and the measured temperature increase in the hot gas layer (HGL) and are summarized in Figure 5.8. In the diagram, the results are classified according to the models used. The investigations were carried out with plume equations (manual calculation methods), zone models and a CFD model. It is clearly visible that the calculations from plume equations are far on the safe side, i.e. the increase in calculated temperatures of the hot gas layer are higher than the values from the experiments.

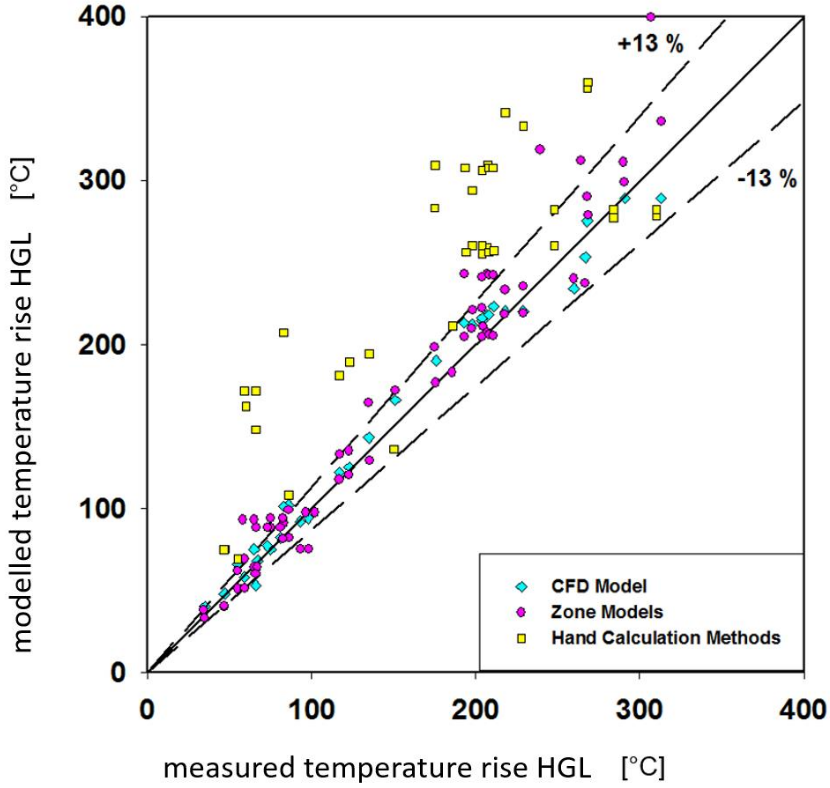


Figure 5.8 Comparison of the results of temperature increases in the hot gas layer (HGL) calculated and experimentally determined using different model approaches [5.82]

For the Fire Dynamics Simulator (FDS), which is often used internationally, the results of a comprehensive validation based on the comparison of the extrema based on different benchmark exercises are summarized in [5.82].

5.4.2.3 The methodology of the time series analysis from experiments and simulation

Within the framework of the validation calculations to review the results of the international research project PRISME [5.80] and [5.81], a methodology for the time series analysis of experiments and simulation is described. The methodology is divided into two parts. On the one hand, a local metric comparison PEAK of the maximum or minimum (peaks) is carried out (5.14):

$$PEAK = \frac{peakY_{Simulation} - peakY_{Versuch}}{peakY_{Versuch}} \tag{5.14}$$

This method allows a very fast and simple assessment of the deviation - in the extreme values - of the time series and reveals major discrepancies. However, it does not allow any statement about the behaviour of the time series in relation to one another over their entire temporal course.

Consequently, on the other hand, a related sum of square errors, NED (≙ "normalized Euclidean distance"), is additionally (5.15) used, which Peacock documented in [5.77] (n= number of measuring points):

$$NED = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_{Versuch,i} - Y_{Simulation,i}\right)^2}{\sum_{i=1}^{n}\left(Y_{Versuch,i}\right)^2}} \tag{5.15}$$

The Peacock relationship used here is a measure of the deviation in form or over the entire course of the time series.

Squaring the deviations at the individual measuring points ensures that positive and negative deviations cannot compensate each other. On the other hand, the reference to the test values allows a direct assessment of the deviation of two or more time series from the test results. This conflict is avoided by referring to the test values as base values. This can also be applied equally to the evaluation of different physical quantities with each other.

To be able to evaluate (t.15) time series in the form of equations, the same number of values should be available for both series, and these values should correspond to the same point in time. Since normally, the experimental and numerical values were not determined at the same time step Δt, it is necessary to subject the time series to a suitable averaging procedure.

After the introduction of thresholds, which must also include considerations of inaccuracies and deviations in the measurement, a final quantitative evaluation of the simulation results can be carried out in a subsequent step. With the help of the values described above, the method quantifies the agreement or deviations of time series. It is not limited to fire protection engineering.

To show both local and global effects in the form of evaluation numbers, a combined presentation of PEAK and NED, in the form of an X-Y plot, is often used. Here, considering evaluations of limiting criteria is a useful supplement to the presentation. Figure 5.9 shows the results of an example investigating the predictability of temperature (TG) and the evaluation of criterion "expanded uncertainty" U_{cw} = 15%.

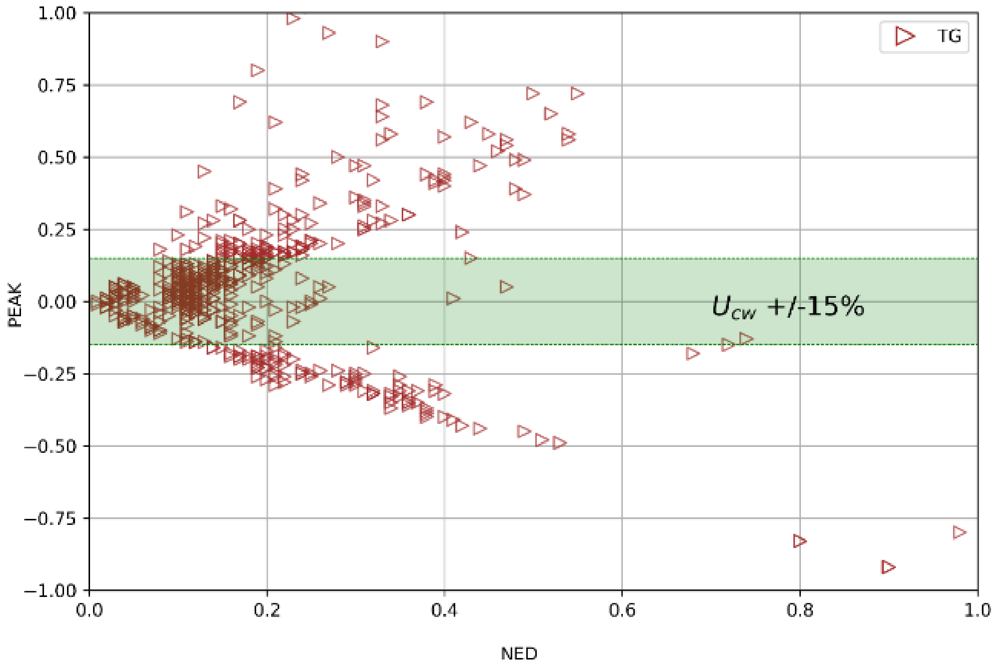


Figure 5.9 PEAK-NED plot for temperatures of the gas phase (TG) with considering the evaluation of limit criterion U_{CW}

5.4.3 Continuous integration

5.4.3.1 General information

In terms of sustainable quality management, Continuous Integration (CI) techniques are becoming increasingly important in the design of new software. This applies in particular to the development of large, heterogeneous simulation tools that are intended to map the interaction of the most diverse physical and chemical phenomena [5.90].

Against this background, the simulation of complex fire scenarios, in particular, represents an extreme challenge since it equally couples processes of fluid and structural mechanics, heat radiation, combustion and pyrolysis, while taking into account the different scales and complex material properties at the same time. Last but not least, the efficient execution of the simulation code on massively parallel high-performance computers must be guaranteed.

An essential component of the CI process is the use of meaningful performance and accuracy metrics to systematically measure the statistical model uncertainties. The results of these measurements enable comparison with previously defined minimum quality requirements and reveal deficiencies at an early stage of development. This enables all project participants to communicate with each other in a goal-oriented and constructive manner, to eliminate problems at an early stage and to make an objective assessment of the current state of the project.

5.4.3.2 Continuous Integration using the example of FDS

The development of the Fire Dynamics Simulator (FDS) is integrated into a comprehensive CI framework, which represents an important and independent component within the overall development process. Under the umbrella of continuous version control, the FDS source code and all associated data (documentation, V&V database, wiki, visualization tools, etc.) are available on a free access server that works as a central code database and enables the coordination of the individual developers [5.90].

Automated generated tests, as well as verification, validation and regression tests, are performed with thematic grouping at regular intervals. These are designed to continuously check and evaluate the individual components of the code and their interaction. On the one hand, these tests involve systematic comparisons between simulation and analytical solutions/benchmarks for isolated individual phenomena and submodels (verification). On the other hand, extensive comparisons between simulation and experiment for a wide range of application scenarios are carried out (validation).

5.4.3.3 Verification Tasks

Starting with the observation of single phenomena, via the targeted testing of single submodels, to comparisons with analytical and benchmark solutions for the applied model equations, the verification of FDS contains an extensive compilation of test series in the following areas (Table 5.2):

Table 5.2 Task fields Verification

Area	Special tasks / partial aspects
Code correctness	Tests on difference methods, boundary conditions, symmetry properties, divergence condition, multi-mesh distribution, etc.
Flow solver	Analytical model problems for testing the advection, pressure and viscosity terms, time integration for non-reactive flows, comparisons with DNS calculations, sensitivity studies, etc.
Turbulence effects	Tests of the LES model, including different SGS models, turbulent boundary effects, etc.
Mass and energy conservation	Tests on the reaction of different gases, reliability of compounds mass fractions, etc.
Heat radiation	Tests on simple cold and hot objects as well as various absorption media, etc.
Thermal conductivity	Analytical model problems on temperature-dependent thermal properties, tests on thermocouple models, etc.
Combustion model	Tests on the mixture fracture and extinction model, on species concentrations, gas properties and reaction rates, etc.
Pyrolysis	Tests for thermal decomposition of materials, different material compositions, etc.
Discrete particles	Tests for using particles, water drops, sprays, etc.
Heating, ventilation and air-conditioning	Tests for leakages, pressure drops, mass balances, etc.

The individual tests included are relatively small in size and require very little computing time so that the complete package can be run through every night. This strict control ensures that the daily code changes do not affect the previous functionality of the code (test for compiler errors, violation of basic verification properties, etc.).

5.4.3.4 Validation tasks

Typically, within the scope of validation, the measurement data in a real experiment are compared with corresponding simulation data, and possible differences are evaluated quantitatively and qualitatively. Both the uncertainties in the experimental measurements and in the definition of the model inputs should be considered [5.90].

Comparing a large number of experiments with different scenarios can provide useful evaluation criteria to control whether the mathematical simulation models used to predict the physical phenomena under study are appropriate. In the case of inaccurate simulation results, it may be possible to draw conclusions about the reasons for failure (e.g. an inadequate description of the fire physics, limited information about the geometry, fuels or materials, etc.).

Against this background, a very large collection of test descriptions, including associated measurement data, has been compiled for FDS over the years. The data originate from real experiments that have been conducted worldwide in various research institutes and laboratories. According to the developers, this database does not claim to be complete.

However, due to the considerable complexity of the individual cases, these series of tests are carried out at greater intervals than the verification tests and with different time intervals depending on the scope of the individual test in question.

The publication of new minor releases (with minor changes to the code functionality) and especially new major releases (with significant changes to the applied algorithms) requires the successful completion of all validation test series and the re-creation of all evaluation plots and statistics.

Usually, within the test series, the heat release rate is prescribed together with the production rates of different combustion products. The older validation studies are mainly concerned with the prediction of heat and smoke gas transport.

Recently, other fire-specific phenomena have become the focus of interest (e.g. speed of flame propagation, activation of sprinkler and detector systems, etc.).

The current results of all test series are summarized in an overview table, stating their fire protection-relevant parameters (e.g. heat release rate, fire diameter, ceiling height, etc.) and can be compared with each other with regard to their applicability. This table also allows a meaningful evaluation of the program quality currently achieved and the project progress across the individual versions.

The following Table 5.3 is an exemplary summary of valid cases that are considered within FDS:

Table 5.3 Tasks Validation

Area	Special tasks / partial aspects
Fire plumes	Derivation of technical correlations based on the results of numerous experiments Investigation of ceiling jets and flame heights Comparison of plume centerline temperatures to empirical correlations

Pool fires	consideration of different fire source sizes and fuels (e.g. methane, ethane, heptane, diesel) Estimation of the vertical and radial velocity profiles and the mass fraction profiles Measurement of the thermal expansion of natural diffusion flames and temperature contours Laser-based investigations of soot distribution for turbulent flames Testing of the RTE solver and the combustion model Prediction of the combustion rate as a function of the diameter Studies on the influence of the numerical grid and the size of the calculation area
Air and gas propagation without the influence of fire	Design of pure ventilation systems (against the background of the low-mach-number assumption for the flow solver) Different ventilation scenarios, evaluation of the indoor air quality Release of flammable gases in simple rooms and open areas
Wind engineering	Calculation of surface pressures and crosswind influences Investigation of obstacles in complex roadways Comparisons of different turbulence models (LES, also in comparison to RANS/Fluent) Subgrid-scale modelling (Smagorinsky, Deardorff, Vreman)
Atmospheric distribution	Specific atmospheric flow properties for fire/smoke in open areas under consideration of wind influences Evaluation of plume and smoke development of large crude oil fires
Spreading fires	Comparisons with fire tests at the Hot Steam Reactor (HDR) in Germany Investigations into the expansion of fire and smoke in large rooms
Flame propagation	The spread of small laminar flames (millimetre to centimetre range) Tests from the cone calorimeter (ISO 5660-1, 2002) to extensive fire tests such as the Room Corner Test (ISO 9705, 1993) Consideration of many different furnishing materials Derivation of recommendations for the use of problem-adapted grid sizes and material properties
Room fires	Large-scale high-rise tests (variations of fire source size and location, convection, radiation and combustion parameters) Measurement of temperature and smoke distribution for realistic multi-room scenarios Prediction of secondary ignition and fire flashover

	Investigations in mechanically ventilated large rooms Turbulence properties of the flow and temperature fields (half-scale ISO Room Fire Test) Investigation of temperature and smoke distributions in realistic multi-room scenarios
Sprinkler and water mist systems	Mapping of activation times Verification of sprinkler activation predictions for high-bay warehouse fires involving chemical storage Absorption of heat radiation by water mist systems
Tunnel fires	Post simulation of tunnel experiments with and without ventilation Heat flow and smoke measurements in connection with sprinklers Qualitative analysis for a truck fire in a tunnel
Smoke detection	Prediction of the activation times of smoke detectors Comparisons of temperatures, gas velocities and concentrations at different detector positions
Combustion model	Comparison of the spectral radiation intensities of small fires Measurement of temperature, air velocity, gas concentration, unburned hydrocarbon and heat flows Comparisons of a methane gas burner with natural ventilation
Soot deposition	Study of the effects of soot deposition on the prediction of smoke concentrations, Smoke detector activation times and detection distance Soot densities and deposits on walls for various fuels
Reconstruction of damage fires	Simulation of known large fires, e.g. WTC, Station Nightclub in Rhode Island, and many more.

5.5 Model application

5.5.1 General information

In the following chapters, the basic steps in the application of mathematical models for fire simulation are shown. The individual application steps are strongly dependent on the individual sub-models, which are provided in the fire simulation models. In [5.53], the fire simulation flowchart is shown in Figure 5.10 proposed for the CFD calculation. The individual steps include the selection of the scenario (Chapter 5.5.2) and the model type (Chapter 5.5.3), as well as the evaluation (Chapter 5.5.4) and the documentation of the results (Chapter 5.5.5).

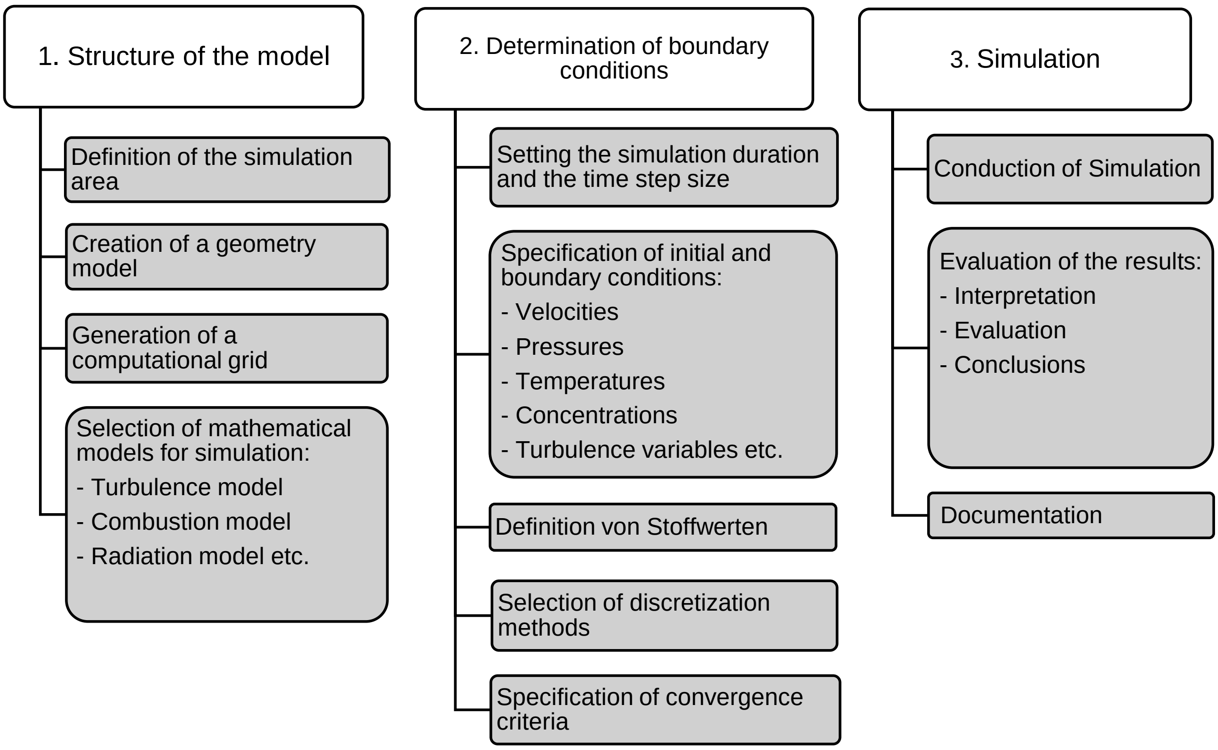


Figure 5.10 Flow chart for fire simulation according to [5.53]

5.5.2 Selection of scenarios

The term fire scenario is understood here as the summary of the essential boundary and initial conditions of a fire simulation. This generally includes the following specifications:

- temporal progression of the combustion or heat release of the fire, if necessary with considering existing effective parameters such as extinguishing measures,
- information on the chemical reaction, especially on yields (e.g. soot),
- location and size of air supply and exhaust openings (e.g. SHEVS), or generally the ventilation conditions,
- the extent of the calculation area (fire zone and adjacent rooms) and
- specific assumptions.

This list is open because, depending on the task, specific boundary conditions are considered and calculated, which have an influence on the input data of a mode. The selection of scenarios results in an investigation of system states that covers the task and is sufficient to answer the relevant questions.

Examples of different scenarios are different fire patterns with identical ventilation conditions or the change in ventilation conditions when a certain temperature is reached. For temperature calculations, different scenarios may be required by considering different locations of heat application.

The selection of scenarios matches their different input data for the simulation. Since CFD models and multi-zone models differ in details, it is possible that the selection of scenarios depends on the choice of model or calculation method.

5.5.3 Selection of the model type

Within the framework of fire protection verification, a number of questions arise, which are deal with using different engineering methods. In addition to the classical tasks, such as the design of smoke extraction systems or the determination of temperature gradients, topics such as thermal radiation, triggering time point of sprinklers or automatic smoke detectors can be considered. Coverage of all possibilities is beyond the introductory character of this chapter, so it is limited to the classic tasks mentioned above.

For the selection of the model type, the task definition is important. For example, as already explained, not all models are equally suitable for the calculation of local temperature values. Zone models should be supplemented by algorithms described in the chapters of plume models and ceiling jet models. If they are not included in the model, separate calculations are possible using the equations given.

While with engineering formulae and simpler calculation procedures, application limits often result from the validity range of the underlying empirical relations and the introduced simplifying assumptions, similar general limitations of the application range cannot be easily determined with the CFD models. This is due to the local description of the smoke and heat propagation. Which takes the fundamental physical conservation laws into account. Basic application limits, e.g. the spatial dimension, the structural complexity or the strength of a fire source, cannot be derived from the field model approach. Practical application limits result from the selected structure for the computational grid (and from the available computational capacity), the selected boundary conditions and the requirement that is suitable for sub-models (e.g. for thermal radiation) which should be integrated for certain questions. For temperature calculations, the modelling of the fire source and the grid size must also be taken into account. With a large grid size and low energy density (large volume source), larger deviations may result depending on the model.

The question of the application limits of a certain field model can ultimately be answered by referring to the specific application case. Therefore, it is generally true that problems involving detailed computational processing of complex room flows (combination of room geometry, buoyant convection flow and ventilation) and the smoke and heat propagation phenomena require the use of a CFD model.

The three-dimensional local field model approach means that a large amount of data has to be managed. Here, suitable visualization and documentation options are required, as they are usually offered by modern programs. For quantitative analysis, timing diagrams (development of gas temperature, component temperature, smoke density or pollutant concentration in locally limited areas or at selected points) as well as two-dimensional sectional images (as colour maps or isoline representations) are the appropriate tools. In order to get an overview of the quite complex smoke gas and ventilation flows, a three-dimensional representation is often helpful, possibly also in the form of video sequences generated during the simulation.

CFD models are used in almost all possible areas, from single room to domestic and large fires, e.g. in industrial halls, atriums, meeting places or office buildings. Because of their ability to calculate the flow conditions inside the buildings, CFD models are often used to simulate smoke propagation and smoke extraction measures. Other important areas of application are automatic fire detection and component design. In the latter case, CFD models also offer the possibility of investigating the thermal loading of partially free structures such as frameworks. Furthermore, CFD models can be used for the reconstruction of fire events and their consequences.

For zone models, there are general restrictions resulting from the theoretical principles, which can influence the accuracy of the calculation or its validity. The following case is based on the guidelines for the application of zone models, which released by the responsible ISO working group [5.72].

Since the momentum equation is not solved, all flow processes are considered instantaneous. This assumption is justified for relatively small spaces; for larger spaces, there are deviations in flow processes which require a different time frame. Although this can lead to conservative results in the initial phase, these can be reversed later. These flow processes generally lead to irregularities in the concentration of smoke gas components, the temperature or the position of the smoke gas lower limit after a certain period of time. This is caused by loss of buoyancy, heat loss, etc. Furthermore, flow processes at openings are only described by a flow coefficient and not by the respective exact geometry. Deviations can also result from that.

The smoke gas transition from the lower air layer (cold gas layer) to the smoke gas layer is described by the plume models. There are different models for this purpose, which can differ considerably in the results. Since these models all rely on so-called entrainment coefficients, the experimental inaccuracies in the determination of these coefficients are transferred to the models. These inaccuracies are due to, for example, the fact that the coefficients were often measured in a laminar flow environment. In contrast, the plume may be significantly influenced by supply airflows or ventilation devices. These flow processes influence the mixing in the smoke gas column (plume) and can lead to considerable mixing processes with corresponding smoke entry into the air layer. An example of this is high air velocities in the area of the plume.

The plume models, or adapted variants, are also used to describe the overflow of smoke gases from one room to another. Here, some assumptions are made which contain a certain range of errors and therefore affect the results. The assumptions again include the entrainment coefficient and the geometric shape of the plume, as well as the introduction of a virtual source. This is also the reason why the subdivision into virtual spaces does not necessarily lead to more accurate results. For example, the so-called spill plume may have a higher entrainment coefficient than the axisymmetric plume. Therefore, flow processes in the plume or through openings contain a number of inaccuracies that can be added in connection with the required input data regarding the room geometry (e.g. non-uniformly shaped smoke areas with different heights), the openings (see above) and the number of rooms. Therefore, it is by no means certain that dividing a room into more rooms will improve the result. Due to the influences mentioned above, even the opposite could happen.

Zone models generally do not describe local effects such as those resulting from isotherms or the smoke gas concentration in a specific area. They are therefore not suitable for the assessment of issues in which such local effects play a role.

Large deviations can generally occur in relatively low rooms. Here, the flame shape occurring in reality (deflections of the ceiling) influences the results as much as the instability of the smoke gas layer at greater distances from the fire location. In particular, obstacles on the ceiling (e.g. beams) influence the results. In general, geometrically complex rooms with complicated ceiling shapes are only to a limited extent suitable for the description by zone models. The closer the geometry corresponds to rectangular shapes, the more suitable the zone models are.

Since zone models require the formation of a relatively uniform stratification (and cannot verify its existence), a relatively small fire in a large room may not be sufficient to meet this requirement. Some researchers have therefore proposed a minimum of 0.1 kW per m³ room volume as a necessary lower limit for the heat release rate. On the one hand, this proposal is very pragmatic. On the other hand, it neglects other effective parameters such as the supply air velocity.

The assumptions and inaccuracies mentioned above also have their effects on the arrangement of virtual rooms, i.e. the division of a given room volume into smaller virtual rooms with openings the size of the room entire width. In this case, the mentioned assumptions and inaccuracies can have a significant influence on the result. The direction in which the results are affected is not determined by physics but by the relatively arbitrary selection of virtual rooms.

In the following Table 5.4, some of the basic properties of zone and CFD models are compared with each other from the point of view of fire protection engineering. The characterisation of the properties needs a subjective assessment of the scope and accuracy and does not yet say anything about the possible application of a particular problem.

Due to the differences in the physical approaches, the meaningfulness of zone and CFD models is different, i.e. the scope of the calculated variables deviates strongly from each other.

Table 5.4 Basic properties of field and zone models (see also [5.36], [5.37], [5.38])

Property	Zone models	CFD models
Geometry acquisition	approximated	approximate to accurate
Ventilation detection	approximated	approximate to accurate
Heat release	approximated	approximated
Model effort	low	high
Statements	global, or average values	local
Validation	elaborate	elaborate
Calculation effort	low to medium	high

For all models equally, errors in the input data lead to corresponding errors in the results.

5.5.4 Interpretation of the results

Before interpreting the results, the user of engineering procedures should perform a plausibility check of the results. This includes, for example, checking temperature distributions for unrealistic values or comparing the temporal development of temperature values, smoke gas layer development, and mass flows in the fire course. Since these values correlate with the heat release rate, they must follow the development over time to a certain extent (at least in the initial phase). In this way, major errors resulting from incorrect entries or exceeding from application limits of the program can be eliminated.

The actual interpretation of the results should be carried out against the background of an extended knowledge spectrum, which includes experimental results as well as knowledge from comparative calculations. This is essentially a matter of determining whether the results from the chosen model are actually applicable or require additional considerations. For example, the result may lead to the conclusion that the scope of application of the chosen model has been exceeded, or the results may at least show a larger error. In this case, the decision should be made whether additional calculations with the same model or calculations with another model are necessary. In any case, this evaluation of the results requires a certain amount of experience in which deals with the applied procedures and knowledge of the physical principles.

There are no binding rules for the work step described, so only examples can be given. For interpreting and evaluating temperature calculations, it is advisable to compare the calculation results with experimental results that have similar boundary conditions. If such results are not available, the user should have carried out comparative calculations with the selected procedure on the basis of available experiments to ensure that the correct procedure was always chosen.

The application of CFD model calculations for temperature determination can depend strongly on the modelling of the fire source. In this case, it is necessary to check whether the calculation result actually describes the worst case that is decisive for the design.

In designing smoke extraction systems, the results should be used to verify that the requirements for the application of the selected model are still fulfilled. For example, this may no longer be the case at medium smoke gas temperatures with a small difference (a few degrees) to the ambient temperatures. In this case, it should be checked on the basis of further results (e.g. optical density of the smoke gases) whether statements can still be made.

Once these considerations have been completed, the design can be carried out in comparison with the desired design objectives.

5.5.5 Documentation requirements

In principle, documentation should make the design process comprehensible. Since complete traceability largely depends on the level of knowledge of the reader, this can result in considerable subjective differences in the demands. These are naturally not predictable by the developer of the document; however, at least certain key data should be available for a reasonable assessment.

The following summary (see Table 5.5) is a list containing the information basically required for the evaluation of a fire simulation (here: for the design of smoke exhaust measurements). In case of further investigation/ other engineering methodological questions, the contents of the documentation should be adapted to the task (e.g. in case of application within the scope of a structural design or special protection goals of the client). Further principles of documentation are contained in [5.73] and [5.74].

Table 5.5 Compilation of basic documentation requirements

Content	Remarks
Task	The objective of the investigation or the smoke extraction concept
Basic data/geometry	Responsible persons, institutions involved Date and version of the submitted documentation Naming of the plans used (designation, plan no., revision date) Naming of the other basics used (e.g. 3D models, voting)

	Description of the object with the intended uses Reference to related fire protection concepts Geometric description of the simulation area
Fire protection measures	Description of the decisive structural (such as smoke sections), technical (such as fire alarm and sprinkler systems), organisational and defensive fire protection measures in connection with SHEVS
Protection goals	Definition and explanation of the protection goals such as (personal protection, effective extinguishing work, preventing the spread of fire, protection of property, additional protection goals) Determination of the evaluation criteria required to assess the fulfilment of the protection goals and their limit values Definition of the periods relevant to the achievement of the protection goals
Smoke extraction concept	Legal / Normative bases Explanation of the smoke extraction concept, if necessary: Visualization in plans Definition of the downstream and extraction points (location, position, size, flow velocity, volume flow) For natural supply air openings / NSHEVs: specification of the geometrically free or aerodynamically effective areas Further requirements for the smoke extraction/smoke ventilation system (e.g. with regard to heat resistance and functional safety) System boundaries
Control and regulation system	Manual / automatic triggering of smoke extraction components Other relevant fire control systems
Smoke and heat extraction system, fire control	Definition of the triggering criteria (such as single or dual detector criterion) Time sequences are taken into account for smoke detection (detection, control, regulation, programmed delays) Explanation of the requirements for fire control with regard to the smoke extraction concept If necessary, measures for handling wind influences
Design fire (in particular, Chapter 4 should be taken as a basis here)	Designation of fire loads, location Derivation and explanation of the relevant design fires, including fire positions and ventilation conditions (fire load controlled / ventilation controlled) Influence of sprinkler systems/measures of the fire brigade Taking into account the influence of sprinkler systems: Description of the consideration of sprinkler effects in the model Response sensitivity (RTI value) Nominal tripping temperature Geometric conditions (room height, sprinkler distances from each other / to the ceiling) Fire parameters: Heat release rate curve The course of the local expansion of the burned area Composition of the fuel The specific heat release rate Combustion model, radiation model Radiant component, calorific value Soot Yield, Other Yields (CO, CO_2, ...)

Boundary conditions	Decisive climatic conditions (wind, temperatures outside / inside) Wall temperatures Consideration of the failure of components (e.g. failure of glazing) Relevant currents in the building, if available
Documentation of the programs/models used	Documentation of the model used, including an assessment of its applicability to the task under investigation Meshing (the type of computational grid, number of grids, number and size of cells)
Documentation of the verification used	Explanation and justification of the evaluation criteria and the chosen form of presentation Graphical evaluations using diagrams or tables Visual evaluations such as horizontal and vertical sections in meaningful time steps (e.g. 5 minutes), if necessary with descriptive captions Discussion/interpretation of the results
Conclusions/ recommendations	Conclusion / Summary

5.5.6 Examples of application limits

In the following, application limits for the use of fire simulation models will be shown by two examples. These limits are transferable to tasks that fire protection engineers regularly face in the determination of the requirements in real buildings. Further typical application cases can also be found in chapter A5.3.3 “Examples and experiments for comparative calculations“ of the appendix.

Example 1

The first example deals with the case of supply air influences. Here the smoke gas layer is in the area of the supply air openings, so a boundary layer is formed where incoming supply air comes into direct contact with outgoing smoke gases at a relatively high speed. Within a short period of time, the resulting instabilities lead to strong turbulence, which is predicted in the CFD simulation. This is shown in Figure 5.11. The presented results are performed in accordance with the smoke tests.

The following boundary conditions were investigated:

- An office floor is approximated by an elongated rectangular plan. This space has a length of 150 m, a width of 20 m and a height of 3.13 m,
- The suspended open grid ceiling is simulated by transversely mounted strips 2 cm wide and 20 cm high. These strips are located at the height of 2.67 m to 2.87 m above the floor,
- On both long sides, there are a total of 9 doors with 0.8 m width and 2.5 m height. There are five doors of the same size in the front wall and 4 in the rear,
- A mechanical extraction system is simulated for smoke extraction. The extraction openings are arranged at 10 m intervals along the center of the longitudinal axis. Each extraction opening has a surface area of 4 m². The total capacity of the extraction plant is approx. 75,000 m³/h in the 1st case and 150,000 m³/h in the 2nd case,

- The fire is assumed to be an office fire, which spreads unhindered for 5 minutes before the sprinkler system is activated and stops the further spreading of the fire. It is conservatively assumed that the heat release rate/burning rate remains constant until the fire is extinguished manually. The maximum heat release rate is 1.2 MW. The source of the fire has an area of 2 m² and is located at a distance of 5 m from the left end of the fire zone on the longitudinal axis,
- The fire simulation was performed with the Computational Fluid Dynamics (CFD) with the aid of the Fire Dynamics Simulator (FDS) program from NIST, USA [5.19], [5.21].

In the 1st case, the turbulence is less strong due to the lower extraction capacity, so that there is a lower smoke gas concentration near the floor. However, the smoke gases spread faster in the longitudinal direction.

In the 2nd case, there is an unacceptably high smoke gas concentration over the entire height. This is caused by the stronger turbulence at the higher extraction rate. However, the front of the smoke gases spreads more slowly than in the 1st case.

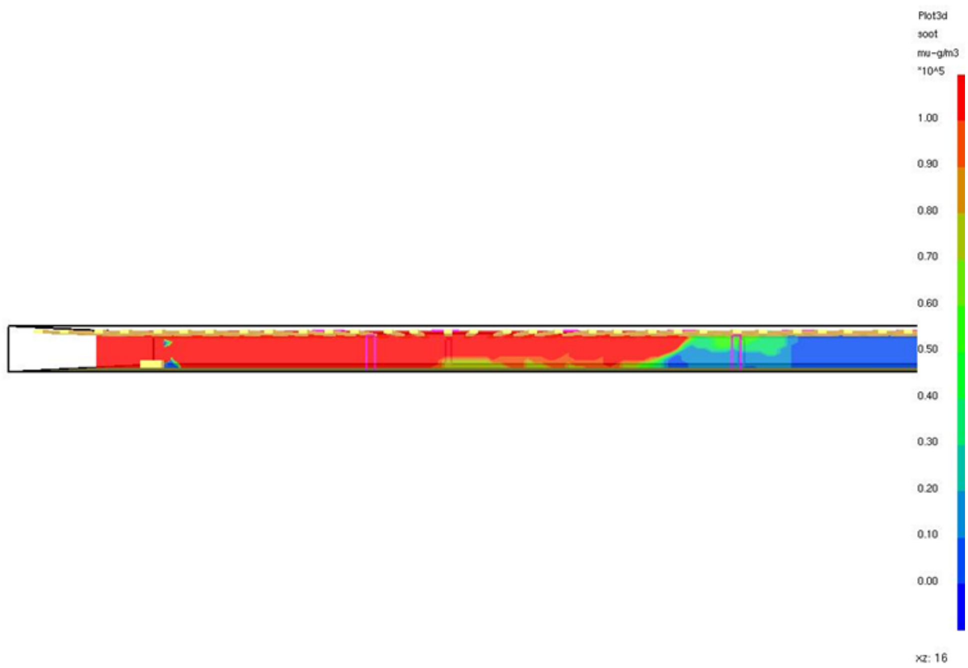


Figure 5.11 Soot concentration in the middle of the longitudinal plane after 600 s, top figure: the capacity of the mechanical exhaust air approx. 75,000 m^3/h, bottom figure: the capacity of the mechanical¬ exhaust air approx. 150,000 m^3/h

Figure 5.12 shows the corresponding results calculated with a zone model for the 2nd case (150,000 m³/h). In this calculation, the room was divided into five segments of 30 m in length. In this way, the smoke spread can also be assessed. The grid ceiling cannot be directly represented in the zone model and can only be taken into account by a finer segmentation, if necessary.

The comparison shows that not only the smoke gas layer is significantly lower, but also the propagation speed of the fire smoke. The resulting turbulence is not recorded.

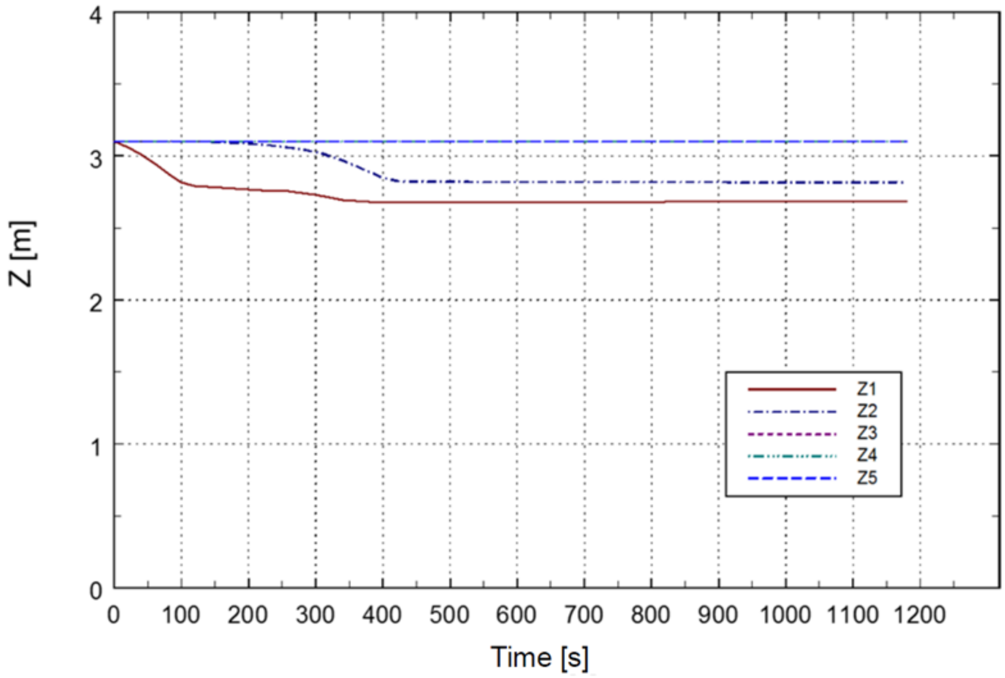


Figure 1.12 Smoke gas-free layer after calculation with CFAST (for segments 1- 5)

Example 2

Example 2 contains the calculation of very high airspace with the following boundary conditions:

- Application: atrium area also used for events in an office building with seven above-ground floors,
- Maximum height of atrium approx. 27 m, variable ceiling height,
- Atrium base area: variable depending on the floor, on the ground floor approx. 17 m x 40 m, on the upper floors approx. 45 m x 20 m,
- Used areas in the upper floors of the atrium partly exist at the edge, the connection of these areas via storey-connecting bridges across the atrium,
- Smoke extraction: Mechanical smoke extraction with three extraction points under the roof of the atrium and a total extraction volume flow of 300,000 m^3/h,
- Supply air ducting: via air inlet openings in the façade on the ground floor,
- Fire scenario: Fire on the ground floor of the atrium (not sprinklerised) with a maximum heat release rate of 6 MW,
- The fire simulation was carried out with the Computational Fluid Dynamics (CFD) by Fire Dynamics Simulator FDS program, version FDS 6.7.0.

Figure 5.13 illustrates the calculation results for the design of the smoke extraction system with the aforementioned CFD model. The optical density is shown. It can be seen that at the selected fire location, the high optical densities occur where the smoke gases accumulated.

Again, a zone model is not expected to reproduce the detailed differences in optical density. This is due to the fact that a zone model cannot take into account the interactions between the supply airflow and the smoke layer that occur due to the high volume flows. The interactions of the plume flow with the geometric obstacles in the atrium would also not be representable with a zone model in this case.

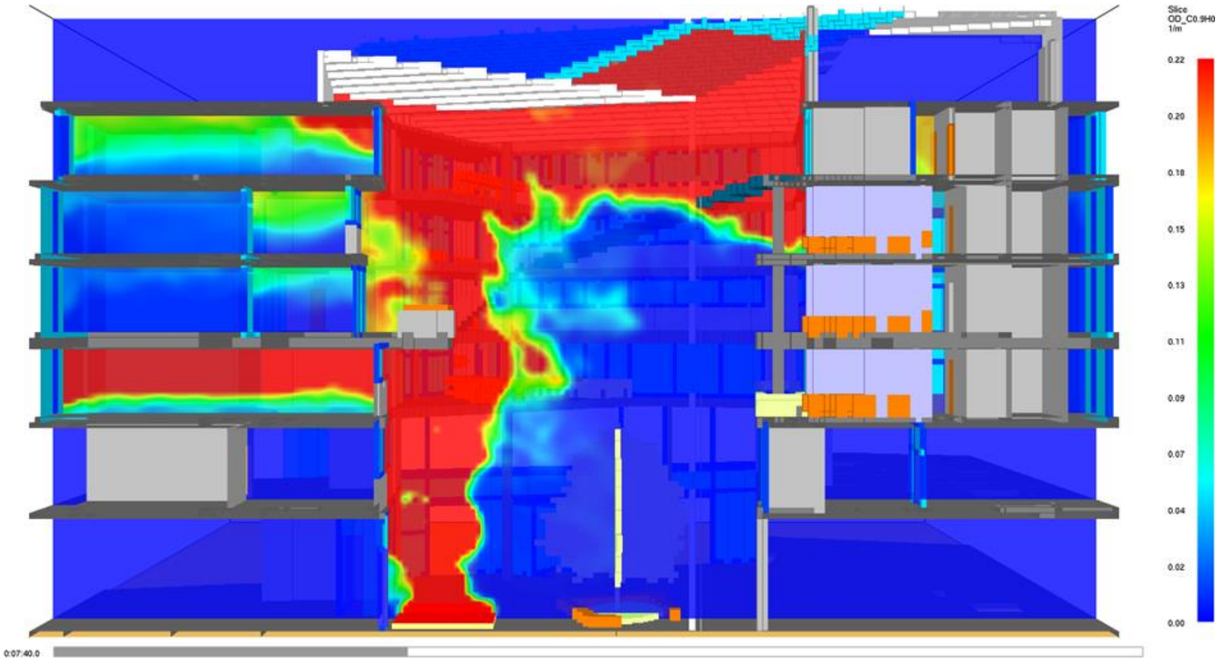


Figure 5.13 Optical density as a calculation result of a field model calculation

The examples show that the user of models must be aware of the boundary conditions before choosing a model type for design. They are also examples of comparative calculations by which the appropriate model form can be qualitatively determined.

Further experiments, which are suitable for evaluation, are described in [5.34], [5.35], [5.70], [5.71]. In the first case, the smoke gas spread over three rooms of different sizes.

5.6 Effects of selected numerical and physical boundary conditions

5.6.1 General Information

With the increasing use of CFD models for fire simulation and the application of new submodels, a multitude large number of fire phenomena can be considered that have not yet been considered in zone models.

In the following, the selected numerical and physical boundary conditions are considered, which on the one hand, influence the predictive capability of simulation models (spatial and temporal discretization) and, on the other hand, require further consideration and go behind beyond the fire modelling of the causal fire (background flows, wind, sprinkler systems).

5.6.2 Selection of the grid resolution

For simulations based on buoyancy plumes, there is a measure for the quality of the numerical resolution of the flow field is the dimensionless expression of $D^* / \delta x$ of the characteristic resolution R^*. Here D^* is the characteristic fire diameter and δx is the size of a grid cell. The characteristic fire diameter is defined by

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/5} \qquad (5.16)$$

The quantity $\dot{Q}$ is the total heat release rate (HRR) of the fire in the unit kW. In the formula, ρ_∞ is the density of air in kg/m³, $c_{p\infty}$ is the specific heat capacity of air in kJ/(kg K), T_∞ is the temperature of the environment in K and g corresponds to the acceleration of gravity in m/s².

If the HRR changes over time, the corresponding change should be taken into account in the resolution, and if it is possible, the relevant time period should be considered for the issues under investigation. The characteristic resolution $R^* = D^* / \delta x$ corresponds to the number of mesh cells cover (not necessarily the physical) diameter of the fire. The more cells cover the fire source, the better the resolution of the calculation. It is better to evaluate the quality of the mesh in relation to the dimensionless parameter than to define an absolute mesh cell size. For example, a cell size of 10 cm may be "appropriate" to evaluate the propagation of smoke and heat through a building from a fire with a high rate of heat release, but may not be enough to investigate a very small smouldering fire source [5.21].

In [5.87], a sensitivity study on the grid size of three different CFD models for the calculation of temperatures and optical densities in an atrium (with an adjacent fire zone) is carried out. In most cases, it was found that a characteristic resolution of R* = 4 for a fire with 1 MW power should be considered as the lowest limit of resolution in order to exclude the dependence of the calculated quantities on the grid resolution. In particular, the investigations show that the type of convergence within the models differs since, for example, different sub-models are used to take turbulence into account.

However, it should be noted that a characteristic resolution for complex building structures can only be used as a guide. The combustion modelling depends to a not inconsiderable extent on the supply air and exhaust air ducting. Since the characteristic resolution only refers to the underlying heat release rate, a too coarse resolution cannot take the supply and exhaust air openings into account.

5.6.3 Selecting the time step

The choice of the time step has an effect on the discretization of the underlying conservation equations for mass, momentum and energy and thus on the stability of the numerical solution methods. If the time step is chosen too large for the calculation, this can lead to the physical equations not being solved correctly.

For CFD models, the Courant-Friedrichs-Lewy number (CFL number) is often used as a stability criterion for the selection of a suitable time step:

$$c = \frac{u \cdot \Delta t}{\Delta x} \qquad (5.17)$$

with

c	Courant-Friedrichs-Lewy number [-]
u	Flow velocity [m/s]
Δt	Discrete-time step [s]
Δx	Three-dimensional discretization step [m]

The CFL number thus indicates how far a considered variable moves within the calculation per time step and whether there are no overlaps in the solution of the transport equations within the time step. In general, it can be said that with a CFL number lower than $1 (c < 1)$, a stable calculation can be performed. The numerical background can be taken from [5.93]. Since the flow velocities can increase in comparison to the start value depending on the fire course, a sufficiently small time step must be selected, or a model must be chosen which selects the time step dynamically so that the CFL condition is satisfied during the entire calculation period.

5.6.4 Background Flow

In structures in which a horizontal background flow is expected, it cannot be assumed that an axisymmetric smoke gas plume is formed. Depending on the flow velocity of the background flow, the smoke gas plume is deflected in the direction of the velocity vector (Figure 5.14). In this case, the smoke gases are no longer layered uniformly, so the use of zone models is not suitable in these cases.

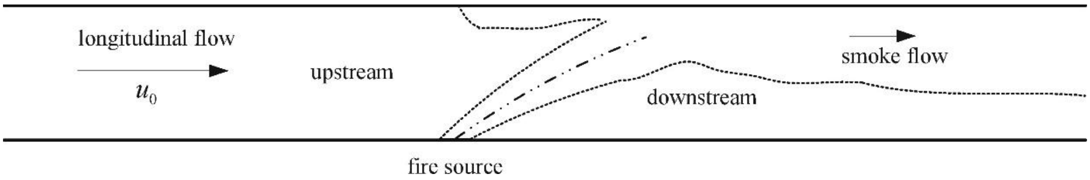


Figure 5.14 Smoke propagation with horizontal background flow [5.95]

If the flow velocities of the backflow exceed a critical value v_{krit} , the smoke comes down to the floor level. This critical flow velocity is not a constant value. It is influenced by the heat release of the fire. In addition to the use of CFD models, empirical correlations exist for determining the critical flow velocity [5.94].

The influence of backflows should be considered, in particular for underground structures such as tunnels and underground infrastructures. Measurements within a subway station [5.96] have shown that these backflows can have velocities of up to 0.6 m/s. Especially in early fire phases, the background flow can have negative effects on the smoke in adjacent areas.

5.6.5 Consideration of wind

The consideration of wind flows in the context of fire or smoke extraction simulations are indicated in some cases. For this purpose, specifications are made in Chapter 4.2.8.2, "Consideration of wind and air flows in fire simulations". In this chapter, general statements for considering wind in CFD models are made.

Especially for modelling forest and wildfires, the consideration of wind is essential, but also for the evaluation of the effectiveness of smoke and heat exhaust systems, the consideration of wind can be of interest. In principle, CFD models are very well adapted to model the effects of wind on the spread of fire and smoke since these models are widely used in wind engineering and meteorology. For considering the wind, it should be noted that these flows occur on different spatial scales compared to the fire-induced flows [5.97]. In addition, it should be noted that neighbouring buildings influence the flow field and should not be ignored. It follows that a significantly larger calculation area in relation to the target building should be selected to take the wind into account. Figure 5.15 shows a recommendation for the size of the calculation area, which is based on wind engineering guidelines.

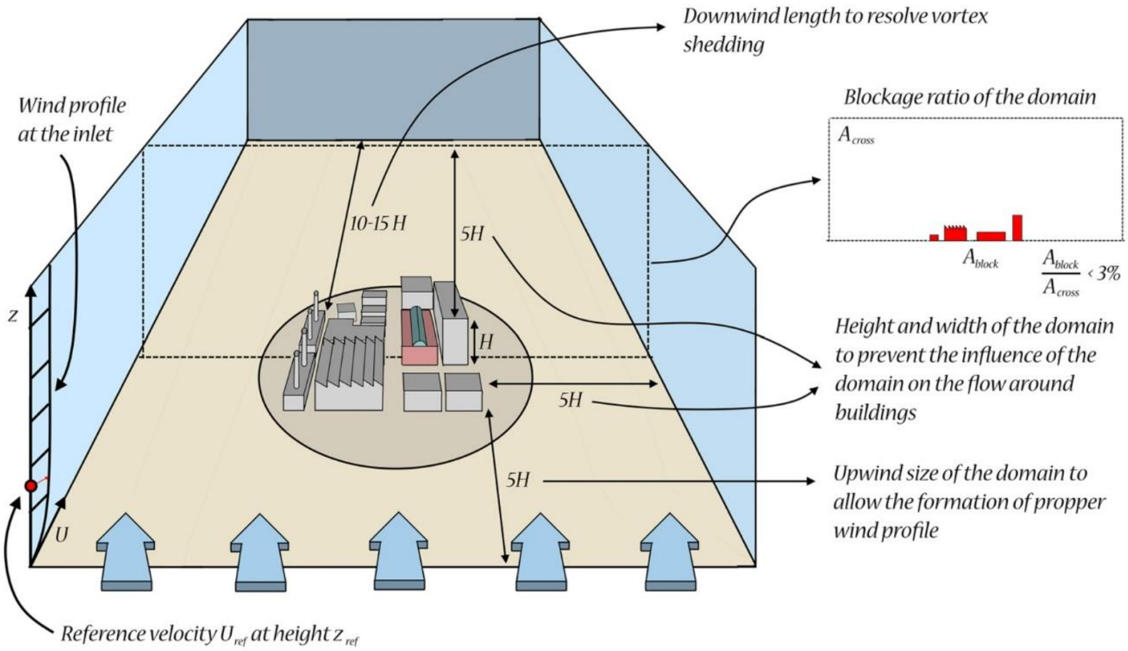


Figure 5.15 Size of the calculation area when considering wind [5.98]

A calculation area that is too small can lead to stalls, especially at the edges of buildings, so that no wind-induced flows occur on the wind-opposed sides.

Furthermore, it should be noted that very high local flow velocities can occur in the area of building edges, which have a negative effect on the CFL number (see Chapter 5.6.3); it is the reason for selecting small time steps.

Like at flows alongside horizontal structural elements, when the wind is taken into account, the wind velocity is not constant over the height. The velocity profile of the wind changes over the height and can be described logarithmically in a simplified way (see Figure 5.15). The wind velocity u depending on height z is:

$$u(z) = \frac{u^*}{\kappa} \ln\left(\frac{z}{z_0}\right) \tag{5.18}$$

with

u^*	Shear stress velocity [m/s],
κ	$\kappa \approx 0{,}4$ Kármán constant,
z_0	Dynamic roughness length [m].

The roughness length takes the surface quality of the soil into account and can be taken from a table, e.g. DIN EN 1991-1-4. Reference speeds u_r of measuring stations are generally recorded at a height $z_r = 10\,\mathrm{m}$ above the ground. If such measurement data are available, the equation is simplified to (5.18):

$$u(z) = u_r \frac{\ln(z / z_0)}{\ln(z_r / z_0)} \tag{5.19}$$

By using the logarithmic wind profile, it should be noted that this wind profile is based on the assumption that the airflow above the ground is neutral laminar, i.e. that the air temperature decreases by 1 K per 100 m.

For considering the temperature profile of the ambient air, e.g. differentiation between summer and winter, it should be noted that the logarithmic wind profile is not applicable in these cases since the temperature differences of the air cause a vertical mass exchange which leads to turbulence.

To consider the stable (temperature in the ground level is lower than the overlying layers, winter case) or unstable (temperature in the ground level is higher than the overlying layers, summer case) stratification of air masses, the submodels are useful that follow the rules of Monin-Obukhov's similarity theory [5.99].

5.6.6 Sprinkler systems

Sprinkler systems have a positive influence on the course of the fire after automatic activation, which is based on the fact that the water takes heat from the flame and the hot gas layer due to heatings up and evaporation.

One approach to consider the influence of sprinkler systems in CFD models is to map the droplets as discrete particles moving through the calculation area. These particles interact with the flow field and the individual sub-models, so this behaviour has to be considered in the individual sub-models, this is, e.g.:

- Pulse conservation between particle and gas phase,
- Absorption and scattering of radiation and
- The reduction of the fuel mass flow resulting from pyrolysis.

In order to make the interaction between water droplets and flow computable, a large number of simplifications and additional submodels are also necessary. This concerns:

- Combination of several drops to one particle,
- Neglecting the impacts between individual drops and
- Model approaches for the atomization of the water jet using probability functions for the droplet diameters.

Current comparative calculations [5.99] using small-scale validation experiments show that the interaction between water droplets and a hot air stream can currently be reproduced inaccurately.

It should be noted that the simulation of sprinkler systems is currently not state of the art and that the application of such sub-models in the context of fire protection is not yet recommended. As an alternative for using discrete particles, it is recommended to consider the effect of sprinkler systems by adjusting the heat release rate (see Chapter 4).

5.7 Literature

[5.1] *YAMANA, T.; TANAKA, T.:* Smoke Control in Large Scale Spaces. Part 1: Analytic Theories for Simple Smoke Control Problems. Fire Science and Technology, Vol. 5 No. 1, 1985.

[5.2] *HANSELL, G. O.; MORGAN, H. P.:* Design approaches for smoke control in atrium buildings, Building Research Establishment, Report BR 258, 1998.

[5.3] *DRYSDALE, D.:* An Introduction to Fire Dynamics, Wiley-Interscience, New York, 1992.

[5.4] *KARLSSON, B.; QUINTIERE, J. G.:* Enclosure Fire Dynamics, CRC Press, 2000.

[5.5] *COX, G. (ED.):* Combustion Fundamentals of Fire, Academic Press, 1995.

[5.6] SCHNEIDER, U.; KERSKEN, M.; MAX, U.: Bewertung von Brandlasten in größeren Räumen. Teil II. Theoretische Untersuchungen. Forschungsbericht der AGB, Institut für Bautechnik, Berlin, Oktober 1991.

[5.7] *BEYLER, C. L.:* Fire Plumes and Ceiling Jets. Fire Safety Journal, 11, 1986.

[5.8] *EVANS, D.:* Ceiling Jet Flows. The SFPE Handbook of Fire Protection Engineering. Section 2. Chapter 4, pp. 2.32 - 2.39.

[5.9] *EVANS, D.:* Calculating Actuation Time in Compartments. Fire Safety Journal, 9, 1985.

[5.10] *ZUKOSKI, E. E.:* Properties of Fire Plumes. Combustion Fundamentals of Fire, Cox, G. (ed.), Academic Press, 1995.

[5.11] *HOSSER, D.; DOBBERNACK, R.; SIEGFRIED, W.:* Rauchabzug in ausgedehnten Räumen ohne und mit Sprinkleranlage – am Beispiel des Industriebaus. vfdb 4 / 97.

[5.12] *HOSSER, D.; SIEGFRIED, W.:* Vergleich von Simulationsmodellen für die brandschutztechnischen Fragestellungen. 5. Fachseminar Brandschutz – Forschung und Praxis. Schriftenreihe des Institutes für Baustoffe, Massivbau und Brandschutz, Heft 103, 1993. ISBN 3-89288-079-4

[5.13] *HESKESTAD, G.:* Engineering Relations for Fire Plumes. Fire Safety Journal, 1984, pp. 25 - 32.

[5.14] *HESKESTAD, G.:* Fire Plumes. The SFPE Handbook of Fire Protection Engineering, 4. Edition, Section 2. Chapter 2, pp. 2.1 - 2.20.

[5.15] *HESKESTAD, G.; DELICHATSIOS, M. A.:* The Initial Convective Flow in Fire: 17th International Symposium on Combustion, Combustion Institute, Pittsburgh, 1978, pp. 1113 - 1123.

[5.16] *RADFORD, M. W.:* An Investigation of the Effects of Sprinklers on Compartment Fires. Fire Engineering Research Report 96 / 6, School of Engineering, University of Canterbury. ISSN 1173-5996, 1996.

[5.17] *DAVIS, W. D.; NOTARIANNI, K. A.; TRAPPER, P. Z.:* An Algorithm for Estimating the Plume Centerline Temperature in the Presence of a Hot Upper Layer. NISTIR 6178, National Institute of Standards and Technology, Gaithersburg, Maryland, June 1988.

[5.18] *DOBBERNACK, R.; HOSSER, D.; PALIGA, K.; BLUME, G.; WILL, J.:* Experimentelle Grundlagen für die brandschutztechnische Auslegung von Gebäuden gegen Naturbrandbeanspruchung. Erschienen in: Forschungsarbeiten 1995 - 1999. Schriftenreihe des Institutes für Baustoffe, Massivbau und Brandschutz, Heft 144, S. 265 - 266, 1999. ISBN 3-89288-123-5.

[5.19] *BLUME, G. W.:* Ingenieurmodell zur brandschutztechnischen Bemessung von Bauteilen auf der Basis von experimentell ermittelten Verbrennungseffektivitäten. Dissertation TU Braunschweig, 2002.

[5.20] *MCGRATTAN, K. B.; BAUM, H. R.; REHM, R. G.; HAMIS, A.; FORNEY, G. P.; FLOYD, J. E.; HOSTIKKA, S.:* Fire Dynamics Simulator (Version 2) – Technical Reference Guide. NISTIR 6783, National Institute of Standards and Technology, November 2001.

[5.21] *McGRATTAN, K.; HOSTIKKA, S. et al.;* Fire Dynamics Simulator User’s Guide, NIST Special Publication 1019, Sixth Edition, NIST, National Institute of Standards and Technology, 2017.

[5.22] *SCHNEIDER, U.; MAX, U.; LEBEDA, CH.:* Untersuchungen zur Bewertung von Brandsimulationsmodellen für die Festlegung ihrer Anwendungsgebiete und Grenzen. VdS-Fachtagung Ingenieurmäßige Verfahren im Brandschutz (2), 1997.

[5.23] *SAVILONIS, B.:* Survey and Evaluation of Existing Smoke Movement Models. Fire Safety Journal 13 (1988) 87.

[5.24] *BEARD, A.:* Evaluation of Fire Models Part I. Fire Safety Journal 19 (1992) 295.

[5.25] *NOVOZHILOV, V.:* Computational fluid dynamics modelling of compartment fires, Progress in energy and Combsution Science 27 (2001) Issue 6.

[5.26] SFPE Handbook of Fire Protection Engineering. NFPA, Quincy, MA, Fifth Edition, 2016.

[5.27] *PEACOCK, R. D.* ET AL.: Issues in Evaluation of Complex Fire Models. Fire Safety Journal 30 (1998) 103.

[5.28] *PATANKAR, S. V.; SPALDING D. B.:* A Calculation Procedure for Heat, Mass and Momentum Transfer in Three-Dimensional Parabolic Flows. Int. Journal of Heat and Mass Transfer 15 (1972) 1787.

[5.29] *SCHNEIDER, V.; LÖFFLER, S.; STEINERT, C.; WILK, E.:* Application of the compartment fire CFD model KOBRA-3D in fire investigation. Proceedings Interflam ’99, Fire Science & Engineering Conference, Edinburgh, 1999.

[5.30] *BAUM, H. R.; REHM, R. G.; BARNETT, P. D.; CORLEY, D. M.:* Finite Difference Calculations of Buoyant Convection in an Enclosure, Siam J. Sci. Stat. 4 (1982) 117.

[5.31] *MCGRATTAN, K. B.; BAUM, H. R.; REHM, R. G.:* Large Eddy Simulations of Smoke Movement. Fire Safety Journal 30 (1998) 161.

[5.32] *YAMANA, T.; TANAKA, T.:* Smoke Control in Large Scale Spaces. Part 2: Smoke Control Experiments in a Large Scale Space. Fire Science and Technology Vol. 5 No. 1, 1985.

[5.33] *DUONG, D. Q.:* The Accuracy of Computer Fire Models. Some Comparisons with Experimental Data from Australia. Fire Safety Journal 16 (1990).

[5.34] *SÖDERBOM, J.:* Smoke Spread Experiments in Large Rooms. Experimental Results and Numerical Simulations. SP Report 1992:52, Swedish National Testing and Research Institute.

[5.35] *HE, Y.; BECK, V.:* Smoke Spread Experiment in a Multi-Storey Building and Computer Modelling. Fire Safety Journal 28 (1997).

[5.36] *SCHNEIDER, U.* ET AL.: Ingenieurmethoden im Baulichen Brandschutz. 3. neubearbeitete und erweiterte Auflage. Kontakt und Studium, Band 531, Expert Verlag, Renningen, 2004. ISBN 3-8169-2290-2.

[5.37] *SCHNEIDER, U.:* Grundlagen der Ingenieurmethoden im Baulichen Brandschutz. 3. Auflage, Werner Verlag, Düsseldorf, 2004. ISBN 3-8041-4189-7.

[5.38] *SCHNEIDER, U., LEBEDA, C.:* Baulicher Brandschutz, Kohlhammer Verlag GmbH, Stuttgart, 2000. ISBN 3-17-015266-1.

[5.39] *HESKESTAD, G.:* Fire Plumes. SFPE Handbook of Fire Protection Engineering. NFPA, Quincy, MA, 1995.

[5.40] *ZUKOSKI, E. E.:* Properties of Fire Plumes in: Cox, G. (Ed.): Combustion Fundamental of Fires, Academic Press, London, 1995.

[5.41] *DITTES, W.:* Methoden zur Darstellung der Luftströmungen in Fabrikhallen und Regeln für eine optimierte Lüftung. Dissertation Universität Stuttgart, 1996.

[5.42] *BIEGERT, B.:* Theoretische und experimentelle Untersuchung der Luftbewegung an wärmeabgebenden Körpern, Universität Stuttgart, IKE, Abt. Heizung, Lüftung, Klimatechnik, HLK 7D-205, 1990 (unveröffentlichte Studienarbeit).

[5.43] *WILK, E.; KOTTHOFF, I.:* Modellversuche zur Lösung brand- und rauchschutztechnischer Probleme. vfdb-Zeitschrift 1 / 2001.

[5.44] *STEINERT, C.:* Skalierung von Bränden – Teil 2: Physikalisches Modell. Brand- und Rauchversuche im originalen und verkleinerten Maßstab. vfdb-Zeitschrift 3 / 2002, S. 108 - 121.

[5.45] *PLATE, E. J. (Ed.):* Engineering Meteorology, Elsevier Scientific Publishing Company, 1982.

[5.46] *GERHARDT, H. J.:* Physikalische Modellierung der Rauchableitung unter besonderer Beachtung des Windeinflusses. Braunschweiger Brandschutztage ´01. 9. Fachseminar Brandschutz Forschung und Praxis. 1. und 2. Oktober 2001 in Braunschweig, Heft 158, S. 251 - 266.

[5.47] WtG-Merkblatt. Windkanalversuche in der Gebäudeaerodynamik, 1996.

[5.48] Grundsätze für Rauchversuche in Gebäuden. Technischer Bericht der vfdb. vfdb-Zeitschrift, Verlag W. Kohlhammer (Hrsg.), Heft 3 / 2001, S. 150 - 152.

[5.49] VDI Richtlinie 6019, Blatt 1, VDI, Mai 2006.

[5.50] *MÜLLEJANS, H.*: Über die Bedingungen von Modellversuchen in der Klimatechnik. Ki 8 / 73, Teil 6, S. 63 ff, 1973.

[5.51] *BACH, H.:* Ähnlichkeitskriterien bei Raumströmungen. KI Luft- und Kältetechnik. 9, 1973, S. 69 – 75.

[5.52] *BREIN, D.:* Rahmenbedingungen der bekannten Freistrahl- bzw. Plume-Theorien. VdS-Fachtagung. Rauchausbreitung und Rauchfreihaltung. Ingenieurmäßige Verfahren im Brandschutz (8), Juni 2003.

[5.53] *SEEGER, P. G.:* Über Brandversuche in der Brandschutztechnik, vfdb Heft 1 und 2, 1970.

[5.54] VDI Richtlinie 6019, Blatt 2, VDI, Juli 2009.

[5.55] *THOMAS, P. H., HINKLEY, P. L.* et al: Investigations into the flow of hot gases in roof venting, Fire Research Technical Paper No. 7, Fire Research Station, 1963.

[5.56] *HINKLEY, P. L.:* Rates of production of hot gases in roof venting experiments, Fire Safety Journal, 10 (1986).

[5.57] *DEMBSEY, N. A., PAGNI, P. J., WILLIAMSON, R. B.:* Compartment fire near-field measurements, Fire Safety Journal, 24 (1995).

[5.58] *MCCAFFREY, B. J.:* Momentum implications for buoyant diffusion flames, Combustion and Flame, 52 (1983).

[5.59] CHOW, W. K.: On the Use of Time Constants for Specifying the Smoke Filling Process in Atrium Halls. Fire Safety Journal 28 (1997), p. 165-177;1997.

[5.60] *STEINERT, C*.: Die Zeitkonstanten nach W.K. Chow - ein Beitrag zur Beurteilung der Verrauchung von Hallen im Brandfall. vfdb-Zeitschrift 3 / 1999, S. 120 - 124.

[5.61] SCHNEIDER, U.; SEIFERT, U.: Aspekte der experimentellen Brandmodellierung, vfdb-Zeitschrift 2/2003, S. 43-58. 2003.

[5.62] *DETZER, R*.: Physikalische Modelle als Grundlage für die Dimensionierung der Rauchableitung. Tagungsband der Braunschweiger Brandschutztage 03. 30.9.+1.10.2003 in Braunschweig, Heft 168, 2003.

[5.63] *STEINERT, C*.: Skalierung von Bränden - Teil 1: Quellterme. vfdb-Zeitschrift 3 / 1999, S. 125 - 130.

[5.64] *SEIFERT, U.; STEIN, J*.: Rauchversuche in Gebäuden. vfdb-Zeitschrift 3 / 2001.

[5.65] *DALHOFF, W.; GERHARDT, H. J.* et al: Rauch- und Wärmeabzugsgeräte mit dem Windkanal. vfdb-Zeitschrift 4 / 77; 1977.

[5.66] *RJABOW, I*.: Das Studium von Bränden in Modellen. UB Wissenschaftlich-technische Beilage 1/1967.

[5.67] *GERHARDT, H. J.; KONRATH, B*.: Maschinelle Rauchableitung in besonderen Bauarten. vfdb-Zeitschrift 4 / 2004.

[5.68] *GERHARDT, H. J.:* Anmerkungen zur Ähnlichkeit von Modellversuchen bei der Rauchableitung. vfdb-Zeitschrift 2 / 2002.

[5.69] *SCHNEIDER, V.:* Mathematical and physical modelling of smoke spread in atria-type experimental set-ups, Proceedings Interflam2007, Fire Science & Engineering Conference, Royal Holloway University of London, 2007.

[5.70] *SCHLEICH, J.-B., FRANSSEN, J.-M., TWILT, L.,* ET AL.: Development of design rules for steel structures subjected to natural fires in large compartments, Final Report EUR 18868, Simulation of the fire tests of the “Parc des Expositions, Paris”, 1999.

[5.71] *SHEPPARD, D. T.:* Fire Environment Tests under flat ceilings, Test Report, Underwriters Laboratories, Society of Fire Protection Engineers, 1997.

[5.72] ISO/TS 13447:2013: Fire safety engineering -- Guidance for use of fire zone models, ISO International Organization for Standardization, 2013.

[5.73] DIN 18009-1: Brandschutzingenieurwesen – Teil 1: Grundsätze und Regeln für die Anwendung, DIN Deutsches Institut für Normung e.V., Beuth Verlag Berlin, 2016.

[5.74] GVZ-MERKBLATT: Leitfaden für die Planung, Ausführung und Abnahme von Rauch- und Wärmeabzugsanlagen (RWA), Gebäudeversicherung Kanton Zürich, https://www.gvz.ch/_file/245/131119-leitfaden-rwa.pdf, Oktober 2013.

[5.75] *PEACCOCK, R. D.* et al: CFAST-Consolidated Model of Fire and Smoke Transport, (Version 7) Volume 1: Technical Reference Guide, NIST Technical Note 1889v1, 2019.

[5.76] *McGRATTAN, K.; McDERMOTT, R.; HOSTIKKA, S.; FLOYD, J.; WEINSCHENK, C.; OVERHOLT, K.:* Fire Dynamics Simulator, Technical Reference Guide, Volume 3: Validation, National Institute of Standards and Technology, NIST, Special Publication 1018-3, 2016.

[5.77] *PEACOCK, R. D.; RENEKE, P. A.; DAVIS, W. D.; JONES, W. W.:* “Quantifying fire model evaluation using functional analysis”, Fire Safety Journal 33 (1999), p. 167-184, 1999.

[5.78] ISO/DIS16730: Fire safety engineering – Assessment, verification and validation of calculation methods, FINAL DRAFT, ISO 2008.

[5.79] ASTM E1355 – 11: Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models, American Society for Testing and Materials ASTM 2011.

[5.80] *RIGOLLET, L.; ROEWEKAMP, M.:* Collaboration on fire code benchmark activities around the international fire research program PRISME, Seminar 2 EUROSAFE 2009.

[5.81] *AUDOUIN, L. et al.:* Quantifying differences between computational results and measurements in the case of a large-scale well-confined fire scenario, IRSN, Nuclear Engineering and Design, Nuclear Engineering and Design 241 (2011) 18–31, 2011.

[5.82] NUREG 1824-2: Verification & Validation of Selected Fire Models for Nuclear Power Plant Applications, Volume 2: Experimental Uncertainty, NUREG-1824 EPRI 1011999, Final Report, May 2007, Table 6-8.

[5.83] *RIESE, O., SIEMON, M.:* Untersuchung der Prognosefähigkeit von deterministischen Brandsimulationsmodellen, Anwendung PRISME DOOR, Bauphysik 36 (2014), Heft 4, Ernst & Sohn Verlag 2014.

[5.84] *McGRATTAN, K.; FORNEY, G.:* Fire Dynamics Simulator (Version 4), Technical Reference Guide,” National Institute of Standards and Technology, NIST Special Publication 1018, September 2004.

[5.85] *McGRATTAN, K.; McDERMOTT, R.; HOSTIKKA, S.; FLOYD, J.:* Fire Dynamics Simulator, Version 5, User's Guide, National Institute of Standards and Technology, NIST, Special Publication 1019-5, 2010.

[5.86] *McDERMOTT, R.; FORNEY, G. P.; FLOYD, J; McGRATTAN, K.; MELL, W. E.:* Fire Dynamics Simulator Version 6: Complex Geometry, Embedded Meshes, and Quality Assessment, National Institute of Standards and Technology, NIST, 2010.

[5.87] *RIESE, O.; KLIPPEL, A.; SCHNEIDER, V.; STOCK, B.:* Einfluss der Gitterweite auf die Ergebnisse von Brandsimulationsmodellen Anwendung: Atrium, Bauphysik, Heft 2, Ernst & Sohn Verlag, April 2019.

[5.88] *MÜNCH, M., KLEIN, R.:* Anforderungen an numerische Berechnungen der Brand- und Rauchausbreitung im Vorbeugenden Brandschutz, vfdb 3/2008.

[5.89] *SCHLESINGER, S.;* Terminology for Model Credibility. Simulation, 32 (3): 103-104, 1979.

[5.90] *KILIAN, S.; ZEHFUß, J.:* Ansätze für ein nachhaltiges Qualitätsmanagement bei der Entwicklung von Brandsimulationsprogrammen, vfdb 2/2019.

[5.91] *YEOH, G.H., YUEN, K.K.:* Computational Fluid Dynamics in Fire Engineering – Theory, Modelling and Practice, Butterworth-Heinemann, 2009.

[5.92] *MERCI, B., BEJI, T.:* Fluid Mechanics Aspects of Fire and Smoke Dynamics in Enclosures, CRC Press, 2016.

[5.93] *EPPLE, B., LEITHNER, R., LINZER, W., WALTER, H.:* Simulation von Kraftwerken und Feuerungen, Springer-Verlag/Wien, 2012.

[5.94] *HANKE-BOURGEOIS, M.:* Grundlagen der Numerischen Mathematik und des Wissenschaftlichen Rechnens, Vieweg-Teubner, 3. aktualisierte Auflage, 2009

[5.95] *LI, Y.Z., INGASON, H.:* Discussions on critical velocity and critical Froude number for smoke control in tunnels with longitudinal ventilation Fire Safety Journal 99 (2018) page 22-26, 2018.

[5.96] *BRÜNE, M., PFLITSCH, A., GOMELL, A.:* Temperatures and natural background airflow in subway systems - an influence factor for smoke propagation in the case of a subway fire, Tagungsband 5th Symposium Structural Fire Engineering – TU Braunschweig, 2018.

[5.97] *WEGRZYNSKI, W., LIPECKI:* Wind and Fire Coupled Modelling – Part I: Literature Review, Fire Technology, 54, 1405 – 1442, 2018.

[5.98] *WEGRZYNSKI, W., LIPECKI, T., KRAJEWSKI, G.:* Wind and Fire Coupled Modelling – Part II: Good Practice Guidelines, Fire Technology, 54, 1443 – 1485, 2018.

[5.99] *GASCH, R., TWELE, J.:* Der Wind, in Windkraftanlagen – Grundlagen, Entwurf, Planung und Betrieb, SpringerVieweg, 2005.

[5.100] *BEJI, T., EBRAHIMZADEH, S. MARAGKOS, G., MERCI, B.:* Numerical Modelling of the Interaction Between Water SPRAYS and Hot Air Jets – Part II: Two-Phase Flow Simulations, Fire Safety Journal 96 (2018), page 143 – 152, 2018.

ANNEX TO CHAPTER 5

A5.1 Empirical modelling of the flames and the flue gas plume

A5.1.1 General information

A number of fire sources are scientifically investigated in the literature. It was found that the interference in the similarity area above the flame ("far-field") can be represented by a power function in which powers of the ascending height and the heat input into the flame determine the resulting mass flow. This assumes that the heat source is a weak plume and that a far-field relative to the fire diameter is considered. For fire loads distributed over a large area, these approaches could be extended by introducing the concept of virtual origin, which essentially led to a correction of the ascent height in the corresponding equation for the point source of the fire. This topic is taken up again for plume temperatures. As this correction depends on the fire diameter, it takes into account the dependence on the fire area [5.12], [5.14], [5.37].

By assuming a circular or square heat source, the result, according to Zukoski, is:

$$\dot{m}_{Pl} = 0{,}071 \cdot \dot{Q}_c^{1/3} \cdot z^{5/3} \quad \text{(A5.1)}$$

with

$\dot{m}_{Pl}$ Mass flow of the plume at the height z [kg/s]

$\dot{Q}_c$ Convective heat release rate in kW

z Height of the plume in m above the base of the fire

This equation can be derived from the general flow equations by the following simplifying assumptions:

- It is a point source.
- The density differences in the plume are small compared to the surroundings.
- The mixing of ambient air into the plume is proportional to the local vertical velocity in the plume.
- The profiles of the vertical velocity component and the buoyancy force are similar on each section of the vertical axis.

This results in equations whose solutions contain details for the plume radius, the vertical velocity and the density in dependence on the height z. A reference for the temperature can be derived from the equation for density through simple conversion. The equation for the plume mass flow is made up of these equations. Verification of this equation is therefore possible indirectly via measurement of the velocity and the temperature. In addition, there is also the option of direct measurement of the plume mass flow.

When examining the outlined interrelationships based on measured values, particular use is made of the fact velocity and temperature can be plotted via a compound variable ($z/Q^{2/5}$). In this respect, two aspects are of interest - namely the form of the resulting curves (see Figure A 5.1) and the fact that none of the variables alone determines this form but the combination of the variables. The precondition for verifying validity is therefore a corresponding variation of this combined variable.

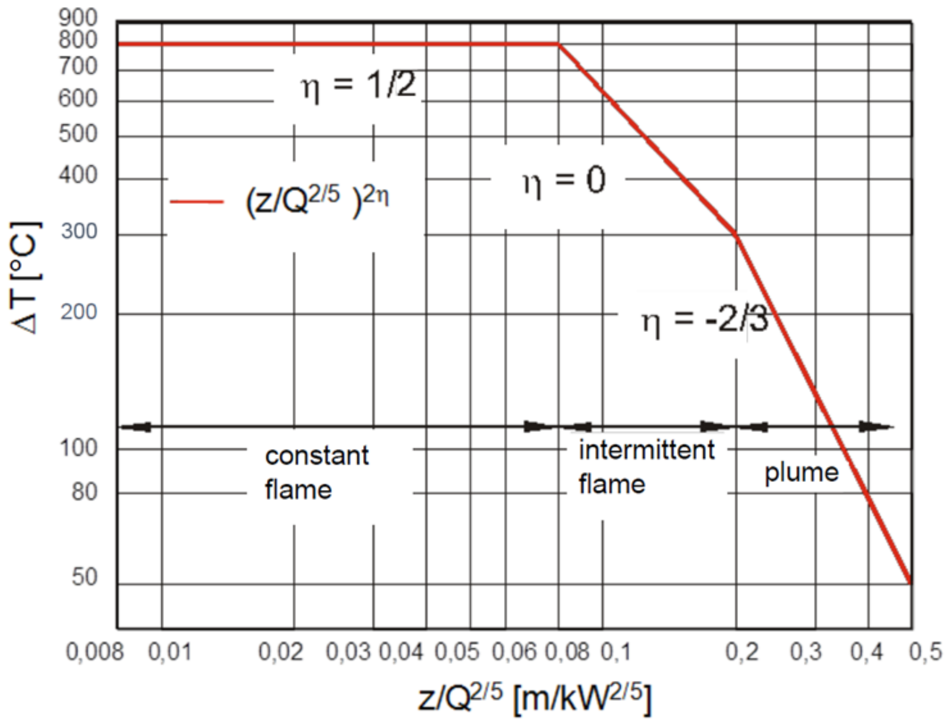


Figure A 5.1 Temperature development over the central axis of the flame and smoke gas plume

Based on the results of the comparisons between the assumptions made and the experiments, it became clear that there are different ranges, and the above equation (A5.1) is only valid above the flame ("far-field"). To obtain corresponding approaches for the flame range, corrections were made based on theoretical considerations and additional experimental results.

As can be seen from the formula for the mean flame height (see equation A5.13), this is a function of the heat release rate and the diameter of the fire source. In the flame zone ("near-field"), the diameter of the fire source (influence of the fire surface) is not negligible and represents an additional length scale which should have an effect on the plume mass flow. Therefore, the above mentioned corrections, such as those included in the approaches of Heskestad [5.12], [5.14], [5.37], also include the diameter D of the burning area. As the rate of heat release increases with height inside the flame, the influence of parameter D at the foot of the flame can be very large. This is the starting point for the approach of Thomas and Hinkley [5.54], who developed a plume model for so-called "large fires", which depends only on the perimeter U of the source of the fire ($U = \pi x\ D$). Originally, the scope of this formula was limited to heights of $z < 1.77$ D. Later, Hinkley was able to show [5.56] hat even for $z < 8$ D, there is a reasonable agreement with experimental results, although theoretical support has not yet been possible. However, this agreement depends on an exact determination of the fire diameter. In contrast, a study by Dembsey et al. [5.57], which compared data from nine different test series, showed that this approach requires modification, especially in the flame range, to achieve an agreement with the measured values and that the McCaffrey approach [5.58] provides good agreement.

The above-mentioned check based on temperature and speed measurements (see also Figure A 5.2) leads to the following subdivision of the areas above a burning surface, which are considered in McCaffrey's approaches:

- The flame zone (near the fire) consists of a continuous flame and an accelerated flow of burning gases,
- The intermittent flame zone is the area of temporary flame formation with almost constant flow velocity,
- The smoke gas plume is an area with decreasing flow velocity and temperature with increasing height.

In Figure A 5.2, the formation of the flame and the plume is shown schematically. In practice, the fire area is either considered a point source or a so-called virtual source point that is assigned to the smoke plume. The angle between the plume axis and plume cone is approximately 15°. It should be noted that the shape of the flame says nothing about the extent of the smoke gases flowing above.

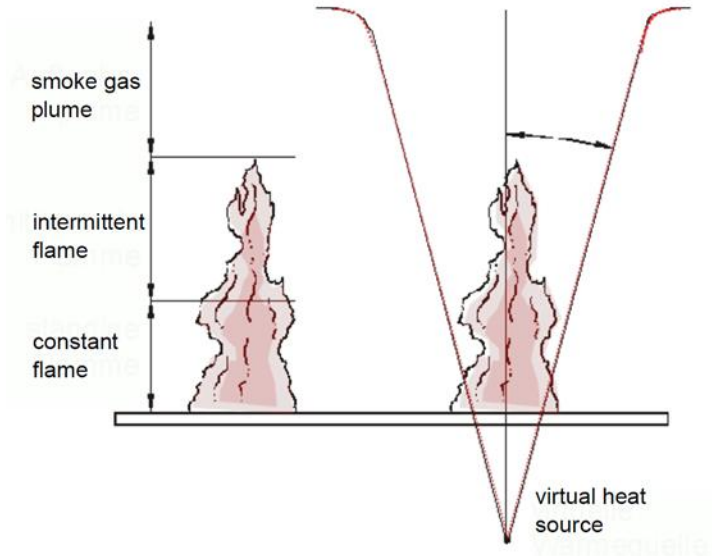


Figure A 5.2 Schematic representation of flame and plume formation according to [5.3], [5.36]

The difficulties in evaluating the individual models are that the upward mass flow can either be measured indirectly, or the recording of the volumetric flow is very difficult, especially in the case of large fire sources, and is almost distorted by other influencing variables. In addition to the usual measurement errors, the measurement results are often affected by turbulent flows, which overlap the plume flow.

Therefore, different plume formulas are used to calculate the smoke gas quantities of the plume (smoke gas column), which differ according to the location of the source of the fire (e.g. on the wall), geometric, dimensions or the structure of the fire source or the smoke gas source. A summary of these formulas can be found in British Standard BSI DD 240, Part 1, 1997: Fire Safety Engineering in Buildings, or Part 2, Commentary on the equations given in Part 1. A summary of these explanations can be found in Brein [5.50], which also summarised the application limits and error ranges. The table on application limits is added to chapter appendix

(Table A5.1). Notes on the application of the respective equations can be found in the further literature, e.g. [5.10], [5.12], [5.14], [5.16].

A5.1.2 Ceiling jet

The term ceiling jet describes the relatively fast smoke gas flow in a flat layer below the ceiling of a fire zone, which is driven by the buoyancy of the fire gases. Starting from the point of impact on the ceiling above the source of the fire, the smoke gases spread radially until they reach the surrounding walls or boundaries. This spread pattern remains unaffected until a defined specific smoke gas layer is formed. However, this is usually the case in the initial phase of a fire. This period typically includes the triggering times of sprinklers after they are heated by the smoke gases flowing around them.

Equations (A5.2) to (A5.5) can be used to calculate ceiling jet temperatures and flow velocities with respect to determining the activation times of sprinklers and heat detectors [5.6][5.8][5.9].

$$v_{jet,t} = 0{,}95 \cdot \left(\frac{\dot{Q}}{z}\right)^{1/3} \qquad \text{for} \qquad \frac{r}{z} \le 0{,}15 \tag{A5.2}$$

$$v_{jet,t} = 0{,}2 \cdot \frac{\dot{Q}^{1/3} \cdot z^{1/2}}{r^{5/6}} \qquad \text{for} \qquad \frac{r}{z} > 0{,}15 \tag{A5.3}$$

$$T_{jet,t} = T_\infty + \frac{16{,}9 \cdot \dot{Q}^{2/3}}{z^{5/3}} \qquad \text{for} \qquad \frac{r}{z} \le 0{,}18 \tag{A5.4}$$

$$T_{jet,t} = T_\infty + \frac{5{,}38}{z} \cdot \left(\frac{\dot{Q}}{r}\right)^{2/3} \qquad \text{for} \qquad \frac{r}{z} > 0{,}18 \tag{A5.5}$$

with

$\dot{Q}$ Heat release rate [kW]

r Distance of the sprinkler from the plume axis [m]

$T_{jet,t}$ Temperature in the ceiling jet at time t [°C]

T_∞ Temperature of the ambient air [°C]

$v_{jet,t}$ Gas velocity in the ceiling jet [m/s]

z Difference between ceiling height and height of the fire source [m]

The constants are experimentally determined and show certain variations depending on the experimental boundary conditions. Since the above correlations are used to determine the triggering times of sprinklers, they contain numerical values of the constants at the lower end of the observable spectrum. This ensures that the time period until the trigger temperature is reached assessed conservatively.

In order to determine the time-dependent temperature development at a sprinkler, only the time-dependent values of the heat release rate should be used. These values can be determined on the basis of known experiments or theoretical processes. From the above equations, location and time-dependent velocity and temperature can be obtained. It is essential that a specific smoke gas layer has not yet formed, as this will change the temperature profiles. This occurs very quickly, especially in small rooms, and must be taken into account. The location of the fire source is also important, as the mixture with ambient air is reduced in the vicinity of walls or corners, which results in cooling reduction over height [5.10]. Another condition for applicability is the possibility of a relatively undisturbed radial propagation. If the flow is interrupted by strongly pronounced beams at the ceiling, or if channel-like flows occur for other reasons, the effects of the changed boundary conditions should be decided for each individual case; and it should be controlled if modified approaches with technical references are available for that.

As the ambient temperature is not directly transferred to a grounded sensor and the sensor first needs to heated to the activation temperature, the temperature of the sensor slightly lags behind the development of the ambient temperature over time. The following equations can be used to take this delay into account [5.9].

$$T_{D,t+\Delta t} = \left(T_{jet,t+\Delta t} - T_{D,t}\right) \cdot \left(1 - e^{-1/\tau}\right) + \left(T_{jet,t+\Delta t} - T_{jet,t}\right) \cdot \tau \cdot \left(e^{-1/\tau} + \frac{1}{\tau} - 1\right) \qquad \text{(A5.6)}$$

$$\tau = \frac{RTI}{\sqrt{v_{jet,t}}} \qquad \text{(A5.7)}$$

with

RTI	Response Time Index, measure for the sensitivity of the sprinkler [(ms)$^{0.5}$]
$T_{D,t}$	Sprinkler temperature at time t [°C]
$T_{jet,t+Dt}$	Temperature in the ceiling jet in the next time step [°C]

Examples of the application of the above equations are given, for example, in [5.11].

A5.1.3 Plume Temperatures

Whereas calculation of the temperatures in the ceiling jet based on the equations (5.20) to (5.23) is designed to permit statements on the activation behaviour of sensor elements or sprinklers, there are also other application areas such as the local heating of structural elements. Prediction of the thermal stress on the structure is relatively easy with almost homogeneous temperature conditions and can be described using a zone model. In very large and high rooms, however, the occurring temperature differences are considerable. This also applies to points of space within the smoke gas layer. This is illustrated using the example of a fire test in a combustion chamber with the internal dimensions 20.4 m x 7.2 m x 3.6 m and a ventilation opening measuring 5.0 x 1.4 m. In the test, two stacks of wooden ribs with a total weight of roughly 1,000 kg were used as the combustible load. The fire was recalculated based on the measured mass burning rate using the HARVARD VI fire simulation model. Figure A 5.3 shows a comparison of the calculated temperature time curve with the measured temperatures at a height of 0.3 m above the floor and 0.3 m below the ceiling of the chamber roughly 5 m from the seat of the fire [5.11].

The calculated smoke gas temperature is roughly in line with the mean of the measured values found at around half room height. The temperatures are up to 170 K higher below the ceiling, however. Based on the mean smoke gas temperature calculated using the zone model, therefore, the dimensioning of the structural elements in the ceiling area would be significantly on the insecure side. Equally, the temperature peaks in the vicinity of the seat of the fire (i.e. in the plume area) are also not taken into account. These local temperature maximums can be calculated using models for the calculation of plume temperatures that are based on the same concept as the plume and ceiling jet models.

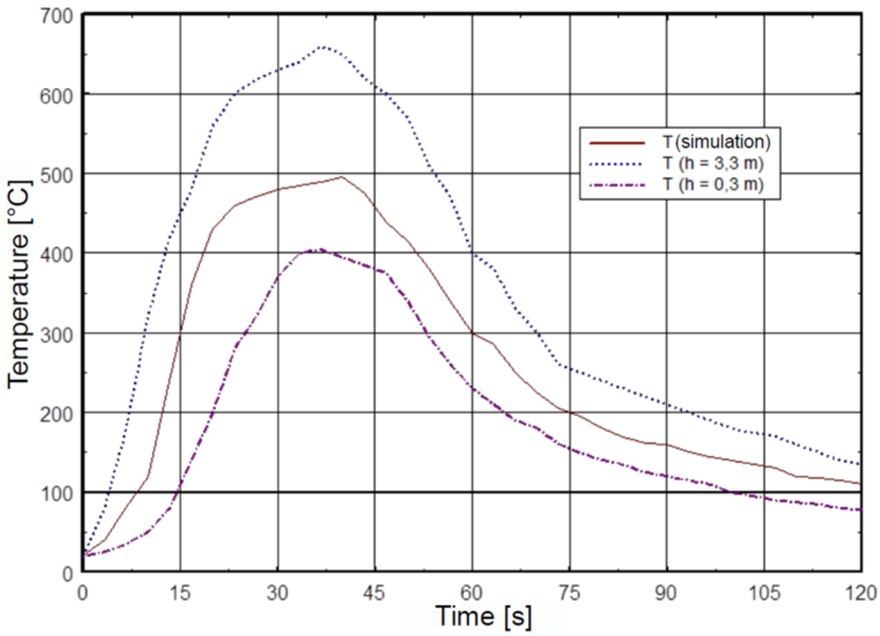


Figure A 5.3 Comparison of the temperatures measured in the fire test with the values from the calculation with HARVARD VI

Numerous studies of international scope have been conducted in order to derive and underpin models for the calculation of plume temperatures [5.12], [5.14], [5.15], [5.16], [5.17]. Alongside the basic influencing factors like heat release rate and distance to the seat of the fire, other factors such as the influence of the fire area (or the spatial structure of the fire source), the occurrence of a pronounced smoke gas layer and the numerical values of the occurring constants have been investigated and determined. The following section first outlines model approaches that do not take account of the influence of a smoke gas layer and are therefore only applicable to this case - in other words, during the initial phase or outdoors.

The Heskestad-Delichatsios model [5.15] (H-D model) is for calculating the temperature rise ΔT_p in the cases without a hot gas layer:

$$\Delta T_p = T_\infty \left(\dot{Q}^*\right)^{2/3} \cdot \left(0{,}188 + 0{,}313 \cdot \frac{r}{z}\right)^{-4/3} \tag{A5.8}$$

$$\dot{Q}^* = \frac{\left(1-\chi_r\right)\cdot \dot{Q}}{\rho_\infty \cdot c_p \cdot T_\infty \cdot g^{1/2} \cdot z^{5/2}} \tag{A5.9}$$

with

$\dot{Q}$ Heat release rate of the real fire [kW]

ρ_∞ Density of the ambient air [kg/m³]

c_p Specific heat capacity of the cold gas layer [kJ/(kgK)]

T_∞ Temperature of the ambient air [K]

T_p Plume temperature [K]

g Gravity [m/s²]

χ_r Radiative part of the heat release rate [-]

z Vertical distance from the surface of the fire source to the calculation location [m]

r Radial distance from the Plume axis [m]

This model offers the advantage of a common equation for the central axis (r = 0 m) and a radial distance r. Especially for the central axis with r = 0 m :

$$\Delta T_p = 9,28 \cdot T_\infty \left(\dot{Q}^*\right)^{2/3} \tag{A5.10}$$

At an ambient temperature of 20 °C (293 K), the following simple formula for the Plume axis is used:

$$\Delta T_p = 25,5 \cdot \frac{\left(\left(1-\chi_r\right) \cdot \dot{Q}\right)^{2/3}}{z^{5/3}} \tag{A5.11}$$

$$T_p = T_\infty + \Delta T_p \tag{A5.12}$$

For conversion to [°C], only the value of 273 K needs to be subtracted.

These kinds of equations are only valid above the mean flame height and if the plume can form freely, i.e. is not located within a smoke gas layer. If we approach the flame area to the distance z, the calculated temperature values generally increase significantly and can assume unrealistically high values. Experiments have determined that a mean temperature of roughly 900 °C is reached inside the flame. This value is somewhat surprising, as it is well below the adiabatic flame temperature, and it is the result of the turbulence occurring with diffusion flames. These turbulent fluctuations in the flow lead to fluctuations of around 38% around the mean temperature in question. The value of 900 °C therefore represents an average value that is accompanied by major fluctuations. It should also be taken into account that this value can certainly also depend on the fuel. Far higher values can also occur depending on soot formation and flame radiation. This is the case with flammable liquids, for example. In most cases, there is a more certain upper limit of 1,000 °C - 1,200 °C. Otherwise, it should be examined in each individual case whether an upper temperature limit of 900 °C is sufficient. Experimental results should be used as a basis for this decision. The mean flame height can be calculated in order to determine whether you are approaching the flame area [5.14][5.16]:

$$Z_f = 0,235 \cdot \dot{Q}^{2/5} - 1,02 \cdot D_f \tag{A5.13}$$

with

Z_f Mean flame height [m]

D_f Fire diameter [m]

Since the flames do not usually have an uniform temperature due to the cooling effects, approaches have been developed which consider this part of the plume in a different way [5.14], [5.15]:

$$\Delta T_p = 78{,}4 \cdot \frac{\dot{Q}^{2/5}}{z} \qquad \text{für} \qquad 0{,}08 \cdot \dot{Q}^{2/5} \leq 0{,}20 \cdot \dot{Q}^{2/5} \tag{A5.14}$$

$$\Delta T_p = 25{,}5 \cdot \frac{\left(\left(1-\chi_r\right) \cdot \dot{Q}\right)^{2/3}}{z^{5/3}} \qquad \text{für} \qquad 0{,}20 \cdot \dot{Q}^{2/5} \leq z \tag{A5.15}$$

The expression $0{,}08 \cdot \dot{Q}^{2/5}$ limits the area directly in flames. Below this limit, the flame temperature is assigned. The validity of the above equations is limited to areas in which a defined smoke gas layer has not yet formed or measured by the room height; this is still of minor importance.

Another parameter is given by the virtual origin z_0. This virtual origin results from the consideration of a point source which have a finite extension at the height of the fire load surface (see Figure A 5.1). If this parameter is taken into account, the quantity z is replaced by $(z - z_0)$ in the corresponding equations, (e.g. plume mass flow or centerline temperature). There are also several approaches to determine z_0 since the experimentally determined results differ according to the structure of the fire load. The clearest results are obtained for pool fires since there is a clearly defined horizontal surface (clear height). In the case of wood cribs, shelf or storage arrangements with horizontally and vertically aligned spaces, a significant proportion of the combustion takes place in the existing spaces; therefore, determination of z_0 leads to different equations and thus to different results. Heskestad [5.14] recommends the use of a special formula. The comparison of the different formulae shows that corresponding error ranges can be expected here.

However, the most important limitation of the equations presented so far for determining the centerline temperature is the superposition of local plume flow and smoke gas layer. By increasing the fire duration, a smoke gas layer is formed, which means the plume after penetration into these layers no longer mixes in cool ambient air but mixes with smoke gases with higher temperature. This reduces the cooling effect. Due to these interrelationships, the above formulas only apply outdoors or in the initial phase of a fire.

In the case of a hot gas layer that has developed during the event of the fire, the above equations should be modified. After entry of the smoke gas column (plume) into the hot gas layer, it is no longer the ambient air with a relatively low temperature that is mixed in, but the warm or hot smoke gas. In this case, an approach for the plume centerline temperature is used, which takes these changed boundary conditions into account when the smoke gas layer enters. The basic concept of this approach is to replace the real fire source with a "virtual heat source", which has a different heat release rate and a different distance to the ceiling than the real fire source.

The basis is the preservation of the enthalpy flow at the interface between the almost smoke gas-free layer and the smoke gas layer. Therefore, the smoke gas temperature T_s, the temperature of the cold gas layer T_∞ and the distance to the smoke gas layer $z_{I,1}$ are required as additional parameters. These values should be determined with the help of fire simulation calculations. The application of this approach [5.17] is described below.

First, the heat release rate $\dot{Q}$ of the real fire source is converted into a dimensionless number.

$$\dot{Q}_{I,1}^{*} = \frac{\dot{Q}}{\rho_{\infty} \cdot c_p \cdot T_{\infty} \cdot g^{1/2} \cdot z_{I,1}^{5/2}} \quad \text{A5.16}$$

with

$\dot{Q}_{I,1}^{*}$	Dimensionless heat release rate of the real fire source [-]
$\dot{Q}$	Heat release rate of the real fire source [kW]
ρ_{∞}	Gas density of the cold gas layer [kg/m³]
c_p	Specific heat capacity of the cold gas layer [kJ/(kgK)]
T_{∞} :	Temperature of the cold gas layer [K]
g	Acceleration of gravity [m/s²]
$z_{I,1}$	Distance of the real fire source to the interface between the upper and lower layer [m]

Subsequently, the dimensionless heat release rate $\dot{Q}_{I,2}^{*}$ of the "virtual heat source" is -calculated, which replaces the real existing heat release rate and lies within a modified smoke gas layer.

$$\dot{Q}_{I,2}^{*} = \left[\frac{1 + C_T \cdot \left(\dot{Q}_{I,1}^{*}\right)^{2/3}}{C_T \cdot \xi} - \frac{1}{C_T}\right]^{3/2} \quad \text{(A5.17)}$$

with

$\dot{Q}_{I,2}^{*}$	Dimensionless heat release rate of the "virtual heat source" [-]
C_T	Constant (9.115) [-]
ξ	Temperature ratio of smoke and cold gas layer (T_s/T_{∞}) [-]

The distance $z_{I,2}$ of the "virtual heat source" to the interface between the upper hot smoke gas layer and the cold gas layer is calculated with:

$$z_{I,2} = z_{I,1} \cdot \left[\frac{\xi \cdot C_T \cdot \dot{Q}_{I,1}^{*}}{\left(\dot{Q}_{I,2}^{*}\right)^{1/3} \cdot \left[(\xi - 1) \cdot (\beta^2 + 1) + \xi \cdot C_T \cdot \left(\dot{Q}_{I,2}^{*}\right)^{2/3}\right]}\right]^{2/5} \quad \text{(A5.18)}$$

with

β^2	0.913 (ratio of temperature to velocity in profile) [-]

These quantities are used for a modified input to the centerline temperature or ceiling jet temperature. They also result in a modified room height H_2:

$$H_2 = H_1 - z_{I,1} + z_{I,2} \quad \text{(A5.19)}$$

and

$$\dot{Q}_2 = \dot{Q}^*_{I,2} \cdot \rho_s \cdot c_p \cdot T_s \cdot g^{1/2} \cdot z^{5/2}_{I,2} \tag{A5.20}$$

ρ_s and T_s are the new ambient conditions with the values from the hot gas layer, where

$$\rho_0 \cdot T_0 = \rho_s \cdot T_s = 353\ \text{kg}/(\text{m}^3\text{K}) = \text{const.} \tag{A5.21}$$

From these values, the temperature under the ceiling (r = 0) is now calculated by inserting the new values into the following equation:

$$T_p = T_s + 25{,}5 \cdot \frac{\left(\left(1-\chi_r\right) \cdot \dot{Q}_2\right)^{2/3}}{H_2^{5/3}} \tag{A5.22}$$

The calculated temperature increase is added to the temperature T_s prevailing in the hot gas layer and results in the temperature under the ceiling above the source of the fire.

If the temperature development at a distance r from the plume axis is calculated, a modified approach for the ceiling jet temperature is available [5.17].

$$\Delta T_{jet} = \frac{C}{r^{\gamma}} \tag{A5.23}$$

$$C = k \cdot r_0^{\gamma} \cdot \Delta T_p \tag{A5.24}$$

$$k = 0{,}68 + 0{,}16 \cdot \left(1 - e^{-d}\right) \tag{A5.25}$$

$$r_0 = 0{,}18 \cdot H \tag{A5.26}$$

$$\gamma = \tfrac{2}{3} - \alpha \cdot \left(1 - e^{-d}\right) \tag{A5.27}$$

$$T_{jet} = T_s + \Delta T_{jet} \tag{A5.28}$$

with:

ΔT_{jet}	Temperature difference between ceiling jet and hot gas layer [°C]
T_{jet}	Ceiling jet temperature [°C]
T_s	Smoke gas temperature [°C]
H	Distance between fire source and ceiling [m]
d	Thickness of the smoke gas layer [m]
α	Constant (0.44) [-]

Even with these modified approaches, the boundary conditions should be taken into account. Just like the approaches without consideration of the smoke gas layer, attention should be paid to the spread and location of the fire source. For example, in the case of fire sources near a wall or a corner, the mixing ratios in the plume change, which leads to changes in temperature profiles.

Table A 5.1 Summary of Plume formulas according to BSI DD 240:Part1:1997 Fire Safety Engineering in Buildings. Guide to the application of fire safety engineering principles and Part 2:1997 Fire Safety Engineering in Buildings.

Line	Geometry	Other conditions, scope of validity	Formula	Range of β according to BSI DD 240: part 2:1997	Comment
1	Axial symmetry, pool fire, small fire surface, no wall influence	$D \leq z / 10$ $z >> z_{fl}$	$\dot{m}_e = 0.071 \cdot \dot{Q}_P^{1/3} \cdot (z - z_0)^{5/3}$	0.7 ... 1.5	Influence of ambient turbulence + 20 % to + 50 %
2	small fire surface, also deviating from axial symmetry, no wall influence	Length < 3 x width (in relation to the base area)	$\dot{m}_e = 0.071 \cdot \dot{Q}_P^{1/3} \cdot z^{5/3}$	not specified	Simplification; without virtual origin
3	flow adjacent to flat wall	$D \leq z / 10$ $z >> z_{fl}$	$\dot{m}_e = 0.044 \cdot \dot{Q}_P^{1/3} \cdot z^{5/3}$	0.6 ... 1.6	Influence of ambient turbulence + 20 % to + 50 %
4	flow adjacent to wall corner	$D \leq z / 10$ $z >> z_{fl}$	$\dot{m}_e = 0.028 \cdot \dot{Q}_P^{1/3} \cdot z^{5/3}$	0.5 ... 2.0	Influence of ambient turbulence + 20 % to + 50 %
5	Axially symmetric smoke gas column, large fire surface, round or square	$D > z / 10$ (i.e. up to limited heights) $z < 2.5 \times U$ $200 < \dot{q}'' < 750$ [kW/m²].	$\dot{m}_e = 0.188 \cdot z^{3/2} \cdot U$ (Gl. 31 DD 240:part 1:1997) $\dot{m}_e = 0.337 \cdot z^{3/2} \cdot U$ (small rooms, prEN 12101-5)	0.75 ... 1.15	

6	Line source	Length D > 3 x width of narrow side z_{fl} < z < 5 x D	$\dot{m}_e = 0.21 \cdot \dot{Q}_P^{1/3} \cdot D^{2/3} \cdot z$	0.86 ... 1.36	Application limit of z ≥ 2 x D, for z ≥ 5 x D Gl. after line 2
7	Line source	Length D > 3 x width of narrow side z > 5 x D	$\dot{m}_e = 0.071 \cdot \dot{Q}_P^{1/3} \cdot z^{5/3}$	not specified	
8	Plume over fire zone opening (1); mass flow from fire zone	b_F / L ≥ 1	$\dot{m}_e = 0{,}09 \cdot \left(\dot{Q}_P b_F^2\right)^{1/3} \cdot h$	0.7 ... 1.1	Developing fire (pre-flashover); bF / hF 1≥
9	Plume above fire zone opening (2), mass flow sucked into the plume above the opening	b_F >> h, for other opening geometries etc. see NFPA 92 B	$\dot{m}_e = 0.23 \cdot \dot{Q}_P^{1/3} \cdot b_F^{2/3} \cdot (z_F + h)$	0.7 ... 1.5	free smoke gas, when leaning against a upright wall reduce $\dot{m}_e$ by 1/3
10	as above, but with balcony and smoke barriers outside the fire zone	l_{RS} >> h_B	$\dot{m}_e = 0.36 \cdot \dot{Q}_P^{1/3} \cdot l_{RS}^{2/3} \cdot (z_B + 0.25 \cdot h_B)$	0.7 ... 1.4	see comment (+++)
11	as before, but without smoke barriers		$\dot{m}_e = 0.36 \cdot \dot{Q}_P^{1/3} \cdot (b_F + b_B)^{2/3} \cdot (z_B + \frac{h_B}{4})$	0.7 ... 1.4	see comment (+++)

(+++) Comment on lines 10 and 11:

At higher levels, it is assumed that the flow becomes axially symmetrical. When z > 5 h or z > 3 h_B, the equation according to line 1 can be used if this leads to a conservative result (i.e. a larger value). However, if the criterion for risk assessment is smoke gas temperature or smoke concentration, then the lower value is used to obtain a more conservative solution. However, the latter comments are independent of the confidence interval of the parameters mentioned in the table.

DESCRIPTION OF THE EXPERIMENTAL MODELS

A5.2 General Information

With regard to the experimental models, a distinction is made between investigations on scaled-down models and specific experiments on a 1:1 scale.

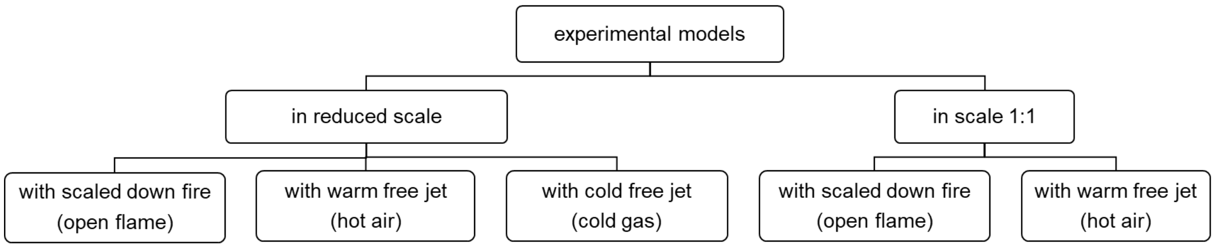


Figure A 5.4 Overview of the experimental models

The representation of a fire event with the aid of an experimental model is not about reproducing the fire itself but rather about the investigation of the fire-influenced airflow beside the investigation of smoke gas distributions and smoke gas flows in buildings and the design of smoke extraction systems.

The flow processes in the building during a fire are essentially determined by the thermal jet (plume) developing above the source of the fire, which acts as a nonisothermal free air jet in the room.

Unlike isothermal free jets, where the increase in volume caused by induction is directly proportional to run length, with warmer jets (in relation to the surroundings) the volume increases disproportionately to the run length of the jet. Even though the term "nonisothermal" refers to an unequal temperature, the difference in density with its buoyancy effect is the decisive criterion. The exponent of the mass increase with an anisothermic free jet over the distance was set at approximately 5/3 determined in [5.37], [5.40]. Several tests showed that this applies equally to thermal jets of lower and higher overtemperatures [5.41], [5.42], [5.59], [5.60].

Simulations with experimental models can be carried out by simulating the thermal jet or by real fires reduced to scale.

A5.2.1 The concept of similarity

The aim of using experimental models is the clear visualization of the smoke, which should be as similar as possible to real events, on a realistic model. Ideally, the model should show identical instantaneous images as in reality for the smoke gas distributions characterised by mixing, dispersion processes, inflow and outflow of the gases - only reduced or enlarged in the length scale with regard to all three dimensions, shortened or stretched in the course of time and correspondingly in other scales.

In the theory of similarity, mechanical similarity is when – with the exception of proportionality of the external measurements in all three dimensions and proportionality of surface properties – proportionality is present for all mechanical parameters involved in the flow [5.42], [5.43].

The laws of model experiments and, consequently, the rules for the implementation and evaluation of model experiments, are obtained from relationships between the values which describe the physical process under consideration. For the nonisothermal, turbulent flows present in a fire, these include the differential equations of:

- Motion and
- Energy

The equations of motion represent the equilibrium of forces related to a unit of volume. Dynamics (motion) is the consequence of acting forces. Equal force ratios (i.e. quotients) of friction, inertia, and acceleration forces lead to similar movements.

The same applies to the balances for energy flow (heat transfer, heat conduction, heat conversion through viscosity). In the energy equation, the equilibrium of the heat output per unit volume is shown by transport and conduction, and in the heat transfer equation, the heat transferred per unit area corresponds to the heat flow transported in the boundary layers.

By forming ratios with two balanced values of force or fluid (of the same unit) in each case, dimensionless values are obtained, the so-called “dimensionless numbers”. These determine the similarity of the processes they characterise. If in the example of the three values which influence motion – drive (e.g. buoyancy, pressure, gravity), inertia and friction – two of them are added to the ratio of forces, the third, neglected, type of force must therefore play something of a minor role.

Table A 5.2 Dimensionless numbers from the field of dynamics and their meanings

Type of the forces	Quotient	Name	Application
Compression: Inertia	$Eu = \frac{p}{w^2 \cdot \rho}$	Euler number	Pressure differences, e.g. suction
Inertia: Gravity	$Fr = \frac{w^2}{g \cdot L}$	Froude number	negligible gas density
Buoyancy: Inertia	$Ar = \frac{g \cdot L}{w^2} \cdot \frac{\rho_\infty - \rho}{\rho}$ $Ar = \frac{g \cdot L}{w^2} \cdot \frac{T - T_\infty}{T_\infty}$	Archimedes number	Relevance of density differences, e.g. Plume
Buoyancy: relative inertia	$Ri = \frac{g \cdot \Delta L}{(\Delta w)^2} \cdot \frac{\Delta\rho}{\bar{\rho}}$	Richardson number	Stability Gas stratification for media with the relative velocity
Inertia: Friction	$Re = \frac{w \cdot L}{\eta/\rho} = \frac{w \cdot L}{\nu}$	Reynolds number	Turbulence behaviour Flow

Equations of motion and derived quantities

For areas of powerful acceleration, where friction can be ignored, all ratios which put a drive value into relation with inertia are relevant – for example, the Euler number Eu with drive from external pressures and the Archimedes number Ar with the buoyancy dominant in the plume area.

If the driving force decreases compared to the frictional force, the ratio of forces between inertia and friction will thus characterise the motion and turbulence of the flow. This is expressed by the Reynolds number Re. Large Re numbers mean a rather turbulent flow; small Re numbers mean a laminar flow, with the transition area for free jets set at 3000. Here, the “thermal plume” of the fire plume is always regarded as a *turbulent* free jet; area fires and the vicinity of larger fires almost always exhibit turbulent flow behaviour.

Energy equations and derived quantities

From the energy equation follow primarily the Grashof number Gr and the Prandtl Number Pr, with the heat transfer equation providing the similarity criterion according to Nusselt Nu.

Table A 5.3 Dimensionalless numbers from the energy sector and their meaning

Meaning of the forces	Quotient	Name	Application
$\frac{\text{Buoyancy}}{\text{Inertia}} \cdot \left(\frac{\text{Inertia}}{\text{Friction}}\right)^2$	$Gr = \frac{g \cdot L^3}{\nu^2} \cdot \frac{\rho_\infty - \rho}{\rho}$ $Gr = \frac{g \cdot L^3}{\nu^2} \cdot \frac{T - T_\infty}{T_\infty}$	Grashof number	Free convection flow on surfaces
Toughness: Thermal conductivity	$Pr = \frac{\eta \cdot c_p}{\lambda}$	Prandtl number	Free and forced convection
Transp. heat quantity: Heat dissipation	$Nu = \frac{\alpha \cdot l}{\lambda}$	Nusselt number	Forced convection

A5.2.2 Properties of the plume and the Archimedes number

Above the combustion zone of a local fire, so-called thermal plume occurs, which is also referred to as the “similarity area”. The thermal plume (like non-isothermal free jets in general) is similar to itself, i.e. at sectional planes at various heights, profiles for velocity, temperature increase and concentration will always be similar across the sectional plane, which expands with height. In addition, the sectional planes of smaller fires are similar to those of larger fires, only at a different plume height, with a different amount of expansion and different peak values. The decrease in the maximum value located on the plume axis takes place in line with [5.51].

temperature increase: $$\Delta T \approx \dot{Q}^{2/3} \cdot h^{-5/3} \tag{A5.29}$$

velocity: $$w \approx \dot{Q}^{1/3} \cdot h^{-1/3} \tag{A5.30}$$

One can compare the temperature increases in the plume of two fires with each other or the same fire at different heights by forming the temperature increases coefficient $M_{\Delta T} = \frac{\Delta T *}{\Delta T}$;

therefore, this temperature ratio can be expressed by the energy ratio $M_Q = \frac{Q *}{Q}$ and

the length ratio ($M_L = \frac{h *}{h}$ the "length scale")

$$M_{\Delta T} = \frac{\Delta T*}{\Delta T} = \left(\frac{Q*}{Q}\right)^{2/3} \cdot \left(\frac{h}{h*}\right)^{5/3} = M_Q^{2/3} \cdot M_L^{-5/3} \tag{A5.31}$$

The same can be done with the velocity, by

$$M_w = \frac{w*}{w} = \left(\frac{Q*}{Q} \cdot \frac{h}{h*}\right)^{1/3} = \left(\frac{M_Q}{M_L}\right)^{1/3} \tag{A5.32}$$

Or by:

$$M_w = \frac{w*}{w} = \frac{h*}{t*} \cdot \frac{t}{h} = \frac{h*}{h} \cdot \frac{t}{t*} = \frac{M_L}{M_t} \tag{A5.33}$$

which requires a "time scale" M_t for illustrating the thermal plume:

$$M_t = M_Q^{-1/3} \cdot M_L^{4/3} \tag{A5.34}$$

For demonstrating fire smoke in the experimental model, the source of smoke generation and all buoyancy-induced air flows are of particular importance. It means the Archimedes number is of primary importance and should have the same value in the model as in reality (with the same reference value and the same location).

The following formula is always true for the thermal plume of fire,

$$M_{Ar} = M_Q^{2/3} \cdot M_L^{-2/3} \cdot M_L^{2/3} \cdot M_Q^{-2/3} = 1 \tag{A5.35}$$

which means that the Archimedes number is a constant for all local fires [5.43],[5.60].

A5.2.3 Reproduction range and reproduction rules

Even with the application of hot smoke or light gas [14]- despite a flow profile which, when introduced by a machine at the outlet, usually differs from the flow profile of the non-isothermal free jet – a fully-developed flow profile of an anisothermal free jet occurs after a certain distance and obeys similar laws to the plume above the combustion zone. In order to transfer volume flows, time scales and density (or temperatures) from the events of the model to a particular fire, the Ar number for the model and the fire must be set equal at relevant points [5.46], [5.62].

This applies in particular to the source area of the smoke development. For the introduction of fire gases by a machine, a fire with pyrolysis, flames and combustion is faded out [15]. Hence there is an interface between the faded out fire and the plume of smoke gas which is produced. Here the density difference, outlet volume flow and the associated outlet area or initial momentum – in relation to the chosen length scaling of the model enclosure – must be taken into account. Thus the actual area to be reproduced only begins considerably above the outlet.

The time scale and the associated scales of velocity, volume flow etc. result from the chosen scale of length of the model and another appropriate relationship (e.g. equal density for light gas).

[14] When using light gas, the flow should be fully turbulent.
[15] When using light gas and elongated buildings, the heat transfer conditions are insufficiently taken into account.

Even with the 1:1 model and reduced heat release compared to the real fire, similarity in smoke production (with more considerable errors in the area of heat transfers) can be reconstructed with a scale factor for time derived from compliance with the Archimedes [5.59], [5.60],[5.63], [5.64].

The plume equations are also used for allocating a heat release equivalent to this model fire for the real scale scenario which, under consideration of the derived time scale and the specified length scale, would result in comparable mixing behaviour, smoke gas volume etc. Unfortunately, numbers describing other relevant aspects (turbulence, heat transfer) cannot be adhered to at the same time. References for different model-related boundary conditions are suggested in [5.43].

A5.2.4 Notes on modelling, model scale and model design

Models should be designed in a way that all details influencing the flow are represented on a real scale. This requires very careful model construction since deviations in geometric similarity can have a very strong effect on the transferability of the results. This also concerns the area of the fire to be simulated [5.46], [5.54].

Through various applications, which began in the 1960s and 1970s [5.52], [5.54], it has been proven that in free, turbulent flows, the Re-number remains of minor influence, and above all, the variables describing the flow process Ar number, and the system boundary Eu number must be observed. It is a necessary condition for investigations of flow processes in models with the reduced scale that the flows are fully turbulent both in nature and in the model. For this purpose, Re > 10,000 for models with reduced scale has proven to be the best choice.

In order to fulfil this condition, the models for the investigation should be as large as possible. The model scale M ≥ 1:20 (1:30 for very large buildings) has proved to be an empirical value, where room heights in the model should not be less than 300 mm. For smaller models M < 1:20, large deviations between natural and model flow are expected, which usually leads to an over dimensioning of the smoke extraction [5.46].

An exception is the flow situation in building aerodynamics because due to separation effects on sharp-edged building models, the total flow in the wind tunnel can be considered as turbulent, and no large temperature differences need to be considered [5.44], [5.46].

Table A 5.4 Fire effects in the original and in the model

Fire effect	Realizable in the model (scaled down)
Real temperatures	Yes, temperature fields are similar; with scale sizes < 1:10 associated with higher uncertainties
Heat release	Yes, it can be converted
Smoke gas flow	Yes, Plume equations apply with consideration of the model scale
Smoke gas propagation	Yes, the similarity of the flow processes
Inflow and outflow gas	Yes, as long as comparable boundary conditions to the environment are maintained
Flame formation	Yes, ≥1:5, flame height, temperature and flow in the flame (only for models according to 5.4.6.1)
Low smoke layer	Yes, observation
The heat load of structural components	no

For the investigation of wind influences, the model should be investigated in a boundary layer wind tunnel. Here, the size of the wind tunnel generally determines the size of the models. Typical model scales are 1:50 and 1:100 for very large buildings. It means, to a certain extent, the effects on internal flows of the room can be qualitatively represented [5.64].

During the smoke observation, smoke or a fog fluid (long-lasting fog) is added to the simulated fire event. The quantification, e.g. of the height of the low-smoke layer, is done visually. The local dilution of fire gases can be quantified using the trace gas method. For fire tests on reduced-scale models, the smoke propagation can also be checked by means of temperature measurement.

A5.2.5 Special features of individual model types

In the following, some specific features of different models will be discussed. For the model types with hot air jet and light gas, see the following references [5.62], [5.67], [5.68].

A5.2.6 The scaled-down fire with identical temperature image

If the fire is scaled in true scale, the temperature behaviour at a similar point in the model and the real fire should be identical, then the heat release of the model must be scaled according to the length scale of the model with $M_{\Delta T} = 1$

$$M_Q = M_L^{5/2} \tag{A5.36}$$

If the heat release is specified according to eq. (A5.36), the scale for time follows the model scale directly (length scale), and consequently, the scales for velocity and volume flow [5.43]

$$M_t = M_L^{1/2} \tag{A5.37}$$

$$M_w = M_L^{1/2} \tag{A5.38}$$

$$M_{\dot{V}} = M_L^{5/2} \tag{A5.39}$$

Especially for the small-scale low-energy fire, with the maintenance of the temperature increase in the thermal plume, far-reaching parallels to the large fire event must be established. For this purpose, length scales of less than 1:10 (better 1:5 and smaller) should be observed since the combustion area cannot be scaled and the combustion zone in the model exceeds the analogous dimensions in the original [5.42].

Checks at different measurement locations show that the Ar, Fr and Eu numbers for the model can be kept within the limits of -15 % to 25 % deviation from reality. For [5.42] the "method of approximate modelling" [5.65] is applied, which means that, depending on the objective, the relevant significant similarity numbers should be considered.

A5.2.7 Tests on a scale of 1:1 (object-related tests)

Object-specific smoke tests can be carried out after the completion of a building to test the fluidic effectiveness of smoke extraction systems.

Practical testing as a functional test of smoke extraction concepts under realistic fire conditions is generally ruled out. Only model tests can be carried out in the building, which should provide results as close to reality as possible.

For practical testing of smoke gas flows in the building, heated air or open pool fires with liquid fuels or gas burners can be used. To visualize the smoke gas flows, aerosols from fog fluids are usually added above the flame zone. Detailed information on acceptance tests can be taken from the technical report of the vfdb [5.47] or the VDI guideline 6019 part 1 [5.53].

The following boundary conditions must be observed for carrying out such tests:

- All equipment necessary for the function of the smoke extraction system (e.g. air supply openings, smoke barriers, alarm systems, backup power supply, door controls) should be installed and functional and should be operated according to the intended function during the performance of the test.
- Details in the building and installations that influence the smoke gas flow (e.g. guard rails, sun protection devices) should be available or carefully reproduced in terms of flow technology.
- Ventilation and air conditioning systems should be available as planned and operate according to the concept of smoke extraction.
- The building envelope and the elements closing the openings should be completely available and functional.

The tests should be adequately documented.

The following procedures are available for carrying out object-specific acceptance tests:

- Heated air (up to approx. 150 kW heat release)
- Heated air (up to approx. 1.5 MW heat release with gas burners or pool fires)

For extrapolating to fires with higher heat release, transfer functions from the similarity theory of fluid mechanics should be applied [5.43].

A5.2.8 Special features of wind tunnel investigations

The simulation of atmospheric wind flow is not possible in the wind tunnels of aerospace engineering. The field of structural aerodynamics, which emerged in the 1960s, necessitated the development of a new type of wind tunnel, which is the boundary layer wind tunnel. In this wind tunnel, the atmospheric wind boundary layer, described by the profiles of the mean wind speed and the turbulence intensities, as well as the spectrum of the turbulence energy. Boundary layer wind tunnels always have a start-up section, in which suitable roughness is applied to the wind tunnel floor. More details about boundary layer wind tunnels and the simulation of atmospheric wind flow can be found in [5.45] and [5.46].

For considering the influences of wind, it is important to scale the size of the turbulence bale (by gustiness) at least approximately according to the applied building scale. The similarity index for considerin this effect is the Jensen number:

$$Je = \frac{h}{z_0} \tag{A5.40}$$

with:

h: Building height

z_o: Roughness parameter

For modelling, the atmospheric wind flows in the wind tunnel, refer to the booklet of the wind technology association (Windtechnologische Gesellschaft -WtG) [5.46].

A5.2.9 Summary

The experimental models are particularly suitable for the creation of smoke extraction concepts and for the evaluation of smoke gas flows in buildings - even with complex structures. The buildings or rooms under investigation should be reproduced in a similar manner on the appropriate scale, including all details relevant to the flow. In addition to the geometric similarity, the physical similarity should be maintained.

The similarities describing the flow processes, which can be derived from the above equations, for motion, energy conservation, and heat transfer for free turbulent flows. This also sets the aforementioned limits on the model scale. In addition to the necessary experience of the modeller, e.g. with regard to the formation of the required turbulent flows on the model, precise knowledge of the boundary conditions and input data is necessary - e.g. to the extent that the simulation - in contrast to zone and CFD models - can only be started in the plane above the flame peaks (flame peaks must always be below the smoke gas layer). For a scaled-down fire, the combustion zone is modelled approximately.

The heat dissipation to components is not represented in the experimental models according to reality - they are therefore not suitable for determining component temperature! Model investigations and comparisons with experimental models, zone and CFD models as well as original fire tests showed a relatively good agreement with regard to smoke gas flows, temperatures and stratification for the scenarios investigated.

The main advantages of the experimental model investigations lie in their very clear presentation of the results, the parameter changes that are easy to make with regard to the flow conditions and effective structural parameters on the model body, with the immediate evaluability of their influences on the result.

Like mathematical "models", a model is always the representation of a real event with certain restrictions, simplifications: i.e., selected phenomena should be considered and investigated, and the other parameters can be neglected (e.g. the thermal destruction of components).

EXAMPLES OF CALCULATIONS WITH MATHEMATICAL MODELS

A5.3 Preliminary remarks

The following sub-chapters have a variety of functions. On the one hand, they are intended to provide an overview of comparative calculations but also to give hints on error ranges and limits for the application.

A5.3.1 Plume temperature and ceiling-jet

In the following, the equations given in Annex A5.1 are used to determine the ceiling temperatures above the fire source in pool fire tests with ethanol. These are tests which were carried out in a fire zone with a floor area of approx. 40 m^2 and a room height of approx. 6.20 m [5.18]. In the carried out tests, the size of the ethanol pool and the heat release rate and the position of the pool in the fire zone were varied. In addition, the ventilation was changed via windows in the walls or via horizontal openings in the fire zone ceiling. Furthermore, the influence of different window materials was investigated:

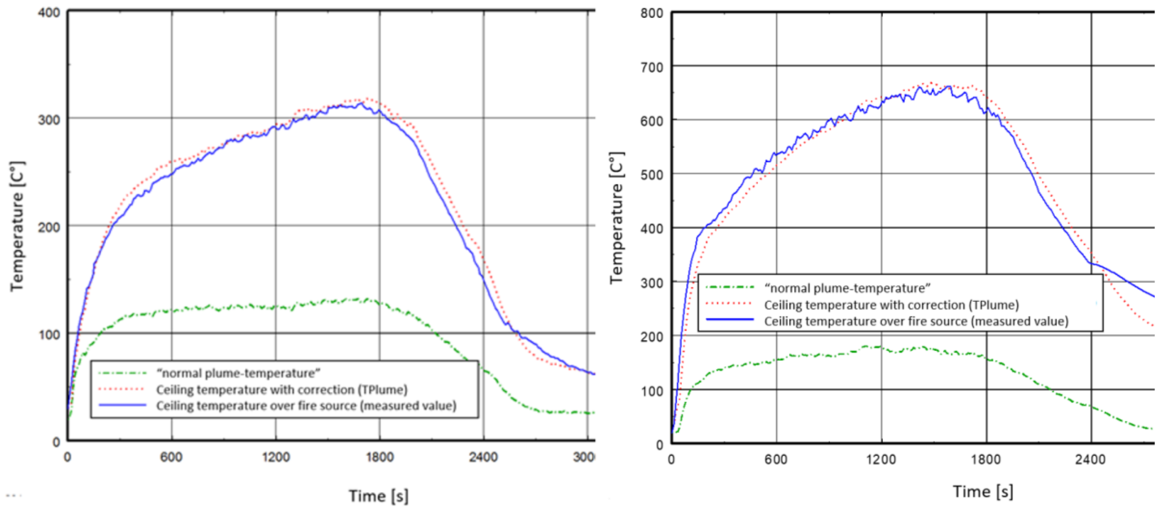


Figure A 5.5 Measured and calculated ceiling temperature in a pool fire, the left figure approx. 1 MW firepower; corner position of the fire source, the right figure approx. 1.8 MW firepower; fire source in the middle of the fire zone [5.18]

Tests with 120 l of ethanol were carried out in two adjacent bathtubs with a total surface area of 1.5 m^2 The result was a fire output of approx. 1 MW. For further tests with the firepower of approx. 1.8 to 2 MW, a fuel quantity of 200 l ethanol in a 3 m^2 bathtub was used. The height of the burning surface was approx. 0.7 m above the floor of the furnace. Figure A 5.5 shows the results of the calculations [5.18]. The calculated values are marked as "normal" temperature without taking the correction into account.

It is shown that the consideration of the correction is necessary to achieve an adequate description of the temperature level.

Further comparisons of the calculated temperatures with the measured values from large fire tests [5.17] show that the above approach approximates the test values well (Table A 5.5).

Table A 5.5 Comparison between measured values and formulas

$\dot{Q}$ [MW]	ΔTp Measured value [K]	ΔTp Eq. (A5.22) [K]
7.7	102	98
15.7	116	126
33	222	217

Another interesting comparative test is provided by the experiments in a hall with 144 m x 65 m x 28 m (L x W x H) dimensions [5.70]. Here, wooden pallets used for fire load (approx. 3,500 kg). In this experiment, temperatures were measured at various locations above the source of the fire at the height of between 10 m and 22 m. Due to the size of the hall and the existing smoke and heat extraction systems in the roof, the average smoke gas temperature in the time range of the maximum fire load was between 40 °C and 60 °C, but the temperature values in the area close to the fire were significantly higher. Another important aspect of this comparison is, although the rate of combustion was measured, it is subject to considerable fluctuations. For the calculation, an effective heating value should be assumed in order to specify the heat release rate. This effective heating value was determined by tests from the cone calorimeter at 12 MJ/kg.

Figure A 5.6 shows the comparison of the measured temperature values with the calculated temperature values. The formulas, according to Appendix A5.1, were used here. Although the heat release rate assumed for the calculation is subject to errors, a remarkably good agreement can be seen in the results.

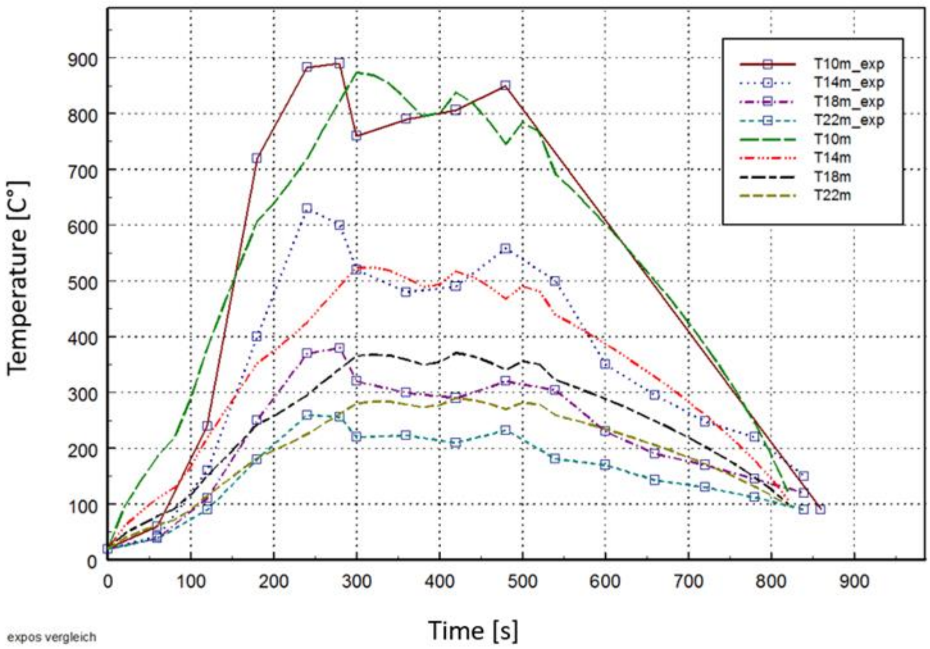


Figure A 5.6 Comparison of the temperature development at different heights above the source of the fire in the experiment and after calculation

From these comparisons with the measured values of fire tests, the following conclusions can be drawn for the application of the presented equations. The comparisons with the temperature values or temperature profiles determined by experiment show that the calculated temperatures on the plume axis are in no way fictitious – they represent the maximum temperatures in the section of the fire area indicated by the measuring grid. As these grids cover a section of the area several cubic metres large, one should certainly not imagine these maximum temperatures as being confined to one spot.

In addition, the individual measured values themselves (Table A 5.5) represent average values over a certain measuring interval, with the fluctuations down to the turbulent structure of the flow in the plume area. For the design of structural elements, it must therefore be checked whether average temperature values or the local maximum temperature, which can be calculated using the above equations, is used. This is particularly advisable for frame members or trusses as part of complex supporting structures. The use of average temperature values must be justified on an individual basis.

Experiments conducted in a large hall of the Underwriters Laboratories provide a large number of possibilities for comparison [5.71]. The special feature is that a ceiling panel with approx. 30 m x 30 m dimensions can be adjusted to variable heights. Figure 5.10 below shows a comparison between experiment and calculation for test-4, which was carried out at a ceiling height of 7.6 m and a heat release rate of approx. 4 MW (at maximum). The above-mentioned equations were used here. In contrast to the previous study, this one includes a comparison of the temperature developments at different distances from the fire site. This is expressed by the numbers shown in the caption (Figure A 5.7).

The exact boundary conditions for the ones presented here can be taken from the literature given.

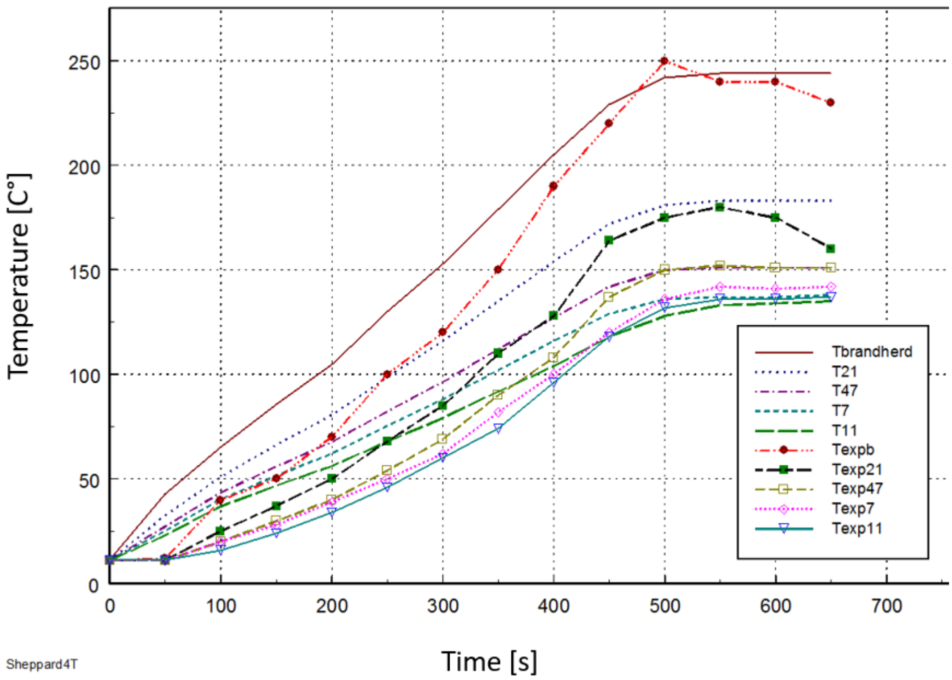


Figure A 5.7 Comparison of the temperature developments in the experiment and calculation at different distances from the fire location (2.1 m, 4.7 m, 7 m and 11 m)

A4.2.1 Examples and experiments for comparative calculations

For the evaluation of models, suitable experiments for comparative calculations are necessary. With regard to the experiments, it is easy to formulate high requirements regarding the scope of the measurement and the reproducibility, but this is the ideal situation. Unfortunately, such experiments, if exist, are available on a very limited basis. Often a limited selection of measurements is available. The comparative calculations should, therefore, be limited to these results.

In addition to these metrologically oriented criteria, there are other cases, e.g. the informative results of the experiment with regard to the practical application, i.e. evaluating the same or similar boundary conditions in practice repeatedly. A further criterion is whether the experiments or examples are suitable for producing the results of different model types.

In the following, an attempt is made to give the first combination of such experiments and exemplar calculations. According to the available data, the minimum information is:

- geometry,
- inlet and outlet air openings,
- information on the fuel and the course of the fire,
- information on the temperature level, and
- information on the height of the low-smoke or smoke-free layer.

Two fire experiments were selected for the evaluation of atria or halls.

Experiment 1

The experiment took place in an atrium with (L x W x H) 30 m x 24 m x 26.3 m size, in which a pool fire generated with the firepower of 1.3 MW [5.32]. The inlet air opening is 3.2 m^{2,} and the SHEVS in the surrounding walls has 6.4 m^2 area. The measurements during this fire test were very extensive, and the values for temperature and smoke-free layer are available with good accuracy. The results of the comparative calculation are shown in Figure A 5.8. It shows that the experimental results are reproduced with sufficient accuracy, and the differences are shown mark the error.

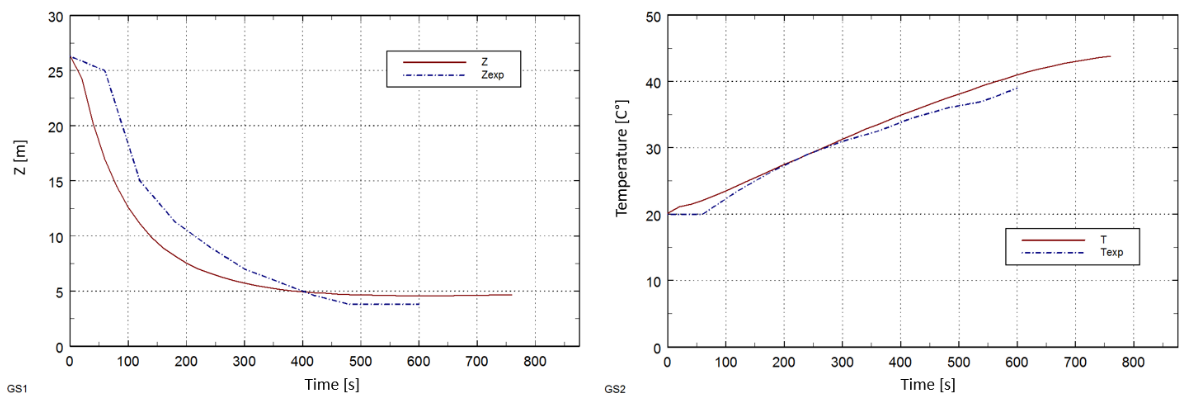


Figure A 5.8 Comparison of the results from the experiment and calculation, left figure: smoke-free layer, right figure: mean smoke gas temperature

Experiment 2

The second experiment took place in an aircraft hangar (90 m x 54.2 m x 15 m, L x W x H) [5.33], in which two different fire courses were investigated. Within this room, an area was separated by smoke barriers (20 m x 21 m), which decreased the height to 12 m. Due to the slight roof curvature, a smoke reservoir with 2.5 m - 3 m height is created. The inlet air opening area in these experiments was 16 $m^{2,}$ and the smoke extraction area in the roof was 68 m^2. The following results were recorded:

- Scenario 1 (4 MW): Temperature 50 °C - 55 °C,
- Scenario 2 (36 MW): Temperature 165 °C - 180 °C.

Unfortunately, no exact determination of the smoke-free layer was made, but the observation showed that in both cases, the smoke gases remained within the reservoir. The values calculated with CFAST are shown in Figure A 5.9.

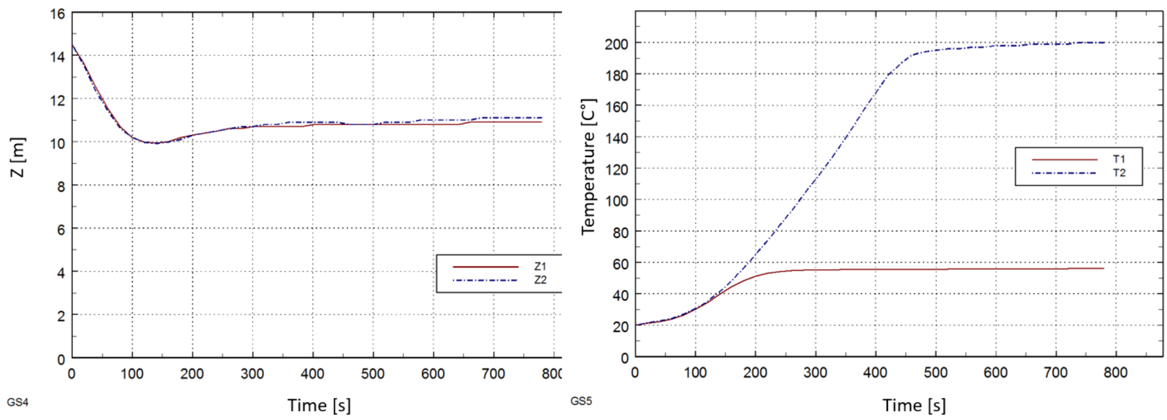


Figure A 5.9 Calculation for the two fire scenarios (4 MW and 36 MW), left figure: the thickness of the smoke-free layer (Z1, Z2), right figure: Average smoke gas temperature (T1, T2)

You can see that the calculated temperature values are at the upper limits of measured values or slightly above them. With regard to the smoke gas layer, it can be seen that the smoke gass extend to a height below the reservoir, i.e. the smoke-free layer is slightly lower than in the experiment. Therefore, the predicted calculation results are on the safe side.

These examples can be supplemented by others, and they show that the zone models provide acceptable results under these boundary conditions with limited areas (see above).

The following systematic application limits can be derived from the experience documented to date: Application limits of zone models are reached in rooms, where the ratios of the spread in the three-dimensional space are below or above certain values. Furthermore, in very high rooms and under boundary conditions, inflow air or other dominant flows have significant influences. For a detailed discussion of the restrictions, please refer to the corresponding chapters of the zone model in the Technical Reference Guide of the CFAST [5.74], which deals with these questions in an exemplary manner. Part of these restrictions can be derived from the basic assumptions of the utilized submodels (see Appendix). For example, the utilized submodel for overflow into other rooms prevents a subdivision into very small zones since the submodel is not suitable for this purpose [5.74].

Unfortunately, exact delimitations cannot be given up to now since relevant experiments are missing. The application limits can be approximated by comparative calculations. This is demonstrated by two examples.

A5.4 Example validation PRISME DOOR

A5.4.1 Experiments carried out

The experiments for the DOOR series (1-5) of the OECD PRISME project [5.81] were carried out in rooms "Room 1" and "Room 2" of the DIVA test facility. This test facility is located in the JUPITER facility, which has a volume of 2,630 m³. Figure 5.10 shows the three-dimensional conditions in which the tests were carried out. Tests 3, 4 and 5 of the test series (PRS_D3, PRS_D4, and PRS_D5) were evaluated.

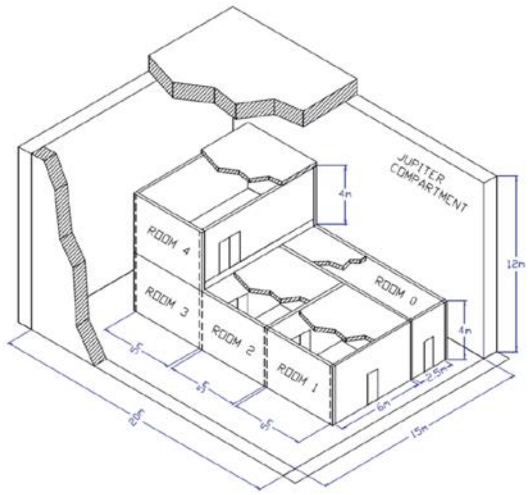


Figure A 5.10 View of the DIVA test facility

Each of the lower, cube-shaped rooms has a volume of 120 m³ with the clear dimensions of 6 m x 5 m x 4 m and is connected to a complex ventilation system, which aerates and deaerates the rooms controlled via inlet (supply air) and outlet (exhaust air) channels. For the DOOR series, the doors between the two rooms involved in the experiment (Room 1 and Room 2) were open. Each door openings size is 0.8 m x 2 m and is located in the middle of the partition walls.

The air exchange rate in the tests PRS_D3 and PRS_D5 was 4.7 1/h and 560 m³/h for both rooms - fire and target room - respectively; in the test PRS_D4, the value was 8.4 1/h and 1,000 m³/h respectively. A rectangular area was modelled as the source of the fire, approximately corresponding to the pool size used in the test (see Table A 5.6).

Table A 5.6 Pool size and air exchange rate during the PRISME-DOOR trials PRS_D3, PRS_D4 and PRS_D5

Trial	Pool size	Air exchange rate
PRS_D3	0,4 m²	4.7 1/h or 560 m³/h
PRS_D4	0,4 m²	8.4 1/h or 1,000 m³/h
PRS_D5	1 m²	4.7 1/h or 560 m³/h

For the "open" comparison calculations, the time courses of the heat release rate (HRR) determined in experiments were known. A value of 45 MJ/kg was used as heat of combustion (HOC). Figure A 5.11 shows the heat release rate for the simulations.

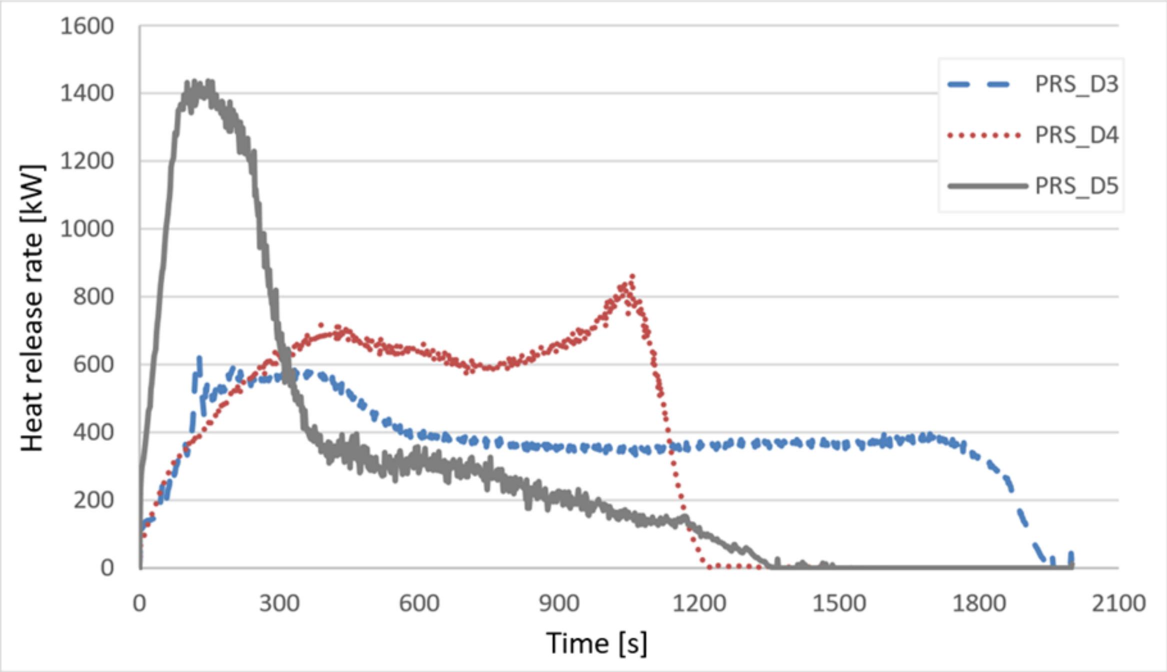


Figure A 5.11 Predefined time curves of the heat release rate (HRR) for the experiments PRS_D3, PRS_D4 and PRS_D5 - open simulation

A5.4.2 Performed simulations

The following Table 5.17 shows the simulations performed with the Fire Dynamics Simulator (FDS). The results of simulations with FDS version 4 [5.84], version 5 [5.85] and version 6 [5.86] are presented and discussed in the following sections.

Table A 5.7 Simulations performed

Trial	Type	Comment	
PRS_D3 PRS_D4 PRS_D5	Open	HRR determined with IRSN proposal ("mechanical method", HOC = 45 MJ/kg); volume flows (Inlet/Exhaust) specified as the boundary condition	FDS version 4.0.7; FDS version 5.5.3 and FDS version 6.0.7
HOC: Heat of Combustion			

The fire simulation model FDS was used without changing the default settings of the respective versions. For the calculations, the temperatures at time t = 0 were measured in the test and were taken as starting temperatures. Objects and enclosure components were thermally considered, and for the one-dimensional heat transfer calculation, the thermal conductivities and the specific heat, if available, were taken as temperature-dependent material properties. For the simulation of the gas phase, a 10 cm grid was used. Controls with finer grids did not show any significant change in the calculated quantities. The calculation of heat conduction into solids is carried out with a much finer grid independent of the gas phase.

A5.4.3 Model structure

Figure A 5.12 shows the used model of the fire and target room with the liquid pool and the inlet and outlet ducts came into the rooms from the top. Furthermore, the examined safety-relevant objects can be seen on the walls in the upper and lower areas of the rooms. The analytical cables (PVC bars) are shown in red, and the real cables in green as cubes.

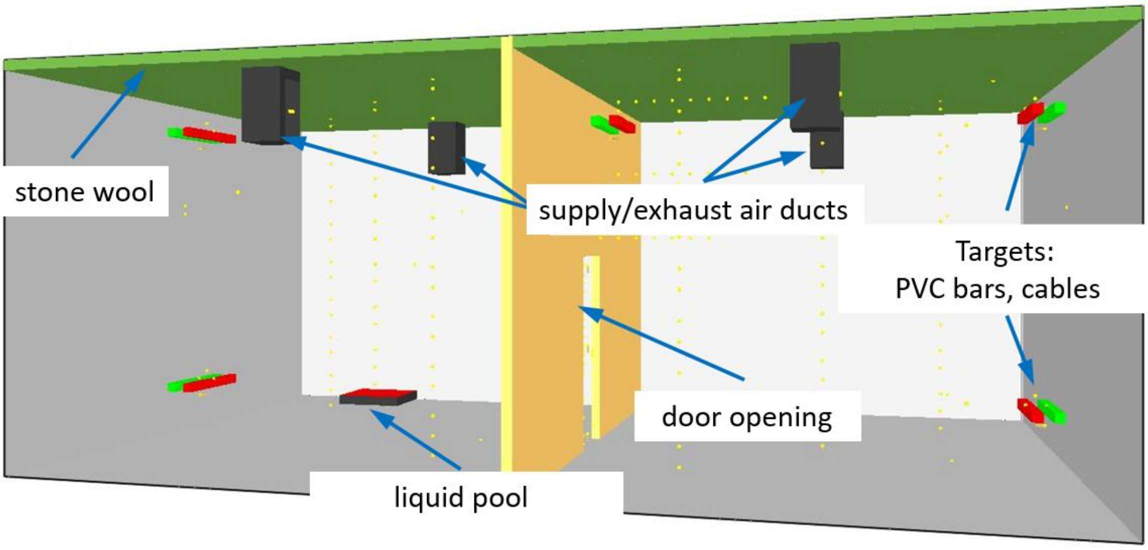


Figure A 5.12 Model of the fire (left, L1) and target (right, L2) room

Table A 5.8 lists the investigated and evaluated measured variables. Although pressure measurements were also carried out, the results on both the test and the simulation were wrong or unrealistic, so this variable was not evaluated.

A5.4.4 Evaluation principles

An evaluation of the results of the DOOR series is based on the approaches from Chapter 1.4.2. The evaluation of the accuracy of numerical predictions is carried out based on the weighted combined expanded uncertainties UCW of the experimental and numerical measured quantities. Table A 5.8 shows the evaluated measured quantities and the specifications for the investigated experiment PRISME DOOR $U_{CW,\,PRS}$. For the evaluation, a data limit was assumed with respect to the evaluation quantities PEAK and NED. Data were excluded from a further evaluation that was outside the interval [-1;1] for PEAK and outside the interval [0;1] for NED. For this investigation, the data that can be inconsistent in the experimental execution or in the model formation in the CFD fire simulation model should be excluded.

Table A 5.8 Evaluated measurements and assumed uncertainties for PRISMEDOOR, $U_{CW,PRS}$, number of evaluated variables

	Evaluated measures	$U_{CW,\,PRS}$ (%)	Number of evaluated variables
CO	carbon dioxide concentration	9	73
CO_2	carbon monoxide concentration	9	58
FLR	Heat flux density Radiative	20	106

FLT	Heat flux density Total	20	197
O_2	Oxygen concentration	9	74
TG	Temperature Gas phase	15	1446
TCA	Temperature of analytical cables	14	135
TCR	Temperature of real cables	14	90
TP	Temperature Surfaces	14	168
V	Speed	20 *)	114
*) assumption was not evaluated in [5.82]			

A5.4.5 Results of the validation

Figure 5.13 shows an overview of all evaluated variables for the experiments PRS_D3, PRS_D4 and PRS_D5 in the form of a scatter plot of the PEAK values above the NED values, differentiated according to the version FDS 4, FDS 5 and FDS 6. In this diagram, the cases in which the simulation values are partly higher than the experimental values, are predominantly assigned to version FDS 4. The results of FDS 5 and FDS 6 show great similarities regardless of the experiments, while the results of the index values for FDS 4 has deviation to some extent.

Evaluation area A indicates the area where the PEAK values do not exceed the estimated uncertainty U_{CW}. For the NED values, a value twice as high as the estimated uncertainty was assumed without further justification. The evaluation area B, this limit was increased in each case by factor 2. In 100% of the evaluated values are located in the C evaluating area, which corresponds (by definition) to a ratio of C = 1.00. The values A, B that are located in the evaluation area A or the evaluation area B are shown (top left) in the figure.

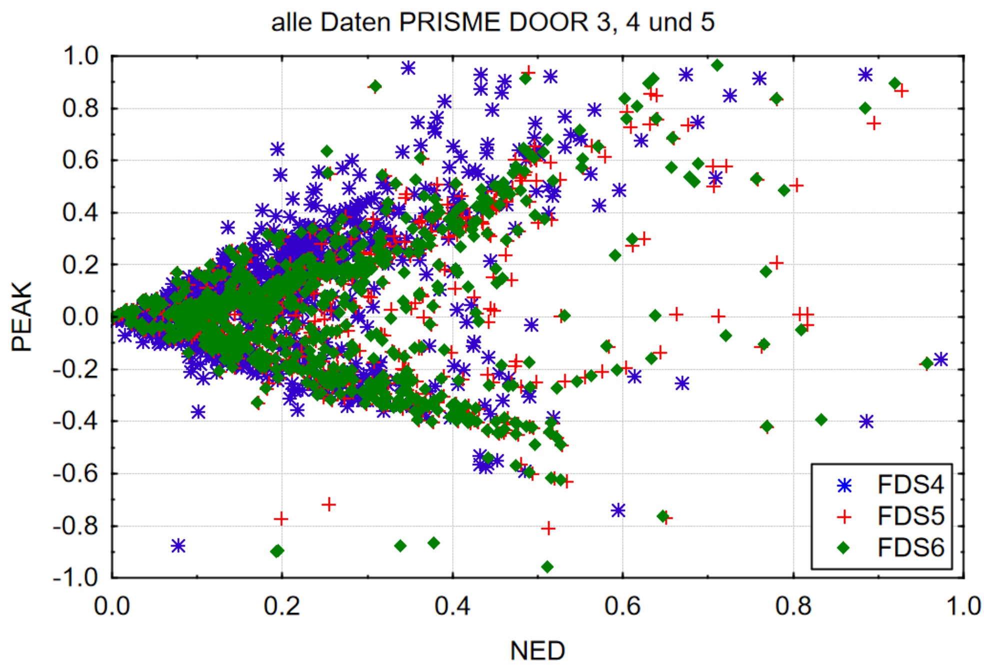


Figure A 5.13 PEAK via NED (all sizes) for PRS_D3, PRS_D4 and PRS_D5 differentiated according to the versions FDS 4, FDS 5 and FDS 6

Figure A 5.14 shows a summary of the frequencies with which the proportions of A and B of the evaluation variables for tests PRS_D3, PRS_D4 and PRS_D5 are available. High frequencies of the proportions correspond to a large agreement between the experimental and numerically data with regard to the evaluation variables PEAK and NED.

The oxygen concentration (O2) and the carbon dioxide concentration (CO2) can be reproduced remarkably well. The results for the temperatures on the surfaces of the enclosure components (TP) are also comparatively good. For the carbon monoxide concentration (CO) and the radiation levels, the median values are larger, and the fluctuations are significantly greater.

Overall, the PEAK values of most of the test parameters are higher than the corresponding values from the experiments, regardless of the version of FDS used. This is not the case at the temperatures of real cable (TCR) and the temperature of analytical cables (TCA); the experimental values are underestimated by the CFD model. This is also the case for the carbon monoxide (CO) values independent of the version of FDS.

With regard to the version, the ratio A for FDS 4 results in lower proportions of oxygen (O2), carbon monoxide (CO), gas temperatures (TG) and radiative heat flux densities (FLR) than in the FDS 5 and FDS 6 versions. These two versions are in better agreement in the comparison values. With regard to proportion B, i.e. basically for larger error limits, higher values for the proportions of version FDS 4 result for all measured variables with the exception of the quantity carbon monoxide (CO).

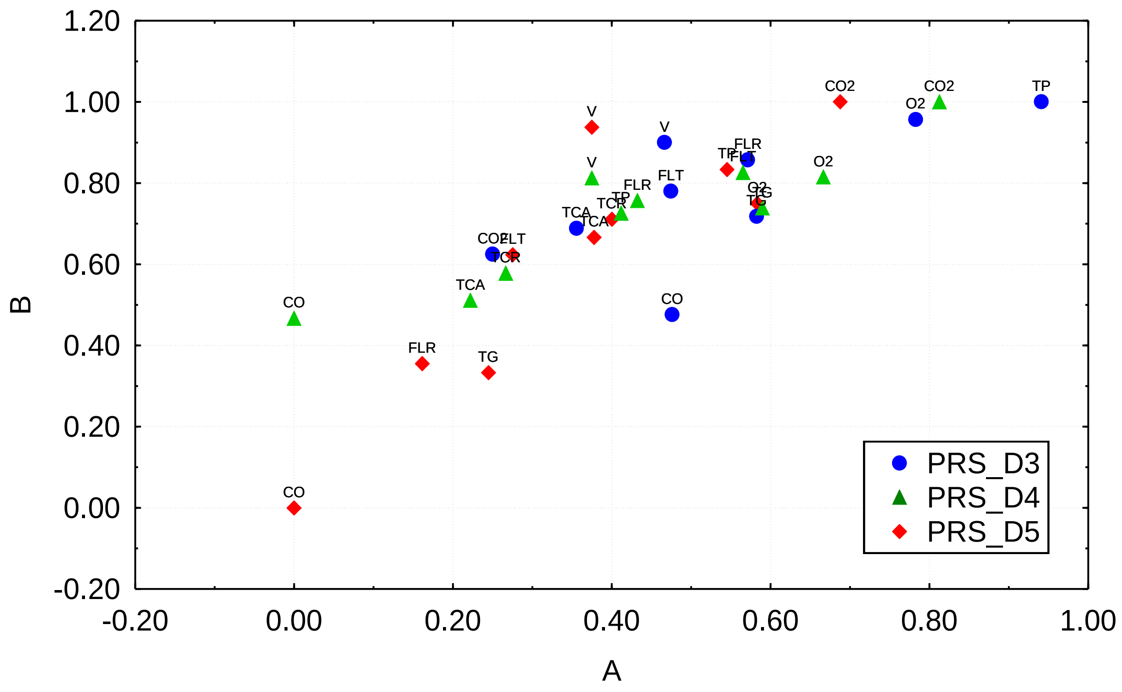


Figure A 5.14 Summarized representation of the proportions A and B of the evaluation variables, experiment PRS_D3, PRS_D4 and PRS_D5

In summary, it can be seen that there is a dependence on the agreement of the results with the test boundary conditions. For the PRS_D3 test, the simulation data agree better with the experimental data for all variables than in the PRS_D4 and PRS_D5 tests. The maximum heat release and ventilation rate of tests are 0.6 MW and 4.7 air changes per hour for PRS_D3, 0.8

MW and 8.4 air changes per hour for PRS_4 and 1.4 MW and 4.3 air changes per hour for PRS_D5, respectively.

6 FIRE SAFETY VERIFICATIONS OF STRUCTURAL ELEMENTS AND STRUCTURES

6.1 Introduction

The fire safety parts of Eurocodes 1 to 6 and 9 [6.1] provide design methods that allow individual fire safety designs for individual structural components as well as for partial and global structures for different utilizations. Alongside fire loads based on nominal temperature curves like the standard temperature-time curve (ISO 834) or the external fire curve, the Eurocodes also allow fire safety design using natural fire curves, which provide a more realistic profile of a real fire (smouldering fire phase, fully-developed fire, cooling phase) than the standard temperature-time curve.

The design rules for structural fire safety engineering are outlined in the parts 1-2 of the Eurocodes, which are hereafter referred to use the abbreviations EC 1-1-2 (for DIN EN 1991-1-2), EC 2-1-2 (for DIN EN 1992-1-2) etc. In addition to the design rules of the Eurocodes, DIN 4102-4 contains specifications and regulations for e.g., design details, dry walls, autoclaved aerated concrete components, historical constructions, special components and lightweight partition walls which are not included in the Eurocodes.

EC 1-1-2 defines the design rules for the action in case of fire. Since fire is an accidental condition design situation, the mechanical actions may be reduced compared to service condition design. The thermal actions on the structural components or the structure can be determined with the help of so-called nominal temperature-time curves or natural fire models.

Heating of the structural components leads to reduced resistance due to the thermally induced decrease in strength coefficients.

For industrial constructions, components can be designed for risk-related fire exposure using the calculation method according to DIN 18230 "Structural fire safety in industrial buildings" (see Chapter 6.9.

6.2 Certification according to the fire safety parts of the Eurocodes

6.2.1 General

For the fire safety design of structural components and structures (Eurocodes 2 to 6 and 9), the fire safety part of Eurocode 1, which considers all building materials and contains information for load assumptions and fire loads, is required in addition to the fire safety part of the building material related Eurocode. In December 2010, the fire safety parts of Eurocodes 1 to 5, 7 and 9 Part 1-2 were published as DIN EN standards (DIN EN 199x-1-2). The first version of the National Annexes was also published in December 2010 with the exception of EC 6-1-2 and EC 9-1-2. The publication of Eurocodes 6-1-2 followed in April 2011 as DIN EN 1996-1-2. The corresponding National Annex was published in June 2013:

EC 1-1-2	DIN EN 1991-1-2	General actions - Actions on structures exposed to fire [6.1].
EC 2-1-2	DIN EN 1992-1-2	Structural fire design for reinforced and prestressed concrete structures [6.2].
EC 3-1-2	DIN EN 1993-1-2	Design of steel structures [6.3].

EC 4-1-2	DIN EN 1994-1-2	Design of composite steel and concrete structures [6.4].
EC 5-1-2	DIN EN 1995-1-2	Design of timber structures [6.5].
EC 6-1-2	DIN EN 1996-1-2	Design of masonry structures [6.6].
EC 9-1-2	DIN EN 1999-1-2	Calculation and design of aluminium structures [6.7].

Currently the Eurocodes are being revised. Drafts are already available for the fire safety parts from EC 1 to EC 5. Basically, this chapter refers to the existing parts of the Eurocodes introduced by the building codes. Insofar as significant changes are planned in the fire safety verifications of the revised Eurocodes, they are presented in this edition of the guideline. The completion of the revision and the introduction of the revised Eurocodes by the building codes is not expected before 2025.

The design rules in the fire safety parts of Eurocodes 2 to 6 and 9 apply only to the building materials and building material qualities listed in the scope of the standards. If other building materials or building material qualities are used, e.g., ultra-high strength concrete with a cylinder compressive strength exceeding 100 N/mm², their suitability in terms of fire safety must be verified by fire tests.

Fire design according to Eurocode 6 Part 1-2 and 9 Part 1-2 is not dealt with in any greater detail in this guideline. The fire safety design of aluminium components is of secondary importance in the field of civil engineering. The design methods in Eurocode 9 Part 1-2 are basically comparable with those in Eurocode 3 Part 1-2 (steel construction).

6.2.2 National Annexes (NA)

For the application of the Eurocodes DIN EN 1991-1-2 to DIN EN 1996-1-2 and DIN EN 1999-1-2, the so-called "National Annexes" (NA) [6.8] have to be taken into consideration. The Eurocodes contain alternative methods and values as well as recommendations for classes with notes where it might be necessary to define national stipulations. The National Annex defines the national determined parameters and the stipulations that are to be defined nationally as well as the application of informative annexes for the issuing country. National Parameters or national specifications stipulations are identified by suitable comments in the Eurocodes (DIN EN). They are only to be seen as points of reference; before they are included in fire safety design, their national definition must be verified in the NA.

6.2.3 Building supervisory regulations

The Eurocodes and their corresponding National Annexes were included in the Technical Building Regulations in Model Administrative Regulation for Technical Building Regulations (MVV TB) and introduced in the federal states by the building supervisory authorities. The current status is available on the information page of the Conference of German Ministers of Construction at http://www.is-argebau.de. DIN 4102-4 has been retained as the technical building regulation solely for the constructional design, special structural components and historical construction design methods as well as integrity components such as lightweight partition walls. In principle, the fire safety design must be carried out according to the fire safety parts of the Eurocodes. The design can only be carried out according to DIN 4102 Part 4 for verifications that are not specified in the fire safety parts of the Eurocodes.

6.2.4 Design method

The Eurocodes provide a total of three different verification levels for the design of the stability of structural elements and structures in the case of fire:

- Level 1: Tabular design methods
- Level 2: Simplified design methods
- Level 3: Advanced design methods

It should be noted that in the different parts of the Eurocodes the verification methods are not listed under uniform terms. In the revised parts the above-mentioned uniform terms will be used.

The tabular design method derived from fire tests is generally on the safe side. The load-bearing behaviour is described more realistic by the upwards complex simplified and advanced design methods. The choice of the appropriate method depends on the required statements and the required accuracy. The possibilities of combinations of the design methods are shown in the flow chart in Figure 6.1. The fire safety parts of the Eurocodes distinguish between verifications for complete structures, structural sections and individual components. The fire safety verification of an entire structure must include the decisive type of failure under the influence of fire and, for this purpose, take into account the temperature-dependent changes in the building materials and the component stiffnesses, as well as the effect of thermal expansion and deformation. In principle, only the advanced design methods (Advanced design methods) are suitable for this type of verification. The simplified design methods (Simplified design methods) and the tabular design methods (Tabulated design methods) are generally used for the analysis of parts of the structure (structural cut-outs) and individual components.

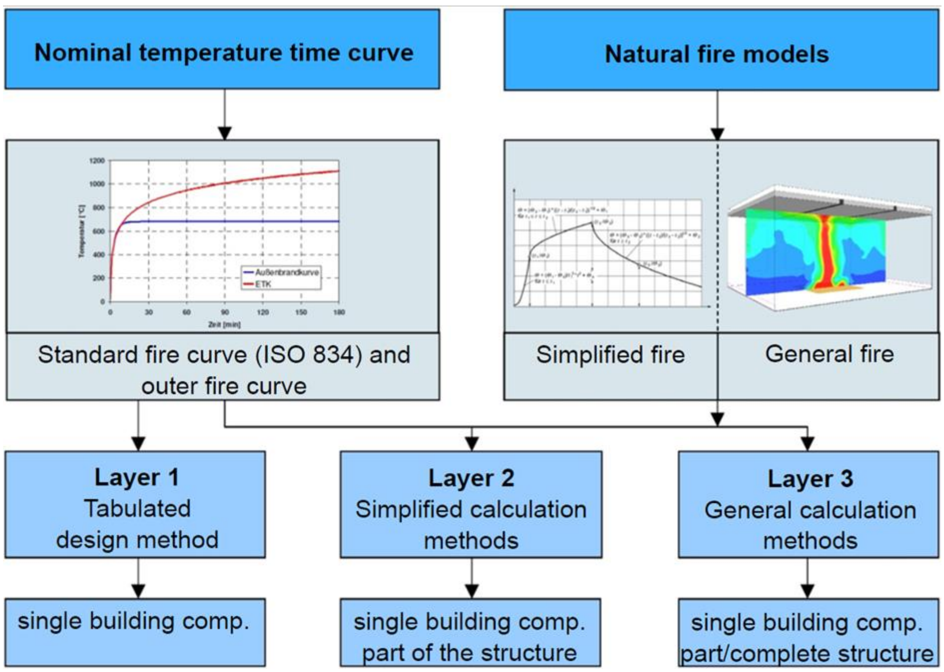


Figure 6.1 Flow chart of fire safety verification procedures according to Eurocode

6.3 Actions in case of fire

6.3.1 Procedure

In general, the fire safety verification is carried out separately in a thermal and a mechanical analysis.

- Within the thermal analysis, the temperatures in the component cross-section are calculated. This is based on the gas temperatures in the fire compartment, which are specified as thermal actions according to Eurocode 1 Part 1-2, Section 5. In this context Chapter 4 and 5 of the guideline contain helpful supplementary information. In case of calculating the temperatures in the component cross-section, the temperature-dependent thermal material properties of the component cross-section and - if present - of the protection layers should be taken into account.
- Within the mechanical analysis, the load-bearing and, in some cases, the deformation behaviour of the structural components exposed to fire are calculated. In this process, on the action side the influences from the load as well as any impeded thermal deformations (constraining forces and moments) and from non-linear geometric influences should be taken into account. On the component resistance side, the influences from the thermo-mechanical material behaviour and the thermal strains should be considered. It should be taken into account that the high-temperature material behaviour may be dependent on the heating rate and may behave differently in the cooling phase, see notes in Chapter 6.5.3.2. The load-bearing behaviour after cooling of the structure, the so-called residual load-bearing capacity in the re-cooled state, does need not be considered in the fire safety design.

6.3.2 Thermal actions

In Eurocode 1 Part 1-2, Section 5.1, the thermal actions on components are given by the net heat flux [W/m²] into the surface of the component, which is composed of a convective component and a radiative component according to equation (6.1).

$$\dot{h}_{net} = \dot{h}_{net,c} + \dot{h}_{net,r} \text{ [W/m}^2\text{]} \tag{6.1}$$

where:

$\dot{h}_{net,c}$ convective component of the net heat flux according to equation (6.2),

$\dot{h}_{net,r}$ radiative component of the net heat flux according to equation (6.3).

The convective portion of the net heat flux is calculated with:

$$\dot{h}_{net,c} = \alpha_c \cdot \left(\theta_g - \theta_m\right) \text{ [W/m}^2\text{]} \tag{6.2}$$

where:

α_c *heat transfer coefficient for convection [W/(m²K)],*

θ_g hot gas temperature in the vicinity of the component [°C].

According to Eurocode 1 Part 1-2 section 3.2 for the standard temperature-time curve and the external fire curve the heat transfer coefficient for convection can be set α_c = 25 W/(m²K). For the hydrocarbon fire curve α_c = 50 W/(m²K) is assumed. On the unexposed side of structural integrity components, the convective component of the net heat flux should be determined using α_c = 4 W/(m²K). Simplified α_c = 9 W/(m²K) should be used if it is assumed that it also covers the heat transfer due to radiation.

The net heat flux due to radiation is determined as follows:

$$\dot{h}_{net,r} = \Phi \cdot \varepsilon_{res} \cdot 5.67 \cdot 10^{-8} \cdot [(\theta_r + 273)^4 - (\theta_m + 273)^4] \quad [\mathrm{W/m^2}] \tag{6.3}$$

where:

Φ factor for taking shading into account [-],

ε_{res} $= \varepsilon_f \cdot \varepsilon_m$ resulting surface emissivity [-],

ε_f emissivity of the flame [-] (see Table 6.1),

ε_m emissivity of the surface of the structural component [-] (see Table 6.1),

θ_r effective radiation temperature of the fire environment [°C],

θ_m surface temperature of the structural component [°C],

5.67×10^{-8} Stefan-Boltzmann constant [W/(m²K⁴)].

As a rule, for simplification the factor Φ= 1.0 and the radiation temperature Θ_r may be set equal to the hot gas temperature θ_g.

Table 6.1 Emissivity of the fire compartment ε_f and the structural component surface ε_m

Fire safety part of the Eurocodes	Emissivity [-]		
	Flame ε_f	Component surface ε_m	Resulting ε_{res}
1, 6	1.0	0.8	0.80
2, 4	1.0	0.7	0.70
3	1.0	0.7*) ***)	0.70
5	1.0	0.8	0.80
9	1.0	0.3**)	0.30

*) Stainless steel: $\varepsilon_m = \varepsilon_{res}$ = 0.4
**) For coated and concealed (e.g., sooty) surfaces: $\varepsilon_m = \varepsilon_{res}$ = 0.7
***) For galvanized steels please refer to Chapter 6.7.7

According to EC 1-1-2, the heat transfer coefficient should be set to α_c = 35 W/(m²K) when using natural fire models according to EC 1-1-2 sections 3.3.1 and 3.3.2. In [6.9], heat transfer conditions on building components in case of fire were investigated. It was found that the emissivity of hot gases can assume values between 0.8 and 1.0 depending on the fire development. The values can vary considerably due to the large local spread in a natural fire, the different positioning of the structural components relative to the flames, the different design of the component surface and the different densities of the smoky hot gas layer.

For the calculation of thermal action due to natural fires, it is therefore suggested that the emissivity values specified for standardised temperature-time curves in EC 1-1-2 can also be used for natural fires by way of approximation.

Nominal temperature-time curves

In EC 1-1-2 Section 3.2, various standardized temperature-time curves are specified to describe the hot gas temperature θ_g as a function of the fire duration t [min]. For the hot gas temperature θ_g, the standard temperature-time curve according to eq. (6.4), the hydrocarbon fire curve according to eq. (6.5) or the external fire curve according to eq. (6.6) can be assumed as:

$$\theta_g = 20 + 345 \cdot log_{10}(8 \cdot t + 1) \text{ [°C]} \tag{6.4}$$

$$\theta_g = 1080 \cdot (1 - 0.325 \cdot e^{-0.167 \cdot t} - 0.675 \cdot e^{-2.5 \cdot t}) + 20 \text{ [°C]} \tag{6.5}$$

$$\theta_g = 660 \cdot (1 - 0.687 \cdot e^{-0.32 \cdot t} - 0.313 \cdot e^{-3.8 \cdot t}) + 20 \text{ [°C]} \tag{6.6}$$

The hydrocarbon fire curve specifies the development of hot gas temperatures in liquid fires and is generally not used for the fire safety design of buildings. The external fire curve may be used to verify integrity of non-load-bearing external walls and attached parapets as fire load from outside. It corresponds to the reduced standard temperature-time curve according to DIN 4102 Part 3 [6.10].

Natural fire models

Eurocode 1 Part 1-2 distinguishes between simplified and advanced natural fire models. The simplified fire models are approximation methods where the temperature-time curve of a natural fire can be calculated in a simple manual calculation or spreadsheet calculation depending on the essential physical input variables such as the fire load density and the ventilation conditions [6.11].

If a natural fire model is used, according to Eurocode 1 Parts 1-2 Section 2.4 the temperature calculation should be carried out for the entire fire duration including the cooling phase.

Advanced fire models consider the gas properties as well as the mass and energy exchange between certain control volumes via iterative methods. Based on the degree of detail, a distinction is made between:

- Single-zone models based on the assumption of a uniform, time-dependent temperature distribution in the fire compartment,
- Two-zone models, which assume an upper hot gas layer and a lower cold gas layer, each with time-dependent layer thickness and a uniform, time-dependent temperature, and
- CFD models, which use fluid dynamics methods to calculate the temperature development in a fire compartment as a function of place and time.

The models and their properties are described in Chapter 5.

The basis for the natural fire models should be a real fire scenario with the corresponding design fire in accordance with Chapter 4 of the guideline. The design fire describes the possible fire course caused by the fire scenario quantitatively in the form of time-dependent fire parameters and is the basis of a risk-appropriate design procedure. The development of the design fire depends on the main fire parameters. With regard to the ventilation conditions, it should be examined whether low ventilation (ventilation-controlled fire) or high ventilation (fire load-controlled fire) is decisive [6.12].

The building should be designed in such a way that in the case of the design fire the safety objectives laid down in the building code can be achieved. The determination of the design fire in the form of a heat release rate is described in Chapter 4. In this way, the design fire can be described physically more clearly than by specifying temperature-time curves. The natural fire certification has to be verified by a qualified fire engineer or expert according to state law.

The MVV TB contains boundary conditions and restrictions for the application of natural fire methods, which ensure the approvability of such certifications within the framework of applications to permit deviations from the building code.

Simplified natural fire models

Simplified natural fire models are based on specific physical variables that are only applicable within specific limits.

For fully-developed fires a uniform time-dependent temperature distribution is assumed. The gas temperatures should be calculated on the basis of physical parameters that take into account of at least the fire load density and the ventilation conditions.

Parametric temperature-time curves which can be used for simplified calculation of fire development in small and medium-sized rooms are listed in Eurocode 1 Part 1-2 Annex A as a simplified natural fire model for fully-developed fires. With regard to the description of a realistic fire course, these parameter curves show deficits and are critically discussed in the literature [6.11]. For this reason, the application of the parametric temperature-time curves in Eurocode 1 Part 1-2 Annex A is not approved for Germany in the National Annex to Eurocode 1 Part 1-2. A majority of European countries have also excluded this annex. As an alternative, the National Annex specifies the simplified natural fire model [6.14], [6.15] which is also outlined in Chapter 4.3.3.4 of this guideline.

If a flashover is unlikely and fire is expected to remain locally confined, the thermal actions can be calculated from a local fire event. For local fires an uneven time-dependent temperature distribution is assumed.

The model for local fires specified in Eurocode 1 Part 1-2 Annex C is based on the plume model of Heskestad (see Chapter 5) and is approved for application in Germany in the National Annex to Eurocode 1 Part 1-2 [6.11].

Advanced natural fire models

Advanced natural fire models should take account of gas properties as well as mass and energy exchange. The single-zone, multiple-zone and CFD models described as advanced natural fire models in Eurocode 1 Part 1-2 are described in detail in Chapter 5 of this guideline.

According to Eurocode 1 Part 1-2 Section 3.3.2, a combination of the results from the two-zone model and the approximation for local fires may be used in the case of a local fire in order to determine the temperature distribution along the length a component more accurately. The temperature field in a structural component may be determined on the basis of the greatest influence at each point as calculated from the two fire models.

Adiabatic Surface Temperature

Calculation of the heating of structural components should take account of both, the convective and radiative portions of the net heat flux. In line with Eurocode 1 Part 1-2, the net heat flux is calculated according to equation (6.1) to (6.3).

Calculation of the temperature development in fire compartments by means of heat balance or CFD-models involves the calculation of gas temperatures. The gas temperature in the vicinity of the component is decisive for the calculation of the convective net heat flux on the regarded component. When calculating the radiative net heat flux, the radiation of the flame or the plume must be taken into account in addition to the proportion from the radiation of the hot gas layer. This applies in particular to components in the vicinity of fire sources comparative calculations have shown that, specifically in high spaces in which large hot gas layers are created, the radiation of the flame or the plume can be ignored with regard to the effect of structural components situated in the hot gas layer. The radiative net heat flux dominates in the cold gas layer.

[6.16] and [6.17] describe an approach for the simplified calculation of the thermal effect on the structural components that takes account of the radiative portions due to the so-called "adiabatic surface temperature" (AST). The AST is an ideal surface temperature calculated on the assumption that the heat transfer onto a surface is the same as the heat release from this surface. Thus, it includes both, the convective and radiative components of the net heat flux impacting on the components. In the heat transfer calculation, this ideal value AST can replace the surface temperature and can be used in thermal analysis to determine the component temperature. Thus, the AST can form the interface between the natural fire model and the model for thermal analysis or between the fire test curve and the model for thermal analysis.

The effect of thermal radiation on AST is shown based on a comparative calculation using the example of a fire room with steel columns (Figure 6.2). The temperatures in the fire room were calculated using the CFD model FDS. In the model, ventilation openings were arranged in such a way that the lower part of the columns is located in the cold gas layer.

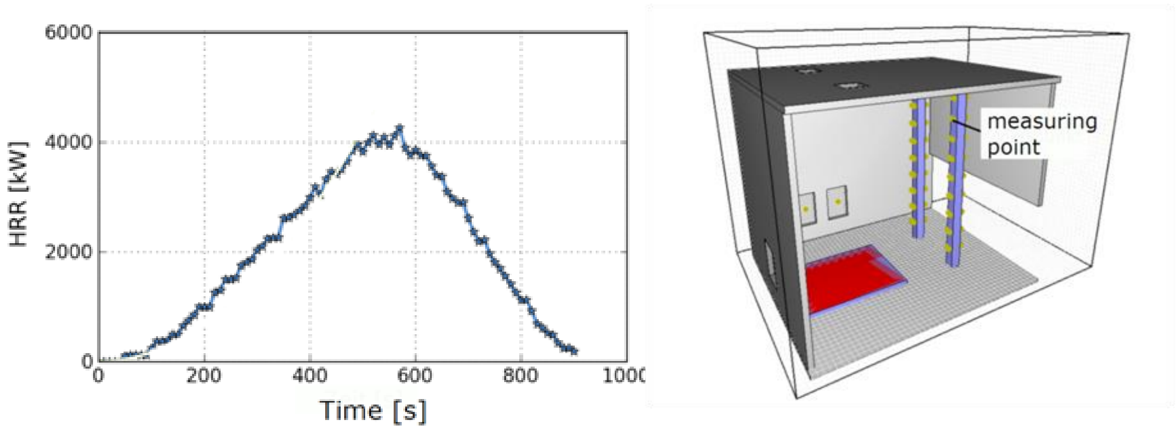


Figure 6.2 Model room for calculation of the AST and estimated heat release rate for the comparative calculation

Figure 6.3 shows the calculated gas and AST temperatures. The difference between gas temperature and AST is clear, especially in the lower section of the column (measuring points at the heights of 1 and 3 m) and is up to 200 °C. The existing ventilation opening avoids a strong heating of the column under the influence of the hot fire gases. This area was mainly heated by the effect of radiation. There are no relevant deviations in the area of the hot gas layer (8 m)

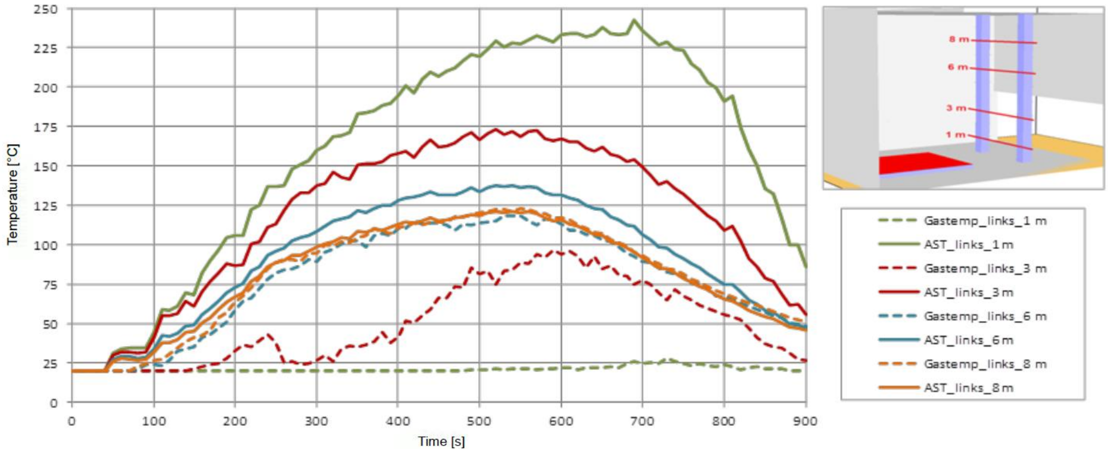


Figure 6.3 Comparison of the gas and AST temperature on the "irradiated" side of the column

6.3.3 Mechanical actions

Eurocode 1 Part 1-2 differentiates between direct and indirect actions. The actions taken into account for the "cold" design (dead load, wind, snow etc.). Indirect actions due to fire exposure are forces and moments that are caused by thermal expansion, deformation and distortion. They do not need to be taken into account in the fire design of individual components and of partial and global structures if they only have a minor influence on the load-bearing behaviour and/or are absorbed by appropriate design of the supports. This should be verified in each individual case. Indirect actions include constraining forces and moments in columns, frame-like structures, continuous beams / girders and the effects of thermal expansion on components that are not exposed to fire. These can also have a favourable effect on the load-bearing capacity in case of fire (reduction of field moments by increasing the support moments).

Fire is considered to be an "accidental situation" that does not need to be superimposed with other unrelated accidental situations. When determining the stresses resulting from the actions, i.e., loads or restraint loads, the design values are generally determined from the characteristic values by multiplication with partial safety factors γ_F and, if applicable, with combination factors for variable actions. In case of fire, only the constant actions are multiplied by the partial safety factor γ_{GA}, while the variable actions are reduced by combination coefficients < 1.0 due to the rarity of the fire event.

For combinations of constant and variable actions, the variable actions may be reduced by combination coefficients according to the Table 6.2. In this way, "frequent" or "quasi-permanent" design values are defined for the actions which can be expected to occur in the real world simultaneously with the rare fire situation. The National Annex of EC 1-1-2 stipulates that the quasi-permanent value $\psi_{2,i}$ $Q_{k,i}$ may generally be used. This does not apply to components whose leading action is wind. In this case, the frequent value $\psi_{1.1}Q_{k,1}$ shall be used for the wind related action.

The combination rule for accidental design situation determines the decisive stress $E_{fi,d,t}$ during the fire action according to Equation (6.7):

$$E_{fi,d,t} = \sum \gamma_{GA} \cdot G_k + \psi_{1,1} \cdot Q_{k,1} + \sum \psi_{2,i} \cdot Q_{k,i} + \sum A_d(t) \qquad (6.7)$$

where:

G_k characteristic value of permanent actions,

$Q_{k,1}$ characteristic value of (the principle value of the) a variable action,

$Q_{k,i}$ characteristic value of other variable actions,

$A_d(t)$ design value of the indirect actions,

γ_{GA} partial safety factor for permanent actions, (generally 1.0, for deviations see Chapter 10),

$\psi_{1,1}$, $\psi_{2,I}$ combination coefficients according to DIN EN 1990 [6.18] (see Table 6.3).

By way of simplification, the actions during fire exposure may be determined directly from the actions at ambient temperature according to eq. (6.8):

$$E_{fi,d,t} = \eta_{fi} \cdot E_d \tag{6.8}$$

where:

E_d design value of the actions according to EC 1-1-1, with consideration of the partial safety factors for permanent and variable actions γ_G, γ_Q,

$$\eta_{fi} = \frac{\gamma_{GA} + \psi_{1,1} \cdot \xi}{\gamma_G + \gamma_Q \cdot \xi} \tag{6.9}$$

Reduction factor, depending on the ratio of the main value of the variable actions to the permanent action $\xi = Q_{k,1}/G_K$.

Figure 6.4 shows the evaluation of equation (6.3) with partial safety factors γ_G = 1.35 and γ_Q = 1.5 for different combination coefficients ψ_{fi}.

Table 6.2 Combination coefficients in building construction (excerpt from [6.19], Table A.1.1)

Actions	Combination coefficient		
	ψ_0	ψ_1	ψ_2
Payloads in building construction			
Residential and office buildings	0.7	0.5	0.3
Assembly areas and retail areas	0.7	0.7	0.6
Warehouse areas	1.0	0.9	0.8
Wind loads	0.6	0.2	0
Snow loads at an altitude lower than 1000 m above sea level	0.5	0.2	0
Snow loads at an altitude above 1000 m above sea level	0.7	0.5	0.2

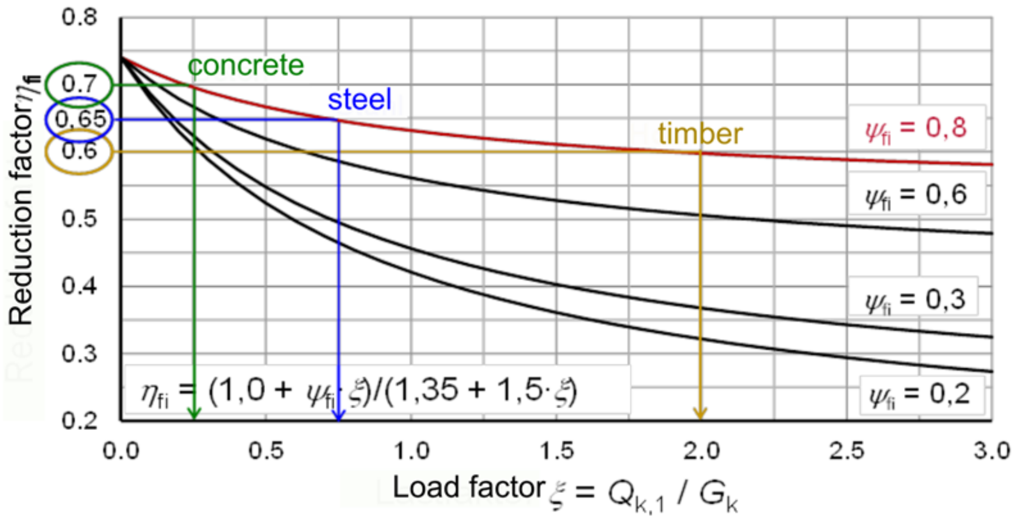


Figure 6.4 Reduction factor η_{fi} as a function of the ratio between permanent and principle variable action (γ_G = 1.35 and γ_Q = 1.5)

The values listed in the Table 6.3 may be used for the reduction factor η_{fi} without precise verification.

Table 6.3 Reduction factor η_{fi}

Fire protection part and NA	Reduction factor η_{fi}
Eurocode 2	0.7
Eurocode 3	0.65 (category E: 0.7)
Eurocode 4	0.65 (category E: 0.7)
Eurocode 5	0.6 (category E: 0.7)
Eurocode 6	0.7

6.4 Material properties

6.4.1 Thermal material properties

6.4.1.1 General information

The differential equation of Fourier (eq. (6.10)) for the description of transient heat transfer in solid objects forms the basis for the calculation of the temperature distribution in structural components. The precondition is that no heat sources or heat sinks are present inside the object.

$$\frac{\partial T}{\partial t} = a \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{6.10}$$

where:

T Temperature [K],

t Time [s],

a $= \frac{\lambda}{\rho c_p}$ Temperature coefficient [m²/s],

λ Thermal conductivity [W/(m·K)],

ρ Density [kg/m^3],

c_p Specific heat [J/(kg·K)],

x, y, z Spatial coordinates [m].

An analytical solution for eq. (6.10) can only be found for the special case of a homogeneous and isotropic body with a one-dimensional heat flow and temperature-independent thermal material properties. In order to calculate the temperature distribution within structural components made of concrete and steel subjected to fire actions, it is necessary to take account of the temperature-dependent thermal material properties of thermal conductivity λ, specific heat c_p and density ρ (Figure 6.5). Thus, the target value of the calculation, namely the temperature, is dependent on temperature-dependent input parameters. Numerical methods such as the finite element method (FEM) or the method of finite differences (using integration procedures over time steps) are used for the solution. For real construction situations the following simplifications can be made:

- The temperature spread in the longitudinal direction of the component is neglected. In bar-shaped components, the temperature spread is only calculated in the cross-sectional area (two-dimensional) and in plane components only across the cross-sectional thickness (one-dimensional).
- Water vapour movements are not taken into account.
- In the case of concrete, the energy consumption for the evaporation of water and other energy-consuming processes is taken into account by the appropriate choice of the calculated value for the specific heat capacity of the concrete in the temperature range between 100 - 200 °C.
- Concrete is regarded as a homogeneous building material with regard to its thermal material properties. The heterogeneous structure, capillary pores and cracks are considered across-the-board in the thermal material laws.

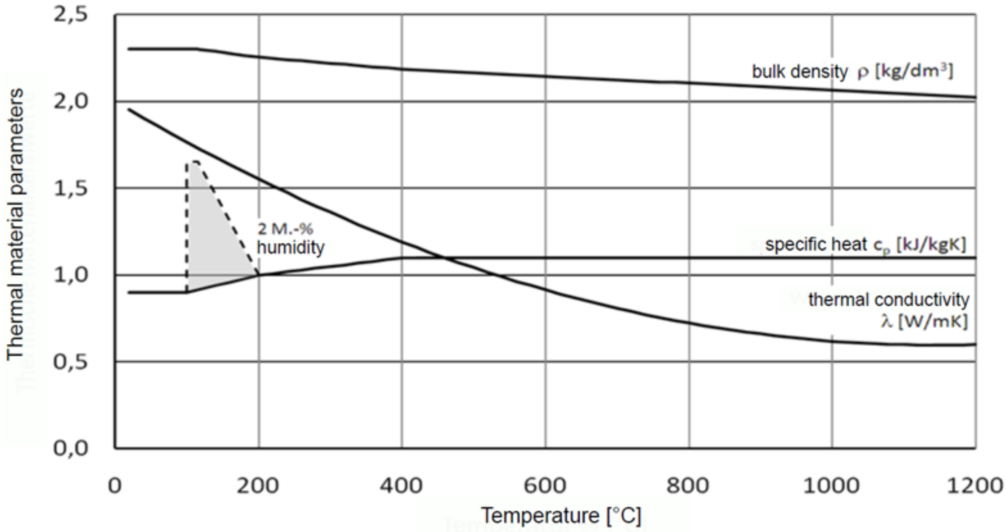


Figure 6.5 Calculated values of the temperature-dependent thermal material properties of concrete according to [EC2-1-2/NA: 2010].

For the calculation of the temperature distribution in typical building components the following hints can be useful. This information is intended to provide assistance for thermal analysis; in individual cases deviations from the numerical values listed may be useful.

- When discretizing the components cross-section, the size of the finite elements should be aligned with the temperature distribution. In the area of large temperature gradients - e.g., at the fire-exposed edges of the cross-section - a finer discretization should be used than in the interior of the cross-section.
- The element sizes should be selected depending on the cross-section size or thickness. For reinforced concrete elements, the edge length of the elements should not exceed 2 - 3 cm. In the case of steel components, considerably smaller elements may also be required; at least three elements should be depicted across the cross-section thickness.
- The length of the element sides should be chosen in a ratio smaller than or equal to 1:4.
- Symmetry conditions with regard to flame exposure should be exploited in order to limit the number of elements.
- The discretization of the thermal and mechanical analysis should be coordinated to each other.
- The time interval for calculation of the temperature distribution should not exceed 30 seconds in case of reinforced concrete, composite and protected steel cross-sections and 5 seconds in the case of non-protected steel cross-sections.
- For reinforced concrete cross-sections with a standard amount of reinforcement and reinforcing bars with a maximum diameter of 30 mm, the reinforcement may be neglected in the thermal analysis. The temperature in the axis of the reinforcing bar corresponds approximately to the temperature in undisturbed concrete [6.20]. If the diameter of the reinforcing bar is greater than 30 mm, significant deviations occur. Thus, neglecting the reinforcement in the thermal analysis is not recommended [6.21].

6.4.1.2 Thermal conductivity of concrete

In Eurocode 2 Part 1-2 (Version 2010) [6.2], an upper and a lower limit function are specified for the thermal conductivity of concrete. Due to moisture transport processes, the measurement of the thermal conductivity is associated with a large measurement uncertainty; experimentally determined values scatter within a wide range. In general, it can be stated that the thermal conductivity of concrete decreases with increasing temperature due to evaporation of bound water [6.21]. In Germany, the upper limit function for the thermal conductivity is specified in the National Annex of Eurocode 2 Part 1-2; some European countries have specified the lower limit function. Both, the upper and the lower limit functions do not reflect measured thermal conductivities, but were determined on the basis of recalculations of carried out tests. Thus, they have to be regarded as effective thermal conductivities that also cover model uncertainties (e.g., moisture transport). In order to accomplish uniformity and to achieve better agreement with recent test results, a new approach ("mixed curve") has therefore been developed for a thermal conductivity function that combines these two functions [6.21]. As shown in Figure 6.6, the new approach function is congruent with the upper limit function according to Eurocode 2 Part 1-2 (Version 2010) in the temperature range up to 140 °C [6.2]. Between 140 °C and 160 °C the thermal conductivity decreases linearly and is congruent with the lower limit function in the temperature range between 160 °C and 1200 °C.

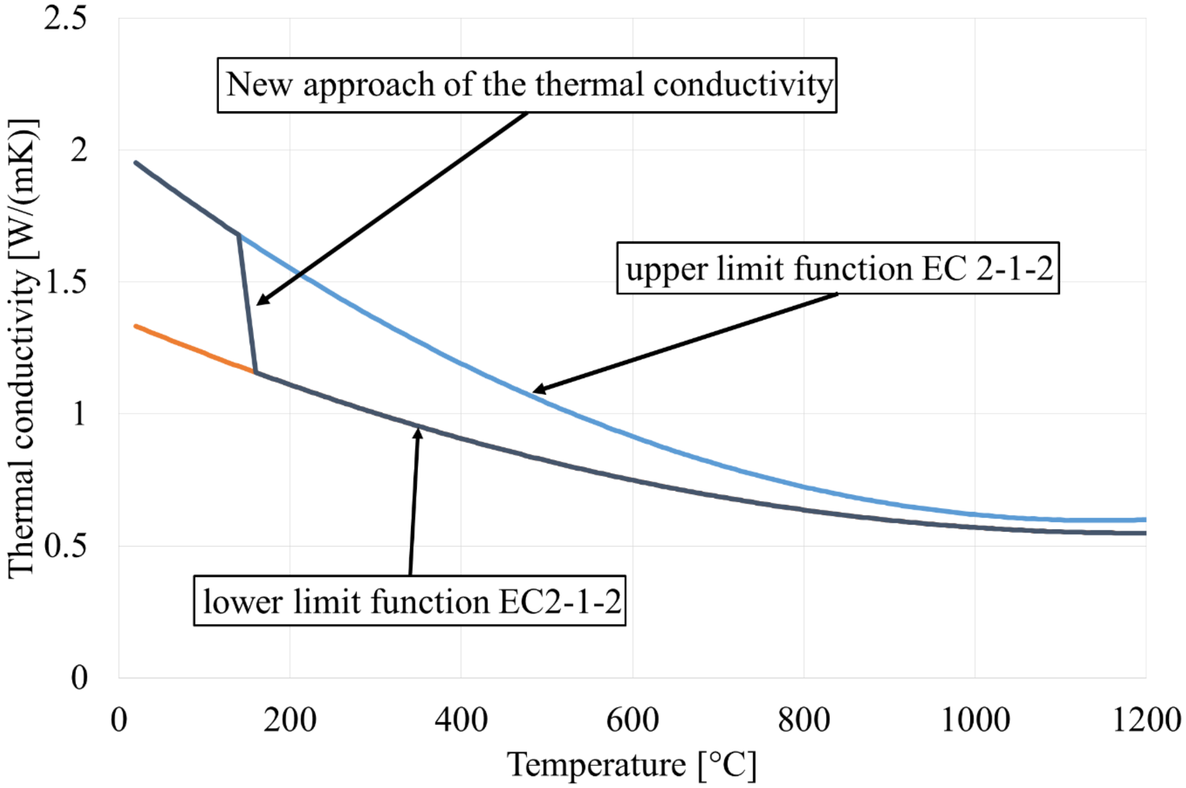


Figure 6.6 New approach "mixed-curve" of the thermal conductivity compared to the functions according to DIN EN 1992-1-2

The new "mixed curve" approach was calibrated on the basis of recalculations in more than 20 fire tests on ceilings, walls and columns, which were carried out by test institutes in Germany, France and Sweden [6.22]. The result showed that the mixed curve approach allows to determine the temperatures in the area of the reinforcement with a better accuracy and predominantly on the safe side [6.21].

6.4.2 Mechanical material properties

6.4.2.1 General information

For structural components and structures, the fire safety design is generally provided by

- Cross-sectional analysis and / or
- Analysis of the system behaviour.

The temperature distribution in the component cross-section calculated according to Chapter 6.3 is used as a starting point; in addition, the temperature-dependent material properties (strength, modulus of elasticity, thermal expansion) are also taken into account.

In the cross-sectional analysis, the plastic load-bearing capacity of the structural component cross-section is calculated and compared with the decisive actions in the event of fire; the deformation behaviour of the components or structures is not calculated. A typical application case are beams or girders that are statically determined, for which the temperature-dependent bending load-bearing capacity $M_{R,fi,d}$ and the maximum moment load $M_{E,fi,d}$ are compared in case of fire. $M_{E,fi,d} \leq M_{R,fi,d}$ is verified in the fire safety verification (Figure 6.7).

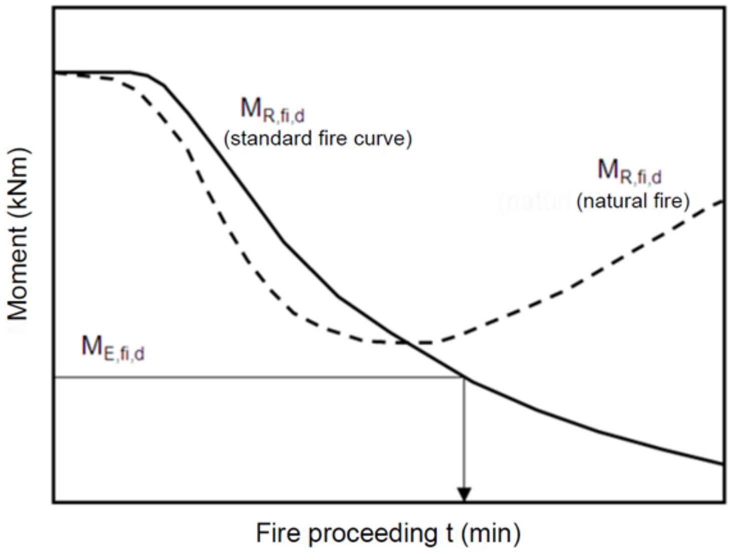


Figure 6.7 Principle course of the bending load-bearing capacity $M_{R,fi,d}$ and the moment load $M_{E,fi,d}$ for a statically determined beam

When analysing the system behaviour of a structural component or structure, the load-bearing and deformation behaviour for the fire situation is calculated.

Typical applications include the fire safety design of slender compression members and statically indeterminate systems, such as frameworks and continuous beams. In these cases, the stress depends on the deformations of the structural component or structure.

Here, the stress depends on the deformations of the component or supporting structure. In case of slender columns, for example, the actions according to the 2nd order theory should be taken into account and in statically indeterminate systems, the thermally induced restraint forces must be considered.

6.4.2.2 Stress-strain relationships and thermal strains

The basis of the fire safety-related component and structural analysis are the temperature-dependent stress-strain curves and thermal strains of the structural materials. The fire safety parts of Eurocodes 2, 3 and 4 contain all main information on the temperature-dependent change of the mechanical building material values.

By way of example, Figure 6.8 shows temperature-dependent stress-strain curves for concrete with aggregate that primarily contains quartzite, Figure 6.9 for hot-rolled reinforcing steel (B 500) and Figure 6.10 for structural steel. Figure 6.11 shows the thermal strains for concrete, reinforcing steel, prestressing steel and structural steel.

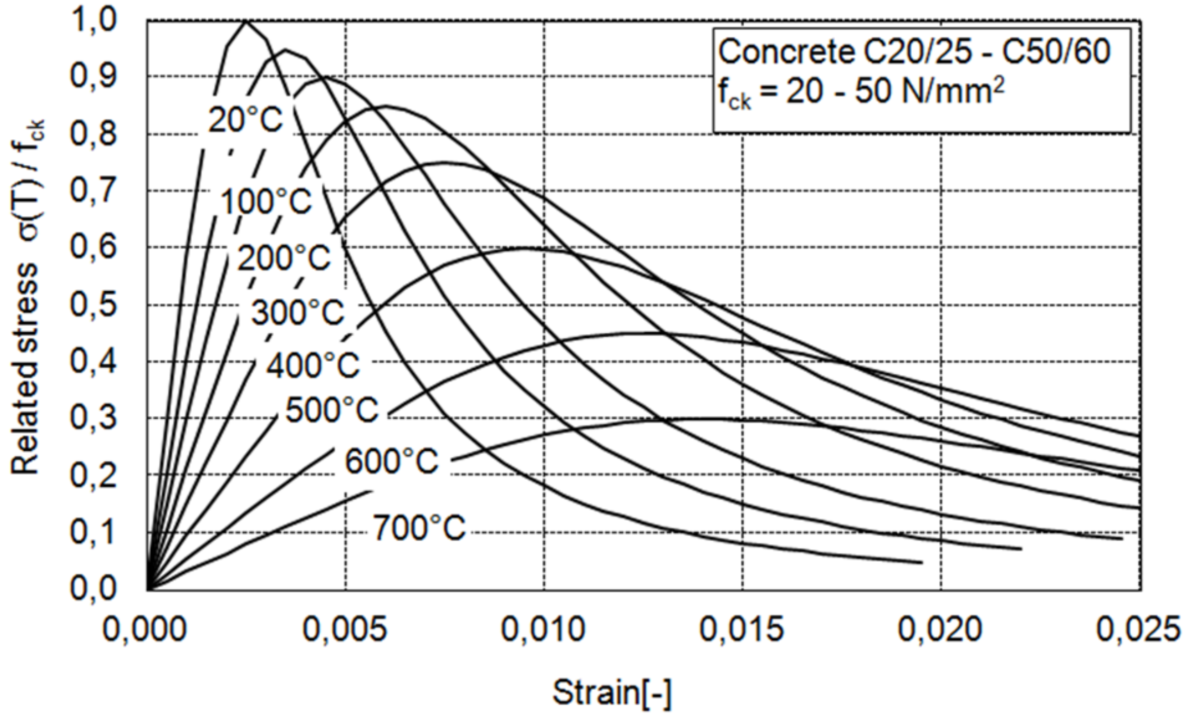


Figure 6.8 Temperature-dependent stress-strain curves of concrete with aggregate that primarily contain quartzite

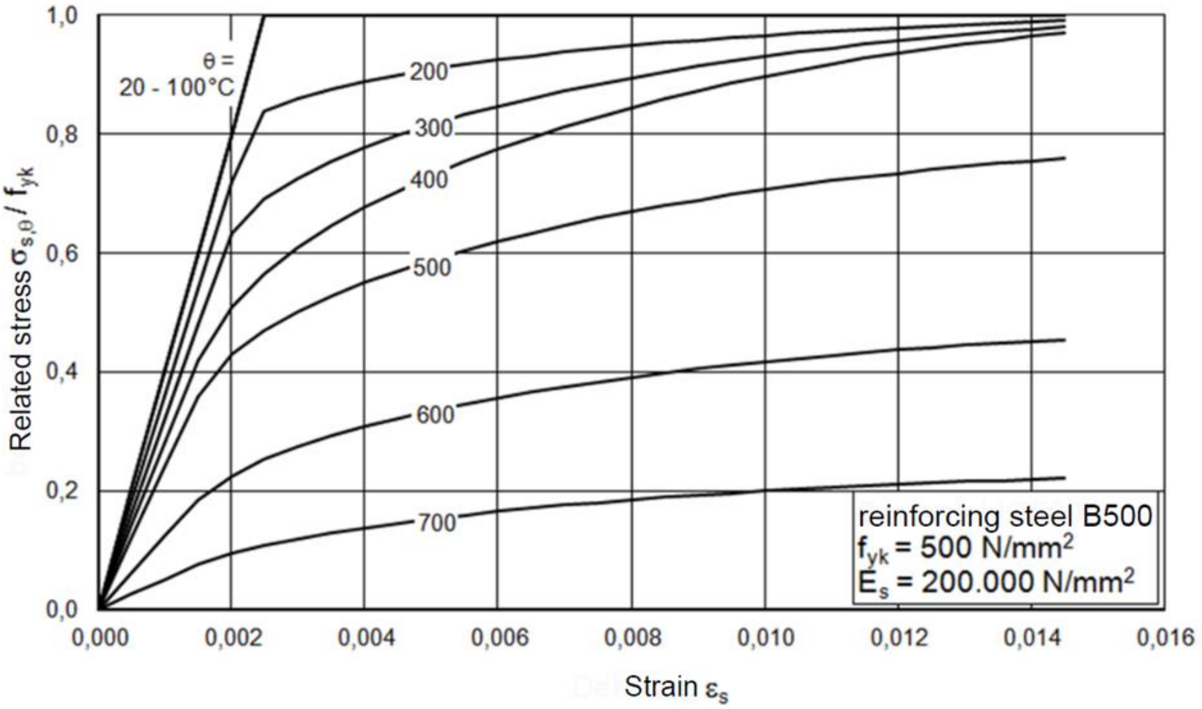


Figure 6.9 Temperature-dependent stress-strain curves of hot-rolled reinforcing steel (B 500)

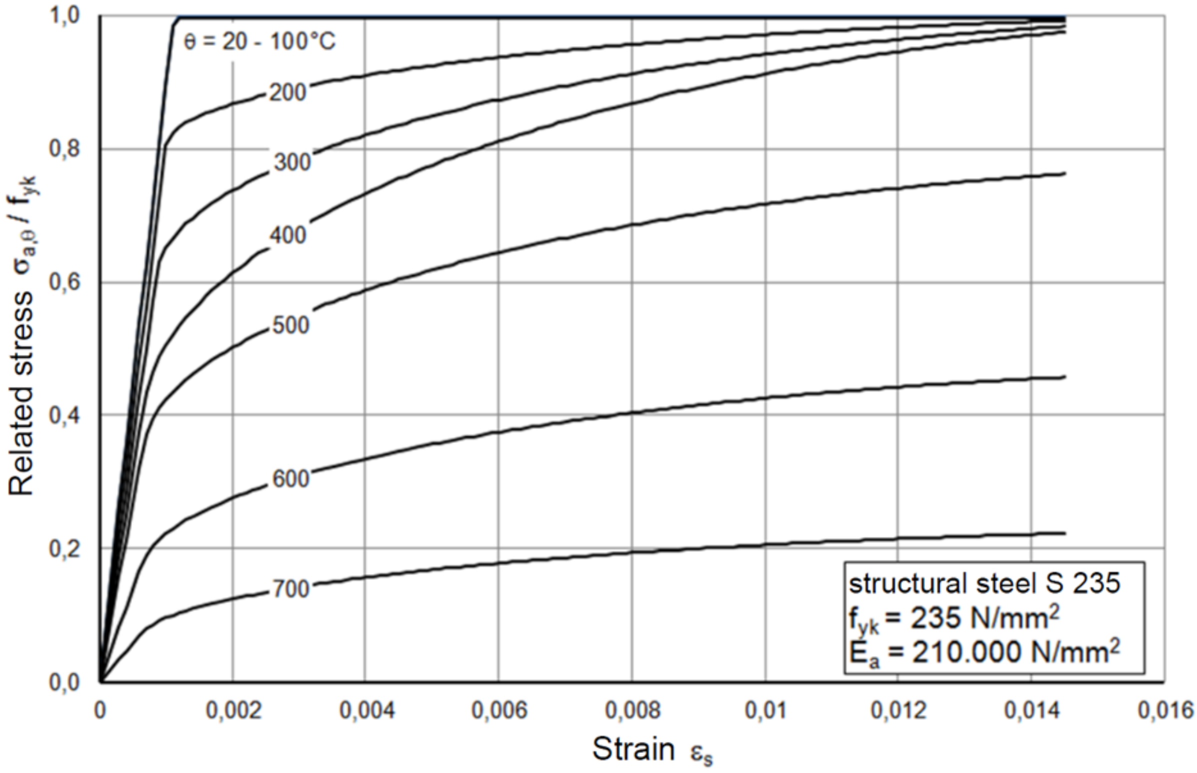


Figure 6.10 Temperature-dependent stress-strain curves of structural steel

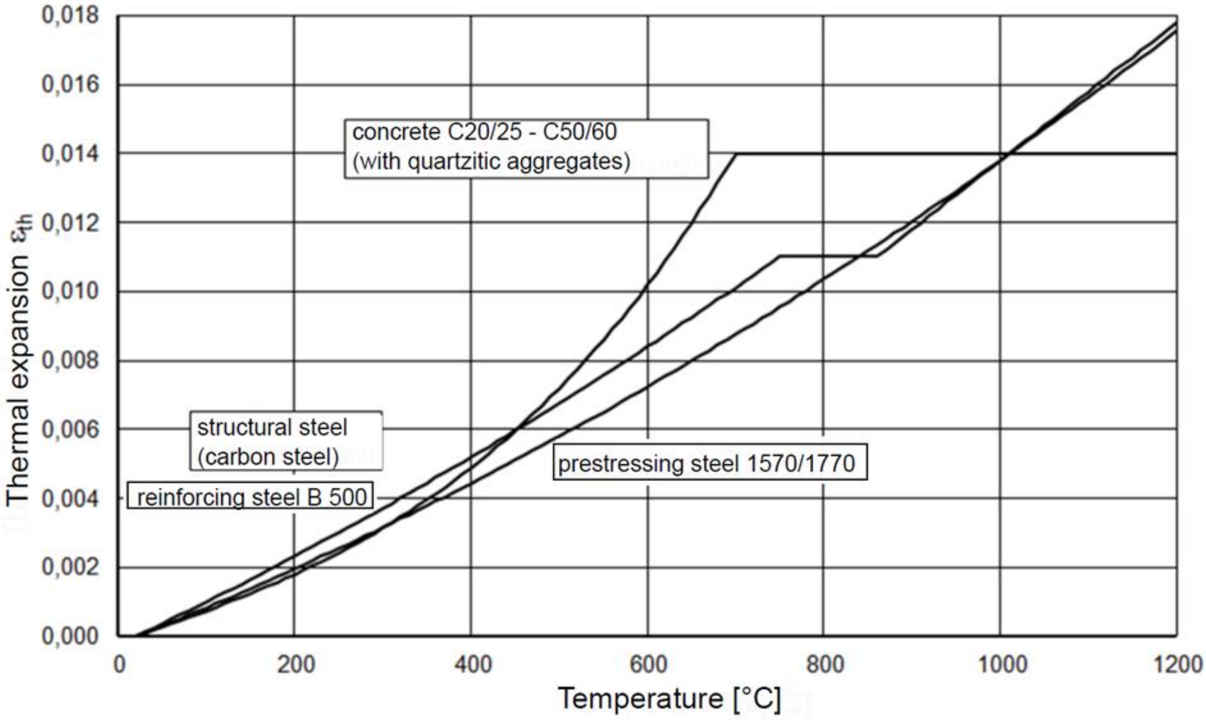


Figure 6.11 Thermal expansion of concrete, reinforcing steel, prestressing steel and structural steel

The fire safety parts of Eurocodes 2, 3 and 4 list equations for the numerical description of the temperature-dependent stress-strain curves and the thermal strains. The input parameters for the calculation of the temperature-dependent stress-strain curves are defined as characteristic values and are based on the 5% fractile of the universe. In the case of concrete, the cylindrical compressive strength f_{ck} is entered as the strength value and in the case of reinforcing steel or structural steel the yield strength f_{yk} or fay is entered. For prestressing steel, the value 0.9 · f_{pk} is entered due to the lack of a pronounced yield strength. To determine the design values, the characteristic values are divided by the partial safety factors γ_M which are dependent on the scatter of the material properties. The design values of the mechanical properties are calculated according to Equation (6.11):

$$X_{fi,d} = k_\Theta \cdot \frac{X_{k,\Theta}}{\gamma_{M,fi}} \tag{6.11}$$

where:

k_Θ temperature-dependent reduction factor for strength and modulus of elasticity of the building material,

$\gamma_{M,fi}$ partial safety factor for the corresponding building material in case of fire.

In general, the partial safety factors for determining the design values of building materials under fire exposure from Eurocodes 2 to 4 Parts 1-2 in combination with the National Annexes are set to $\gamma_{M,fi}$= 1.0.

In EC 5-1-2, the design values of the strength and modulus of elasticity are defined, in deviation from eq. (6.11), as 20 % fractiles of the strength or stiffness at ambient temperature, multiplied by the modification coefficient in case of fire $k_{mod,fi}$ and divided by the partial safety factor $\gamma_{M,fi}$= 1.0. Annex B of EC 5-1-2 lists the input parameters for the thermal and mechanical material values of timber.

In deviation from EC 2-1-1, EC 2-1-2 does not specify a design method for the shear load-bearing capacity due to the fact that such a method does not currently exist for the case of fire. Tests have shown that the shear resistance of beams, ribbed slabs and slabs only becomes decisive for a fire resistance time of 90 minutes and more [6.23]. Up to the present, the design regulations are adequate to dimension reinforced concrete beams for fire resistance classes up to R90. In order to achieve higher fire resistance classes, however, special measures should be undertaken in many cases. This concern, for example, continuous girders with a fire resistance time of 180 minutes, which should have considerably larger cross-sections than single-span beams. For flat slabs (point-supported slabs), the shear load-bearing capacity can be decisive and therefore they cannot be verified with a calculation method.

6.4.2.3 Failure criteria

To determine the failure time of a structure, the ultimate limit state according to DIN EN 1990 is reached when failure or excessive deformation of the structure or its parts occurs. This only concerns the load-bearing capacity criterion, but not the space closure or the thermal insulation properties.

In general, the load-bearing capacity for the specified fire resistance duration t should be verified by:

$$E_{d,fi} \leq R_{d,t,fi} \tag{6.12}$$

where:

$E_{d,fi}$ design value of the internal forces in case of fire,

$R_{d,t,fi}$ corresponding rated value of resistance in case of fire.

According to Chapter 6.5.3, for the design with the advanced calculation method a cross-sectional analysis or a system analysis can be performed. In the cross-sectional analysis, the plastic load-bearing capacity of the cross-section of the component is calculated and compared with the decisive actions in case of fire. In the system analysis, the load-bearing and deformation behaviour of the partial or the complete structure exposed to fire is calculated. According to EC 2-1-2 for the fire safety design of global or partial structures, the decisive failure type in fire situation must be gathered. In addition, the deformations occurring in the ultimate limit state must be limited in order to ensure the interaction of all parts of the structure. This raises the question of suitable failure criteria.

Possible failure criteria for the advanced calculation methods are presented below:

Assessment of load-bearing capacity with reference to DIN EN 13501-2 and DIN EN 1363-1

The aforementioned standards [6.19] and [6.24] refer to the failure criteria of components exposed to bending stress in fire tests. It should be noted that only individual components are considered in the tests. The applicability of the failure criteria presented here should be reviewed for global structures. If the boundary conditions are comparable to those of a single-span beam, the criteria can be applied directly. If the structural system differs from a single-span beam, then the span must be adjusted in line with the deformation figure on a single-span girder.

(a) Deflection: $D = L^2/(400\ d)$ [mm],

(b) Deflection rate: $dD/dt = L^2/(9000\ d)$ [mm/min].

where:

L the clear span in mm,

d is the distance in mm from the outermost edge of the compression zone to the outermost edge of the tensile zone of the load-bearing section, both in cold-state design.

The criterion of the deflection rate is only valid after a deflection of L/30 is exceeded.

The deformations occurring in the event of fire can damage adjacent components and possibly even impair their function. Since these criteria cannot be applied in the calculations on system behaviour, either suitable deformation limits shall be applied to comply with these requirements or measures must be undertaken to compensate for the occurring deformations.

In addition, the bearing conditions of the adjacent structural components should also be taken into account - e.g., glass structural components or walls. Moreover, it should also be ensured that the structural component cannot slide off the bearing support due to deflection.

Consideration of the temperature criterion (I-criterion)

EC 2-1-2 provides the following information to verify the temperature criterion of components:

In the heating phase until the maximum hot gas temperature in the fire compartment is reached, the average temperature rise on the non-exposed surface of the component may not exceed 140 K and the maximum temperature rise may not exceed 180 K. During the cooling phase, the mean temperature rise on non-exposed surface of the component may not exceed 200 K and the maximum temperature rise may not exceed 240 K.

ISO PDTR 15657 [6.25], specifies a maximum radiation rate of 3 kW/m² for the side facing away from the fire as an additional criterion for partition walls in escape routes.

6.5 Design method

6.5.1 Tabulated design methods

Tabulated design methods are contained in EC 2-1-2, EC 4-1-2 and EC 6-1-2, in EC 3-1-2 and EC 5-1-2 only computational verification methods are included for structural components.

Tabulated data design methods generally do only compare cross-sectional measurements or lining thicknesses of a structural component with the values that are required to achieve the targeted fire resistance time based on the results of fire tests.

Depending on the fire resistance class, the tabular data contain minimum values for the cross-sectional dimensions and - for reinforced and prestressed concrete components - the minimum axis distances of the reinforcement or, for composite structural components, the supplementary reinforcement required in case of fire. For reinforced concrete columns, loaded reinforced concrete walls and composite columns and girders, the load utilization factor is given as an additional parameter.

Linear interpolation is permitted between the specified values in the tables. Further calculation rules allow the individual determination of the critical temperature for reinforced concrete beams and ceilings with statically determined supports and the determination of the current load utilization factor for reinforced concrete columns and loaded reinforced concrete walls.

The normative part of Eurocode 2 Part 1-2 provides the Method A and B and in Annex C the Tables C.1 to C.9 for the fire safety design of reinforced concrete columns. In the National Annex of Eurocode 2-1-2, only the application of Method A is approved. Method A provides the option of tabular determination of minimum cross-sectional dimensions and axis distances for columns with rectangular or circular cross-section as well as the calculation-based determination of the existing fire resistance time while taking account of the key load-carrying parameters such as extent of degree of utilisation, axis distance, effective length in the case of fire, concrete cross-section and amount of reinforcement.

For the design of columns, new design tables have been developed in addition to Method A. These tables can also be used to design cantilever columns that are included in the third draft of the revised EC 2-1-2 [6.26] in Annex B. Furthermore, the third draft of EC 2-1-2 [6.26] has extended the tables for columns and walls exposed to unilateral fire loads for different load utilizations and support situations.

The design tables in Annex B of the third draft of EC 2-1-2 [6.26] were developed on the basis of a simplified design procedure [6.27]. First, a reduced concrete cross-section is determined according to the zone method. For the reduced concrete cross-section and the mean reinforcement and concrete temperature, the column capacity is determined using the M/N interaction curve. The design tables can be used for cases where the effective column length is the equal in case of fire and at ambient temperature ($l_{0,fi} = 1.0\ l_0$) such as cantilever columns and for the case $l_{0.fi} = 0.7\ l_0$. An application for the case $l_{0,fi} = 0.5\ l_0$ is not possible. Here, Method A or simplified or advanced design methods may be used. For the application of the design tables according to [6.27], it is possible to determine the approvable effective length of the column for the design at ambient temperature $l_{0,max}$ depending on the parameters fire resistance time R, cross-section dimensions b, load utilization factor μ_{fi}i, eccentricity e_0 and axis distance a. In some cases, multiple interpolations are required. Validation calculations with the advanced design method show that the design tables according to [6.27] are on the safe side (Figure 6.12).

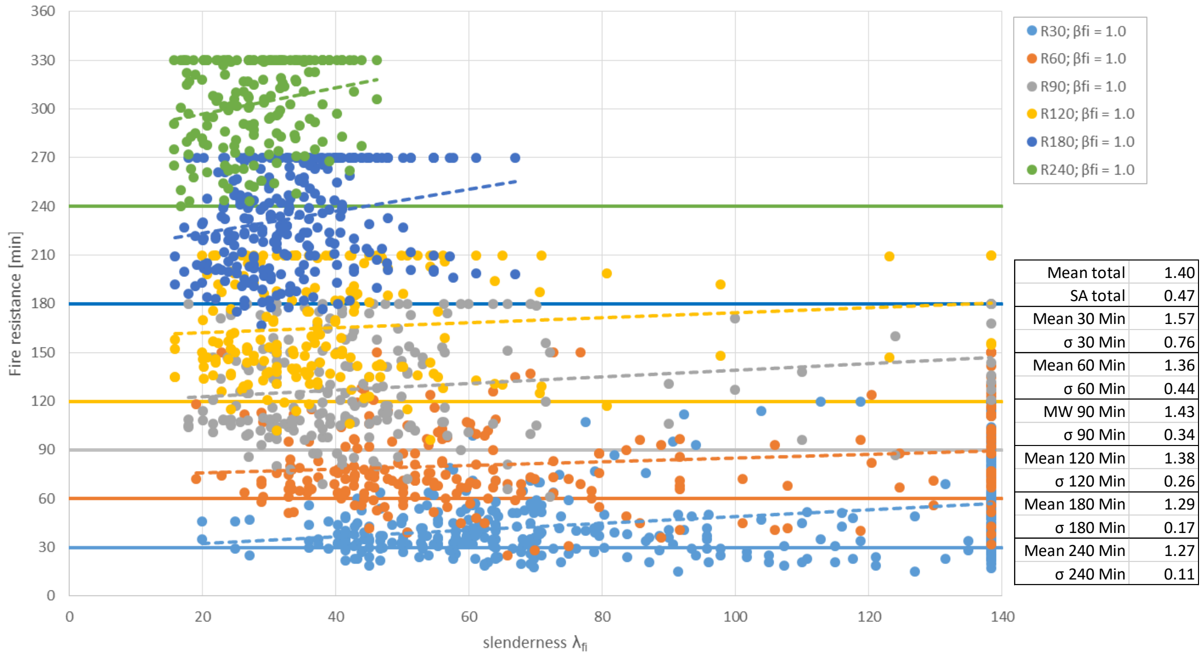


Figure 6.12 Comparison of the calculated fire resistance time of the design tabulated data [6.27] with the advanced design method for different slenderness and same effective length at ambient and fire conditions ($l_0 = l_{0,fi} = l$)

In the design table of Method A, only minimum dimensions with a load utilization ratio $\mu_{fi} = 0.7$ and for the effective length $l_{0,fi} = 0.5\ l_0$ are given in [6.2] for columns exposed to fire on one surface. Thus, with Method A the fire safety design of columns exposed to fire on one surface leads to conservative results for load utilization ratios $\mu_{fi} < 0.7$. Furthermore, no tabular data is available for the cases $l_{0,fi} \neq 0.5\ l_0$ so far. For the above-mentioned reasons, new design tables for columns exposed to fire on one surface have been developed for the third draft of Eurocode 2 Part 1-2 [6.26] on the basis of calculations with the advanced design method, which take into account a wider range of applications with regard to the load utilization factor (μ_{fi} = 0.2; 0.5; 0.7) and the effective length ($l_{0,fi} = 0.5\ l_0$; $l_{0,fi} = 1.0\ l_0$) of the column [6.28].

The design table for load-bearing walls contained in EC 2-1-2 [6.2] was transferred from DIN 4102-4:1994-03. This design table contains only two load utilizations. The change from the global to the semi-probabilistic safety concept was not taken into account during the transfer process of the design table for load-bearing walls in [6.2]. Thus, four new design tables for load-bearing walls were developed for the third draft of Eurocode 2 Part 1-2 [6.26] based on calculations with the advanced design method for the load utilization factors μ_{fi} = 0.2; 0.5; 0.7: for load-bearing walls with a integrity function (exposed to fire on one surface) with $l_0 \leq 3.0$ m; $\beta_{fi} = 1.0$ and $l_0 \leq 4.50$ m; $\beta_{fi} = 0.5$, and for walls exposed to fire on two surfaces with $l_0 \leq 3.0$ m; $\beta_{fi} = 1.0$ and $l_0 \leq 4.50$ m; $\beta_{fi} = 0.5$ [6.29].

Eurocode 4 Part 1-2 contains design tables for composite beams comprising steel beams with partial concrete encasement as well as composite columns (totally encased steel sections, partially encased steel sections, concrete filled hollow sections).

In general, the design tables in EC 6-1-2 contain no design values. Therefore, the design tables in the National Annex [6.8] are required for the fire safety design of masonry components. [6.8] contains tabulated values for

- non-supporting walls with an integrity function,
- supporting walls with an integrity function,
- supporting walls without an integrity function,
- supporting pillars and
- Compartment wall.

For verification of load-bearing walls and pillars, a load utilization factor should be determined. For sand-lime masonry made of solid bricks this factor can be calculated directly with $\alpha_{fi} = N_{E,d,fi}/N_{R,d}$ [6.30] in accordance to tables [6.8] NA.B. 2.2, NA.B. 2.3 and NA.B. 2.4.

For all other masonry blocks a utilization factor $\alpha_{6,fi}$ is defined. This corresponds essentially to the α_2-value in accordance to DIN 4102-4 (March 1994 edition). However, the calculation of the utilization factor should be adjusted for the design in accordance to EC 6-1-2, since the fire tests on which the tables are based on were mostly carried out with loads according to DIN 1053-1. Henceforth, the utilization factor $\alpha_{6,fi}$ takes into account that the design values of the compressive strength of masonry according to European standards differ from the previous values according to DIN 1053-1 [6.31]. Furthermore, the factor ω is introduced, which adapts the test results to the different types of bricks. It is defined as: $\omega = 0.7 \cdot f_k / \sigma_0$.

6.5.2 Simplified design methods

6.5.2.1 General information

With simplified design methods it is generally verified that the decisive load actions $E_{fi,d}$ based on Eurocode 1 Part 1-2 for the required fire resistance time t are smaller than the structural component resistance $R_{fi,d,t}$. The measures that are taken to achieve this, include simplifications with regard to the determination of temperature for the cross-sections of the structural components and with regard to the description of the failure condition in the event of fire.

6.5.2.2 Eurocode 2 Part 1-2

The simplified calculation method of the zone method contained in Eurocode 2 Part 1-2, Annex B.2 and approved for use in the National Annex is used to determine the reduction in the load-bearing capacity of structural components exposed to fire due to the temperature-dependent reduction of structural component cross-sections and the temperature-based reduction of strength coefficients for a certain fire resistance time (Figure 6.13). Due to the reduction of the concrete cross-section, the external concrete areas that are directly exposed to the fire and are mainly worn down are not taken into account when determining load-bearing capacity. With the remaining cross-section, the ultimate limit state design can be performed analogously for ambient temperature according to [6.10], taking into account the temperature-related reduction of material properties of concrete and reinforcing steel.

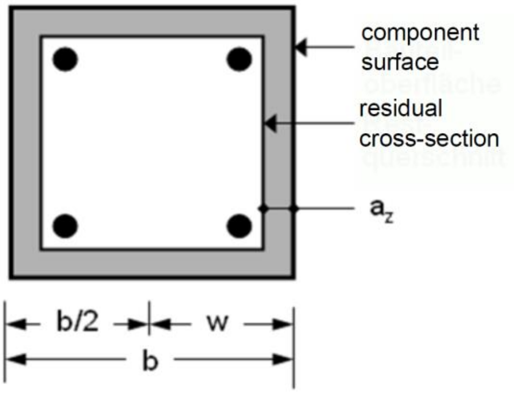


Figure 6.13 Remaining cross-section of a reinforced concrete column exposed to fire on 4 sides according to Eurocode 2-1-2

The reduced cross-section of the structural component and the temperature-dependent reduction of the strength coefficients can be determined for rectangular cross-section shapes or cross-section shapes made up of right angles with the help of the equations and diagrams in Eurocode 2-1-2, Section 4.2.4 and Annex B.2.

Another simplified design method for calculating the "hot" resistance of single span and continuous beams and slabs, approved for use in the National Annex, is given in the informative Annex E of Eurocode 2-1-2. The approximation method is particularly suitable for structural components where the existing axis distance of the reinforcement is smaller than the value required as a minimum value in the tables of Eurocode 2-1-2. A prerequisite for the application of the simplified design method is that the cross-sectional dimensions otherwise at least correspond to the values specified in the tables of Eurocode 2-1-2.

The simplified design methods in Eurocode 2 Part 1-2, Annex B.1 (500°C isotherm method) and Annex B.3 (method for assessment of a reinforced concrete cross-section exposed to bending moment and axial load by the method based on estimation curvature) are not approved for use in the National Annex.

For the fire safety design of reinforced concrete cantilever columns for which Method A cannot be applied due to their static-constructive boundary conditions, the National Annex of Eurocode 2-1-2 in Annex 1 contains a simplified verification procedure for the fire resistance class R 90, in which the design can be carried out using four so-called standard diagrams. The standard diagrams are valid for reinforced concrete cantilever columns

- made of normal concrete with a strength class C30/37,
- with cross-sectional dimensions h = 300 mm, h = 450 mm, h = 600 mm and h = 800 mm,
- with single-layer reinforcement consisting of reinforcing steel B500B, with the referenced axis distance of the longitudinal reinforcement u/h = 0.10 and a geometric reinforcement ratio of 2% and
- with a four-sided fire exposure.

Due to the extension of the scope of application to parameters that deviate from the values in the standard diagrams a broad spectrum of applications that are of practical relevance can be covered.

6.5.2.3 Eurocode 3 Part 1-2

In Eurocode 3 Part 1-2, approximation methods are provided for simplified mathematical verifications of structural components at the load-bearing capacity level and temperature level.

For the method on the level of resistance, verification is based on the limit state of load-bearing in case of fire analogue design for ambient temperature:

$$E_{fi,d,t} \leq R_{fi,d,t} \tag{6.13}$$

where

$E_{fi,d,t}$ design value of the actions in case of fire, if applicable including the effects of thermal expansion and deformation,

$R_{fi,d,t}$ corresponding value of design resistance in case of fire (indices: fi for fire; d for design; t for time).

In the method on the level of resistance the reduction in young's modulus and yield stress due to the increased temperatures is taken into account. As with the procedure at the temperature level, the design steel temperature is decisive, which is assumed to be homogeneous over the cross-section and over the longitudinal axis of the member. This assumption is on the safe side in certain cases, e.g., for continuous beams. By way of simplification, the load-bearing capacity in fire situation in this case may be determined using an adaption factor.

In the case of verification on the level of critical temperature, the θ_{cr}-method, it is shown that the highest steel temperature $\theta_{a,max}$ occurring in the case of fire remains below the critical steel temperature θ_{cr}. The critical steel temperature θ_{cr} is the temperature at which the resistance of the structural component is just as high as the stress due to mechanical loads.

$$\theta_{a,max} \leq \theta_{cr} \tag{6.14a}$$

For the calculation of steel temperatures of non-protected and protected cross-sections inside buildings, DIN EN 1993-1-2 lists equations for the determination of the temperature increase $\Delta\theta_{a,t}$ at the time interval Δt. [6.32] lists approximation equations that can be used to determine the structural component temperatures in dependence on the fire duration and the section factor in the case of stress according to the standard temperature-time curve (Figure 6.14). Steel temperatures outside a building can be determined in accordance with EC 1-1-2 Annex B.

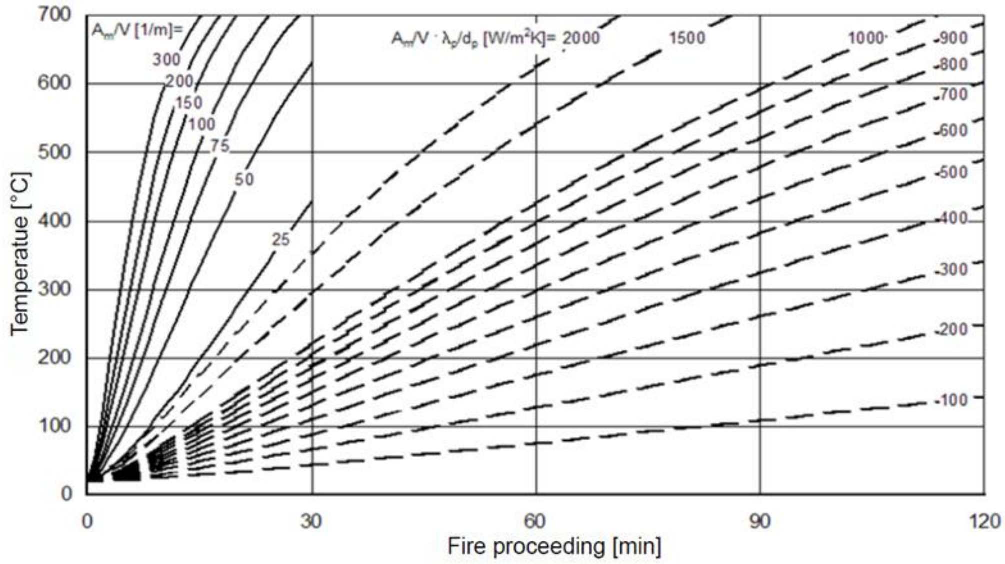


Figure 6.14 Temperatures for unprotected (A_m/V) and clad steel sections ($A_p/V \cdot \lambda_p/d_p$) (according to [6.32]) exposed to the standard fire

The critical steel temperature can be determined in dependence on the degree of utilization. The degree of utilization is calculated from the ratio of actions and load-bearing resistance at the beginning of the fire (t = 0):

$$\mu_0 = \frac{E_{fi,d}}{R_{fi,d,t=0}} = \frac{\eta_{fi}}{\gamma_{M,20°C}} = \frac{\eta_{fi}}{1.1} \qquad (6.14b)$$

The reduction factor acc. to EC 3-1-2 2.4.2 (3) and National Annex may be set on the safe side at η_{fi} = 0.65, so that μ_0 = 0.59. This results in a critical steel temperature of 557°C. Unless deformation criteria or influences from stability have to be considered, the critical steel temperature θ_{cr} may be calculated for the utilization factor μ_0 assuming a uniform temperature distribution in the component with

$$\theta_{a,cr} = 39.19 \cdot ln\left(\frac{1}{0.9674 \cdot \mu_0^{3,833}} - 1\right) + 482 \qquad (6.15)$$

where

$$\mu_0 = \frac{E_{fi,d}}{R_{fi,d,0}} \qquad (6.16)$$

μ_0 utilisation factor for components of cross-section class 1, 2 or 3 according to Eurocode 3 Part 1-1 and for tension members

$E_{fi,d}$ stress in case of fire

$R_{fi,d,0}$ component resistance at time t = 0 min

For structural steel components without stability influence, $\gamma_{M,20°C}$ =1.0 may be used. This results in μ_0 = 0.65 and a critical temperature of θ_{cr} = 540 °C.

For the fire safety design, the connections should be dimensioned in the way that they are not utilized more than the connected structural components. Due to the higher mass in the area of the connections caused by screws, stiffeners, head plates, etc., the heating and also the cooling of the connections, including the fasteners, is usually delayed in comparison to the connected components. In Eurocode 3, Part 1-2, simplifications are given which allow a dimensioning without exact modelling of connections [6.33]. If protected and unprotected steel components are connected, the connection may be considered as protected according to the draft of EC 3-1-2 [6.34] if the cladding or the intumescent paint is extended at least 500 mm beyond the connection. According to DIN 4102-4 a range of 300 mm is sufficient for fire resistance classes F 30 to F 90 600 mm is required for fire resistance classes F 120 to F 180. In the draft of EC 3-1-2, the simplified design procedure for cross-sections of cross-section class 4 is modified and transferred from the informative annex to the standard Part 1-2. The new procedure enables higher load-bearing capacities in case of fire, because the effective yield point is now used instead of the proportional limit. For the cross-section class 4, with the exception of tension components, it is still possible to verify the critical temperature with θ_{crit} = 350°C.

6.5.2.4 Eurocode 4 Part 1-2

Eurocode 4 Part 1-2 provides simplified design methods for protected and unprotected composite slabs, composite beams with and without encased concrete, steel beams with encased concrete and composite columns.

The simplified design method for the design of composite slabs contained in EC 4-1-2 Annex D is based on [6.35]. In contrast to girders and columns, the design of composite slabs requires the verification of both the load-bearing capacity and the integrity function. The calculation process covers verification of the positive (and for continuous systems the negative) moment load-bearing capacity and the thermal insulation criterion. The cross-sectional temperatures are calculated in simplified mode separately for the upper and lower flange, web of the section as well the reinforcing steel in dependence on the type of concrete (normal or lightweight) and the targeted fire resistance class. The bending moment load-bearing capacity is reduced due to reduction in material strengths as a result of heating. In Germany, composite ceilings are currently subject to national technical approvals (abZ), which are also based on fire tests. Comparison calculations [6.36] have shown that the method in EC 4-1-2 leads to uneconomic results compared to the abZ.

EC 4-1-2 Annex F specifies a method for the fire design of partially encased steel beams. This method takes account of the temperature influence for the cross-sectional areas of upper steel flange, slab and concrete encasement by means of area reduction. For the remaining areas – web and lower flange of the steel section as well as reinforcing steel in the concrete encasement and in the slab - reduction factors for strength are listed in dependence on the fire resistance time. The method can be used for single-span and continuous girders (continuously concreted ceiling slab, steel profile may be non-continuous) for fire resistance classes R 30 to R 180.

The load-bearing capacity of composite girders without concrete encasement, where the steel profile is no higher than 500 mm and the thickness of the concrete slab is greater than 120 mm, can be estimated based on the critical temperature and the temperature-based reduction in steel strength. For composite girders with a steel profile higher than 500 mm or with a concrete slab smaller than 120 mm, the bending load capacity can be determined with the help of the bearing load method. Detailed information on this is given in EC 4-1-2 Annex E.

EC 4-1-2 Annex G outlines a simplified calculation method in which the temperature calculation is "bridged" using simplified approaches by directly determining the reduction in strength for defined cross-sectional areas in dependence of the fire resistance time and cross-sectional massiveness. In order to calculate the plastic limit normal force and the effective bending strength in fire situation, the cross-section of the column is subdivided into the partial cross-sections "flanges of the steel cross-section", "web of the steel cross-section", "concrete encasement" and "reinforcing bars". This method takes into account the loss of stability of the column due to the temperature-dependent decrease in rigidity [6.37]. The influence of slenderness is taken into account by special buckling stress curves that are valid for fire situation [6.38].

The simplified calculation method contained in EC 4-1-2 Annex H can be used to design concrete-filled hollow profiles with a buckling length up to 4.50 m and a width between 140 mm and 400 mm which are exposed to fire on all sides in line with standard time-temperature curve. The temperature distribution in the cross-section is calculated by means of thermal analysis using the advanced calculation method. The design of limit load capacity is carried out with the help of load-bearing charts.

6.5.2.5 Eurocode 5 Part 1-2

In Eurocode 5 Part 1-2, the load-bearing behaviour of timber structural components in fire situation are influenced not only by the temperature development in the cross-section, but above all by the combustion of the outer cross-section zone that is directly exposed to the fire. For the fire safety design of load-bearing timber components, two simplified design methods are offered. Both methods are based on the combustion rate v and therefore calculate a specific combustion depth d after t minutes fire time. The combustion rate is specified in Eurocode 5-1-2, Table 3.1, depending on the type of wood (solid wood, laminated timber etc.).

In the Δd-method or in the method with reduced cross-sections, the combustion depth $d_{char,n}$ is increased by an amount $\Delta d = k_0 \cdot d_0$ (Figure 6.15). In simplified terms, the amount Δd takes account of the material properties in the residual cross-section that have to be reduced due to the increased temperatures. The load-bearing capacity verification for the effective residual cross-section may then be performed with the strength and deformation properties at normal temperature. The value Δd is defined in EC 5-1-2 Table 4.1 as a time-dependent variable. It must additionally be taken into account whether the ignited surface is exposed to the fire in protected or unprotected manner.

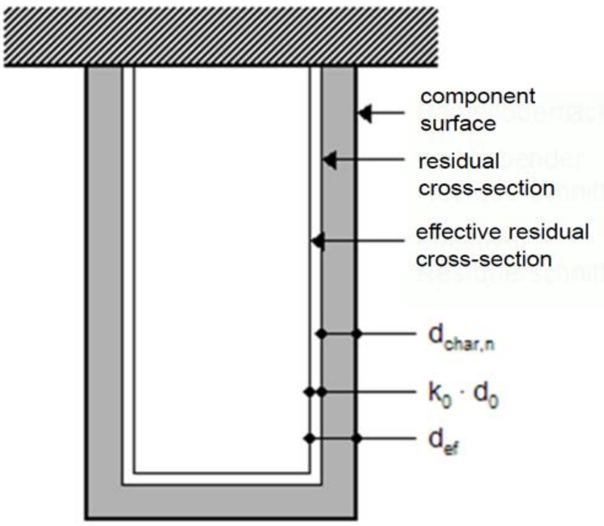


Figure 6.15 Residual cross-section for bar-shaped timber structural components

Alternatively, the T_m-method or the method with reduced material properties may be used for pinewood with a rectangular cross-section which are three or four-sided exposed to fire as well as for round timber with standard fire load from all sides. Fire safety design is performed using the remaining residual cross-section as shown in Figure 6.15. For temperature-depended reduction of bending, compressive and tensile strength as well as modulus of elasticity, calculation functions are defined which are depended on the ratio of the residual cross-section to the area of the residual cross-section.

Application rules for connections stressed with shear loads are listed in EC 5-1-2 in Chapter 6.2 and 6.3. The rules apply exclusively to double-shear connections with a symmetrical design. Here as well, there are two alternatives for verification. On the one hand, the simplified method in EC 5-1-2 Table 6.1 specifies fire resistance time up to a maximum of 20 minutes that were designed at ambient temperature according to EC 5-1-1. The fire resistance times can be enhanced by increasing the dimensions relative to the required values according to EC 5-1-1. This allows verification of fire resistance times of maximum 30 minutes. Alternatively, higher fire resistance times up to a maximum of 40 minutes can be achieved using the method with reduced loads without increasing the structural component dimensions. For higher fire resistance times of up to 60 minutes, the structural component dimensions should be increased analogous to the simplified method. A further improvement of the fire resistance time is possible by the arrangement of a cladding. Design rules for bolts exposed to pull-out stress are shown in Chapter 6.4 of EC 5-1-2. There are no design rules in EC 5-1-2 for carpentered connections.

The informative Annex E of EC 5-1-2 lists approximation methods for verification of the temperature increase $\Delta T \leq 140$ K and $\Delta T \leq 180$ K on the side facing away from the fire for fire integrity-constructions. The fire resistance time can be calculated in dependence on the protection on the room side and the side facing away from the fire, the insulation in the cavities of the structural components and the dimensioning of the columns, ceiling beams and rafters. When calculating the fire resistance time of the components, the temperature flow at the different points of the cross-sections must be taken into account according to Figure 6.16.

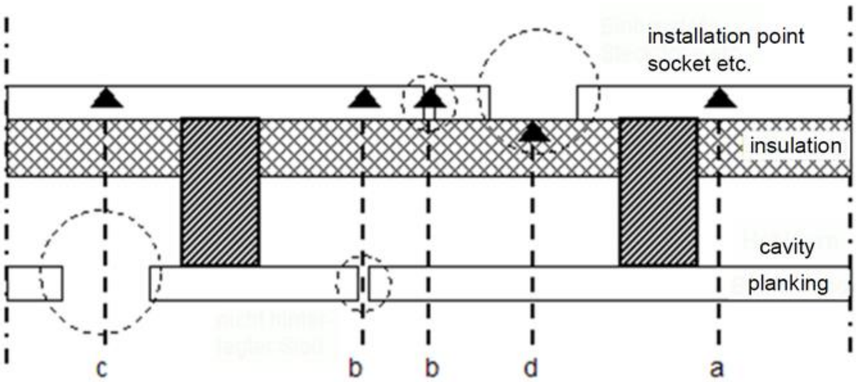


Figure 6.16 Temperature flow in sections a - d across fire integrity timber construction

The "first draft" for the revision of EC 5-1-2 [6.39] announces some innovations for the fire safety design of timber components. On the one hand, it has been agreed that a fire resistance time of at least 90 minutes can be verified with all design methods. In addition, compared to the 2010 edition of EC 5-1-2, design tables will probably be included again as the first step in fire safety design. The type and scope of the design tables have not been conclusively clarified yet, so that no further details can be given at this stage.

In the course of a simplification of the Eurocodes, from the outset the aim of the revision was, to delete one of the two equal simplified level 2 design methods. Since the method with a reduced cross-section is universally applicable for softwood and hardwood with rectangular and round cross-sections in different fire exposure situations, while the method with reduced material properties may only be used for three or four-sided exposed to fire rectangular cross-sections and round cross-sections of softwood exposed on all sides, the "first draft" only contains the method with reduced cross-section. This is remarkable since the method with reduced properties led to more economical results in some cases. The included char-model is extended by additional equations for the determination of the failure time of fire protection claddings.

A simplified method for the design of cross laminated timber elements is newly included, which is based on the method with a reduced cross-section. Here, a distinction is made between the cases, whether on the one hand, the cross laminated timber is initially protected from charring by a cladding or not and whether on the other hand, the adhesive joint is thermally resistant or fails prematurely under the influence of the increasing temperature in case of fire.

The methods for determining the combustion rate of wall studs and ceiling beams in fully insulated and uninsulated structures, which were previously contained in the informative Annexes C and D, have been revised and will be contained in the Part 1-2 of Eurocode 5. The same applies to Annex E for the calculation of the integrity function of wall and slab components. Furthermore, the rules for the calculation of fastener and component connections have been revised.

For the "second draft", it is also planned to include a design method for wood-concrete composite slabs (HBV) (see Chapter Wood-concrete composite ceilings). At present, the design is primarily based on the general building authority approvals of the composite material, taking into account the general design principles of Eurocodes 1, 2 and 5. However, the lack of normative design regulations makes a complete assessment of the load-bearing capacity of HBV-Concrete slab systems difficult, which is to be changed in the future with the publication of a European product standard and for fire safety design by the inclusion in EC 5-1-2.

6.5.2.6 Summary of simplified design methods

In summary, it should be noted that it is possible to calculate the load-bearing capacity of the structural components exposed to standard fire for a given fire resistance time using the simplified calculation method outlined in the fire safety parts of Eurocodes 2 to 5. The verification methods do not provide any information about the deformations that occur in the event of fire. With the exception of Eurocode 5-1-2, it is not possible to verify the integrity function and thermal insulation (T criterion). There are also no verification methods for the shear and composite load-bearing behaviour and for the spalling behaviour of reinforced concrete components.

6.5.3 Advanced design methods

6.5.3.1 General information

Advanced design methods can be used for the fire safety design of individual structural components as well as partial and global structures with any type and shape of cross-section and for fully-developed fires or local fires. For the purpose of design, calculation parameters are needed to determine the temperature and load effects. These parameters can be found in

Eurocode 1 Part 1-2. Moreover, data on the temperature-dependent change in the thermo-mechanical properties of the building materials (thermal conductivity, strength, thermal expansion etc.) are also required. The necessary information and data can be found in the specialised literature and the fire safety parts of Eurocodes 2 (concrete), 3 (steel) and 4 (composite structures). The fire safety parts of Eurocodes 5 (timber) and 6 (masonry) contain no or only very general information. The following information therefore primarily focus on concrete, steel and composite construction elements.

Moreover, when designing structural components, it must be ensured that possible types of failure which are not covered by the advanced calculation method (e.g., inadequate rotation capacity, spalling or falling of concrete coverings, local buckling, shear and b and composite failures as well as anchorage failure) are prevented by means of suitable design measures.

According to the third draft of EC 2-1-2 [6.26], an imperfection with a sinusoidal course and a pass of L/1000 has to be used for the calculation of centrally loaded columns. For eccentrically loaded columns an imperfection can be neglected. According to EC 3-1-2 [6.3] the same applies for steel columns.

According to the National Annex to Eurocode 1-1-2, advanced design methods may only be used for fire safety design of individual components, partial and entire structures if they have been validated. Corresponding validation examples can be found in Annex CC of the National Annex and are explained in Chapter Validation of the guideline. The verification should be reviewed by a qualified test engineer or test expert.

6.5.3.2 Decreasing component temperatures

The fire models characterized in Chapter 5 of the guideline describe the development of the hot gas temperatures for a natural fire development with rising and decreasing temperatures. As a result of the decreasing hot gas temperatures, the cross-section of the component initially cools down only on the outside, but as time progresses it also cools down in cross-sectional areas further inside of the component. Transient cross-sectional heating becomes transient cross-sectional cooling. The thermal material properties in Chapter 6.3 have to be modified for calculation of the decreasing component temperatures. For example, vaporisation of the pore water in the concrete is not a reversible process, which means that the definition given in Figure 6.5 for the specific heat capacity is only valid for the period with increasing temperature development.

For decreasing component temperatures, it is necessary to take account of irreversible thermal material properties. For the calculation of decreasing temperatures [6.40] recommends calculations from the turning point of the temperatures (point K in the Figure 6.17) using the temperature conductivity coefficient linked to the maximum temperature until full cooling is complete.

The effects of the irreversible thermal material parameters on the temperature distribution in a square concrete cross-section where b = 200 mm is shown in Figure 6.18. The figure shows the isotherms after a fire duration of 60 minutes: the thick lines are based on consideration of the irreversible thermal material parameters, while the thin lines do not take these parameters into account.

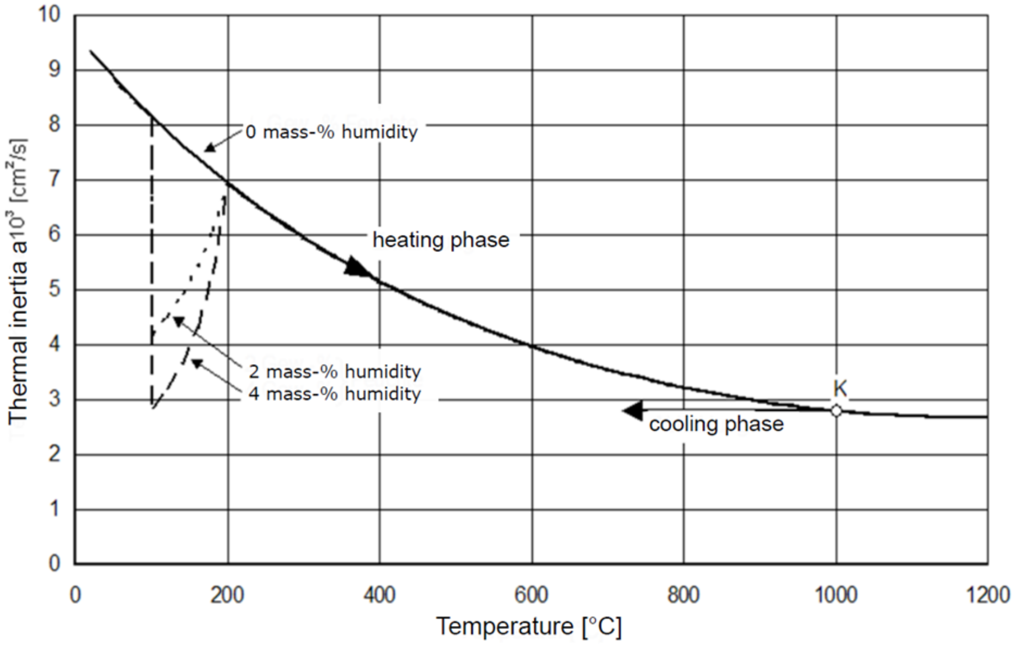


Figure 6.17 Temperature conductivity coefficient a of normal concrete with primarily siliceous aggregates for the heating and cooling phase

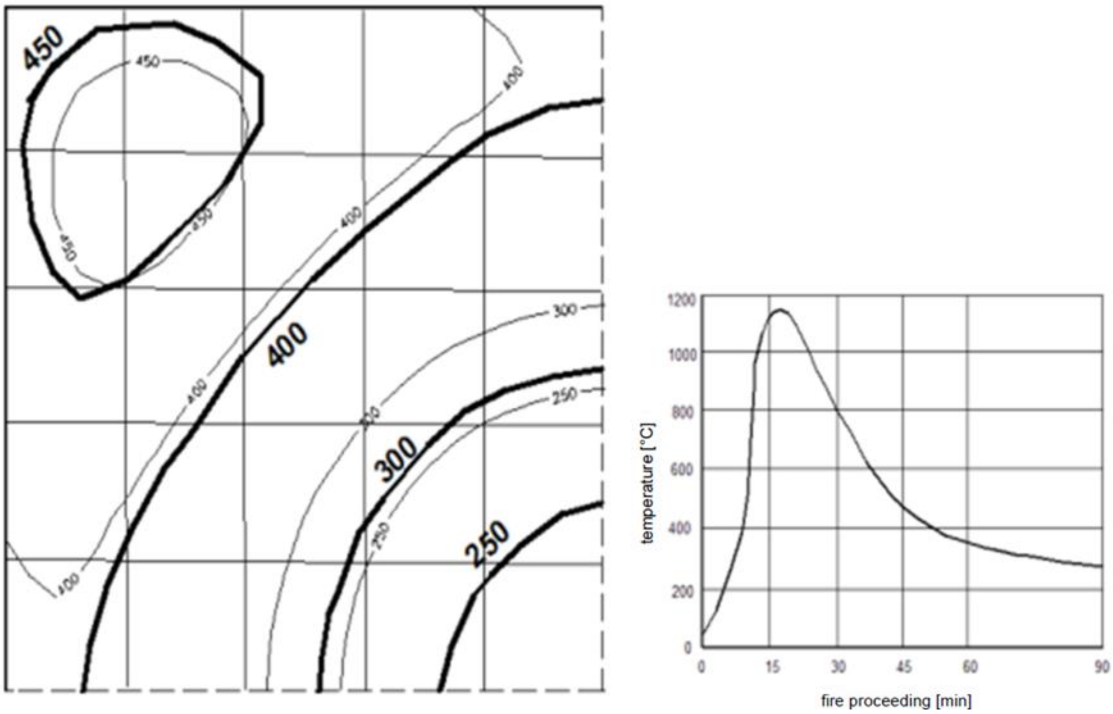


Figure 6.18 Left: isotherms after a fire time of 60 minutes with (thick) and without (thin) consideration of the irreversible thermal material parameters; right: hot gas temperatures

The temperature-dependent stress-strain curves and the thermal strains outlined in the Eurocodes are based on evaluations of material tests at high temperatures. The stress-strain curves are based on measured values from high-temperature creep while the thermal strains are based on measured values from heating tests with constant heating rate. Thus, for example, the strains of the stress-strain curves contain both temperature-dependent elastic and plastic components as well as the much greater high-temperature transient creep components [6.41]. The material investigations and the subsequent evaluations result in imitations with regard to the application of stress-strain curves and thermal strains.

The temperature-dependent stress-strain curves are only suitable:

- For heating rates between 2 and 50 K/min,
- for rising structural component temperatures ($\delta T/\delta t \geq 0$), and
- are not suitable for the calculation of constraining forces in structural components with a low elongation.

The thermal strains are only suitable for rising temperatures of the structural component ($\delta T/\delta t \geq 0$).

The limitations should be taken into account in the calculation of the load-bearing and deformation behaviour of structural components and structures. In particular these accounts in the case of fire according to Chapter 5 of the guideline, where hot gas temperatures that characterise a natural fire development with increasing and decreasing temperatures are calculated using fire simulation models.

In the case that the fire safety design of structural components and structures is to be carried out on the basis of the natural development of a fire, the fire safety parts of Eurocodes 2, 3 and 4 recommend the use of alternative or modified stress-strain curves and thermal strains. These must be validated by testing. In addition, approximations are offered, which are compiled and explained below.

Due to the rapidly rising hot gas temperatures, heating rates of over 50 K/min can occur in the outer margin zones of reinforced concrete, prestressed concrete and composite structural components in the first minutes of fire exposure. In this marginal zone, which is only a few centimetres wide, the temperature-related material softening can set in extremely rapidly. This reduces the contribution of the margin zone to the load-bearing capacity of the overall cross-section. With longer fire periods, heating rates of less than 2 K/min will only occur inside the cross-section, in particular with massive cross-sections. The temperatures for these cross-sectional areas remain close to the initial temperature for the entire duration of the fire exposure, which means that here the stress-strain curve for $T \approx 20$ °C can be used without limitations.

In steel structures, heating rates of more than 50 K/min will only occur in unprotected structures where failure will occur after less than 15 minutes of fire duration. The heating rates of protected steel structures generally remain within the range from 2 K/min and 50 K/min.

The fire safety parts of Eurocode 2 and Eurocode 4 contain approximation models for calculations with falling component temperatures ($dT/dt < 0$). According to these models, the stress-strain curves for structural steel and hot-rolled reinforcing steel may be used as a sufficiently accurate approximation for increasing and decreasing steel temperatures.

The informative Annex C to Eurocode 4-1-2 shows stress-strain relationships for concrete which are adjusted for natural fires with cooling phase. The peak value of the concrete compressive strength is reduced for the cooling phase depending on the maximum temperature reached. Figure 6.19 shows temperature-dependent stress-strain curves up to the maximum temperature $\theta_{max} = 400$ °C and the subsequent cooling to $\theta_{max} = 20$ °C. This approximation approach does not take into account the irreversible compressions that occur during cooling [6.40].

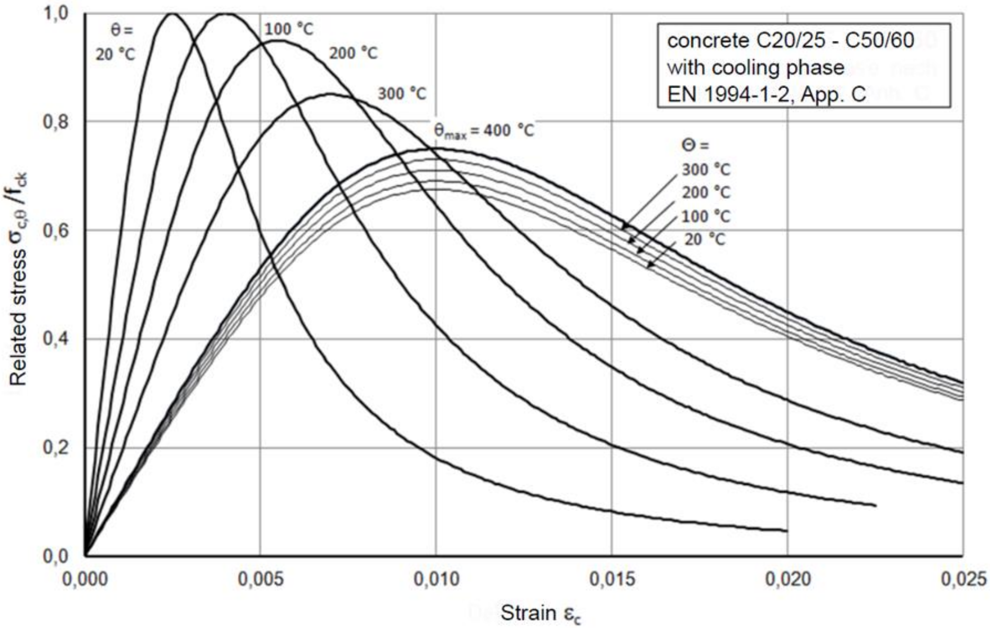


Figure 6.19 Temperature-dependent stress-strain curves of concrete with a cooling phase according to Eurocode 4-1-2, Annex C

The Eurocodes do not contain calculation information on deformations and thermal strains for decreasing temperatures. In [6.42], some measurement results of high-temperature transient creep tests with concrete specimens are published. They show pronounced irreversible residual strains depending on the maximum temperature reached. Figure 6.20 show that residual strains of approx. 4 mm/m occur in no-load samples following cooling after the samples had been heated to approx. 800 °C (curve 1). If the tests are performed with 10% (curve 2) or 60% (curve 3) load utilisation, the residual expansion strains in cooled-down state are in the region of - 5 mm/m.

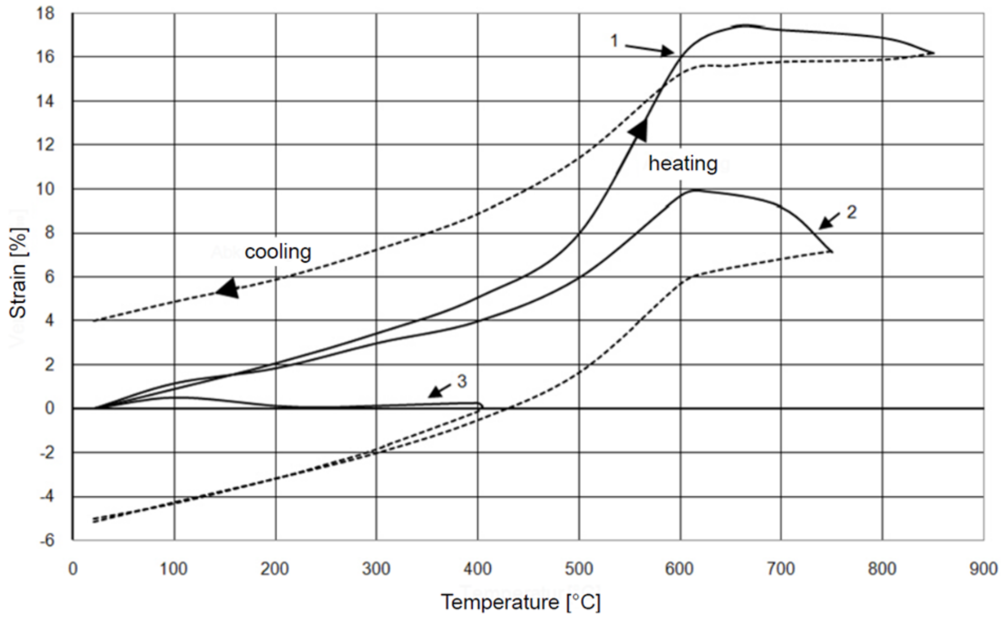


Figure 6.20 Strain of normal concrete after heating and cooling

For the investigation of the material behaviour of concrete under natural fire exposure, three representative concrete mixtures were analysed in [6.43], [6.44], [6.45], [6.46]. These are normal concrete (C 30/37), high-performance concrete (C 80/95) and ultra-high-performance concrete with a compressive strength of more than 150 N/mm². In addition to the thermal material parameters (density, specific heat capacity, thermal conductivity), the strength behaviour in the cooling phase was investigated by means of steady-state tests and the deformation behaviour by means of transient creep tests. The investigations have shown that depending on the considered parameters (thermal conductivity, density, thermal expansion, reduction in strength, etc.) there are differences of varying degrees between the material parameters in the heating phase and in the cooling phase. Furthermore, it should be taken into account that many different temperature profiles can develop during a natural fire.

In summary, it applies for the stress-strain curves in case of decreasing temperatures that the concrete compressive strength must be reduced and that the calculation basis for rising temperatures can be used unchanged for structural steel and hot-rolled reinforcing steel. There are no validated stress-strain curves for cold-formed reinforcing steel, and for cold worked and quenched steel and tempered prestressing steel. This means that fire safety design with calculation models for structural components containing these construction materials is only possible up to the point where the maximum temperature is reached.

For the deformations and thermal strain of concrete in the area of decreasing temperatures, there are no sufficient experimental values available that would allow the definition of validated calculation assumptions. By way of rough approximation, it is therefore suggested to use the same thermal strain parameters for the heating and cooling of concrete. This procedure can also be used for the thermal expansion of reinforcing steel, prestressing steel and structural steel. Using these approximations, it is only possible to provide an approximately valid picture of the load-bearing behaviour of the structural components and structures exposed to fire, but deformations can only be inadequately gathered or not gathered at all. Therefore, the requirement from the fire parts of the Eurocodes, where the calculated deformations should be reviewed with regard to their compatibility with support conditions and adjacent structural members, can only be carried out with limitations and considerable difficulties.

6.5.3.3 Thermal material properties of fire protective claddings and reactive fire protection systems

Within the framework of [6.47] temperature-dependent material properties for fire protective claddings and intumescent coatings under natural fire exposure and recommendations for the application of suitable test methods for their determination have been developed. The following fire protection materials have been investigated:

- gypsum plasterboard and gypsum fibre plasterboard,
- Calcium silicate boards, and
- solvent-based and water-based intumescent fire protection systems.

Up to now, temperature-independent material parameters based on components tests under the fire exposure of the standard fire only existed for selected fire protection materials [6.8]. In [6.47], thermal material properties for various fire protection claddings, plasters and intumescent coatings were investigated in laboratory scale and calibrated and validated by means of a large-scale fire test.

It was shown that the thermal material properties of fire protective claddings and intumescent coatings are irreversible and have to be determined for the heating and cooling phase. In addition, especially in the heating phase, a heating rate dependence of the thermal material properties of fire protective claddings and intumescent coatings was shown. Temperature-independent constant values for the thermal material properties do not cover the thermal material behaviour realistically. Figure 6.21 shows a comparative consideration between the steel temperatures determined in a real scale test and the steel temperatures calculated by simulations at the same temperature measuring point. Within the scope of the numerical investigations, the material properties contained in EC 3-1-2 and those determined in [6.47] were used.

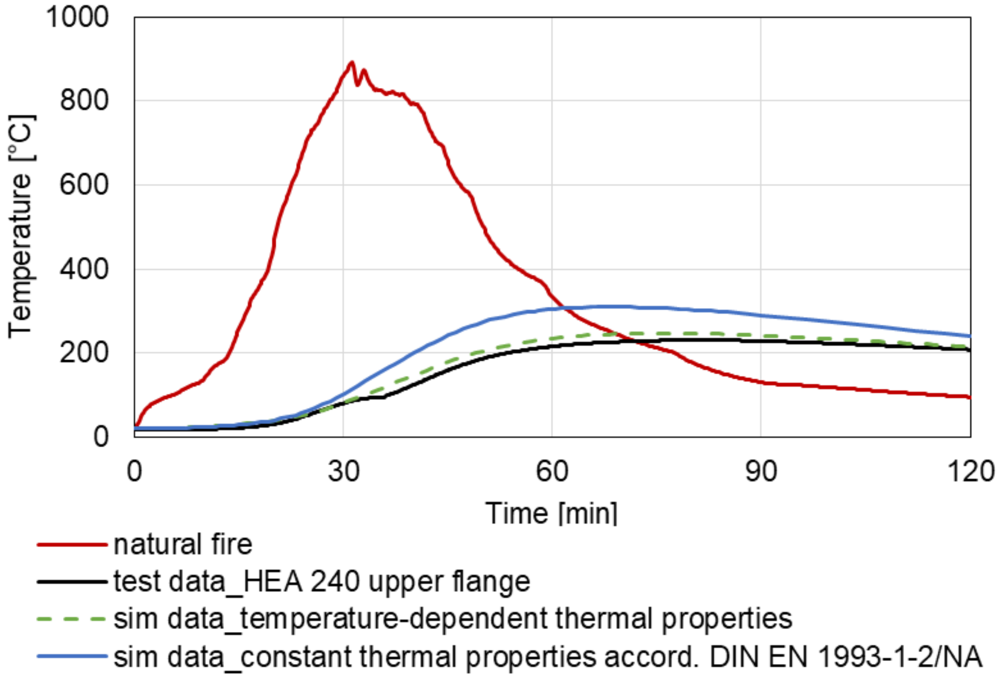


Figure 6.21 Comparative consideration between test data and calculated cross-sectional temperatures using the constant Eurocode material properties and the temperature-dependent material properties determined in [6.47]

Recommendations for suitable test application and thermo analytical measuring methods are summarized in [6.47].

6.5.4 Application assistance

6.5.4.1 General information

As the Eurocodes offer design methods on three levels (tabular design methods, simplified calculation methods, and advanced calculation methods) the user often has the choice between formally equivalent verifications. The calculation time, but also the accuracy, increases with each level. The following tables provide an overview of which calculation methods are available for which structural components, provide some indication of the special features of the verification process, and show whether the increased calculation time is justified.

Table 6.4 Overview of the verification alternatives; EC 2-1-2

Structural component	Level 1	Level 2	Level 3	Remark:
Simply supported beams	EC 2-1-2; Table 5.5 for standard fire	EC 2-1-2; Annex B.2 for standard fire EC 2-1-2; Annex E for standard fire	EC 2-1-2; Chap. 4.3 for standard fire and natural fire	A
Continuous beams	EC 2-1-2; Table 5.6 (und 5.7) for standard fire	EC 2-1-2; Annex B.2 for standard fire EC 2-1-2; Annex E for standard fire	EC 2-1-2; Chap. 4.3 for standard fire and natural fire	A
Beams exposed on all sides	EC 2.1.2; Chap. 5.6.4	EC 2-1-2; Annex B.2 for standard fire	EC 2-1-2; Chap. 4.3 for standard fire and natural fire	A
Simply supported slabs	EC 2-1-2; Table 5.8 for standard fire	EC 2-1-2; Annex B.2 for standard fire EC 2-1-2; Annex E for standard fire	EC 2-1-2; Chap. 4.3 for standard fire and natural fire	A
Continuous solid slabs	EC 2-1-2; Table 5.8 for standard fire	EC 2-1-2; Annex B.2 for standard fire EC 2-1-2; Annex E for standard fire	EC 2-1-2; Chap. 4.3 for standard fire and natural fire	A
Flat slabs	EC 2-1-2; Table 5.9 for standard fire	--/--	--/--	B
Simply supported ribbed slabs	EC 2-1-2; Table 5.10 for standard fire	EC 2-1-2; Annex B.2 for standard fire	EC 2-1-2; Chap. 4.3 for standard fire and natural fire	A

		EC 2-1-2; Annex E for standard fire		
Ribbed slabs with at least one restrained edge	EC 2-1-2; Table 5.11 for standard fire	EC 2-1-2; Annex B.2 for standard fire EC 2-1-2; Annex E for standard fire	EC 2-1-2; Chap. 4.3 for standard fire and natural fire	A
Floor columns	EC 2-1-2; Table 5.2a for standard fire	EC 2-1-2; Annex B.2 for standard fire	EC 2-1-2; Chap. 4.3 for standard fire and natural fire	C
Cantilever columns	--/--	EC 2-1-2/National natural fire; Annex AA	EC 2-1-2; Chap. 4.3 for standard fire and natural fire	D
Non-load-bearing walls (partitions)	EC 2-1-2; Table 5.3	--/--	EC 2-1-2; Chap. 4.3 for standard fire and natural fire	
Load-bearing solid walls	EC 2.1.2; Table 5.4	EC 2-1-2; Annex B.2 for standard fire	EC 2-1-2; Chap. 4.3 for standard fire and natural fire	E
Fire walls	EC 2-1-2; Chap. 5.4.3	--/--	--/--	F
Tensile members	EC 2-1-2; Chap. 5.5 with Table 5.5	--/--	EC 2-1-2; Chap. 4.3 for standard fire and natural fire	

NF: natural fire

re. A) In case of standard fire, the first task is to carry out design based on tabulated data (Level 1). Levels 2 and 3 are only meaningful if the boundary conditions of the table are not met or if Level 1 does not supply the desired result. The 500°C isotherm method in line with Annex B.1 as alternative simplified calculation method was not approved via the NA. The available simplified calculation methods are Annex B.2 (zone method) and Annex E. *)

re. B) EC 2-1-2 only contains a tabulated data for flat slabs. The simplified calculation methods may not be used, as the punching shear verification may be the key factor in fire situation. Verification against punching shear is also extremely difficult using the simplified calculation methods, as the shear characteristics in fire situation have not yet been fully investigated.

re. C) Table 5.2a applies only to floor columns of a horizontally braced structure for which a restraint can assumed in firre situation. The zone method in line with Annex B.2 is not validated for the verification of columns. If the zone method is used for column verification, the additionally required assumptions should be published in the literature (EC 2-1-2/National Annex, NCI to "Annex B Simplified calculation methods"). *)

e. D) Table 5.2a does not apply to cantilever columns. Design diagrams for the fire safety design of cantilever columns that take account of the influence based on the theory of the 2^{nd} order can be found in Annex AA of the National Annex to EC 2-1-2. *)

re. E) In case of standard fire, the first task is to carry out design based on tabulated data (Level 1). One-sided fire exposure is to be assumed for partitions, while two-sided fire exposure is to be assumed for walls without integrity function. The zone method according to Annex B.2 is not validated for the verification of walls. If the zone method is used, the additionally required assumptions should be published in the literature (EC 2-1-2/National Annex, NCI to "Annex B Simplified calculation methods"). *)

re. F) Verification of mechanical impact stress can only be carried out using tabulated data, as the advanced calculation methods do not yet supply any valid results for this parameter either.

*) In the case of natural fire exposure, the only feasible method is the advanced calculation method. If the zone method is used, the Equations (B.11) to (B.13) should be evaluated, the reduction in compressive strength and cross-section in line with Fig. B.5 only apply in the case of a fire exposure in line with the standard temperature-time curve.

Eurocode 3 Part 1-2

Table 6.4: Overview of the verification alternatives EC 3-1-2

Structural component	Level 1	Level 2	Level 3
Tension members	--/--*	EC 3-1-2; Chap. 4.2.3.1 for standard fire and NF EC 3-1-2; Chap. 4.2.4 for standard fire and NF	EC 3-1-2; Chap. 4.3 for standard fire and NF
Compression members (CSC 1-3)	--/--*	EC 3-1-2; Chap. 4.2.3.2 for standard fire and NF EC 3-1-2; Chap. 4.2.4** for standard fire and NF	EC 3-1-2; Chap. 4.3 for standard fire and NF
Beams (CSC 1, 2)	--/--*	EC 3-1-2; Chap. 4.2.3.3 for standard fire and NF EC 3-1-2; Chap. 4.2.4** for standard fire and NF	EC 3-1-2; Chap. 4.3 for standard fire and NF
Bending (CSC 3)	--/--*	EC 3-1-2; Chap. 4.2.3.4 for standard fire and NF EC 3-1-2; Chap. 4.2.4** for standard fire and NF	EC 3-1-2; Chap. 4.3 for standard fire and NF
Members subject to combined bending and axial compression (CSC 1-3)	--/--*	EC 3-1-2; Chap. 4.2.3.5 for standard fire and NF EC 3-1-2; Chap. 4.2.4** for standard fire and NF	EC 3-1-2; Chap. 4.3 for standard fire and NF
Members (CSC 4)	--/--*	EC 3-1-2; Chap. 4.2.3.6 for standard fire and NF EC 3-1-2; Chap. 4.2.4** for standard fire and NF	EC 3-1-2; Chap. 4.3 for standard fire and NF
CSC: cross-section class			
NF: natural fire			
*: There is no "Level 1" (tabulated data) for EC 3-1-2; alternative method: "Euro-nomogram" (see Chapter 6.5.4)			
**: Only applicable if deformation criteria or influences due to stability problems are ruled out			

6.5.4.2 Eurocode 4 Part 1-2

Table 6.5 Overview of the verification alternatives EC 4-1-2

Structural component	Level 1	Level 2	Level 3
Composite beams comprising steel beams with no concrete encasement	--/--	EC 4-1-2 Chap. 4.3.4.2 and Annex E as well as D.5 for standard fire	EC 4-1-2 Chap. 4.4 for standard fire and NF
Composite beams comprising steel beams with partial concrete encasement	EC 4-1-2 Table 4.1, 4.2 und 4.3 for standard fire	EC 4-1-2 Chap. 4.3.4.3 and Annex F for standard fire	EC 4-1-2 Chap. 4.4 for standard fire and NF
Composite columns with fully concrete-encased steel cross-sections (concrete has load-bearing function)	EC 4-1-2 Table 4.4 for standard fire	EC 4-1-2 Chap. 4.3.5.1 for standard fire	EC 4-1-2 Chap. 4.4 for standard fire and NF
Composite columns with fully concrete-encased steel cross section (concrete only for insulation)	EC 4-1-2 Taböe 4.5 for standard fire	EC 4-1-2 Chap. 4.3.5.1 for standard fire	EC 4-1-2 Chap. 4.4 for standard fire and NF
Composite columns with partial concrete encasement	EC 4-1-2 Table 4.6 for standard fire	EC 4-1-2 Chap. 4.3.5.2 and Annex G for standard fire	EC 4-1-2 Chap. 4.4 for standard fire and NF
concrete filled hollow sections	EC 4-1-2 Table 4.7	EC 4-1-2 Chap. 4.3.5.3 or 4.3.5.4 and Annex H for standard fire	EC 4-1-2 Chap. 4.4 for standard fire and NF
Unprotected composite slabs	--/--	EC 4-1-2 Chap. 4.3.2 and Annex D for standard fire	EC 4-1-2 Chap. 4.4 for standard fire and NF
Protected composite slabs	--/--	EC 4-1-2 Chap. 4.3.3 and Annex D for standard fire	EC 4-1-2 Chap. 4.4 for standard fire and NF
NF: natural fire			

6.5.4.3   Eurocode 5 Part 1-2

Table 6.6 Overview of the verification alternatives EC 5-1-2

Structural component	Level 1	Level 2	Level 3	Remark:
Rectangular cross-sections made of softwood, exposed to fire on three or four sides	--/--	EC 5-1-2; Chap. 4.2.2 for standard fire and NF EC 5-1-2; Chap. 4.2.3 for standard fire and NF	EC 5-1-2; Chap. 4.4 for standard fire and NF (Calculated values; Annex B)	A
Pole form cross-sections made of softwood, exposed to fire on all sides	--/--	EC 5-1-2; Chap. 4.2.2 for standard fire and NF EC 5-1-2; Chap. 4.2.3 for standard fire and NF	EC 5-1-2; Chap. 4.4 for standard fire and NF (Calculated values; Annex B)	A
All structural components	--/--	EC 5-1-2; Chap. 4.2.2 for standard fire and NF	EC 5-1-2; Chap. 4.4 for standard fire and NF (Calculated values; Annex B)	A
Assemblies whose cavities are completely filled with insulation	--/--	EC 5-1-2; Annex C for standard fire	EC 5-1-2; Chap. 4.4 for standard fire and NF	
Assemblies with void cavities	--/--	EC 5-1-2; Annex D for standard fire	EC 5-1-2; Chap. 4.4 for standard fire and NF	
Unprotected connections	EC 5-1-2; Table 6.1 for standard fire	EC 5-1-2; Chap. 6.2.2.1 for standard fire	EC 5-1-2; Chap. 4.4 for standard fire and NF	B
Protected connections	EC 2-1-2; Table 6.1 for standard fire	EC 5-1-2; Chap. 6.2.2.2 for standard fire	EC 5-1-2; Chap. 4.4 for standard fire and NF	B
Axially loaded screws	--/--	EC 5-1-2; Chap. 6.4 for standard fire	EC 5-1-2; Chap. 4.4 for standard fire and NF	
Determination of the separating function	--/--	EC 5-1-2; Annex E	EC 5-1-2; Chap. 4.4 for standard fire and NF	

re. A) With the simplified calculation methods, the component verification is to be carried out on the residual cross-section in line with EC 5-1-1, taking into account the temperature-depended reduction in strength. The mass burning rates listed in Table 3.1 only apply for standard fire exposure. The cross-section reduction in case of a natural fire may be determined in line with EC 5-1-2; Annex A.

re. B) The calculation rules of Levels 1 and 2 apply to symmetrical, two-shear connections subject with standard fire exposure.

6.5.5 Assessment of calculation methods and verification of evidence

6.5.5.1 General information

Various softwares are available for the calculation-based fire safety design of structural components and structures using advanced calculation methods, but the basic characteristics of the softwares vary widely, as the way in which the softwares are validated based on results from fire tests. The National Annex of EC 1-1-2 proposes a systematic procedure based on [6.48] for the systematic investigation of the physical, mathematical and mechanical calculation bases of calculation softwares with regard to thermal analysis, cross-sectional analysis and system analysis. The aim is to evaluate the applicability of the softwares for structural fire safety engineering by means of a sufficient number of validation and calibration examples. The idea is also to assess the applicability of the calculation models to real structures. The individual verification steps are validated one after the other using clear assessment criteria. For this purpose, a test matrix is used to check the calculation accuracy of the software used for the respective evaluation criterion, depending on the parameters. For the examples the testing matrix lists either existing analytical solutions or results of calculations using recognised calculation software for comparison purposes. Thus, the results obtained with the calculation software to be tested can be compared. Deviations should be within admissible tolerances. If these tolerances are not observed for all assessment criteria, limited approval of softwares is also possible. For example, softwares that do not adequately gather the system behaviour (bearing conditions, load) are not suitable for the fire safety design of statically indeterminate systems and/or systems whose stability is risky. However, the softwares can be used for the fire safety design of simply supported structural components [6.49].

[6.48] outlines assessment benchmarks which can be used to ensure that in case of the application of the softwares the safety level in Germany is keep.

The evaluation criteria are divided into

- Software verification,
- Validation and falsification, and
- Testing through calibration examples.

Due to software verification a mathematically exact verification of the correctness of the software can be carried out. Validation or falsification can be used to verify the general calculation principles of softwares based on a systematic testing methodology. Testing of softwares based on calibration examples, which allow practically a simulation of a fire test, takes into account all variables that influence the fire resistance time of a structural component.

6.5.5.2 Software verification

The calculation softwares for fire safety design are based on iterative methods that are used to determine approximation solutions, as there are generally no self-contained solutions to the differential equations on which the problems are based on. Therefore, a verification of softwares used for computational fire safety design will only be possible in exceptional cases. For engineering practice, test methods must be used with which the correctness of the softwares can be verified with high probability for a widest application range.

6.5.5.3 Validation

Validation is used to review certain areas of a software for correctness with the help of a systematic testing methodology (e.g., heat conduction in solid objects). The precondition for this is the existence of a clearly defined solution that can be worked out by means of manual calculation or based on calculations using generally recognised softwares. Due to the different boundary conditions with regard to the experiment and calculation processes, experimentally determined results generally cannot be used for this purpose. [6.48] contains validation examples for:

- The thermal analysis
  - Heat transfer during heating
  - Heat transfer during cooling
  - Heat transfer with multiple layers
- The cross-sectional analysis
  - Thermal expansion / extension
  - Temperature-dependent material properties
  - Limit load-bearing capacity (maximum of the σ-ε-T diagram)
- The system behaviour
  - Static boundary conditions (supports)
  - Theory of the 2nd order
  - Development of constraint forces

The validation examples developed in [6.48], provide a catalogue which can be used for the systematic assessment of the fundamental suitability of softwares for structural fire safety design of bar-shaped structural components based on individual sub-analyses. In the National Annex of Eurocode 1 Part 1-2, the validation examples have been aligned with the current EN versions of the Eurocode fire parts and reviewed for comprehensibility and plausibility.

6.5.5.4 Testing through calibration examples

With the help of calibration examples, software -calculated and experimentally determined results are verified with regard to their conformity. It should be taken into account that an experiment generally only provides an excerpt of "reality", as experimental results are only available under certain conditions (supporting conditions, eccentricities, load application) for structural components and partial structures, and only in the most seldom of cases for global structures. Alternatively, design results according to the tables of DIN 4102 Part 4 or the fire parts of Eurocodes 2 and 4 can be used as feasible substitutes for test results, if all boundary conditions of the tables are known. [6.48], contains calibration examples for

- Reinforced concrete beams with low and high percentage of reinforcement,
- Reinforced concrete columns, and
- Axial loaded steel-composite columns with partial concrete encasement.

The calibration examples serve to verify the correctness of a software based on comparison with experimental results. The consequence is that the calculation results are subject to a certain degree of fluctuation. The admissible deviations (tolerances) from predefined solutions that are chosen must be far larger than with the validation examples, for which a clearly defined solution is generally available.

The available verification examples must be extended to other construction methods such as structural steel or timber construction in order to cover all application areas of advanced design methods.

6.5.5.5 Admissible deviations

With the validation examples, and in particular with the calibration examples, there will be differences between the solutions computed by different softwares. Various aspects need to be taken into consideration when defining admissible limiting deviations (tolerances) from the predefined solutions. Different solutions may be calculated due to different numerical methods (FEM, difference equations) and equation solvers (iteration conditions and limits) [6.50]. Therefore, it is conceivable that some softwares approximate the results of the validation and calibration examples well in some cases with low deviations and less well in other cases.

The admissible deviations from model calculations in the validation and calibration examples must be based on stochastic model uncertainty. Since there are usually clear solutions for the validation examples, only small deviations can be accepted. In the case of calibration examples based on the experimental results, higher admissible deviations must also be accepted when assessing the softwares due to the greater model uncertainty.

The admissible deviations were defined in the collection of examples in the National Annex CC to EC 1-1-2 [6.38] as 1% to 3% of the reference variable for the validation examples that are used to investigate systematic calculation principles and as 5% to 10% of the reference variable for the calibration examples.

6.5.5.6 Sample collection in the National Annex

National Annex CC of Eurocode 1 Part 1-2 contains validation and calibration examples that can be used to review the applicability of softwares for the structural fire safety design of components and partial structures, and therefore also for the investigation of the suitability for application to real structures. The collection of examples consists first and foremost of eleven examples that can be used to review the main calculation principles for heating as well as the temperature-dependent load and deformation behaviour in validation examples and, secondly, the overall calculation process using calibration examples by re-calculating a fire test.

The validation examples serve to validate the individual steps of verification one after the other based on clearly defined assessment criteria. To this end, the calculation accuracy of the software used for the assessment criterion in question is reviewed on a parameter-dependent basis with the help of a test matrix. The test matrix lists either existing analytical solutions or results of calculations of recognized softwares for the respective example for comparison in question for the purpose of comparison. In a next step this is used for comparison of the results obtained with the calculation software to be reviewed. Deviations should be within admissible tolerances.

The calibration examples can be used to re-calculate the “entire calculation process” as with the simulation of a fire test. The collection of examples in National Annex CC currently only contains three calibration examples for reinforced concrete structural components as well as one example for a steel composite girder.

The collection of examples was compiled as part of the research project [6.48] and adapted to the current versions of the Eurocode fire safety parts. The collection of examples cannot claim to be exhaustive; in other words, even if all examples are successfully processed, this is no guarantee that a software is free of errors. However, the validation of a software on the basis of the collection of examples guarantees a minimum standard.

The collection of examples can be expanded in the future as described above. In the final analysis, however, the responsibility for the correctness of the software remains with the creator of the software and for the application of the software with the user, who has to review the plausibility of the obtained results.

National Annex CC of EC 1-1-2 states that the creator of a calculation software designed to perform verifications based on the advanced calculation methods should independently calculate the validation examples before the software is used for fire safety design verifications that are of relevance in terms of the building codes and regulations. The input data and calculation assumptions should be used unchanged according to the software description. Using the tabular overviews contained in the National Annex to EC 1-1-2, a documentation should be prepared about the results obtained by the software creator within the scope of the validation. Deviations from the model results should be within the specified admissible deviations.

6.5.5.7 Ring calculation

In practice, the fire safety design of load-bearing components is increasingly carried out with advanced design methods. The design or simulation of fire exposed structural elements or load-bearing structures is generally more cost-effective than real-scale fire tests. Within the framework of a ring calculation, comparative calculations were carried out by different users considering a fire exposed steel and a reinforced concrete column using different software softwares. Ring calculations serve to evaluate the scattering of results within a precise question due to the influences of different parameter settings of the softwares and different users.

The presented ring calculation is based on two real scale fire tests, which were carried out at the Institute of Building Materials, Concrete Construction and Fire Safety of the TU Braunschweig. A detailed test description and evaluation of the simulations is given in Annex A6.1.

In the first fire test, an unprotected HEB 300 steel column with a steel grade of S355 was investigated. The length of the double-sided hinged supported column in the fire test was 3.64 m. This included steel plates (40x40x4 cm^3) on both sides, which were necessary for the installation of the column into furnace. The column was loaded with 1,530 kN and then exposed to a four-sided standard fire. The mechanical load was applied with an eccentricity of 3 cm. During the test the horizontal deformation was measured in mid-high of the column. In addition, the surface temperatures of the web and of one flange were measured.

The numerical investigations have shown that the calculated temperatures agree very well with the experimental results in 4 out of 5 simulations. In all simulations, the calculated failure time is shorter than the actual failure time in the test.

In the second fire test, a reinforced concrete column with a cross-section of 200 mm x 200 mm and a concrete strength class C 20/25 was examined. The influence of different pre-deformations was also investigated in the ring calculation. In [6.51], for axial loaded columns it was determined, that assuming a parabolic pre-deformation along the length of the column with a pass of L/2000, leads to a very good agreement between the test and calculation results using the advanced design method. According to EC 2-1-1, a pre-deformation of L/400 is required [6.52]. In the course of the ring calculation, the pre-deformation (L/1000, L/1500, L/2000) was the varying parameter.

With regard to the thermal analyses, the calculated temperatures in the cross-section centre of the reinforced concrete column and in the bar axis of the longitudinal reinforcement agree well with the test results.

Due to the different selected support conditions of the users within the framework of the model development and the real support situation in the furnace, shorter and longer failure times were calculated in the simulations compared to the failure time in the test. On the basis of the numerical investigations, it was determined that for identical boundary conditions including the same user and the software, the influence of the pre-deformation with regard to the calculated failure time is minor importance.

6.6 Concrete spalling

Rapid heating and high temperature effects can lead to concrete spalling which can cause serious damage to the concrete structural components. Spalling is subdivided into explosive spalling, aggregate spalling and the falling away of concrete layers. The falling away of concrete layers occurs as a result of the attrition of the concrete after prolonged exposure to fire. Aggregate spalling occurs when individual aggregate particles break off due to the mineralogical structure of the aggregate. Explosive spalling occurs at the beginning of a fire. A major cause of this is the moisture content of the concrete. The mass transport in the form of water, water vapour and air through the pore system of the concrete leads to tension as the concrete heats up. In addition, internal stresses occur in the cross-section, which are caused by the different expansion behaviour of the concrete components and by the non-linear temperature distribution in the concrete cross-section. Several factors have an influence on the internal stresses that arise, such as the temperature rise at the beginning of a fire, the external mechanical loads, the geometry, the type of aggregate, the moisture content, the permeability and the concrete strength.

The explosive spalling can damage the concrete cross section to such an extent that the load-bearing capacity is endangered. The rule of thumb is that the denser the concrete, the greater the risk of explosive spalling. As there are many factors that influence spalling, however, the measures outlined here are based on EC 2-1-2 and a publication on tunnel fires [6.53].

In case of designing concretes of strength classes up to and including C50/60 using the tables according to EC 2-1-2 the effect of spalling is already taken into account and no further measures are required. When using simplified and advanced design methods, spalling shall be considered separately if the minimum cross-sectional dimensions of the design tables are not met.

For high-strength concrete up to strength class C100/115, suitable measures should be selected, such as increasing the tabulated minimum cross-sectional dimensions. The values for this are given in EC 2-1-2 Chapter 6.4.3. In order to limit spalling, polypropylene fibres can also be used. Experimental verifications are required for concretes and structural components that cannot be complied with these measures. The application of fire protection cladding is a further possibility to reduce spalling.

In the third draft of EC 2-1-2 [6.26], the design regulations regarding spalling are intensified. Fire tests have shown that structural components exposed to the standard fire with a concrete strength < 70 MPa generally show little or no spalling, but from a strength of 70 MPa onwards spalling is to be expected to be more frequent. For structural components with a concrete strength of at least 70 MPa, experimental verification is therefore either required in order that no significant spalling occurs or the concrete mixtures has to include 2 kg/m³ polypropylene fibres.

6.7 Special construction methods

6.7.1 High strength and ultra high strength concrete

Structural components made of high-strength concrete can also be designed in accordance with EC 2-1-2 [6.2] based on the methods for normal concrete. For certain conditions, the tabular data can also be used for the design of components made of high-strength concrete.

Chapter 6 of EC 2-1-2 lists data on the mechanical properties of high-strength concrete which can be used for design purposes. The thermal properties can be taken from those for normal concrete.

Figure 6.22 shows the reductions in strength for high-strength concrete in line with Eurocode 2. A distinction is made between three classes based on the strength of the high-strength concrete. Class 1 comprises concrete C 55/67 and C 60/75, class 2 comprises C 70/85 and C 80/95, and class 3 comprises C 90/105. In the case of concrete types with strengths higher than class 3, the material parameters should be determined by experimental means.

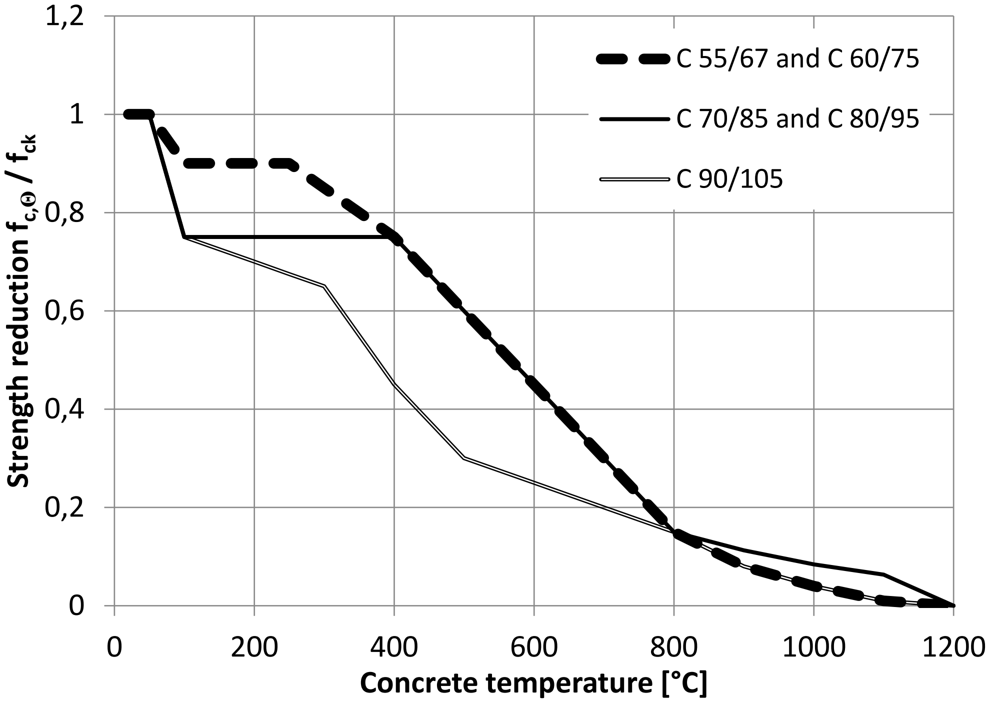


Figure 6.22 Strength reduction $f_{c,\Theta}$ / f_{ck} of high strength concrete

The stress-strain curves for the various classes can be determined with the help of strength reduction and the values for the parameters of the stress-strain relationships for normal concrete at elevated temperatures. Figure 6.23 shows by way of example the stress-strain curves for concrete of strength class C 70/85 and C 80/95 (class 2).

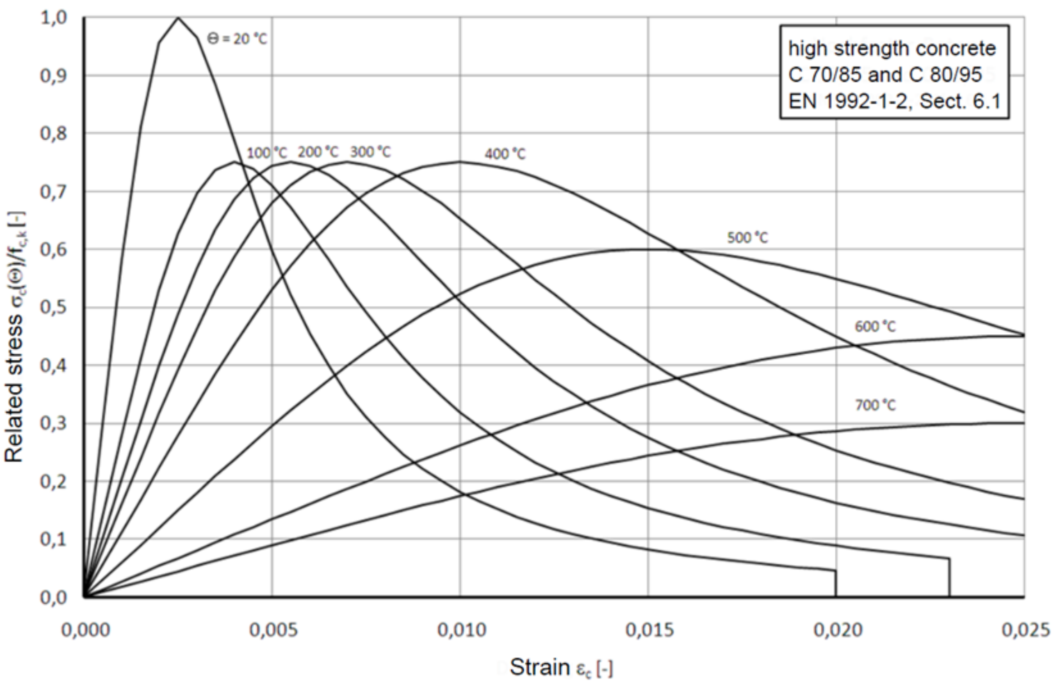


Figure 6.23 Stress-strain curves of high-strength concrete; in this case class 2

In addition, it is necessary to take the possibility of explosive concrete spalling into account; this spalling may be far more serious in the case of high-strength concrete than with normal concrete due to the higher density. Concrete classes C 55/67 to C 80/95 with a content of silica fume of less than 6% of the cement weight are subject to the same regulations as normal concrete. EC 2-1-2 outlines various methods (A to D) to avoid explosive concrete spalling in the case of higher content of silica fume or higher concrete classes.

In more recent research studies, concretes with strength classes higher than C100/115 (ultra-high strength concretes (UHPC)) are considered [6.54]. At the Technische Universität Braunschweig temperature-dependent thermal material and stress-strain relations for ultra-high strength concrete have been developed. The focus was in particular on spalling behaviour as, due to the high density, the explosive spalling at the beginning of a fire can cause considerable damage that pose a threat to load-bearing ability. In order to reduce the spalling capacity, different amounts of polypropylene fibres were added to the UHPC mixture during the investigations. With regard to the spalling behaviour of UHPC, it has been demonstrated as set out in [6.54] that by adding a PP-fibres content of 2 kg/m³ or more, spalling can be limited to a negligible level. The single components of the concrete mixture design have been continuously developed so that even higher concrete compressive strengths can be achieved with an even denser structure. This may require an increase of the PP fibre content. However, in this context it should be taken into account that an excessively high PP fibre content can cause strength reductions. At present, there are no design regulations for UHPC within the scope of Eurocode 2 Part 1-2. Thus, the application of UHPC can only be made by approval in individual cases.

6.7.2 Self-compacting concrete

Self-compacting concrete is characterised by the fact that there is no compaction effort need after placing the concrete into the formwork. This includes venting and filling the spaces between the reinforcements. For rheological reasons, the fine aggregate content of self-compacting concrete must be increased, which reduces permeability. Analogous to high-strength and ultra-high-strength concretes, this also increases the spalling risk. Thus, appropriate measures (e.g., PP fibres) must be provided. In [6.55] it was determined in a series of tests on self-compacting concrete samples that a PP fibre content of 1.5 kg /m³ is too low to prevent explosive spalling in water-stored concretes. However, in the case of air-stored concrete samples this content proved to be sufficient.

Self-compacting concrete has special fresh concrete properties. In order to ensure these properties, the German Committee for Reinforced Concrete (Deutscher Ausschuss für Stahlbeton) published corresponding specifications in a guideline [6.56], which has been added to the building codes. With regard to the properties of hardened concrete, self-compacting concrete does not differ from normal concrete and is therefore not dealt separately in the fire parts of the Eurocodes [6.2] [6.4].

6.7.3 Lightweight concrete

The design methods for normal concrete contained in Eurocode 2-1-2 [6.2] also apply to lightweight concrete up to strength class LC55/60. However, temperature-dependent material properties of lightweight concrete are not included. Eurocode 4-1-2 provides thermal and thermo-mechanical material properties of lightweight concrete with densities between 1,600 and 2,000 kg/m³ that deviate from the material properties of normal concrete contained in [6.2].

For example, compared to normal concrete the compressive strength of lightweight concrete is reduced from a temperature above 400 °C (normal concrete at 300 °C); at higher temperatures, the strength of lightweight concrete decreases more rapidly compared to normal concrete. Furthermore, the temperature-dependent thermal conductivity of lightweight concrete is below the lower function contained in Eurocode 2-1-2 [6.2] (see Chapter 6.4.1.2).

6.7.4 Carbon concrete or textile concrete

The reinforcement in carbon concrete consists of carbon fibres, lamellae or textile scrim structures. As a result of a low glass transition temperature of adhesives and impregnating materials (50°C to 100°C) an early decrease in strength properties occurs, which is why the application range for bonded CFRP lamellas is below the glass transition temperature of the adhesive and the lamella. From the fire safety point of view, textile scrims (fibres) which are embedded in the concrete are more advantageous. In [6.57], investigations are reported which show that carbon fibres oxidise at approximately 550°C and are completely thermally decomposed at approximately 760°C. In [6.57], the tensile strength of carbon concrete specimens of different material combinations was investigated and compared with further literature references. It is found that the tensile strength of carbon concrete at 200°C decreases to approximately 80% of the initial strength, at 300°C still reaches approximately 60% and at 500°C still approximately 20% of the initial strength. Therefore, carbon concrete components require higher concrete coverings or additional fire protection measures such as claddings.

6.7.5 High strength reinforcing steel

The application of high-strength reinforcing steels (e.g., SAS 670/800) is increasing. So far, little is known about the high-temperature behaviour of these high-strength reinforcing steels. Tests [6.58] have shown that the high-temperature behaviour corresponds to that of B 500 when the strength is modified. However, since the tests were carried out as structural component tests, no reliable information concerning the material behaviour is available. Thus, for the application of high-strength reinforcing steels, the thermal material properties must first be determined by tests. The design can be carried out with the values of the test results according to EC 2-1-2.

6.7.6 High-strength structural steel

Steel grades with higher strengths are being developed for steel construction. These include the normalized fine-grained structural steel S460N and the thermomechanical rolled fine-grained structural steel S460M. In [6.59], the mechanical properties of two steel grades S 460 M and S 460N were compared with those of DIN EN 1993-1-2. It turned out that the thermomechanical rolled steel S460M is covered by these material properties, but the steel S460N material behaviour is more disadvantageous (see Figure 6.24).

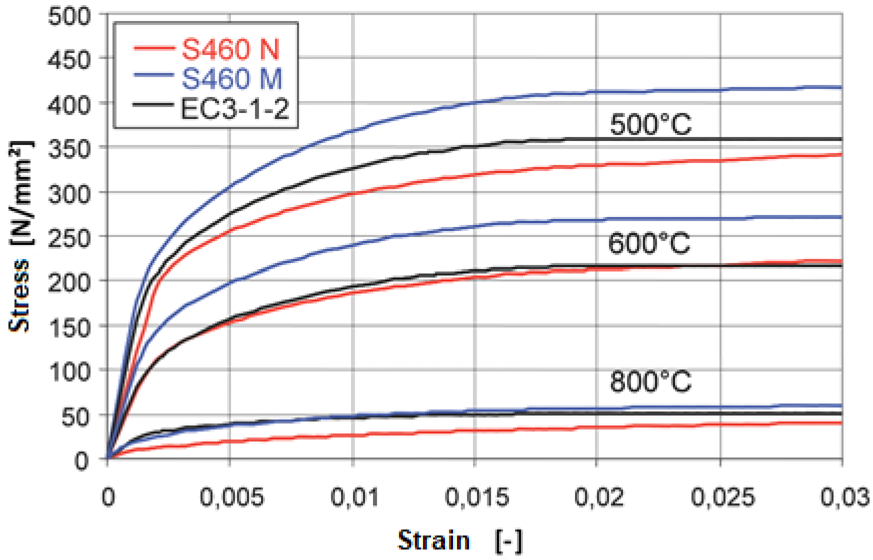


Figure 6.24 Comparison of stress-strain relations of S460N, S460M and the material properties according to EC 3-1-2, taken from [6.59]

For the fire safety design of structural components made of S460N steel the temperature-dependent reductions in the yield strength should therefore be made as shown in the Figure 6.25.

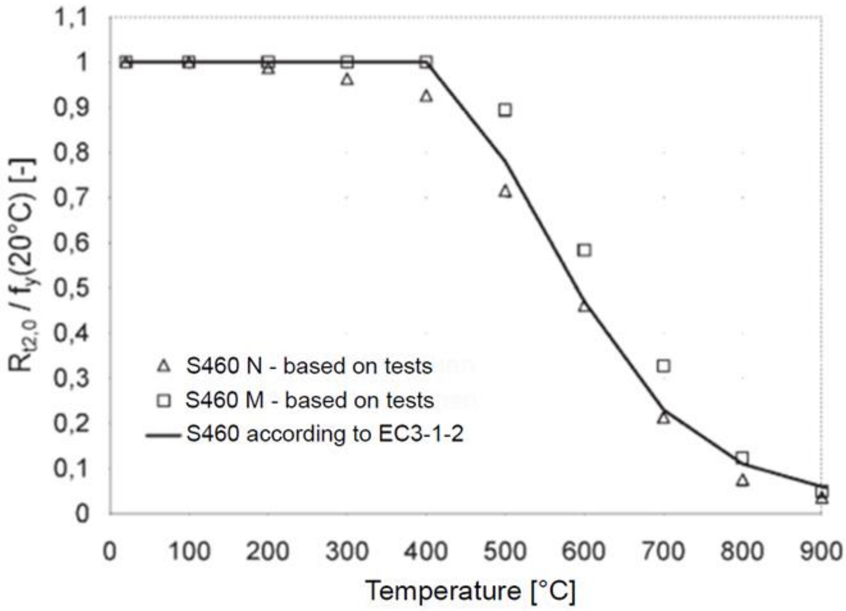


Figure 6.25 Reduction of the yield strength $R_{t2.0}$ derived from tests and according to Eurocode [6.59]

6.7.7 Galvanized steel

Hot-dip galvanised structural steel components have a better heating behaviour compared to bare structural steel. This is due to the different surface properties, expressed by the emissivity. In [6.60] a two-stage emissivity concept was developed which will also be included in the next

Eurocodes DIN EN 1993-1-3 and DIN EN 1994-1-2 generation. The Emissivity εm in dependence of steel surface temperature is shown in Table 6.7.

Table 6.7 Emissivity ε_m in dependence of the steel surface temperature

Surface temperature	T ≤ 500°C	T ≥ 500°C
Structural Steel	0,70	
Hot-dip galvanized structural steel1	0,35	0,70

Hot-dip galvanised structural steel according to DIN EN ISO 1461 and a steel composition according to categories A and B of DIN EN ISO 14713-2.

The potential of the galvanization is shown in Figure 6.26 for a bending component which has a fire resistance class of 30 minutes on the basis of the utilization factor of µ0 at the time t = 0. According to this for massive components galvanizing leads to almost a doubling of the load capacity. Assuming a simplified μ_{fi} = 0.65 for common buildings, only small reserves have to be provided in the cold design and the verification of the fire resistance class R 30 is possible without passive fire protection measures. It should also be noted, however, that profiles with lower masses and with galvanisation in cold design may only have very low utilisation in order to be able to fulfil the verification of fire resistance class R 30 without protective measures.

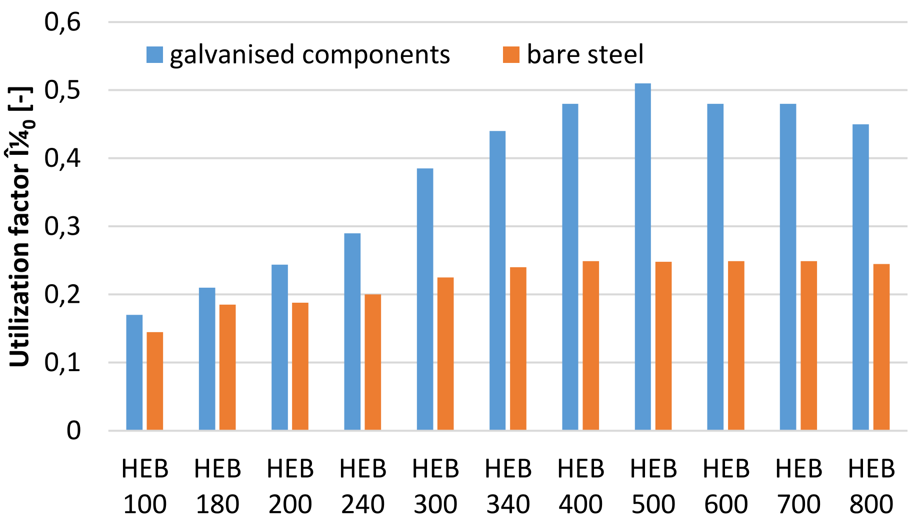


Figure 6.26 Comparison of the utilization factors μ_0 for galvanized and ungalvanized components for a fire resistance time of 30 minutes based on [6.60]

6.7.8 Composite columns with adjustable profiles

A sophisticated arrangement of the materials structural steel and concrete in the cross-section enables competing demands on load-bearing capacity, fire resistance and slenderness of composite columns with adjustable profiles. As a result of the low thermal conductivity and high heat capacity of concrete, the heating of the internal steel profile is significantly delayed in the event of fire. Furthermore, the concrete in combination with adjacent steel elements forms a composite cross section and thus contributes to a particularly economical construction method. In order to ensure a fast construction process and an optically appealing surface, a hollow steel profile is used as the outer element of the columns.

For practical purposes, different profiles are used as adjustment profiles in order to increase certain properties, such as the bending stiffness. Inside the concrete filled hollow columns, standard rolled or welded profiles as well as sheet metal packages or solid steel cores can be arranged. Composite columns with an adjustable profile can be designed individually via the dimensions of the individual cross-sectional components with regard to the required load-bearing capacity and fire resistance time. Generally, fire resistance times of 90 or 120 minutes without additional fire protection measures can be achieve in dependence of the selected adjustment profile and the thickness of the concrete cover. Here, the concrete serves and is dimensioned specifically for the thermal protection of the steel profile.

In general, EC 4-1-2 allows the design of concreted hollow profile columns with adjustment profiles, but there are no holistic and applicable design methods available for composite columns with adjustment profiles.

In [6.61], a simplified design method for concreted hollow section columns with adjusted double-T sections is presented. The method includes a simplified temperature determination as well as a load-bearing capacity determination on the basis of reduced strength and stiffness values using the equivalent member method. In [6.62] a design method for concreted hollow section columns with solid steel cores is presented. Here, the columns made of "thermally protected steel core columns" are designed on the basis of EC 3-1-2. For the determination of the steel core temperature, analytical relationships are given, which include the cross-section geometry and the fire resistance time.

In [6.63] approaches for the design of concreted hollow section columns with a second adjusted hollow section (so-called "double-tube" or "double-skin" columns) were developed.

6.7.9 Wood-concrete composite ceilings

Wood-concrete composite ceilings are gaining more and more importance in the construction industry. Wood-Concrete composite ceilings are ceiling systems with linear or planar wooden components that are connected usually to a monolithic concrete slab with a special metallic or form-fitting composite material to form a shear-resistant composite cross section. In order to create the composite load-bearing capacity, special bonding elements are provided in the wood, which connects the woods with the commonly applied site concrete layer. In recent decades, especially in multi-storey timber construction it has been applied as a successful system for covering large spans. With regard to sustainable and resource-saving construction methods, the minimization of the consumption of steel and concrete on solid ceilings by replacing the tension zone with wood represents an ecologically and statically efficient alternative to pure solid construction. In the event of fire, the wood on the side facing the fire protects both, the concrete layer and the remaining cross-section of the wood by burning off in the form of an insulating carbon layer. This reduces the temperature effect on the remaining composite cross section as well as the composite joint. The temperature susceptibility of the composite material can be counteracted by an appropriate framed wood covering. The smoke tightness of the ceilings is reliably ensured by the monolithically applied concrete layer.

For the design of the wood-concrete composite ceilings see Chapter Eurocode 5 Part 1-2.

6.8 Verifications according to DIN 4102 Part 4

When the ARGEBAU conference of German construction ministers in the various federal states decided to introduce the Eurocodes as binding standards for design at normal temperature and for fire situation in 2012, it became necessary to remove the verifications that already existed in the Eurocode as conflicting provisions in DIN 4102-4 [6.64]. However, it is necessary to retain DIN 4102-4 as the "residual standard" for fire protection design rules that are not included in the Eurocodes, such as special components and historical construction methods, so that no "verification gap" arises [6.65]. In contrast to the Eurocodes, the fire resistance classes are still indicated with the national abbreviation F, since the underlying fire tests were carried out on the basis of national test standards.

All interior constructions- drywall construction, suspended ceilings, etc. - are retained in DIN 4102-4 and are supplemented by more recent test results. The verifications of DIN 4102-4, which are included in the Eurocodes, such as the design tables for reinforced concrete components, are not included in DIN 4102-4 anymore. All previous verifications of DIN 4102-4 that are not regulated in the Eurocodes remain in DIN 4102-4.

Table 6.8 shows the structure of DIN 4102-4 [6.64]. The section classified concrete structural components contains structural components made of reinforced concrete and prestressed concrete slabs as well as prestressed hollow-core slabs, reinforced concrete and prestressed concrete ceilings and roofs made of prefabricated elements, reinforced concrete and prestressed concrete ribbed ceilings, reinforced concrete and prestressed concrete slab beam floors as well as brick floors according to DIN 1045-100. The list continues with reinforced concrete and prestressed concrete beam ceilings and corresponding ribbed ceilings with intermediate components. The fire resistance classes of reinforced concrete ceilings in combination with concrete-embedded steel girders and vaulted ceilings are retained, as are the reinforced steel roofs and reinforced steel columns as well as reinforced concrete and prestressed concrete tension components. Classified reinforced concrete walls are now included. The chapter concludes with notes on high-strength concrete and lightweight concrete with closed and porous structures.

Table 6.8 Structure of the content of DIN 4102-4

Section	Building products	Content
	-	Foreword
	-	Introduction
1	-	Area of application, basic principles
2	-	Normative references
3	-	Terms
4	Building materials	Building materials
5	Structural Components	Concrete, light concrete

6		Aerated concrete
7		Structural Steel
8		Timber
9		Masonry
10	Interior construction	Drywall constructions
11	Special construction	Special components
		Literature

The section with classified building components made of reinforced aerated concrete includes ceiling and roof slabs and load-bearing and non-load-bearing walls made of reinforced aerated concrete panels.

The section with classified structural steel components contains design methods and fire resistance classes of protected steel beams and columns as well as fire resistance classes of steel tension elements. Apart from this, the verifications for load-bearing steel components that are covered by Eurocode 3 Part 1-2 are not included.

The section with classified timber structures covers basic design methods of timber structures as well as fire resistance classes of ceilings in timber panel design, timber beam ceilings, roofs made of timber and wood materials, special timber structural components and joints. This is followed by classified walls made of timber constructions like 2-layer walls made of wood-wool lightweight boards, timber-framed walls, walls in timber panel design and walls made of solid wood. In addition to the regulations in the main standard, an amendment A1 to DIN 4102-4 is prepared, which contains further verifications for timber constructions.

The section with classified masonry walls includes load-bearing and non-load-bearing masonry walls.

In the drywall construction section, all classified wall and suspended ceiling constructions are summarized. Here, a few construction details are added which are needed and requested for practical purposes. In addition, some more recent test results are taken into account. Further classified drywall constructions will be regulated in future by the amendment A1 to DIN 4102-4.

In the section with special constructions, the non-load-bearing exterior walls, ventilation ducts, installation shafts and installation ducts are summarised. The section on roofing has been considerably expanded due to recent findings.

6.9 Industrial buildings

According to the building regulations of the federal German states, industrial buildings are classified as special types of buildings and spaces or for special utilisation purposes. In combination with DIN 18230 Part 1 [6.66] and the application of Section 7 of the German Model Industrial Buildings Guideline using the method of equivalent fire duration creates a uniform process for the fire safety design of industrial buildings that takes account of the specific aspects and requirements of industrial use. Although the application of the Eurocode fire safety design in industrial construction is formally excluded according to MVV TB, however, from a scientific point of view it would be possible.

DIN 18230-1 is used to determine the analytically required fire resistance time of the structural components in fire compartments of industrial buildings. The fire safety assessment takes into account boundary conditions such as building dimensions, fire loads, opening areas, enclosure components and installation systems. It is assumed that, in the event of a fire, failure of individual structural components will not occur with sufficient probability or will not lead to collapse of the supporting construction (partial structure, overall structure) and that firefighting inside the building is feasible over an appropriate period of time. By converting the fire load into an equivalent fire duration by taking account of ventilations and enclosing components, the fire effect on a structural component in a natural fire is reduced to the fire effect in a standard fire. Taking evaluation and safety factors into account, the fire effects are used to calculate the analytically required fire resistance time erf t_f of the structural components is calculated and is assigned to the fire resistance classes according to DIN 4102 or DIN EN 13501-2 [6.19].

The calculation method in DIN 18230-1 determines the admissible area and the requirements for structural components based on safety classes for a fire compartment. The equivalent fire duration t_{eqv} is determined according to equation (6.17).

$$t_{eqv} = q_R \cdot c \cdot w \tag{6.17}$$

where

q_R Calculated fire load in kWh/m^2

c Conversion factor c in min · m^2/kWh

w Ventilation factor to take account of ventilation conditions [-]

The determination of t_{eqv} is always considered global for the entire fire compartment. It may, however, also be necessary to take multiple levels, partial areas and partial compartments into consideration. The principle for determination of the equivalent time of fire exposure is outlined in Figure 6.27. The equivalent fire duration t_{eqv} describes the point in time at which approximately the same fire effects occur in a standard fire as in a natural fire. As a measure for the fire effect, the component temperatures of a natural fire and the standard fire are compared. Here, the equivalent fire duration t_{eqv} is the time at which the structural component temperature in a standard fire reaches the maximum value of the structural component temperature in a natural fire.

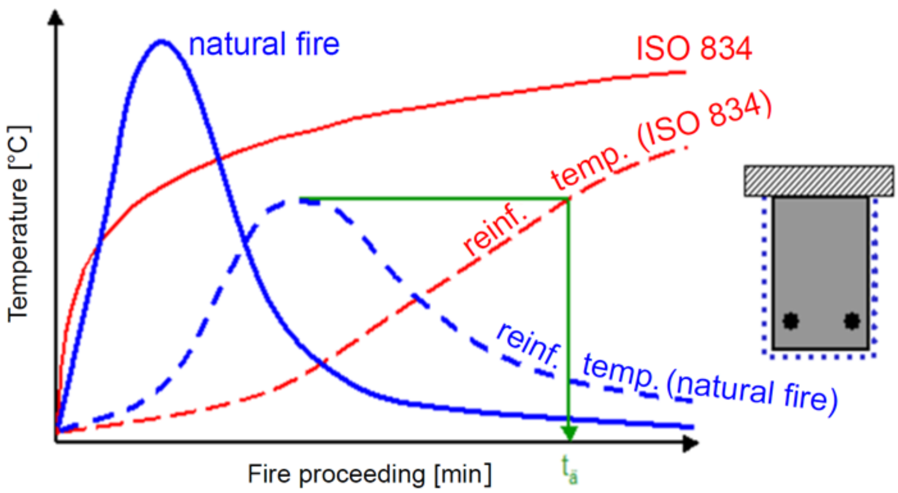


Figure 6.27 Determining the equivalent fire duration t_{eqv}

The analytically required fire resistance time erf t_F is determined according to equation (6.18).

$$\text{erf}\ \ t_F = t_{eqv} \cdot \gamma \cdot \alpha_L \tag{6.18}$$

where

γ Safety factor for components of fire safety class SK_b 3, SK_b 2 and SK_b 1

α_L Additional coefficient to take account of system-based fire protection

Finally, the analytically required fire resistance time erf t_f based on equation (6.18) is allocated to the designation of fire resistance classes according to DIN 4102 or DIN EN 13501-2.

If DIN 18230-1 is applied, all boundary conditions of the standard relating to the assessment of protected and unprotected fire loads, heat combustion and combustion factor of combustible materials, the number of building storeys, and the firefighting compartments with sub-compartments or sub-areas should be taken into account.

6.10 Summary

In this chapter, the different possibilities for the verification of structural elements and structures in case of fire are presented. The fire resistance classes "fire resistant for 30 minutes", "fire resistant for 60 minutes" and "fire resistant for 90 minutes", specified in the building regulations of Germany's federal states are firmly tied to the standard temperature-time curve. For the fire protection verification, the Eurocodes basically offer three equivalent verification methods on different levels.

The verifications on Level 1 (tabulated data) can be performed by means of a simple comparison with the tabulated values. The simplified calculation methods on Level 2 are based on the verifications for structures at normal temperature and are therefore known to structural engineers. However, special fire protection characteristics also have to be taken into account. The advanced calculation methods on Level 3 permit exact numerical simulation of the load-bearing and deformation behaviour of any structural components or global structures exposed to fire.

The tabular method known from DIN 4102-4 is suitable for rapid verification of a wide range of reinforced concrete structural components and composite structural components with low workload. If the application preconditions of the tables are not met, or if the minimum dimensions for the required fire resistance class are not observed, the simplified calculation methods offer an alternative with only a slightly increased calculation workload. The results for the same structural components are generally slightly more favourable than with tabular verification. If the design goal is still not achieved, the advanced design method for the complete numerical simulation of the load-bearing behaviour remains the last alternative, which, however, requires a higher calculation effort. This requires suitable software which is validated for the application in question as well as in-depth knowledge and experience on the part of the user. The results of the advanced calculation method are in turn more favourable for identical structural components than those provided by the simplified calculation method. In addition to the structural fire safety design based on standard temperature-time curve, performance-based design based on a natural fire can also be performed in line with the Eurocodes. Fire safety verifications based on natural fire models represent a deviation from the requirements formulated by the building authorities on the basis of the standard temperature-time curve, which require approval by the building authorities. For this reason, it has to be agreed by the approving authorities. With one exception of the simplified calculation method for steel structures, where only the advanced calculation method on Level 3 may be used for the thermal and mechanical analysis of the structural component or structure. The component should withstand the entire duration of the fire. As it is not possible to clearly predict which point in time is the critical one, the entire fire course should be calculated.

If the advanced calculation methods are used, it should be taken into consideration that the numerical modelling of the spalling behaviour of concrete and masonry structures remains unsolved, and that the behaviour of structural components and structures in terms of shear load-bearing capacity, avoidance of local buckling in the case of steel structures, composite characteristics and sufficient rotation capability in continuous systems should be ensured by constructional design measures, suitable dimensioning and cross-sectional design as well as meaningful reinforcing in the case of reinforced concrete structural components. The thermal material properties and temperature-dependent mechanical properties specified in the Eurocodes are only validated for rising temperatures in the components. Adequate knowledge is not yet available for the cooling phase of a fire in order to verify the existing material models. The consistency of deformation and load-bearing behaviour must always be assured. In practical application, a structure that does not fail based on calculations but whose deformations increase excessively due to the thermal action cannot be classified as adequately dimensioned in terms of fire safety design. This chapter provides information on the assessment of admissible deformation.

6.11 Literature

[6.1] DIN EN 1991-1-2:2010-12, Eurocode 1 – Grundlagen der Tragwerksplanung und Einwirkungen auf Tragwerke – Teil 1-2: Einwirkungen auf Tragwerke – Brandeinwirkungen auf Tragwerke; Deutsche Fassung EN 1991-1-2:2002 + AC:2009.

[6.2] DIN EN 1992-1-2:2010-12, Eurocode 2 – Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken – Teil 1-2: Allgemeine Regeln – Tragwerksbemessung für den Brandfall; Deutsche Fassung EN 1992-1-2:2004 + AC:2008.

[6.3] DIN EN 1993-1-2:2010-12, Eurocode 3 – Bemessung und Konstruktion von Stahlbauten – Teil 1-2: Allgemeine Regeln – Tragwerksbemessung für den Brandfall; Deutsche Fassung EN 1993-1-2:2005 + AC:2009.

[6.4] DIN EN 1994-1-2:2010-12, Eurocode 4 – Bemessung und Konstruktion von Verbundtragwerken aus Stahl und Beton – Teil 1-2: Allgemeine Regeln Tragwerksbemessung für den Brandfall; Deutsche Fassung EN 1994-1-2:2005 + AC:2008.

[6.5] DIN EN 1995-1-2:2010-12, Eurocode 5 – Bemessung und Konstruktion von Holzbauten – Teil 1-2: Allgemeine Regeln – Bemessung für den Brandfall; Deutsche Fassung EN 1995-1-2:2004 + AC:2009.

[6.6] DIN EN 1996-1-2:2011-04, Eurocode 6 – Bemessung und Konstruktion von Mauerwerksbauten – Teil 1-2: Allgemeine Regeln – Tragwerksbemessung für den Brandfall; Deutsche Fassung EN 1996-1-2:2005 + AC:2010.

[6.7] DIN EN 1999-1-2:2010-12, Eurocode 9 – Berechnung und Bemessung von Aluminiumkonstruktionen – Teil 1-2: Allgemeine Regeln – Tragwerksbemessung für den Brandfall.

[6.8] Nationaler Anhang zu DIN EN 1991-1-2/NA, Ausgabe September 2015
Nationaler Anhang zu DIN EN 1992-1-2/NA, Ausgabe Dezember 2010
Nationaler Anhang zu DIN EN 1993-1-2/NA, Ausgabe Dezember 2010
Nationaler Anhang zu DIN EN 1994-1-2/NA, Ausgabe Dezember 2010
Nationaler Anhang zu DIN EN 1995-1-2/NA, Ausgabe Dezember 2010
Nationaler Anhang zu DIN EN 1996-1-2/NA, Ausgabe Juni 2013
Nationaler Anhang zu DIN EN 1999-1-2/NA, Ausgabe März 2011
Beuth Verlag, Berlin.

[6.9] *STEINERT, C.*: Bestimmung der Wärmeübergangsbedingungen auf Bauteile im Brandfall. Abschlussbericht im Auftrag der Deutschen Forschungsgemeinschaft, Bonn, Az.: Ko 204 / 38 - 1, Braunschweig, 1996.

[6.10] DIN 4102. Brandverhalten von Baustoffen und Bauteilen. Teil 3: Brandwände und nichttragende Außenwände, Begriffe, Anforderungen und Prüfungen. Ausgabe September 1977.

[6.11] *HOSSER, D.; KAMPMEIER, B.; ZEHFUSS, J.*: Überprüfung der Anwendbarkeit alternativer Ansätze nach Eurocode 1 Teil 1-2 zur Festlegung von

Brandschutzanforderungen bei Gebäuden. Schlussbericht des Forschungsvorhabens Az. ZP 52-5-3.83-1041/03 im Auftrag des Deutschen Instituts für Bautechnik, Berlin. Institut für Baustoffe, Massivbau und Brandschutz (iBMB) der Technischen Universität Braunschweig, Dezember 2004.

[6.12] *ZEHFUSS, J.*: Naturbrandverfahren für die Bauteilbemessung – Möglichkeiten und Anwendungsgrenzen. In: Jahresfachtagung 2013 der vfdb, Weimar, 27. bis 29. Mai 2013, Tagungsband. Altenberge: Vereinigung zur Förderung des Deutschen Brandschutzes e. V. (vfdb), 2013.

[6.13] Änderungen der Musterliste der technischen Baubestimmungen vom September 2012. www.is-argebau.de.

[6.14] *ZEHFUSS, J.; HOSSER, D.*: Vereinfachtes Naturbrandmodell für die brandschutztechnische Bemessung von Bauteilen und Tragwerken, In: Bauphysik 27 (2005) Heft 2. S. 79-86.

[6.15] *ZEHFUSS, J.; HOSSER, D.*: A parametric natural fire model for the structural fire design of multi-storey buildings. In: Fire Safety Journal 42 (2007), Elsevier Ltd., S. 115-126.

[6.16] *SANDSTRÖM, J.*: Temperature calculations in fire exposed structures with the use of adiabatic surface temperatures. Technische Universität Lulea, Schweden, 2008.

[6.17] *WICKSTRÖM, U.*: Adiabatic Surface Temperature for calculating heat transfer to fire exposed structures. Swedish National Testing and Research Institute (SP), Boras, Sweden.

[6.18] DIN EN 1990:2002-10. Eurocode: Grundlagen der Tragwerksplanung. Deutsche Fassung EN 1990:2002.

[6.19] DIN EN 13501-2:2010-02, Klassifizierung von Bauprodukten und Bauarten zu ihrem Brandverhalten – Teil 2: Klassifizierung mit den Ergebnissen aus den Feuerwiderstandsprüfungen, mit Ausnahme von Lüftungsanlagen; Deutsche Fassung EN 13501-2:2007+A1:2009.

[6.20] *KORDINA, K.; EHM, H; POSTEL, R.*: Erwärmungsvorgänge an balkenartigen Stahlbetonbauteilen unter Brandbeanspruchung. Deutscher Ausschuss für Stahlbeton, Heft 230, Berlin, 1975.

[6.21] *SPILLE, J.; ZEHFUSS, J.*: Neuer Ansatz der thermischen Leitfähigkeit von Beton für die Brandschutzbemessung in Eurocode 2. In: Bautechnik, Berlin, 2019.

[6.22] *ZEHFUSS, J.; SPILLE, J.*: Bewertung überarbeiteter Rechengrundlagen zur Wärmeleitfähigkeit im Zuge der Novellierung von EN 1992-1-2. Abschlussbericht im Auftrag des Deutschen Instituts für Bautechnik (DIBt). Fraunhofer IRB Verlag, Stuttgart, 2018.

[6.23] *KORDINA, K.; MEYER-OTTENS, C.*: Beton Brandschutz Handbuch. 2. Auflage, Verlag Bau+Technik, Düsseldorf, 1999.

[6.24] DIN EN 1363-1:2012-10, Feuerwiderstandsprüfungen – Teil 1: Allgemeine Anforderungen; Deutsche Fassung EN 1363-1:2012.

[6.25] ISO PDTR 15657 FRT – Guidelines for computational structural fire design. 20.01.2012.

[6.26] prEN 1992-1-2 (2019-10): Eurocode 2: Design of concrete structures – Part 1-2: General – Structural fire design.

[6.27] *JENSEN, J. F.*: New Annex B – tabulated data for columns. Version 2019-04-09.

[6.28] *FINGERLOOS, F.; ZEHFUß, J.; CYLLOK, M.*: Heißbemessung von Stahlbeton- und Spannbetonstützen – Zur praktischen Anwendung von Methode A in DIN EN 1992-1-2. In: Beton- und Stahlbetonbau 113, Heft 08/2018, S. 564-570.

[6.29] *ZEHFUSS, J.; FELIX, D.*: Derivation of alternative design tables for the fire design of concrete walls with advanced calculation methods according to EN 1992-1-2. Report PraxisRegelnBau, 2019.

[6.30] *MITTMANN, T.*: Brandschutzbemessung im Mauerwerksbau. In: Hosser, D.; Zehfuß, J. (Hrsg.): Brandschutz in Europa – Bemessung nach Eurocodes. Erläuterungen und Anwendungen zu den Brandschutzteilen der Eurocodes 1 bis 6. Beuth-Kommentar, 3. Auflage 2017 Berlin, Wien: Beuth Verlag.

[6.31] *ZEHFUß, J..; KAMPMEIER, B.*: Baulicher Brandschutz. In: Holschemacher, K. (Hrsg.).: Entwurfs- und Berechnungstafeln für Bauingenieure. 8. Auflage. Beuth-Verlag, Berlin, 2019.

[6.32] *SCHAUMANN*, P.: Brandschutznachweise für ungeschützte Stahlkonstruktionen – Näherungsformeln für die Erwärmung nach ETK. Bundesbaublatt, Heft 7, S. 69-71, 1999.

[6.33] *HOSSER, D*. (Hrsg.): Brandschutz in Europa – Bemessung nach Eurocodes. Beuth-Kommentar. Erläuterungen und Anwendungsbeispiele zu den Brandschutzteilen der Eurocodes 1 bis 5, 2. Auflage. Beuth-Verlag Berlin, 2012.

[6.34] prEN 1993-1-2 (2019-10): Eurocode 3: Design of steel structures – Part 1-2: General – Structural fire design.

[6.35] *BOTH, C.:* The Fire Resistance of Composite Steel-Concrete Slabs. Dissertation TNO Building and Construction Research, Delft, 1998.

[6.36] *SCHAUMANN, P., KETTNER, F., HEISE, A., HOTHAN, S*.: Tragwerksbemessung für den Brandfall bei Verbundtragwerken. Abschlussbericht zum DIBt-Forschungsvorhaben Z 52-5-17.17-1124/04, 2005.

[6.37] *DORN, T.*: Brandschutzbemessung im Verbundbau. Beitrag in: Brandschutz in Europa – Bemessung nach Eurocodes, Beuth-Kommentar, Beuth Verlag GmbH, Berlin, Wien, Zürich. 1. Auflage 2000.

[6.38] *HOSSER, D.; DORN, T.; EL-NESR, O.*: Vereinfachtes Rechenverfahren zur brandschutztechnischen Bemessung von Verbundstützen aus kammerbetonierten Stahlprofilen. Stahlbau 63, Heft 3, 1994.

[6.39] prEN 1993-1-2 (2019-05): Eurocode 5: Design of timber structures – Part 1-2: General – Structural fire design.

[6.40] *HAKSEVER, A.; KRAMPF, L.*: Möglichkeiten, nachträglich die in einem Betonbauteil während eines Schadenfeuers aufgetretenen Temperaturen abzuschätzen. Beitrag in: Deutscher Ausschuss für Stahlbeton, Heft 352, Berlin, 1984.

[6.41] *RICHTER, E.*: Zur Berechnung der Biegetragfähigkeit brandbeanspruchter Spannbetonbauteile unter Berücksichtigung geeigneter Vereinfachungen für die Materialgesetze, Heft 80 des Instituts für Baustoffe, Massivbau und Brandschutz der TU Braunschweig, 1987.

[6.42] *SCHNEIDER, U.; DIEDERICHS, U.; WEIß, R.*: Hochtemperaturverhalten von Festbeton. Sonderforschungsbereich 148 – Brandverhalten von Bauteilen. Arbeitsbericht 1975 - 1977. Teil II, Technische Universität Braunschweig, Juli 1977.

[6.43] *ZEHFUSS, J.; LYZWA, J.*: Theoretische und experimentelle Untersuchungen zur Erweiterung der Berechnungsgrundlagen unterschiedlicher Betone bei Naturbrandbeanspruchung. Durch Deutsche Forschungsgemeinschaft gefördertes Forschungsvorhaben, Abschlussbericht, 2019.

[6.44] *ZEHFUSS, J.; LYZWA, J.*: Thermische Materialeigenschaften von Beton in der Abkühlphase. Braunschweiger Brandschutztage ’2017. Tagungsband. Institut für Baustoffe, Massivbau und Brandschutz (iBMB) der TU Braunschweig, Heft 232, 2017.

[6.45] *LYZWA, J.; ZEHFUSS, J.*: Thermo-mechanical material properties of concrete in the cooling phase. The seventh international conference on structural engineering, mechanics and computation (SEMC 2019) in Cape Town, ZAF, 2019.

[6.46] *LYZWA, J.; ZEHFUSS, J.*: Experimental Investigations of ultra-high performance concrete exposed to natural fires. In: Fire Safety Journal, zur Veröffentlichung eingereicht.

[6.47] *ZEHFUSS, J.; SANDER; L.; SCHAUMANN, P.; WEISHEIM, W.*: Schlussbericht „Prüfverfahren für thermische Materialkennwerte von Brandschutzbekleidungen und reaktiven Brandschutzsystemen für die Bemessung von Stahltragwerken bei Naturbränden“, IGF-Projekt Nr. 19176 N, Institute für Baustoffe, Massivbau und Brandschutz Technische Universität Braunschweig, Institut für Stahlbau Leibniz Universität Hannover, 2018.

[6.48] *HOSSER, D.; RICHTER, E.; ZEHFUSS, J.*: Erarbeitung von nationalen Anwendungsrichtlinien für rechnerische Nachweise nach den Brandschutzteilen der Euro-codes 2 - 5. Abschlussbericht im Auftrag des Bundesministers für Raumordnung, Bauwesen und Städtebau, Bonn, Az.: RS III - 4 - 6741 - 97.120, Braunschweig, März 2002.

[6.49] *ZEHFUSS, J.; RICHTER, E.*: Bewertungskriterien für rechnerische Brandschutznachweise nach den Eurocodes. Braunschweiger Brandschutztage ’99. 8. Fachseminar Brandschutz – Forschung und Praxis, Institut für Baustoffe, Massivbau und Brandschutz (iBMB) der TU Braunschweig, Heft 145, Braunschweig, 1999.

[6.50] *ZEHFUSS, J.*: Bewertungskriterien für Rechenprogramme von Eurocode-Nachweisen. vfdb-Zeitschrift 02/2013 S. 63-69. Ebner Verlag, Bremen.

[6.51] *HASS, R.*: Zur praxisgerechten brandschutztechnischen Beurteilung von Stützen aus Stahl und Beton, Dissertation, Institut für Baustoffe, Massivbau und Brandschutz, Technische Universität Braunschweig,1986.

[6.52] DIN EN 1992-1-1:2011-01, Eurocode 2 – Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken – Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau; Deutsche Fassung EN 1992-1-1:2004 + AC:2010.

[6.53] *SCHUCK, W., HAACK, A.; RICHTER, E., STÄDING, A.*: Brandschutz bei Eisenbahntunneln mit einschaligem Tübbingausbau. In: Taschenbuch für den Tunnelbau 2011, VGE Verlag GmbH, Essen.

[6.54] *HOSSER, D; SIEMON, M.; KAMPMEIER, B.; HOLLMANN, D.; KRUSE, D.; DEPPE, B.*: Theoretische und experimentelle Untersuchungen zur Ermittlung und Optimierung des Brandverhaltens von ultrahochfestem Beton (UHFB), Abschlussbericht im Rahmen des SPP 1182, Institut für Baustoffe, Massivbau und Brandschutz (iBMB) der TU Braunschweig, 2013.

[6.55] *HORVATH, J.; DEHN, F.*: Abplatzverhalten von selbstverdichtendem Beton (SCC), Zement + Beton Handels- und Werbeges.m.b.H, 2003.

[6.56] Deutscher Ausschuss für Stahlbeton (2012-09): Selbstverdichtender Beton, SVB-Richtlinie.

[6.57] *HOLZ, K.; CURBACH, M.*: Zugtragverhalten von Carbonbeton unter Hochtemperaturbeanspruchung. In: Beton- und Stahlbetonbau 115 (2020) Heft 1, S 1-9.

[6.58] *FALKNER, H.; GERRITZEN, D.; JUNGWIRTH, D.; SPAROWITZ, L.*: Das neue Bewehrungssystem; Druckglieder mit hochfestem Betonstahl SAS 670/800 - Teil I: Entwicklung, Versuche, Bemessung und Konstruktion. Beton- und Stahlbetonbau 103 (Heft 5) S. 304-317, 2008.

[6.59] *LANGE, J.; WOHLFEIL, N.*: Untersuchungen zum Werkstoffverhalten des Feinkornbaustahls S 460 unter erhöhten Temperaturen. In: Bautechnik 84 (2007), Heft 10, S. 711-720.

[6.60] *MENSINGER, M.*: Feuerwiderstand von feuerverzinkten, tragenden Stahlkonstruktionen im Brandfall. Schlussbericht zu IGF-Vorhaben Nr. 18887 N. München, 27.11.2018.

[6.61] *BERGMANN, M.*: Zur Bemessung von Hohlprofilverbundstützen im Brandfall, Institut für Konstruktiven Ingenieurbau, Dissertation, Bergische Universität Wuppertal, 2013.

[6.62] *KLEIBÖMER, I.*: Zum Verbundverhalten ausbetonierter Hohlprofilstützen mit massivem Stahlkern im Brandfall, Dissertation, Institut für Stahlbau, Leibniz Universität Hannover, 2018.

[6.63] *ROMERO, M. L.* et al.: Slender double-tube ultra-high strength concrete-filled tubular columns under ambient temperature and fire. Engineering Structures (2015), Vol. 99, S. 536-545.

[6.64] DIN 4102-04:2016-05, Brandverhalten von Baustoffen und Bauteilen – Teil 4: Zusammenstellung und Anwendung klassifizierter Baustoffe, Bauteile und Sonderbauteile.

[6.65] *HAHN, C.*: DIN 4102-4 - Ergänzende Regelungen zu den Brandschutzteilen der Eurocodes. Braunschweiger Brandschutz-Tage 2011. Tagungsband. Institut für Baustoffe, Massivbau und Brandschutz (iBMB) der TU Braunschweig, Heft 214, 2011.

[6.66] DIN 18230-1:2010-09, Baulicher Brandschutz im Industriebau – Teil 1: Rechnerisch erforderliche Feuerwiderstandsdauer.

ANNEX TO CHAPTER 6

A6.1 Ring calculation

A6.1.1 Steel column

Boundary conditions:

- fire load: standard fire (all sides)
- load: 1530 kN
- eccentricity: 3 cm
- welded on steel plate at the on both sides of the column
- length of the column: 3.64 m
- flamed length of the column: 3.24 m
- static system (in test furnace): double-sided hinged supported

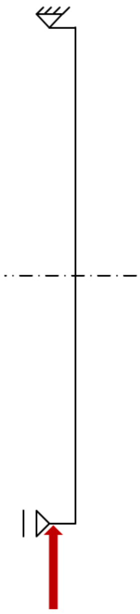
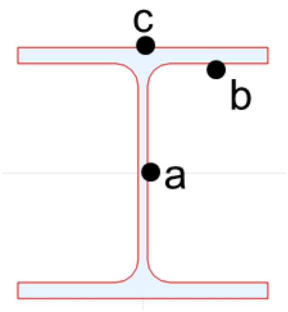


Figure 6.28 Installed column in the test furnace (left) and static system (right)

Evaluation of 5 simulations with different softwares (A-E):

1. Temperature-time curves (°C / min) at a height of 1.60 m measured from the base of the column
    a. Surface temperature centre of web
    b. Surface temperature lower edge of flange ¼ point
    c. Surface temperature Upper edge of flange centre



2. Horizontal deformation (in mm) at 1.60 m measured from the base of the column

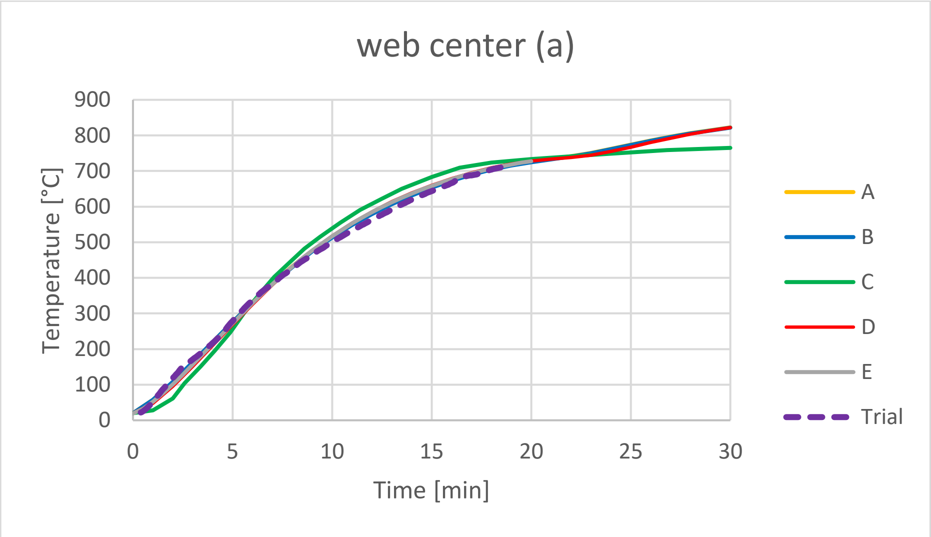


Figure 6.29 Temperature-time curve at the measure point a (web center)

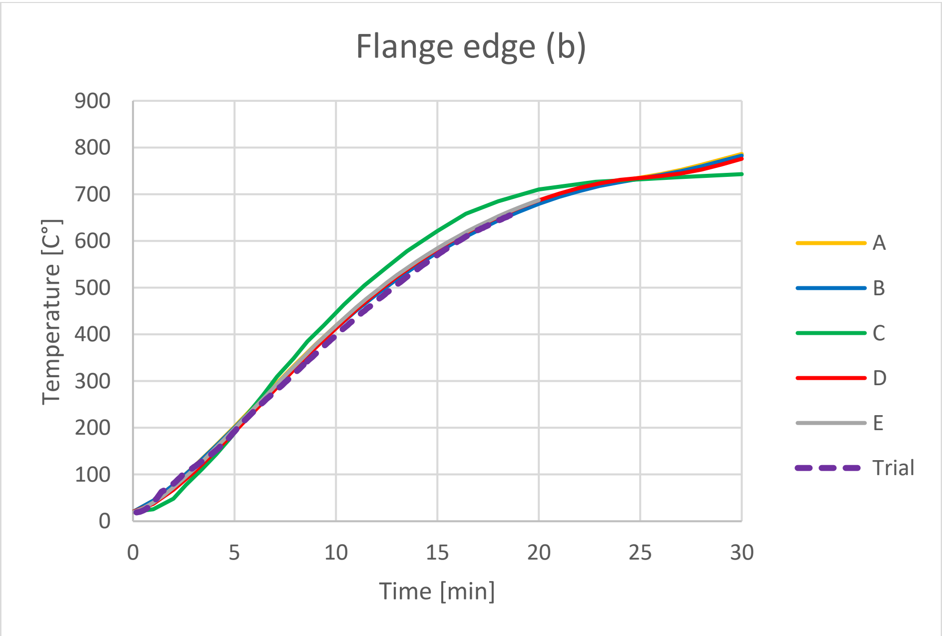


Figure 6.30 Temperature-time curve at the measure point b (lower edge of flange ¼ point)

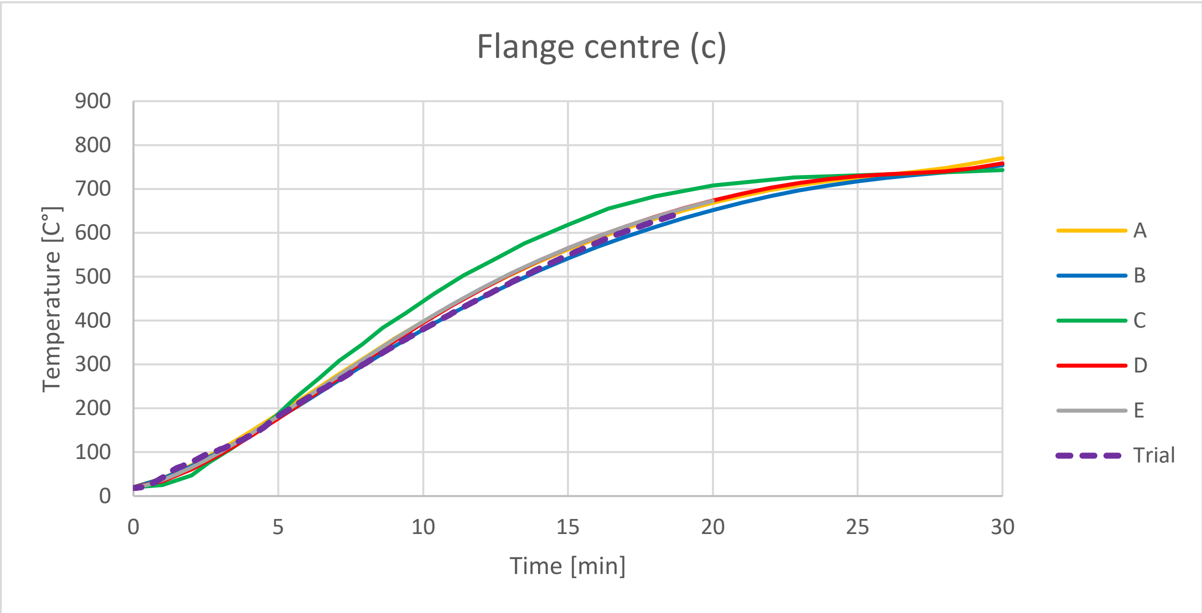


Figure 6.31: Temperature-time curve of the measure point c (upper edge of flange center)

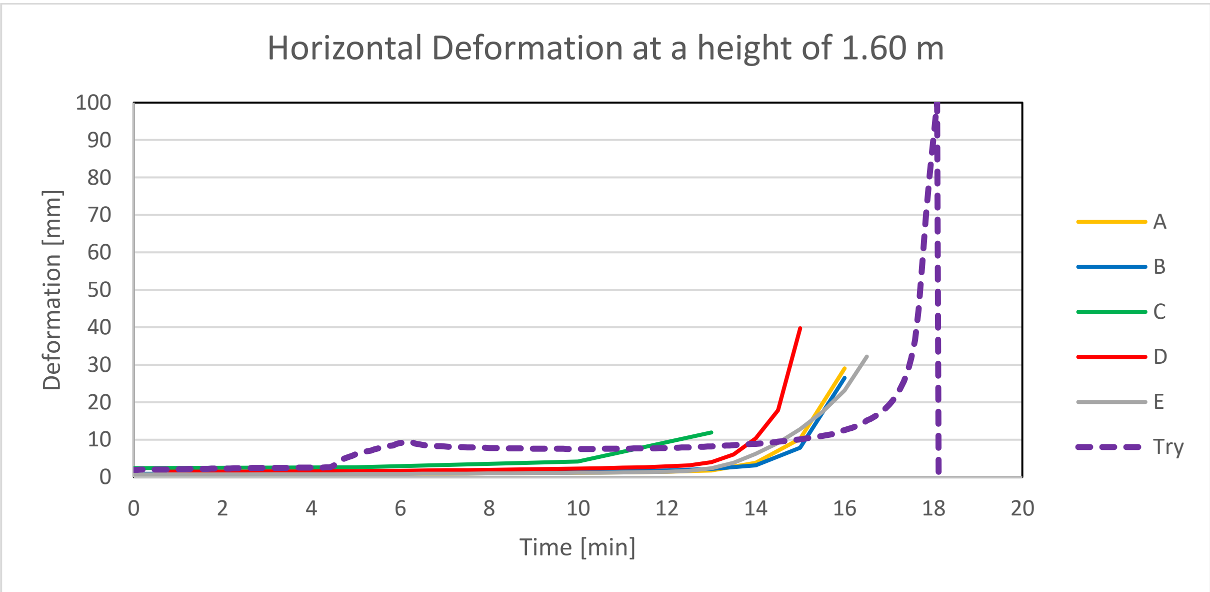
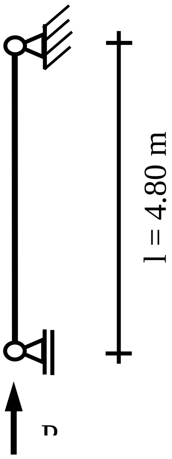


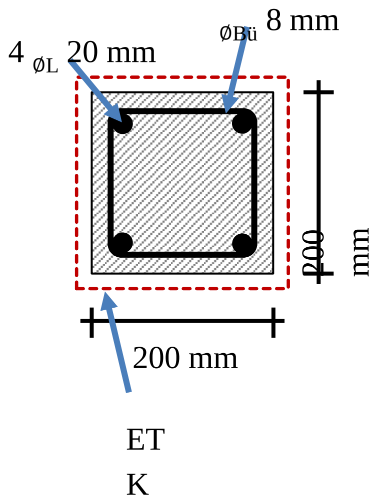
Figure 6.32 Deformation-time behaviour at a height of 1.60 m measured from the base of the column

A failure of the steel column occurred in the test in minute 18 (see Figure 6.32). With regard to the thermal analyses, in 4 of 5 simulations the calculated temperatures agree very well with the test results (see Figure 6.29 and 6.31). In all simulations, the calculated time of failure occurs before the actual failure time in the test.

A6.1.2 Reinforced concrete column

Static system (in the test furnace):





Actions:

Applied load in test:	P= 340 KN with e_0=0 mm
Temperature:	standard fire
Flamed area:	standard fire on all sides in over the clear height in the furnace
Pre-deformation:	Varying parameter (L/1000, L/1500 and L/2000)

Measured pre-deformation: deflection after load v_0= 0.4 mm (t=0) at a height of 2.05 m with a column length of 4.80 m

Column length:

Column length:	4.80 m
Clear height in the fire room:	4.60 m (from upper edge of floor to lower edge of ceiling; flamed length of the column)

Column cross-section:

Column dimensions:	w/h= 200 / 200 mm
Axis distance:	40 mm
Longitudinal reinforcement:	4 Ø 20

Stirrup reinforcement:	Ø $_{Stirrup}$ = 8 mm
Stirrup spacing:	a = 20 cm

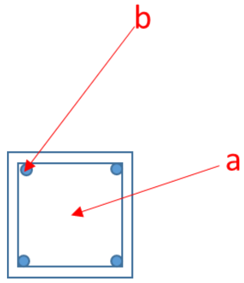
Building materials:

Concrete:	C 20/25, the measured concrete strength is 22.3 N/mm², the moisture content of the concrete is 3 %.
Reinforcement:	BSt 420/500

The pre-deformation is to be applied parabolic.

Evaluation of 5 simulations with different softwares (A-B, D-E):

1. Temperature-time curves (°C / min)
   a. Cross section centre
   b. Temperature in the bar axis of the longitudinal reinforcement



2. Horizontal deformation (mm) at 2.05 m measured from the base of the column

Evaluation:

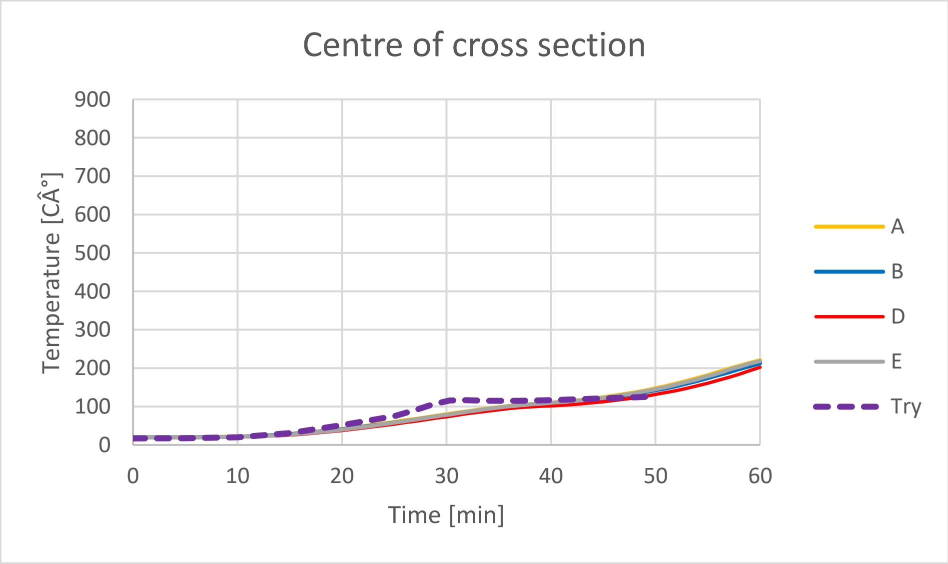


Figure 6.33 Temperature-time curve at the measure point a (centre of cross-section)

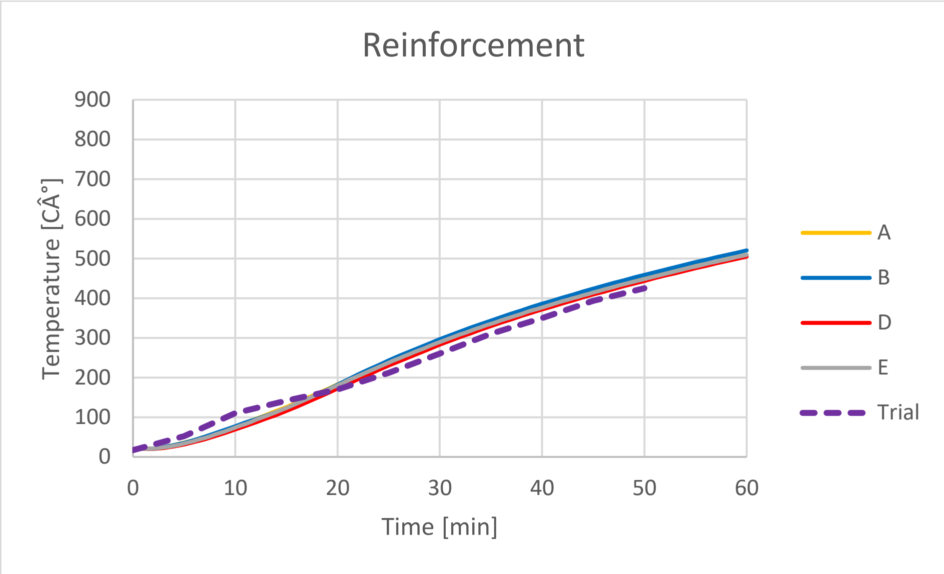


Figure 6.34 Temperature-time curve at the measure point b (axis of the longitudinal reinforcement)

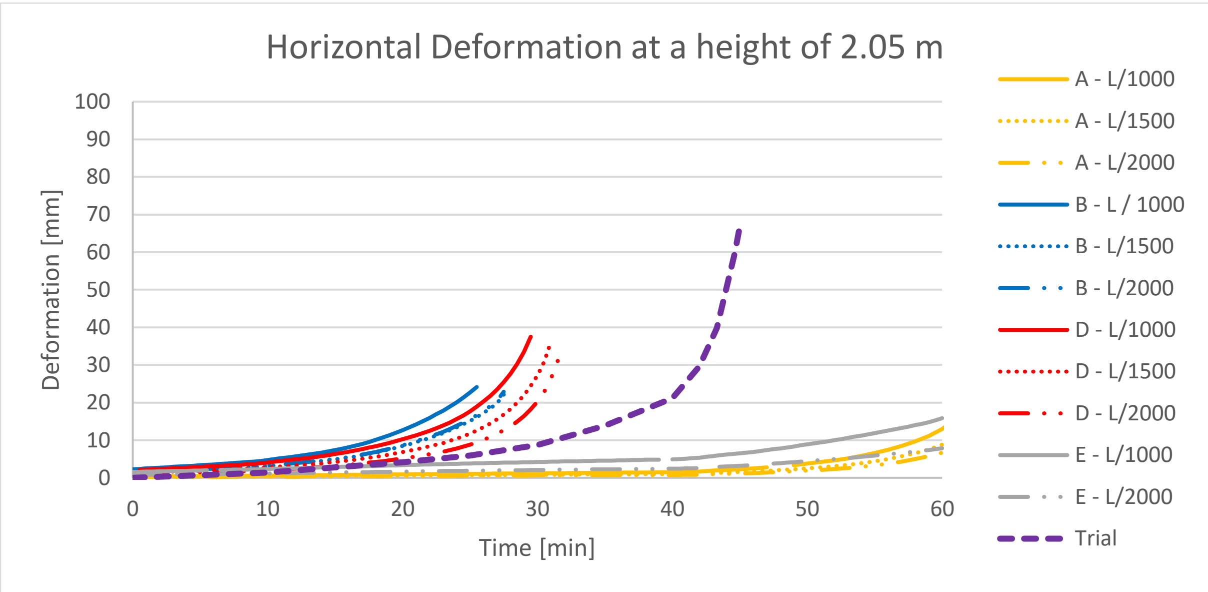


Figure 6.35 Deformation-time curves at a height of 2.05 m measured from the base of the column

A failure of the reinforced concrete column in the test occurred in minute 48 (see Figure 6.35). With regard to the thermal analyses, the calculated temperatures in the centre of the cross-section and in the axis of the longitudinal reinforcement correspond well with the test results (see Figure 6.33 and 6.34). In two cases the calculated failure time is before the actual failure time, in the other two cases it is above it. These differences can be explained, among other things, by the support conditions selected in the course of modelling. While in the cases of the shorter fire resistance durations, a double-sided hinged support was used as a basis for the calculation, for the other cases, a support with rotation restriction on both sides was assumed. Due to the experimental design of the support, the actual support condition to be assumed is between an ideally hinged and a rotationally restrained support. The numerical investigations have shown that the influence of the varying parameter pre-deformation is low.

7 PLANT ENGINEERING AND AVERTING FIRE PROTECTION

7.1 General

Plant engineering and averting fire protection measures can significantly influence the duration of fire development and the associated direct and indirect fire consequences and thus effectively contribute to risk limitation. The following should be considered under this aspect:

- Fire alarm systems,
- Fire extinguishing systems,
- Smoke and heat extraction systems, and
- the fire brigade's firefighting operation.

The effect of these fire protection measures on the fire scenario is not directly (quantitatively) taken into account in the typical (prescriptive) fire protection design (see Figure 1.1. in Chapter 1), but indirectly (qualitatively) used to compensate for deviations from the usual building code requirements for structural fire protection or for increased fire risks (type of building and its use). Only in industrial construction is the compensation of structural fire protection measures by technical and defensive measures also quantitatively visible, in that the fire protection infrastructure is included in the requirements with regard to the fire resistance duration of the building components either in a simplified way by means of the classification into safety categories [7.1] or by means of an evaluation factor α_L [7.1] derived from probability considerations.

Within the framework of engineering methods of fire protection, the favourable effect of plant-engineering measures on the fire scenario can be quantitatively recorded on the one hand via the time course of the heat release rate. On the other hand, the influence on the reliability of the entire fire protection measures must also be taken into account, because the fire protection infrastructure can fail with a certain probability in the event of a requirement. Therefore, different fire scenarios - with the design effect of the technical and/or fire protection measures have to be considered.

The effectiveness W (also effectiveness) of protective measures is determined from the relationship between the actually achieved protection goal and the specified protection goal (design criterion) in the case of a requirement, i.e. in a real fire [7.61].

$$W_{Effectiveness} = \text{protection goals (achieved)/protection goals (specified)} \qquad (7.1)$$

Effectiveness is understood to mean the effectiveness of a system in the event of a fire. In order to develop their effect on the course of the fire and to achieve the highest possible effectiveness, it is necessary that the systems/measures function reliably. Reliability is understood as the property of a fire protection system to perform the functions defined in the specification without failure under the design conditions during a certain time interval. It is given as the probability that the function will not fail within the time interval [7.30].

It should be noted at this point that the smouldering fire phase is not normally taken into account when applying engineering methods, but a fire with the appearance of flames is assumed. Especially the smouldering and smouldering fire phase (as a special form of glowing fire) can be reliably detected by the available fire alarm sensor technology.

A more detailed analysis of the overall system of fire protection measures is possible with the methods in Chapter 10 of this guideline based on the work in [7.2], [7.3], [7.4] but is generally too costly for practice. Simplified, the more critical authoritative fire scenario can be determined on the basis of risk considerations - taking into account the probability of failure of the infrastructure or extinguishing measures of the fire brigade on the one hand and the associated stronger fire development and higher fire damages on the other hand - and only this scenario can be examined more closely. This procedure was chosen in [7.1], [7.1] that the fire protection design is based on the scenario of a fully developed fire that occurs with the failure probability of the infrastructure measures.

Of decisive importance here is the question at which point in time from the start of the fire an influence on the course of the fire can be assumed, because the maximum heat release rate and other related fire consequences depend on this (see Figure 7.1).

The development of fires in buildings depends on many factors. In addition to the building fabric, which can be relatively easily assessed at the start of construction, the constantly changing fire load of the technical and use-dependent facilities and the effects of the building's daily use should be taken into account. These are difficult to grasp. Experience shows that fire events of solid combustible materials often start as smouldering fires, i.e. low-energy oxidation processes with very low heat and usually very intensive fire gas and smoke development. The intervals between the beginning of a smouldering fire and the development of an open fire vary greatly and can last from minutes to several hours. Due to the strong development of fire gas and smoke during the smouldering fire phase, the use of fire alarm systems with automatic smoke detectors can have a particularly favorable effect on the duration of fire detection (detection time) [7.23].

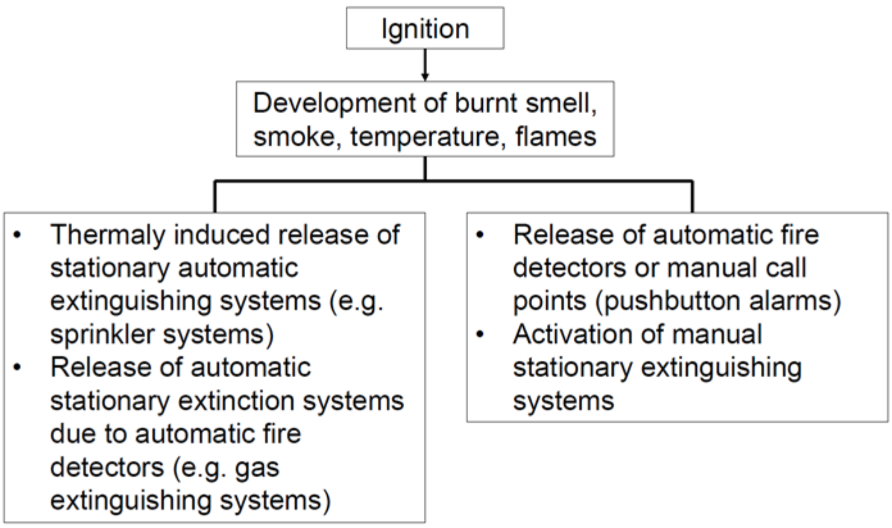


Figure 7.1 Diagramm for firefighting by extinguishing systems

Automatic fire detection systems shorten in particular the detection time and the reporting time [7.23], so that the firefighting of the fire brigade can start at an earlier time. They thus primarily influence the total energy content of the heat release rate curve of the fire scenario to be considered for the design.

In order to ensure that the release of heat not only affects the temperature development but also the development of fire gas and smoke, automatic fire alarm systems in conjunction with the early initiation of effective firefighting can also contribute to the reduction of the total amount of fire gas and smoke released.

Effective and reliable extinguishing and firefighting systems reduce the maximum heat release rate and limit the extent of a fire, so that the fire brigade is supported by effective extinguishing measures.

Smoke and heat exhaust ventilation systems can reduce the thermal load on the supporting structure, but in conjunction with the existing supply air downstream openings they can also increase the supply of atmospheric oxygen and thus the maximum heat release rate of a ventilation-controlled fire. Smoke ventilation systems can reduce the thickness of a hot gas layer and thus reduce the negative effects of visibility, temperature and toxic gas concentrations on people.

7.2 Fire alarm systems

7.2.1 General information

The task of an automatic fire alarm system (BMA) with a connected acoustic alarm system is to detect a fire in the initial fire phase, to alert people in the building, to automatically control fire protection and operating equipment, to alert the fire brigade or other emergency services and to locate the danger zone (according to DIN 14675 [7.47]).

The planning and project planning of fire alarm systems should be carried out in accordance with the recognised rules of technology, in particular DIN VDE 0833 [7.48] Hazard Alarm Systems for Fire, Burglary and Robbery Part 1 and 2 and DIN 14675 [7.47] observed. The BMA is usually part of the fire protection concept, so that its mode of operation is also based on the parameters described therein.

7.2.2 Types of automatic fire alarm systems

Fire alarm systems are differentiated with regard to their scope of protection (categories) into full protection, partial protection, protection of escape routes and object protection. Fire alarm systems can also be used to control fire protection systems (e.g. extinguishing systems, smoke and heat extraction systems). A BMA usually consists of a fire detection system, automatic fire detectors, manual call points (non-automatic detectors, e.g. push-button detectors), transmission devices, alarm devices, fire control systems, etc.

The alarm forwarding of an extinguishing system alarm (usually thermal triggering) to the responsible fire brigade is also carried out via a fire alarm system. Here, the fire detection system performs the function of alarm forwarding, not the function of fire detection.

In order to be able to detect fires in their early stages, the selection of suitable point-type, linear and linear fire detectors is essential. Fire characteristics for different types of fire detectors are smoke, heat, flames, etc.

The following types are used:

- Heat detector (differential, maximum/limit)
- smoke detector (transmitted light, scattered light)

  Smoke detectors are divided into ionisation smoke detectors, optical smoke detectors, linear smoke detectors and air sample smoke detection systems (aspirating smoke detection systems - RAS)

- Flame detector (infrared, ultraviolet)
- Multi-sensor/multi-criteria detector

  In practice, multi-sensor and/or multi-criteria detectors are increasingly used. They detect different fire phenomena, evaluate different criteria and are therefore much more robust with regard to deception variables. Optical smoke detectors can be influenced by particles in the air such as dust or exhaust gases. By evaluating the temporal course of the sensor signals and including various fire parameters (e.g. smoke and temperature) in the evaluation, multi-sensor/multi-criteria detectors are able to distinguish such deception variables from real fires

- Manual call point

  The manual call points (push-button detectors or spring button detectors) are non-automatic fire detectors. They are used for manual alarming in the event of fire

The fire alarm control panel is used to display, operate, monitor and process the signals of the connected devices. It compares them with the stored values and activates the corresponding signaling devices and fire control systems. Optical and acoustic alarm devices alert and orientate the persons in the building as well as the internal and external intervention and/or danger prevention forces.

7.2.3 Effect of fire alarm systems on the fire scenario

Fire alarm systems with connected acoustic alarm devices or voice alarm systems (in accordance with DIN VDE 0833-4 [7.48]) have a dual effect when assessing the effects of fire scenarios:

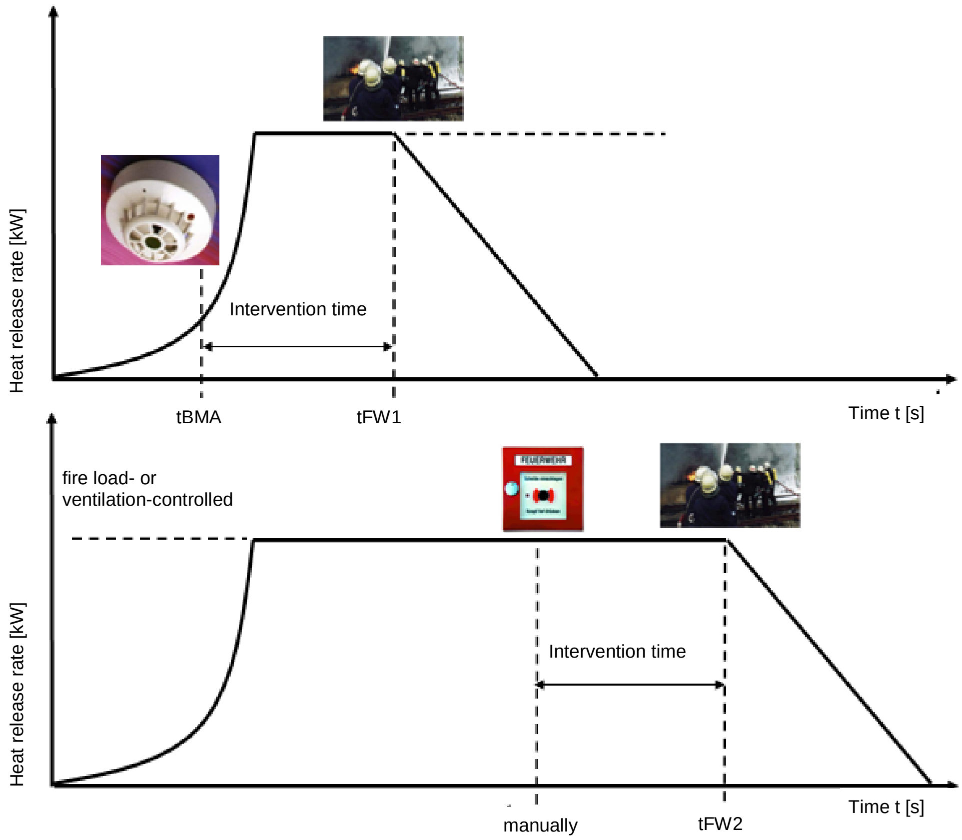
- By means of technical fire detection via a BMA and activation of the optical and/or acoustic alarm system, the persons present in the building are alerted. This means that the deployment of the works or public fire brigade can be limited to the rescue of persons who are unable to rescue themselves if the operational fire protection system is working.
- The fire development time, i.e. the time until firefighting is started, is shortened, which has the consequence that the stability of buildings in case of fire can be positively influenced.

The fire development period begins with the outbreak of a fire and ends when the firefighting measures take effect. For effectiveness and efficiency considerations, the time periods to be taken into account are composed of up to 10 different time periods (see also DIN 14011 [7.23]). These time periods can be influenced by different measures. The time period with the time intervals from the detection of a fire to the alerting of the emergency response forces (reporting time, dispatching time and alerting time [7.23]) is influenced by the following parameters, among others:

- Fire development: Depending on the type and progress of the fire, different quantities or intensities of the various fire characteristics are produced.
- Building geometry: In high and large rooms the time until detection can be longer than in small rooms with lower ceilings.
- Type of fire load: With smoke detector monitoring and fire loads that burn with heavy smoke development, faster detection can be expected.
- Scope of monitoring according to DIN 14675 [7.47]: If smoke detectors are only installed under the roof in a three-storey shopping mall, the time until detection is much longer than with full protection according to DIN 14675 [7.47].
- Characteristic value of the detectors: In many fire scenarios/fire loads smoke detectors trigger more quickly than e.g. heat detectors.
- Type of measure against false alarms according to DIN VDE 0833 [7.48]: Personnel measures against false alarms can lead to a longer time delay until the transmission device is activated than technical measures such as e.g. the 2-message dependency [7.26], [7.28].

In individual cases, the time until detection can be conservatively estimated as a function of the above parameters. The application of suitable fire protection engineering methods, such as the use of time-dependent, general natural fire models, such as CFD models, can be helpful in determining the release time.

Fire alarm systems with automatic detectors, in conjunction with the provision of a company fire brigade (plant fire brigade), have an influence on the fire scenario assumed in the engineering proofs, in that the total energy content of the heat release curve is reduced from the time of firefighting phase (Figure 7.2).



tFW1Period of time until the first firefighters attack the fire **with** automatic detectors
tFW2Period of time until the first firefighters attack the fire **without** automatic detectors

Figure 7.2 of automatic fire alarm systems on the time course of the heat release rate (intervention time according to DIN 14011 [7.23])

If automatic detectors are available, fire detection can usually be assumed in the fire development phase. The time span from the time of fire detection to the time of fire extinguishing (intervention time [7.23]) and thus to the beginning of extinguishing measures is shortened, so that the decay phase starts earlier. A quantification of the effect of automatic detectors can currently be carried out well in connection with plant fire brigades, because the period of assistance of public fire brigades is associated with greater uncertainties and can only be estimated with difficulty despite country-specific specifications or local fire protection requirement plans.

In the context of evacuation verifications with personnel flow simulation models according to Chapter 9 fire detection systems with automatic detectors in connection with alarm systems have the effect of shortening the alarm and reaction time and thus reducing the required evacuation time (see Chapter 9.3).

7.2.4 Reliability of fire alarm systems

The operational safety of fire alarm systems (BMA) is very high due to product standardization. The components of BMA comply with the standards aiming at reliability: DIN EN 54 Parts 1 to 32 [7.49]; DIN VDE 0833 Parts 1, 2, and 4 [7.48] and DIN 14675 [7.47] for the construction and operation of BMA. It can be further increased by certain measures:

- Certified service measures for planning, design, erection and commissioning of BMA (according to DIN 14675[7.47]),
- Fail-safe, bidirectional networking of the peripheral elements,
- Fail-safe, bidirectional networking of the fire alarm control panels and the remote operating units,
- Automatic self-monitoring of all system components once per second,
- Emergency redundancy independent of the basic computer and software units,
- Redundant construction through double computers in the various modules,
- Regular professional maintenance measures, and
- Timely modernisation.

Plants that meet these requirements and are competently planned and maintained achieve a reliability (availability) of 99.91% [7.29], [7.29]. The failure duration rate is 8.07 h/a, the probability of failure is

$$p_{f,BMA} = 0.00092.$$

Possible causes that can lead to the failure of an automatic fire alarm system in case of fire are primarily

- Insufficient maintenance ⇒Human Error,
- Incorrect selection of the sensor system due to planning errors or changes in use not observed ⇒ Human Error,
- Failure of the networking (e.g. damage to the lines),
- Change in hardware behaviour due to long-term negative environmental influences (recognising and remedying this is part of maintenance), or
- Unauthorized operation of the system (e.g. alarm accumulation to an unoccupied location) ⇒Human Error.

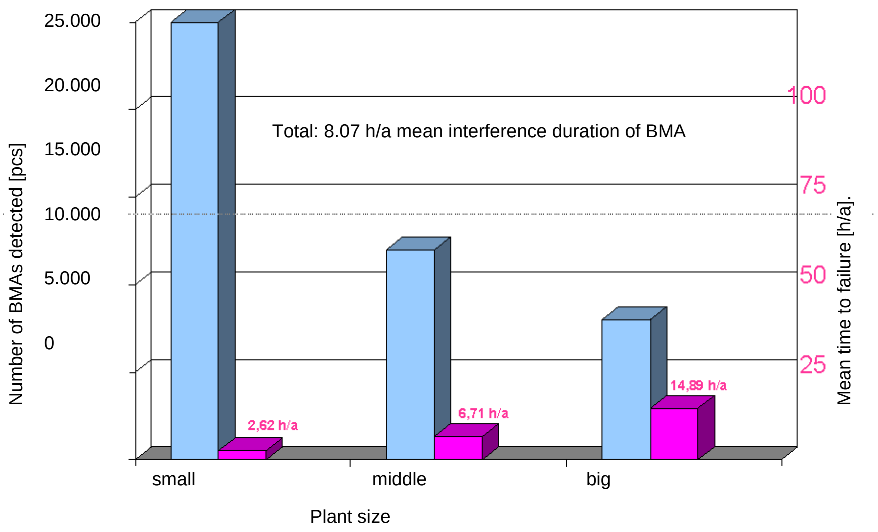


Figure 7.3 On the availability of BMA [7.10], [7.18]

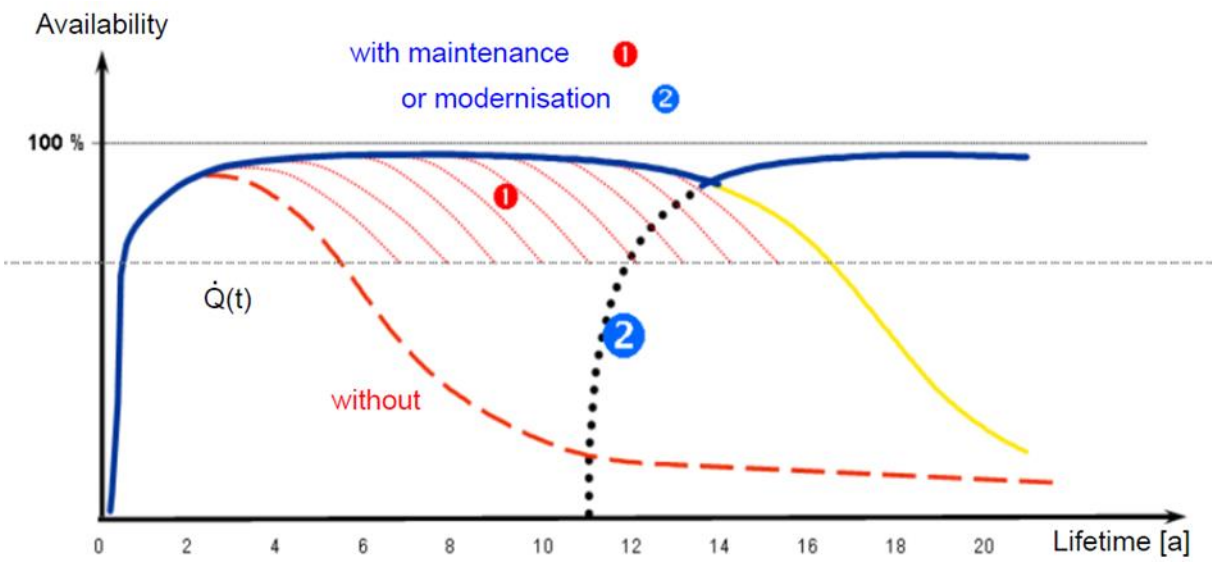


Figure 7.4 Maintenance and modernization are essentially responsible for the availability of a fire detection system [7.10], [7.18]

This list makes it clear that a large part of the causes are based on human error. The recurring testing of fire alarm systems is therefore very important. The probability of the proportion of personnel actions (human error) caused by production, planning and installation of such systems can be determined by extensive evaluations for fire detection, fire extinguishing and firefighting systems, depending on the type of action and the source of error with an error rate of 0.02 (2%) to 0.03 (3%) [7.31], [7.33], [7.33]. Conservatively, therefore, a probability of failure of 2 to 3% can be assumed in practice (see also 7.3.4 Reliability of extinguishing systems).

7.2.5 Effectiveness of fire alarm systems

The effectiveness of automatic fire alarm systems (BMA) can be assessed on the basis of various damage criteria in accordance with the objectives and desired effect on the fire scenario. On the basis of the vfdb fire damage statistics (Phase I and II with 5,016 mission reports from 28 fire brigades and a total of 1,216 real fire events [7.61]), information on real building fires was collected, from the origin and spread of the fire, alerting of the fire brigade and the fire protection measures initiated (in terms of plant engineering) up to the damage (cf. e.g. [7.37], [7.38], [7.39], [7.40], [7.41]). Thus, quantitative risk analyses can be performed within the framework of a site-specific safety concept. Typical fire events and damage patterns can be evaluated with regard to the necessary use of plant engineering and the influence of the plant engineering on the fire course.

However, the user should check in each individual case whether the data are plausible and whether it is reasonable to use them.

Table 7.1 shows the determined statistical effects on the fire damage criteria depending on the alarm path [7.39], [7.61]. Listed is the alarming via telephone (fixed network and mobile phone together) compared to the BMA. It becomes clear that when alarming via fire alarm systems, a fire results in significantly lower estimated property damage (in 84% of the cases the estimated property damage is less than 1,000 EUR) than with manual alarming with 68%. This is despite the fact that buildings equipped with a BMA are usually more complex and thus have a higher damage potential. With automatic alarming, the fire was limited to one object or device in 86 % of cases when the fire brigade arrived. This was only true in 71 % of cases where the alarm was raised by telephone [7.40]. In addition, the recorded fires show that the smoke had spread relatively further (into the apartment, staircase, corridor or over several floors) at the time the fire brigade arrived when the alarm was triggered via telephone than when the alarm was triggered by BMA [7.40]. In particular, the escape and rescue routes were then more often still usable at the time of arrival of the fire brigade (with BMA in 80 % with 160 of 202 cases) than if they had been alerted by telephone (59 %). The type of alarm also affects the use of firefighting water: For example, in 19 % of the cases, more than 500 litres of extinguishing water were used by the emergency services in the case of manual alarms, whereas this was only necessary in 4 % of the cases when alarms were issued via fire alarm systems. This shows that fire alarm systems have a positive effect on the quantity of extinguishing water and thus also on the duration of the fire brigade's deployment and thus support extinguishing work more effectively.

The effectiveness of the use of automatic fire alarm systems can therefore be statistically proven using various damage criteria. A positive influence on the course of fire can be qualified and quantified.

Table 7.1 Evaluation of fire damage criteria for alerting the fire brigade via automatic fire alarm systems (BMA) in the event of a fire in comparison with manual telephone calls (landline and mobile telephones) (source: vfdb fire damage statistics [7.61]; Phase I and II with 5,016 building fire operations by 28 fire brigades, including 1,216 actual fires; see [7.37], [7.38] and [7.40])

Acquisition criterion		Alerting BMA [number]	Telephone [number]	Share BMA [%]	Phone [%]
Property damage	< EUR 1,000	134	544	84	68
	< EUR 10,000	21	158	13	20
	< EUR 100,000	5	83	3	10
	< EUR 500,000	0	10	0	1
	< 1.000.000 EUR	0	2	0	0
	> 1.000.000 EUR	0	3	0	0
	No specification possible	23	85	---	---
	Total	183	885	100	100
Extent of fire	Subject	171	655	86	71
	Room	19	166	10	18
	Several rooms	4	31	2	3
	Apartment	0	13	0	1
	Floor	2	16	1	2
	Several floors	0	10	0	1
	Fire compartment	0	9	0	1
	Several fire compartments	0	4	0	0
	Stairwell	2	4	1	0
	Overall building	0	15	0	2
	Further buildings	0	2	0	0
	Total	198	925	100	100
Smoke Spreading	Not significant	95	410	47	42
	Room, Shaft	60	158	30	16
	Apartment	21	186	10	19
	Floor	8	61	4	6
	Stairwell	6	80	3	8
	Corridor	9	37	4	4
	Several floors	3	53	1	5
	Total	202	985	100	100
	Smoke stratification visible	25	172	---	---
	Escape route usable	160	585	---	---
LW insert	No fire water	133	312	71	34
	< 500 L	48	425	26	47
	< 2500 L	5	117	3	13
	> 2500 L	2	53	1	6
	Total	188	907	100	100

If the determined statistical effects and the fire damage criteria are compared depending on the triggered plant technology, the result is Table 7.2. Here, fire cases in which automatic fire alarm systems were triggered are compared with fires in which no system technology was present in the building. Table 7.2 shows a comparable picture to the result with regard to the type of alarm.

Table 7.2 Evaluation of fire damage criteria for the triggering of automatic fire alarm systems (BMA) in the event of fire in comparison to operations where no system technology was available (source: vfdb fire damage statistics [7.61]; Phase I and II with 5,016 building fire operations by 28 fire brigades, including 1,216 actual fires; see [7.37], [7.38] and [7.40])

Acquisition criterion		Triggered BMA [number]	Triggered "no plant technology" [number]	Share BMA [%]	Share "no plant engineering" [%]
Property damage	< EUR 1,000	128	452	83	69
	< EUR 10,000	22	132	14	20
	< EUR 100,000	5	59	3	9
	< EUR 500,000	0	10	0	2
	< 1.000.000 EUR	0	1	0	0
	> 1.000.000 EUR	0	1	0	0
	No specification possible	23	76	---	---
	Total	178	731	100	100
Extent of fire	Subject	166	534	85	71
	Room	20	133	10	18
	Several rooms	5	22	3	3
	Apartment	0	9	0	1
	Floor	2	14	1	2
	Several floors	0	7	0	1
	Fire compartment	0	8	0	1
	Several fire compartments	0	2	0	0
	Stairwell	2	3	1	0
	Overall building	0	13	0	2
	Further buildings	0	2	0	0
	Total	195	747	100	100
Smoke Spreading	Not significant	92	374	46	48
	Room, Shaft	56	117	28	15
	Apartment	23	119	12	15
	Floor	8	54	4	7
	Stairwell	7	48	4	6
	Corridor	7	25	4	3
	Several floors	5	37	3	5
	Total	198	774	100	100
	Smoke stratification visible	20	158	---	---
	Escape route visible	156	446	---	---
LW insert	No fire water	127	216	69	29
	< 500 L	45	375	25	51
	< 2500 L	7	105	4	14
	> 2500 L	4	45	2	6
	Total	183	741	100	100

7.2.6 Compensation of structural fire protection measures through fire alarm systems

As indicated in Section 7.1, the compensation of building authority requirements by fire alarm systems can be examined more closely with a time-dependent system reliability calculation [7.4] (see Chapter 10).

In the following, regulations anchored in the building supervisory ordinances and guidelines with the status of 2020 are listed in which compensation of structural fire protection measures by fire alarm systems is possible. It should be remembered that in many cases the compensation of a structural fire protection measure is only possible with a package of several system components. Accommodation facilities with more than 60 beds, for example, are not permitted simply because of the presence of a BMA, but two structural escape routes must be available. The situation is similar with other special buildings where an extension of the area of use requires additional measures as a package. When compensating structural fire protection measures by a BMA, it should be taken into account that the escape routes are also attack routes for the fire brigade.

As an example, the compensation of structural fire protection measures by BMA will be illustrated using the model industrial building code. According to this, the permissible escape route length may be increased in the presence of a BMA with an additional alarm device depending on the clear room height:

- from 35 m to a maximum of 50 m or
- from 50 m to a maximum of 70 m with a room height of at least 5 m.

7.3 Fire extinguishing systems

7.3.1 General information

The task of extinguishing and firefighting systems is, on the one hand, to effectively limit the extent of a fire until the fire brigade arrives, thus enabling intrinsically safe firefighting in the event of increased fire risks, and, on the other hand, to ensure firefighting in cases where timely intervention by the fire brigade is not to be expected due to rapid fire spread, a long journey or difficult access to the fire site.

Oxygen reduction systems are not extinguishing or firefighting systems, their task is to prevent the formation or spread of flames in the protected area by adding nitrogen to the room atmosphere. Oxygen reduction systems are used for preventive fire protection, they avoid fires.

7.3.2 Types of extinguishing systems

7.3.2.1 General information

The following stationary and semi-stationary extinguishing and firefighting systems are used in practice, in industry and commerce and in other special buildings:

- Water extinguishing systems
    - Sprinkler systems
    - Water spray extinguishing system

    - Water mist extinguishing systems (single and dual substance technology)
- Foam extinguishing systems
- Gas extinguishing systems
    - CO2 extinguishing systems
    - Inertgas/Inert gas mixture extinguishing systems
    - Extinguishing systems with halogenated hydrocarbons (Note: Designed as a gas extinguishing system, but extinguishing effect is primarily the inhibition effect)
- Powder extinguishing systems

If one differentiates between extinguishing systems according to the extinguishing agent used, water extinguishing systems are mainly used, and here water mist extinguishing systems and sprinkler systems.

7.3.2.2 Water mist extinguishing systems (single-material technology)

There are different water mist extinguishing systems with different water mist technologies. Experience from fire tests is not yet very extensive, as is the case with classic sprinkler systems, so that deviations from the planning basis are more difficult to assess. At the same time, this means that even more careful planning is required than for traditional sprinkler systems. The following technical regulations are available:

- VdS 3188 - Water mist sprinkler systems and water mist extinguishing systems (high pressure systems), planning and installation,
- VdS 2562 - Procedure for the recognition of new extinguishing technologies,
- VdS 3115 - Procedure for the recognition of new protection concepts,
- bvfa leaflet on water mist extinguishing systems, and
- NFPA 750 - Standard on Water Mist Fire Protection Systems.

In contrast to other extinguishing systems (e.g. sprinkler systems), there are no generally valid design criteria for water mist extinguishing systems. For this reason, these systems are developed manufacturer-specifically and designed to suit the respective object to be protected. The components used are not interchangeable. The design parameters of a system cannot be transferred to systems of other manufacturers. Independently confirmed proof of effectiveness must be available for the respective area of application (e.g. VdS Schadenverhütung or FM-Global).

Because of the small drops, water mist is much more susceptible to thermals and air currents. Where a sprinkler droplet falls down through the thermal lift of a fire, water mist can be deflected in such a way that no effective firefighting is possible at the source of the fire.

In international usage, "water mist" is referred to as "water mist" and in Germany also as fine spray technology. Water mist refers to extinguishing water which is sprayed in droplet diameters of less than 1 mm. "HDWN" is commonly used as an abbreviation for "high pressure water mist". The extinguishing systems are classified as follows based on the system operating pressure:

- CEN/TS 14972:2008
    - Low pressure < 12.5 bar (low pressure)
    - Medium pressure > 12.5 and < 35 bar (medium pressure)
    - High pressure > 35 bar (high pressure)
- according to VdS 3188
    - Low pressure up to 16 bar (fine spray)
    - High pressure over 16 bar (water mist)

As with spray water extinguishing and sprinkler systems, a distinction is made in system design between open (water mist extinguishing systems) and closed (water mist sprinkler systems) pipe systems.

There are different technical possibilities to generate the necessary pressure for the water mist:

- Cylinder systems:
  Pressure vessels with limited water quantity, where the extinguishing water is discharged by a propellant gas under pressure.
- Pump systems:
  The pressure is generated by pump(s). The pumps are driven e.g. by electric or diesel engines.
- Compressed air pumps:
  In this special form of pump system, the high-pressure pump is driven by compressed air stored in cylinders. The compressed air must be dimensioned so that the pump(s) have at least twice the operating time from the extinguishing time determined in the fire tests.

A water mist system does not exist if the main extinguishing effect is caused by extinguishing gases and the water is only added for cooling purposes (two-substance systems as gas-water extinguishing systems).

As with traditional sprinkler and water spray extinguishing systems, a distinction is made between

- Water mist sprinkler with thermal release element (glass ampoule or fusible solder element) and
- open water mist nozzles.

Furthermore, the following trigger mechanisms are distinguished in open systems:

- Electronic release:
    - Automatically by detection elements via fire alarm system/extinguishing control panel or

- by hand switch via fire alarm system/extinguishing control panel.

- Pneumatic/hydraulic release:
  - Automatically by excitation systems with thermal detection elements.

7.3.2.3 Sprinkler systems

Sprinkler systems are most frequently found in practice, which can be explained on the one hand by their efficiency and on the other by their proven reliability. A distinction is made between the following types of sprinkler systems:

- Wet system,
- Drying plant,
- Wet-drying plant,
- Pilot operated system, or
- Tandem system.

Table 7.3 shows the sprinkler types, their water distribution, the scope of protection and suitability.

Table 7.3 Sprinkler types (Note: LH = light hazard, (uses with low fire risk); OH1 = ordinary hazard, group 1, (uses with medium fire risk group 1 according to VdS CEA 4001[7.11])

Sprinkler type	Type of installation	Water distribution	nominal protection area	particularly suitable for
Standard sprinkler	hanging and standing	spherical	9 - 21 m^2	flammable ceilings
Umbrella sprinkler	hanging and standing	paraboloidal	9 - 21 m^2	-
Flat screen sprinkler	hanging and standing	flat paraboloidal shaped	does not apply to shelf protection	Cavity protection grid ceilings
Side wall sprinklers	standing	unilaterally paraboloidal	12 - 21 m^2	Low room height LH / OH 1
Horizontal side wall sprinklers	horizontal	increased litter range	12 - 21 m^2	LH / OH 1
ESFR sprinklers	hanging and standing	Paraboloidally directed towards the ground	max. 9 m^2	high spaces

The design of a sprinkler system is carried out according to VdS CEA 4001 [7.11] and includes six steps:

1. Determination of the fire hazard class,
2. Determination of the type of plant,

3. Determination of effective area, water exposure, minimum operating time and protective surface (characteristic values for planning and installation),

4. Selection of suitable sprinkler nozzles (Table 7.3 shows the sprinkler types, their water distribution, the scope of protection and suitability),

5. Dimensioning of the water supply (hydraulic calculation), and

6. Dimensioning of the energy supply.

7.3.3 Effect of extinguishing systems on the fire scenario

Since reliable statistical data on the effectiveness and reliability of manually triggered (semi-automatic) fire extinguishing systems are not currently available, the following explanations concentrate on automatic as well as stationary or automatic fire extinguishing systems and especially on sprinkler systems, for which the most extensive empirical values are available.

The time course of the heat release rate in case of fires, which is influenced by the effect of an appropriately dimensioned automatic or self-acting extinguishing and firefighting system according to the selected protection objective and scope of protection, depends primarily on the following parameters:

- Fire development in the initial fire phase (type, arrangement, fire development time t),
- Response sensitivity (distance) of the closure elements sprinkler nozzle or triggering elements (Response-Time-Index RTI) or the fire detectors for triggering the extinguishing system and thus triggering the system,
- Special structural and technological features (room height, room tightness or enclosure for gas extinguishing systems),
- Ventilation conditions,
- Chemical and physical properties of the fuels,
- Nozzle arrangement and classification in the extinguishing area (application and performance characteristics),
- Effectiveness of the extinguishing agent application (surface of the fire material, reaction zone of the flame).

It is generally assumed that the systems - provided they are designed, installed and operated in accordance with the recognized rules of technology - start in the initial fire phase, here especially in the phases of "independent burning", "strong burning" and "spreading fire", before the flashover phase has been reached and the fire is controlled by ventilation or fire load (Figure 7.5).

One measure of the response sensitivity of sprinklers is the Response Time Index (RTI value). The lower the RTI value, the faster the sprinkler closure (glass barrel or fusible link) is triggered under comparable heat exposure (

Table 7.4).

Table 7.4 Response sensitivity of sprinklers

Response sensitivity class	Response Time Index [$(ms)^{0.5}$]
standard	> 80 200≤
special	50 to 80
quickly	< 50

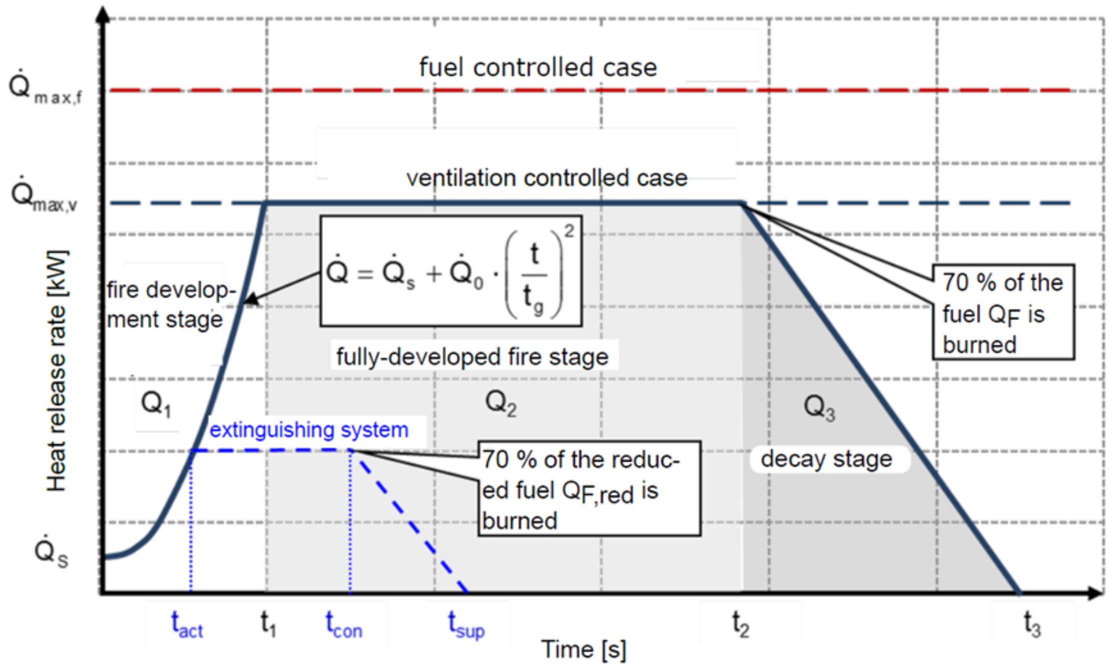


Figure 7.5 Course of the heat release rate when limited by fire load, ventilation or extinguishing systems. At time t_2, 70 % of the fire loads are consumed and the decay phase begins

Furthermore, the triggering time is influenced by the radial distance of the sprinkler axis from the plume axis. In order to quantify the effect of the sprinklers on the course of the fire, their triggering times should be determined as a function of the spread of the fire, the height of the building, the sensitivity of the triggering element and the distance from the plume axis. It should be considered that a fire centrally under a sprinkler is to be classified as a less favourable variant in terms of extinguishing success than the extinguishing success of the same fire *between* two sprinklers if *both* sprinklers are triggered.

For example, for sprinkler nozzle arrangement heights of up to 7 m, taking into account the influence of natural and mechanical smoke and heat extraction systems, it can be specified that the first sprinklers in the immediate vicinity of a heat source will be triggered from heat releases of 300 kW. Only above 400 kW / 600 kW are further sprinklers in the immediate vicinity and further away from the source of the fire (3.75 m radius, 3 m x 3 m protective surface with a diagonal of approx. 2.1 m) opened with triggering times of 2 to 6 min [7.34].

According to [7.13] it can be assumed in a simplified way that the heat release rate after sprinkler activation (t_{act}) remains constant for 5 minutes (t_{con}) and then decreases linearly over a period of 25 minutes to zero (t_{sup}). The linear decrease of the heat release rate in the decay phase represents a computational simplification. In reality, a concave curve is obtained analogous to the fire development phase (see Figure 4.1 in Chapter 4).

The time until fire control/fire suppression is assumed to be the same $\dot{Q}_{LK}$ for each heat release rate, on the grounds that a larger fire area will also trigger a larger number of sprinklers. It is assumed that the flow pressure does not drop too much even if several sprinklers are used (system design).

The heat release rate is calculated as follows (see [7.3])

0 - t_{act}: $$\dot{Q}(t) = \left(\frac{t}{t_\alpha}\right)^2 \quad \text{[MW]} \qquad (7.1)$$

t_{act} - t_{con}: $$\dot{Q}(t) = \dot{Q}_{LK} \quad \text{[MW]} \qquad (7.2)$$

t_{con} - t_{sup}: $$\dot{Q}(t) = \frac{\dot{Q}_{LK}}{t_{sup} - t_{con}} \cdot \left(t_{sup} - t\right) \quad \text{[MW]} \qquad (7.3)$$

with

t_{act}	Sprinkler activation time [s],
t_{con}	Time of the start of fire control by the fire department [s],
t_{sup}	Time of fire containment [s],
$\dot{Q}_{LK}$	Maximum heat release rate during fire control by the extinguishing system [MW].

Figure 7.6 shows as an example the fire course determined on this basis with a fire development time of 150 s, a room height of 6 m, a radial distance of the sprinklers from the plume axis of 2.8 m and an RTI value of 80 $(ms)^{0.5}$.

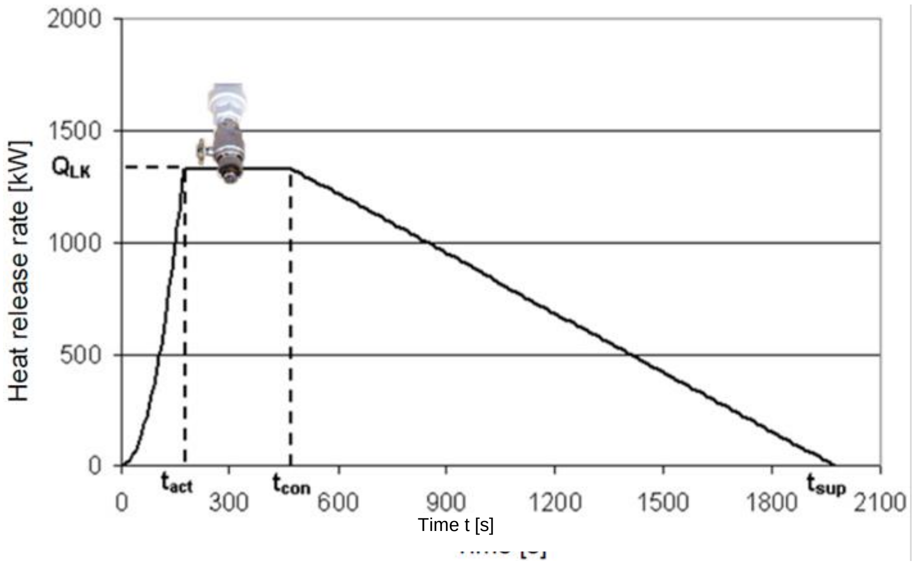


Figure 7.6 Course of a fire in the form of the course of the heat release rate when using a sprinkler system (all model sizes with their nominal values use)

An approximate approach for the mathematical description of fire development under the influence of sprinkler systems was developed in the USA [7.18], [7.20]. The algorithm describes the effect of sprinkler water on the heat release rate of a fire source using equation [7.4]:

$$\dot{Q}(t) = \dot{Q}(t_{act}) \cdot \exp\left[-\frac{(t - t_{act})}{3.0 \cdot w^{-1.85}}\right] \quad \text{in kW/m}^2 \tag{7.4}$$

for $t \geq t_{act}$

with

$\dot{Q}(t)$ Heat release rate under sprinkler protection in kW,

t Time since start of fire in s,

t_{act} Time from start of fire at which the first sprinkler nozzle opens in s,

$\dot{Q}(t_{act})$ Heat release rate when opening the first sprinkler nozzle (tact) in kW,

w specific water admission of the sprinkler system in mm/s.
(≥ 0.07 mm/s)

Figure 7.7 shows an example of the decrease in the heat release rate for a heat release rate when the first sprinkler nozzle is opened of $\dot{Q}(t_{act}) = 500$ kW.

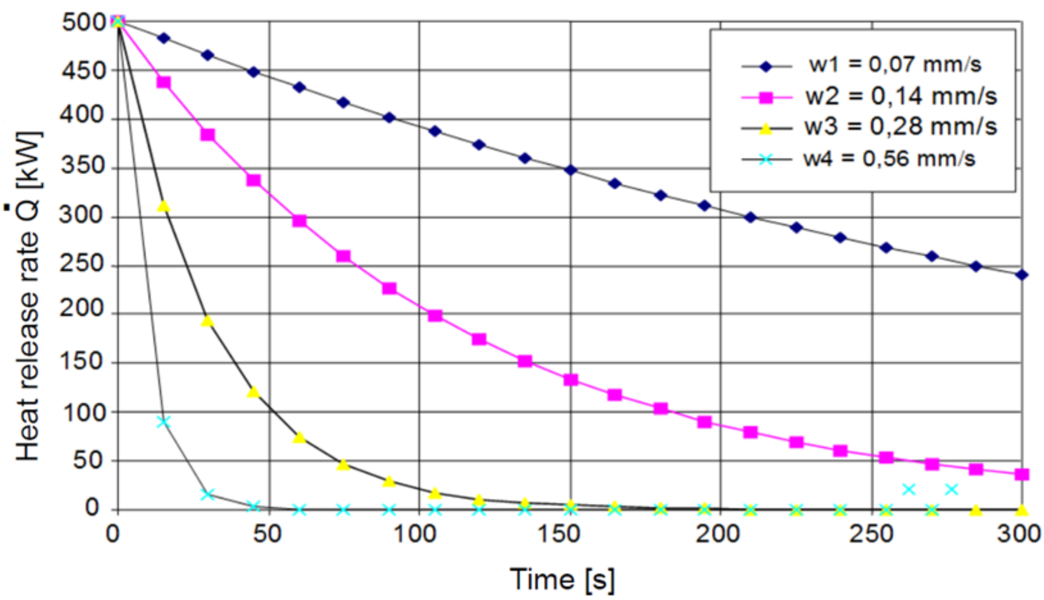


Figure 7.7 The sprinkler effect on the heat release rate as a function of water exposure and extinguishing time

Because of the uncertainty of the limits of use of this algorithm, according to Fleming [7.21] its application should be limited to "light risks" [7.22] with slow to medium fire development. This approach does not take into account special features resulting from the successive activation of several sprinklers. It should be possible to extinguish the fire loads at least as well as wooden cribs.

Special calculations, e.g. for special room or fire configurations, can be performed with fire simulation models. These models allow the approach of several sprinklers and can represent the interaction between fire and sprinkler effects. A final validation of these sprinkler models is still pending (see Chapter 5.6.6).

7.3.4 Reliability of extinguishing systems

Extensive data on the reliability of automatic extinguishing systems are available from property insurers. Because of the great importance of sprinkler systems in practice, the statistical data of the VdS [7.13] for sprinkler systems were primarily evaluated and compared with international surveys (e.g. Australia). In addition, independently requested expert statements were used, e.g. from the German Federal Association of Fire Extinguishers and Systems (BVFA). The results of this research are summarised in With regard to the failure of sprinkler systems, the statistics record both cases in which the system was not activated due to technical failure as well as cases in which the system was activated but the fire exceeded the effective area.

Table 7.5.

With regard to the failure of sprinkler systems, the statistics record both cases in which the system was not activated due to technical failure as well as cases in which the system was activated but the fire exceeded the effective area.

Table 7.5 Probability of failure of sprinkler systems from different sources

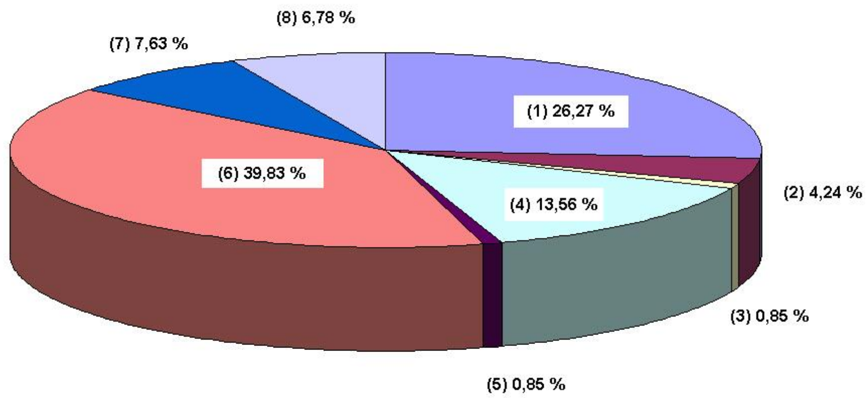
Source	Failure probability p per requirement
VdS (Schadenverhütung testing institution for fire protection) loss prevention [7.14]	0.019
Australia [7.15]	0.041
Expert statements BVFA	0.020

The following circumstances lead to the technical failure of the extinguishing effect of a sprinkler system due to lack of maintenance, material defects or human error:

- Pressurised water as exhaustible water supply,
    - Water filling level insufficient,
    - No water in the tank,
    - Tank pressure inadequate,
    - Fault in the replenishment devices for air and water,
- Water pipeline as inexhaustible water supply,
    - Inadequate performance capability,
    - Shut-off gate closed,
    - No supply to the intermediate tank due to technical failure of the float valves,
    - Intermediate tank without extinguishing water,

- Insufficient replenishment of the intermediate tank due to partially closed gates or soiling of the stone trap,
- Pumps as inexhaustible water supply,
  - Shut-off gate closed,
  - Failure of automatic pump start-up due to defect in a contact switch,
  - Failure of pump system due to technical fault in the switch cabinet,
  - Failure of the automatic starter of the diesel motor,
- Lack of valve stations,
  - Shut-off gate closed,
  - Dry valve pipe networks filled with water,
  - Quick opener out of order,
- Other defects,
  - Alarm shut-off tap closed,
  - Water supply line to the sprinkler system inadequate for new utilisation,
  - Blockage of the water supply line to sprinklers,
  - Unsuitable extinguishing agent.

Other causes for the failure of the sprinkler component are poor design and sabotage. Within the framework of a sprinkler statistics compiled by the VdS on behalf of the European Committee of Insurers (CEA), 7,047 cases of fires and leakages from all over Europe were evaluated. The period covered by the statistics extends from 1985 to 2002. As a result of these statistical evaluations, the causes of the failure were recorded in percentage terms (Figure 7.8).



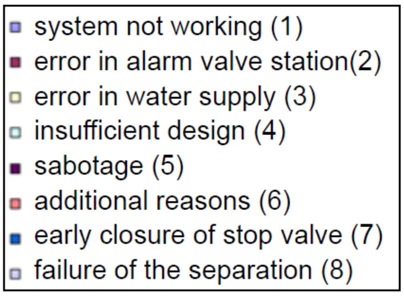


Figure 7.8 Percentage of causes for sprinkler system failure

In view of the fact that international standards regarding the installation and maintenance of sprinkler systems may be less stringent than the VdS requirements and because the values determined on the basis of statistics are rather conservative, the following value is assumed for the probability of failure of sprinkler systems in case of demand:

$p_{f,\ sprinkler} = 0.02.$

7.3.5 Effectiveness of extinguishing systems

Comparable to the effectiveness of fire alarm systems (see Chapter 7.2.5), the effectiveness of fire extinguishing systems (FLA) can be analysed on the basis of the vfdb fire damage statistics [7.61]. As already explained in Chapter 7.2.5 the starting point of the survey is currently 5,016 reports on building fires in Germany from 28 fire brigades with a total of 1,216 real fires (Phases I and II, see e.g. [7.37], [7.38], [7.39], [7.40], [7.41]). The case numbers of the vfdb fire damage statistics are low with regard to the fires in buildings with FLAs: Of the 5,016 building fire deployments recorded, information on FLAs is available in 128 cases, whereby more differentiated information on the damage criteria is only available for a maximum of 12 real fires - with multiple mention of the extent of the fire. The proof of effectiveness is therefore statistically not yet statistically resilient.

The data collected on the origin and spread of the fires as well as on the damage caused and fire protection measures introduced in real fire operations do not yet allow a final assessment of the effectiveness of the use of FLA and its effect on the course of the fire. If necessary, this information can be used in individual cases for quantitative risk analyses for object-specific safety concepts. However, the user must check in each individual case whether the data is plausible and whether its use makes sense. In particular, the following aspects, which are not collected by the vfdb fire damage statistics, must be taken into account:

- FLA are generally used in buildings with a higher concentration of values and/or fire load. Thus, the damage potential in buildings with FLAs is usually many times higher than in single-family homes, for example.
- The statistics provide no information on design criteria or protection goals of the FLA. For example, sprinkler systems are also used to compensate for deviations in structural fire protection. The protection goal can be the reinforcement of a fire wall and not primarily firefighting within a fire compartment.
- It is also not known according to which standard/guideline the FLA was designed and installed.

The result of the evaluation of the fire damage criteria when FLAs are triggered in comparison with fires in which no system technology was present in the building is shown in Table 7.6 (comparable to the evaluation of the fire alarm systems in Table 7.2). Due to the small number of cases, the percentage values were not shown for lack of significance.

It can be seen that in the building fire missions in which plant technology was present, in no case was the property damage greater than EUR 100,000. Due to the high concentration of values in objects with FLAs, it can be assumed that the prevented property damage in fires with FLAs was significantly higher than in objects without FLAs. In no case where FLA was present, the fire did spread to the entire fire compartment. On the other hand, in 32 of 747 cases without FLA, the fire spread to at least the entire fire compartment or several floors. The smoke spread shows that in 10 of 12 of the fires with FLA, the fire was limited to one apartment. In 16% of the cases where FLA was present, the smoke spread via an apartment to the floor and stairwell, whereas in the case of fires without FLA, in a total of 21% of the cases several floors (5%), the corridor (3%), stairwell (5%) or one floor (5%) were affected. The escape and rescue routes were usable with 58 % (7 of 12 cases with FLA and 446 of 774 cases without FLA) of the same dimensions at the time of arrival of the fire department. The reduced use of additional extinguishing water (less than 500 l in 9 of 11 cases) together with the reduced fire spread shows that FLAs tend to have a positive effect on limiting the spread of fire and supporting effective extinguishing operations.

Table 7.6 Evaluation of fire damage criteria for the triggering of automatic fire extinguishing systems (FLA) in the event of fire in comparison to operations where no FLA was available (source: vfdb fire damage statistics[7.61]; Phase I and II with 5,016 building fire operations by 28 fire brigades, including 1,216 actual fires; cf. [7.37], [7.38] and [7.40])[1]

Acquisition criterion		Triggered FLA [number]	"no FLA" [number]
Property damage	< EUR 1,000	3	452
	< EUR 10,000	2	132
	< EUR 100,000[2]	3	59
	< EUR 500,000	0	10
	< 1.000.000 EUR	0	1
	> 1.000.000 EUR	0	1
	No specification possible	3	76
	Total	11	731
Extent of fire	Subject	8	534
	Room	1	133
	Several rooms	2	22
	Apartment	0	9
	Floor	1	14
	Several floors	0	7
	Fire compartment	0	8
	Several fire compartments	0	2
	Stairwell	1	3
	Overall building	0	13
	Further buildings	0	2
	Total	13	747
Smoke Spreading	Not significant	4	374
	Room, Shaft	3	117
	Apartment	3	119
	Floor	1	54
	Stairwell	1	48
	Corridor	0	25
	Several floors	0	37
	Total	12	774
	Smoke stratification visible	3	158
	Escape route usable	7	446
LW insert	No fire water	5	216
	< 500 L	4	375
	< 2500 L	0	105
	> 2500 L	2	45
	Total	11	741

[1] Due to the small number of cases, percentages are not given for lack of meaningfulness.

[2] Due to the large concentration of values and the loss potential, the prevented property damage with triggered FLAs is likely to be significantly greater than without FLAs.

7.3.6 Compensation of structural fire protection measures through extinguishing systems

As indicated in Section 7.1, the compensation of approving authority requirements by fire alarm systems can be investigated in more detail with a time-dependent system reliability calculation taking into account the individual boundary conditions [7.4] (see Chapter 10).

Alternatively, a simplified semi-probabilistic method [7.3], [7.4] can be used. In this case, the natural fire scenario is considered which would result from the functioning of the respective plant-engineering measure. The individually existing failure probability of the plant engineering, the scatter of the model variables used in the verification and the uncertainties of the calculation model are taken into account by means of probabilistically derived partial safety factors.

The following are examples of some of the regulations anchored in the model ordinances for special buildings with the status of 2014 for sales premises and the status of 2008 for garages for the reduction of certain requirements in the presence of a sprinkler system.

- Without sprinkler protection, load-bearing walls, pillars and supports in the case of ground-floor retail outlets must be fire-retardant, whereas if a sprinkler system is present no requirements are placed on the load-bearing structure.
- The smoke section size of unsprinklerised closed garages is 2,500 m^2, and if a sprinkler system is present, the smoke section size may not exceed 5,000 m^2.
- Project-related fire and extinguishing tests, especially from 1992 until today, with the aim of compensating for structural measures with an equally high safety level, have shown that the use of water-based extinguishing and firefighting systems for the protection of unprotected wood, steel and glass constructions with the application of specific fire alarm/nozzle combinations (saftey fire detection for longitudinal and transverse ventilation up to 6 m/s and heat release rate up to 15.0 MW as well as heat flow density up to 460 kWh/m²), as a plant-specific compensation is possible. Depending on the selected distribution type and intensity of the extinguishing agent water (effect directly on the component surface/fuel surface and/or spatial effect in the vicinity of the reaction zone of the flame and the hot fire and smoke gas layer rising from the source of the fire), the following results, among others, could be achieved:
- No temperature increase of components and constructions above 90°C (for wood not above 50°C),
- No temperature increase of the ambient air to over 30°C with a vertical temperature gradient of up to 10°C,
- Creation of acceptable visibility conditions of up to 15 meters and more,
- Reduction of the heat radiation passage to values below 8 to 10 kW/m², in some cases to below 2.5 kW/m².

7.4 Smoke and heat exhaust ventilation systems

7.4.1 General information

The term smoke and heat exhaust ventilation system (SHEVS) is a collective term for natural smoke and heat exhaust ventilation systems (NSHEVS), mechanical smoke and heat exhaust ventilation systems (MSHEVS), pressure differential systems (PDS) as well as heat exhaust systems (HES), which in the advanced stage of fire allow thermal relief with the aid of meltable surfaces [7.61].

The so-called smoke and heat extraction openings cannot be directly assigned to the smoke and heat extraction systems. These also use thermal lift, but only meet the minimum requirements of the building regulations. No reliable predictions can be made for the functional safety, effectiveness and efficiency of such smoke extraction openings. Therefore, they are not sufficiently suitable in the verification procedure, e.g. with engineering methods.

Smoke and heat exhaust ventilation systems, if correctly dimensioned, fulfill the following tasks in the event of fire:

- Support of an intrinsically safe and effective firefighting by the fire brigade by improving the sighting of the source of the fire,
- Support in the rescue of persons by reducing smoke and fire gases, so that breathing is improved, escape routes are easier to recognise and rescue services can find them more quickly,
- Prevention or delay of the fire leap (flash-over),
- Reduction of consequential fire damage caused by smoke and fire gases (protection of smoke-sensitive material assets) and thus securing the company,
- Reduction of thermal stress on building components by dissipating the heat of fire.

The required opening area of natural smoke ventilation systems or the flue gas volume flow of mechanical smoke ventilation systems depends in particular on the following boundary conditions:

- Use of space,
    - Height of the room,
    - required height of the low-smoke layer,
- existing fire loads,
- expected time of fire development,
- size and height of the supply air area,
- height of the smoke curtains,
- plant-related interactions (e.g. ventilation systems, extinguishing systems).

7.4.2 Types of smoke and heat exhaust ventilation systems

7.4.2.1 Natural smoke and heat exhaust ventilation system (NSHEVS)

The effect of the NSHEVS is based on the discharge of smoke and fire gases via natural buoyancy forces and a pressure difference to the outside air which is created under the ceiling. For this purpose, a smoke layer of at least 1 m thickness must be stabilised under the ceiling. A sufficiently large supply air downstream flow that is as close as possible to the floor and acts promptly after the opening of the NSHEV is an essential prerequisite for the smoke extraction effect.

The limitation of the smoke section is required for the stability of the smoke layer, as well as the prevention of additional flows within the smoke layer in case of fire (e.g. continuing room ventilation systems). Essential information on NSHEVS is published in DIN EN 12101-2 [7.50], the principles for planning and installation of NSHEVS are published in DIN 18232-2 [7.51], VdS 2098 [7.52], VDI 6019-1 and -2 [7.43]. The height of the low-smoke layer and the mode of operation of the intended smoke extraction system are calculated and the necessary smoke extraction areas or volume flows and the required supply air downstream flow are determined. Figure 7.9 shows typical components of a NSHEVS.

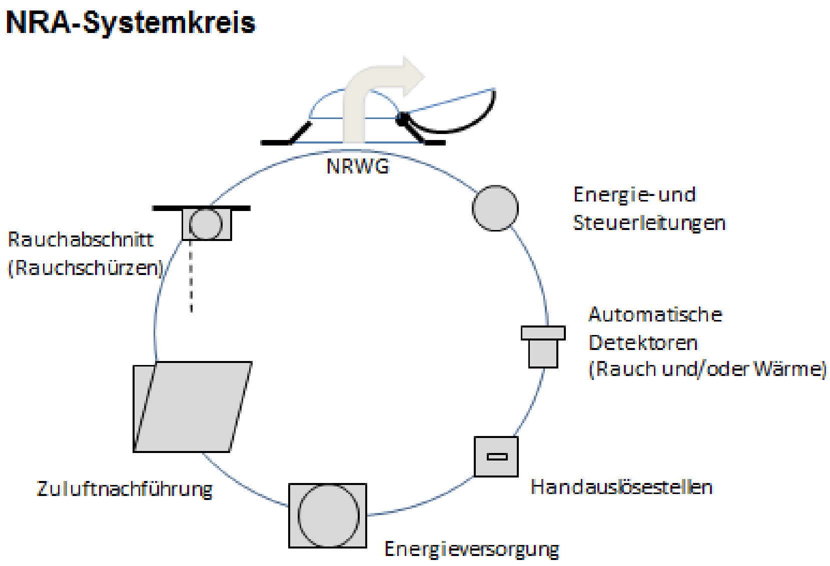


Figure 7.9 A natural smoke and heat exhaust ventilation system

7.4.2.2 Mechanical smoke and heat exhaust ventilation system (MSHEVS)

The effect of the MSHEVS is based on the removal of smoke and fire gases through mechanically generated volume exchange from the smoke layer into the outside air. For this purpose, an at least 1 m thick smoke layer must be stabilised under the ceiling. A supply air downstream flow as close as possible to the floor at low velocities (< 1 m/s) is an essential prerequisite for the smoke extraction effect even before the MSHEVS is activated.

The limitation of the smoke section is necessary for the stability of the smoke layer, as well as the prevention of additional flows within the smoke layer (e.g. continuing room ventilation systems).

Essential information on flue gas fans is published in DIN EN 12101-3 [7.53], basic information on planning and installation of MSHEVS is published in DIN 18232-5 [7.54] and VDI 6019-1 and -2 [7.43]. Figure 7.10 shows typical components of a NSHEVS.

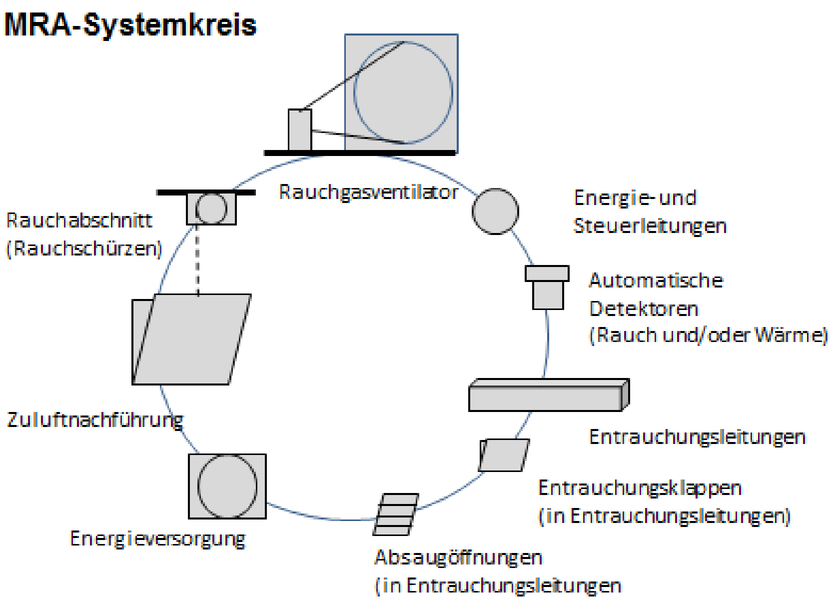


Figure 7.10 A mechanical smoke and heat exhaust ventilation system

7.4.2.3 Pressure differential systems (PDS)

PDS use mechanically generated overpressure to ensure that the room to be protected, e.g. the safety stairwell in high-rise buildings, is smoke-free. With the pressure difference method, fans generate a controlled overpressure in the room to be protected (staircase, air lock, staircase anteroom), which prevents smoke and fire gases from entering the area to be protected when the doors are closed. The force required to open the connecting door must be reduced to a maximum of 100 N so that users can safely enter the protected area with such limited door opening forces. Thus, for example, the necessary door closer is also part of the PDS.

If a door is opened, the existing pressure difference is not sufficient to prevent smoke from entering the area which is to be protected. Instead, a sufficient air flow should be generated to fill the entire door opening and flow from the area which is to be protected into the adjacent room. These volume flows are then discharged to the outside in the fire floor via a sufficient air outlet opening. If this outflow opening is missing or if it is opened too late, smoke would also flow into the area which is to be protected after a very rapid pressure equalisation. The PDS is designed in such a way that a specified air volume flow (e.g. 2 m/s) in the open door prevents smoke from entering the area to be protected.

Essential information on PDS kits is published in a completely revised DIN EN 12101-6 [7.55]. The 2005 version of DIN EN 120101-6 [7.55] contains errors and should no longer be used. Essential information on project planning, installation, commission and maintenance of PDS is published in a new DIN EN 12101-13 [7.56] (until publication, VDMA 24188 [7.57] may be used as an alternative).

The project planning of the PDS depends in particular on the following boundary conditions:

- height of the building (or staircase),
- pressure resistances in the area to be protected (e.g. size of the stairwell, design of the railings),
- area of leakage (pressure losses),
- area of the doors and forces of the door openers,
- design of the floor plans (with or without anteroom, protected or unprotected, with or without connected corridor) as well as location and size of the air discharge,
- entrance doors in case of fire mainly closed or open (a mainly open house entrance door may require a separate shaft for the supply of air on each floor,
- design criteria for the intended use of doors in case of fire,
- type of system control and pressure relief selected (with doors closed), and
- interactions in the system (e.g. to ventilation systems, extinguishing systems).

PDS works closely together with other measures of structural fire protection, plant fire protection and building services. A PDS must always be activated automatically (usually via a comprehensive fire alarm system). The PDS project planning is to be included in the building planning at the earliest possible stage.

Before the start of building use and after any relevant change, the system settings of the PDS must be determined and adjusted if necessary. A PDS must be checked annually by a competent person for its function and adjustment and must be maintained regularly. Figure 7.11 shows the components of an PDS.

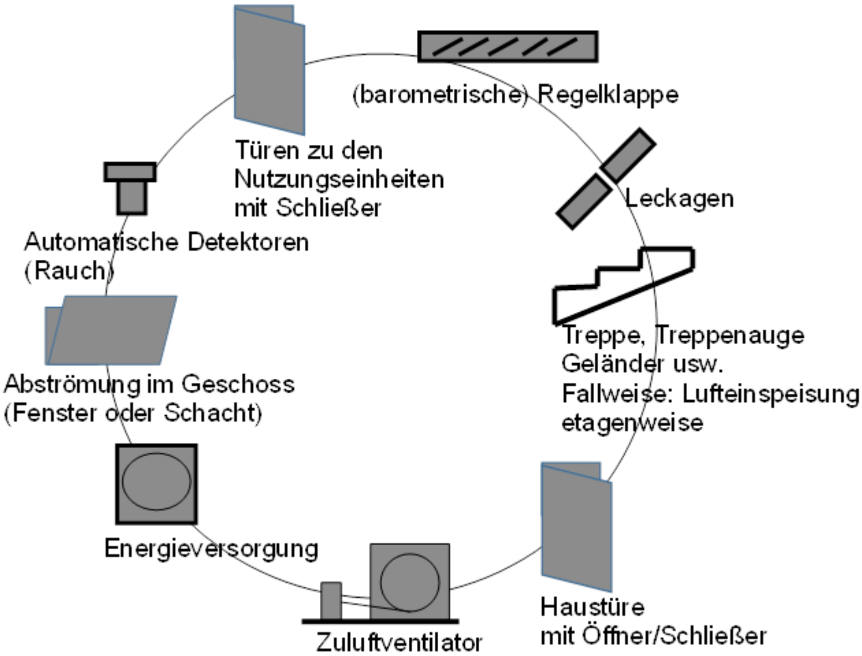


Figure 7.11 a pressure differential system (PDS)

7.4.2.4 Heat exhaust system (HES)

In the case of the dominant heat release during the course of the fire, melting light surfaces (HES) can be used in addition to the existing NSHEVS and MSHEVS to provide thermal relief in order to extend the stability of the load-bearing building components. These are taken into account, for example, in the verification according to MIndBauRL in order to increase the permissible size of fire compartments and firefighting sections for industrial buildings or to reduce the requirements for the fire resistance of the building components.

Important information on heat extraction can be found in DIN 18230-1 [7.1], DIN 18232-4 [7.58] and DIN 18232-7 [7.59]

7.4.3 Effect of smoke and heat ventilation

The consideration of the effect of SHEVS on the fire scenario results from the change in ventilation conditions. A distinction is made here between ventilation-controlled and fire load-controlled fires. This has an influence on the temporal course of the heat release rate, if the fire is ventilation-controlled (Figure 7.12). In addition, the heat extraction reduces the hot gas temperature, which, e.g. in the MIndBauRL [7.1], leads to a possible enlargement of the fire compartment or a reduction of the fire resistance requirements. The influence of the improved heat removal due to the enlargement of the ventilation openings for calculating the mean hot gas temperature is taken into account in the fire load controlled case (Figure 7.13).

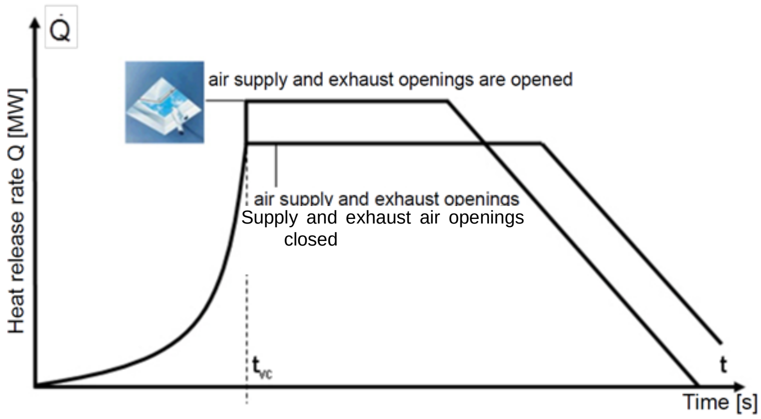


Figure 7.12 Influence of smoke and heat extraction on the heat release rate in a ventilation-controlled fire

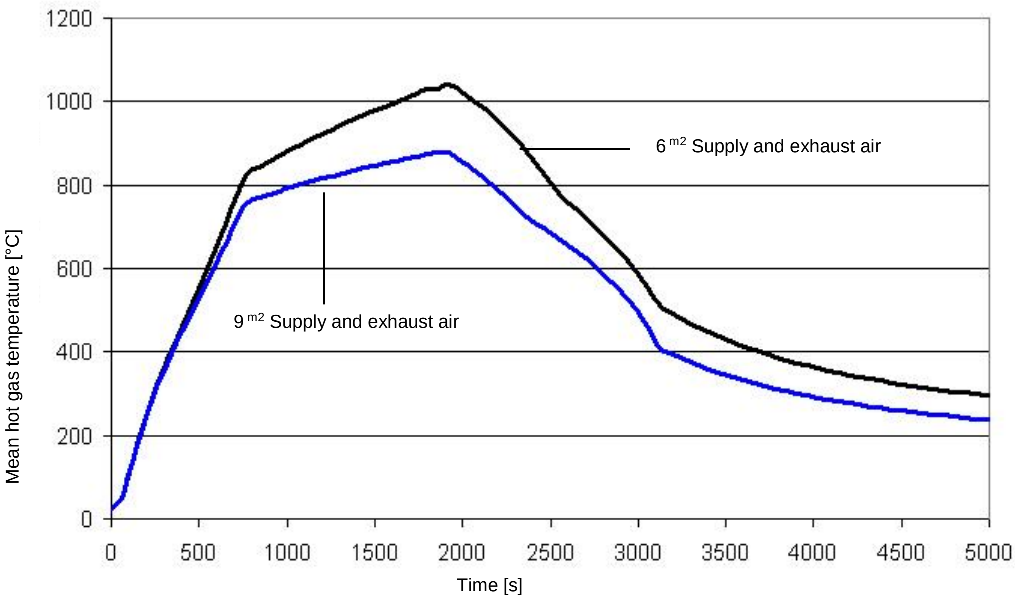


Figure 7.13 Influence of the improved heat extraction through larger ventilation openings on the mean hot gas temperature in a fire load-controlled fire

7.4.4 Reliability of SHEVS

For evaluating the reliability of smoke and heat exhaust ventilation systems statistical data are published at https://www.vfdb.de/themen/statistiken/publikationen/quellen-zur-funktionssicherheit. TÜV e.V. records the defect rates of smoke and heat exhaust ventilation systems annually during the initial and repeat inspections carried out by TÜV (Table 7.7). The SHEVS inspected by TÜV (in 2016 approx. 8,000 smoke and heat ventilation devices/openings) are not differentiated in the statistics into the most varied types of design (MSHEVS, openings for smoke extraction, with or without automatic or even manual triggering, etc.). The quality of the installation and maintenance condition of these SHEVS was not subject to any special requirements. Therefore, the average condition of the building stock is described here. The poorer defect rate in the recurring inspections is due, among other things, to a lack of or inadequate maintenance in individual buildings.

Table 7.7 Defect rates RWA Building Law Report 2016 VdTÜV [7.60]

	first-time audit	recurring test
flawless	49.6%	44.6%
minor faults	27.2%	32.5%
substantial defects	23.2%	22.9%
Total	100.0%	100.0%

Several hundred thousand natural smoke and heat exhaust ventilators, most of which were planned, installed and regularly maintained by recognised specialist companies in accordance with the generally recognised rules of technology (e.g. DIN 18232 [7.51], VdS 2098 [7.52] and DIN EN 12101 [7.50]), have been recorded by the FVLR as part of regular maintenance (Table 7.8).

Table 7.8 Functional states of NSHEVS recorded by FVLR e.V. before the respective maintenance (https://www.fvlr.de/rwa_stat_funktionssicherheit.html)

Inspection within the scope of maintenance	
functional	98.98%
on-site damage	0.02%
improper use / omitted provision	0.01%
intervention by the customer / obstruction of the opening	0.62%
faulty NSHEVS installation	0.12%
Failure of NSHEVS components	0.10%
different reasons	0.16%
Total not functional	1.02%

For the evaluation of the functional safety of smoke and heat exhaust ventilation systems (without differentiating the type of system), the defect rates determined by the TÜV during the expert inspection can preferably be used for the verification of older systems or systems whose system technology probably does not comply with the generally accepted rules of technology.

For the evaluation of the functional efficiency of natural smoke and heat exhaust ventilation systems, which are planned, installed and regularly maintained in accordance with the generally accepted rules of technology, the values determined by the VAVR during maintenance can be used.

Reliability values for mechanical smoke and heat exhaust ventilation systems, pressure differential systems and heat exhaust systems are not available.

In the event that NSHEVS are opened manually by operating personnel when a fire is detected, [7.6] provides some rough reference values for reliability based on an expert survey. However, these cannot be transferred to modern smoke and heat exhaust ventilation systems, which always provide for automatic activation.

7.4.5 Effectiveness of smoke and heat ventilation systems

On the basis of the vfdb fire damage statistics (see e.g. [7.37], [7.38], [7.39], [7.40], [7.41], [7.61], Phase I and II with 5,016 mission reports of 28 fire brigades with a total of 1,216 real fire events), the effectiveness of smoke and heat exhaust ventilation systems (SHEVS) can be assessed according to various fire damage criteria (see Chapter 7.2.5 and 7.3.5).

Table 7.9 shows the evaluation of the fire damage criteria when natural and mechanical smoke and heat exhaust ventilation systems are triggered in comparison with cases where no system technology was available according to the fire brigades. Of the 5,016 building fire incidents recorded, 38 cases of SHEVS were available with differentiated information on the damage criteria. This low number of cases is due, among other things, to the fact that SHEVS are mainly installed in more complex buildings. These cases can therefore also involve a higher loss potential than the average building stock. The proof of effectiveness for SHEVS is therefore statistically not yet completely reliable, but already allows more than just tendentious conclusions - similar to the case with fire extinguishing systems (see Chapter 7.3.5).

A trend with regard to the effectiveness of SHEVS can be derived from the

Table 7.9. In the presence of smoke and heat ventilation, no fire cases were recorded in which the property damage was estimated to be greater than EUR 100,000 and only 8 fire cases (22%) in which the estimated property damage was greater than EUR 10,000 - and this despite the fact that buildings with smoke and heat ventilation are expected to have a high damage potential. In comparison, the extent of the fire is similarly often limited to one object (67 % for fires with SHEVS triggered). With regard to smoke spread, the proportion of fires spreading into the stairwell is significantly higher in fires with triggered SHEVS (26 % compared to 6 % in fires without SHEVS). This can be deduced from the building law requirement of the smoke extraction opening in the stairwell and the natural flow paths in the building. Different SHEVS systems are used to combine different mechanisms of action (smoke extraction, keeping smoke free as well as SHEVS to create a low-smoke layer) to achieve different protection goals. With the number of cases recorded for SHEVS, it is not yet possible to differentiate the effectiveness according to the various systems. In general, it can be seen that when SHEVS are triggered, less extinguishing water is used compared to fires where no SHEVS are present. Thus, in 45 % of the cases no extinguishing water was used (29 % in fires without SHEVS). Therefore, the damage criteria can be used to demonstrate a positive influence of smoke and heat ventilation systems on the effectiveness of mobile firefighting measures by the emergency services. This reflects the rapid localisation of the source of the fire with comparably better visibility and thus prompt extinction of the source of the fire as well as early heat dissipation.

Table 7.9 Evaluation of fire damage criteria for the triggering of natural and mechanical smoke and heat exhaust ventilation systems (SHEVS) in the event of fire in comparison to operations where no SHEVS were present (source: vfdb fire damage statistics [7.61]; Phase I and II with 5,016 building fire operations by 28 fire brigades, including 1,216 actual fires; see [7.37], [7.38] and [7.40])

Acquisition criterion		Triggered SHEVS [number]	Triggered "no SHEVS" [number]	Share SHEVS [%]	Share "no SHEVS" [%]
Property damage	< EUR 1,000	18	452	50	69
	< EUR 10,000	10	132	28	20
	< EUR 100,000	8	59	22	9
	< EUR 500,000	0	10	0	2
	< 1.000.000 EUR	0	1	0	0
	> 1.000.000 EUR	0	1	0	0
	No specification possible	2	76	---	---
	Total	38	731	100	100
Extent of fire	Subject	24	534	67	71
	Room	9	133	25	18
	Several rooms	1	22	3	3
	Apartment	0	9	0	1
	Floor	0	14	0	2
	Several floors	0	7	0	1
	Fire compartment	1	8	3	1
	Several fire compartments	0	2	0	0
	Stairwell	1	3	3	0
	Overall building	0	13	0	2
	Further buildings	0	2	0	0
	Total	36	747	100	100
Smoke Spreading	Not significant	4	374	7	48
	Room, Shaft	9	117	17	15
	Apartment	14	119	26	15
	Floor	5	54	9	7
	Stairwell	14	48	26	6
	Corridor	6	25	11	3
	Several floors	2	37	4	5
	Total	54	774	100	100
	Smoke stratification visible	12	158	---	---
	Escape route usable	25	446	---	---
LW insert	No fire water	17	216	45	29
	< 500 L	14	375	37	51
	< 2500 L	5	105	13	14
	> 2500 L	2	45	5	6
	Total	38	741	100	100

7.4.6 Compensation of structural fire protection measures through SHEVS

SHEVS serve to create a low-smoke zone (layer) of corresponding height in the room. The building code requirement for SHEVS serves in particular to support the fire brigade in the case of external rescue and to carry out effective extinguishing work in the sense of the protection target. Smoke removal from escape routes to ensure usability in the phase of personal rescue is not provided for in standard buildings. Corresponding definitions of the protection goals can be found in the policy paper of the expert commission on construction supervision - "Rescue of Persons" and "Effective Extinguishing Work" - protection goals under building law with regard to smoke extraction [7.46]. In addition, SHEVS serve to protect material assets and to ensure the continued existence of companies by thermally relieving components.

Under building law, SHEVS are used for protection targets

- that in addition to the minimum requirements of the building regulations are necessary or desired,
- as compensation for deviations and facilitations to the building regulations, or
- as part of the application of engineering methods.

The possibility of compensating for building authority requirements by smoke and heat exhaust ventilation systems can be examined more closely with a time-dependent system reliability calculation (see Chapter 10). For this, however, dependable values for the reliability in case of requirements would have to be available.

In the following, some examples of regulations anchored in the model ordinances for special buildings with a status of 2020 for the reduction of certain requirements in the presence of smoke and heat ventilation systems are summarised:

- In the presence of effective SHEVS in the shopping mall of sprinkled sales outlets, the escape route in the shopping street may have an additional length of 35 m in accordance with MVkVO.
- According to the model industrial building guideline, depending on the safety category and fire compartment area, there are no requirements for the fire resistance duration of load-bearing and bracing components in single-storey industrial buildings of limited dimensions if the heat extraction area is at least 5% of the floor area (NSHEVS are counted towards the HES area).
- According to the model industrial building code, a larger fire compartment area can be constructed in conjunction with a fire alarm system and the installation of at least 1 NSHEV per 200 m² floor area with a smoke extraction area of at least 1.5 m² Aw.
- In accordance with MHHR, a safety staircase protected by an PDS replaces the second structural escape route in high-rise buildings up to 60 m high.

7.5 Activation of fire protection systems

7.5.1 Type of activation

Fire protection systems are activated either automatically by a fire detection linked to the fire protection system or manually by persons.

Automatic triggering requires automatic fire or smoke detection. Typical triggering elements are elements that react to smoke, heat or flames.

Fire alarm systems are controlled by electronic detectors when triggered automatically, these are smoke, heat and flame detectors, carbon monoxide sensors can also be used.

Automatic extinguishing systems can be triggered automatically either by thermal triggering elements (glass ampoule, fusible link, mainly in sprinkler systems) or electronic triggering elements (smoke detectors, heat detectors, flame detectors, e.g. gas extinguishing systems, water extinguishing systems with open nozzle networks).

In addition, pneumatic-hydraulic triggering systems (exciter systems with thermal detection elements) of extinguishing systems belong to the automatic triggering systems.

The automatic triggering of smoke and heat ventilation systems is either by thermal triggering elements (glass ampoule, fusible link) or electronic triggering elements (smoke detector, heat detector, flame detector).

7.5.2 Triggering times

7.5.2.1 General information

When determining the triggering times of the different fire protection systems, the thermal triggering elements (glass ampoule, fusible link) and the electronic triggering elements (smoke detector, heat detector, flame detector) can each be considered in combination due to their own triggering characteristics.

There are no reference values for triggering times of manually triggered fire protection systems.

7.5.2.2 Trigger element glass ampoule

Automatic tripping by glass ampoules is used in extinguishing systems with closed pipe systems, primarily for sprinkler systems and water mist extinguishing systems. In addition, natural smoke and heat extraction devices are often equipped with such a trigger on the device.

The triggering time of the glass ampoules of natural smoke and heat extraction devices can be determined approximately analogous to the triggering times of sprinkler systems.

The triggering time tact of sprinkler systems with a closed pipe network (glass ampoules) was empirically determined for different fire intensities, room heights as well as response classes and inertial indices in [7.43]

7.5.2.3 Electronic triggering elements

Automatic tripping by means of electronic tripping elements is mainly used for extinguishing systems with open pipe systems (sprinkler systems, water mist extinguishing systems, gas extinguishing systems), for pilot-controlled extinguishing systems, if necessary, for fire alarm systems and for the control of natural or mechanical smoke and heat extraction systems.

According to [7.43] the triggering time of smoke detectors is set at 120 s. Investigations of the triggering times for standard fires under laboratory conditions [7.43] resulted in permissible scatters for smoke detector series of the same design which call into question a formula-based determination of triggering times.

For heat detectors, triggering times can be determined using [7.44].

The determination of triggering times for flame and multi-sensor/multi-criteria detectors is currently not covered by formulas.

7.6 Defensive fire protection

7.6.1 Effect of extinguishing work on the fire scenario

7.6.1.1 General information

The decisive factor regarding the influence of a fire brigade on the temporal course of the heat release rate is the beginning of the extinguishing work or the time necessary until the fire is controlled. In the case of recognised industrial fire brigades, it is assumed that they will arrive at the scene 5 minutes after being alerted. The prerequisite for this is that the fire alarm has been automatically triggered.

In individual cases, an operational-tactical study, for example in the context of object-specific operational planning or local fire protection requirements planning (political determination of the local level of protection), should be carried out to determine which periods are to be expected, since these periods are influenced by several factors. The following factors can be considered:

- the type of fire alarm,
- the presence of operating personnel,
- an automatic fire alarm,
- the location of the property (inner-city or out-of-town) in relation to traffic density,
- the number of personnel available in a secure manner, and
- the equipment of the fire brigade, etc.

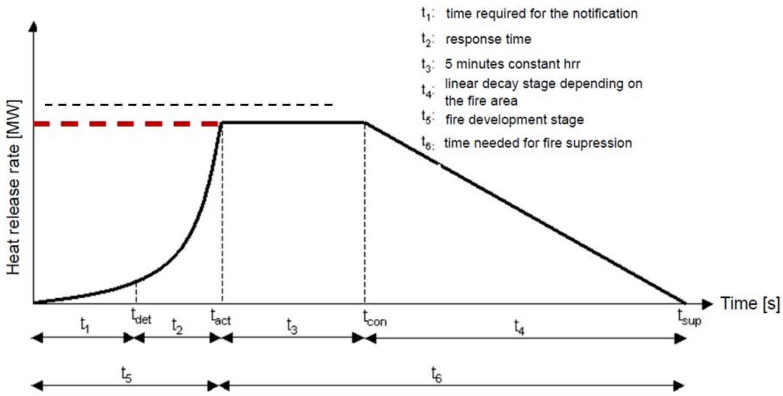


Figure 7.14 Time course of the heat release rate (qualitative) when a fire brigade is deployed

The decisive factor in answering the question of whether the fire brigade can be assumed to have any influence at all on the heat release rate at a certain scale of a fire is the fire area at the time of the start of extinguishing work, depending on the development of the fire. In the industrial building sector, and on the basis of investigations by Schubert [7.16] limit values for the calculation of extinguishing areas were determined, taking into account the conditions that are found in industrial construction, especially in single-storey halls, as a function of the forces and means of the fire brigades. There are no comparable investigations for non-industrial buildings. For completeness, it should be mentioned here that the research project "Innovative Security Architecture of Non-police Hazard Prevention (TIBRO)" [7.46] also supported by the vfdb, has no significance for the application of engineering methods, neither in terms of its objectives nor of its results.

It can be conservatively assumed that the heat release rate remains constant for a period of 5 minutes after the start of the extinguishing work and then diminishes linearly. Figure 7.14 shows the qualitative course of the heat release rate. Regarding the maximum heat release rate, a distinction should be made as to whether the time tact is in the fire development phase ($\dot{Q}_{FK}$) or in the fire load or ventilation controlled fire phase ($\dot{Q}_{fc}$ or $\dot{Q}_{vc}$). The linear description of the decreasing line represents a computational simplification. In reality, a concave curve is produced analogous to the fire growth phase (see Figure 4.1 in Chapter 4). The gradient of the decreasing line depends on the maximum fire area. The larger this fire area can become, the longer it takes until the fire is completely contained.

The maximum heat release rate can be approximately deduced from the fire surface. The limit values have been determined on the basis of expert statements:

$$\dot{Q} \leq 20\ \text{MW} \qquad t_4 = 30\ \text{min} \tag{7.4}$$

$$20\ \text{MW} < \dot{Q} \leq 50\ \text{MW} \qquad t_4 = 45\ \text{min} \tag{7.5}$$

$$\dot{Q} > 50\ \text{MW} \qquad t_4 = 60\ \text{min} \tag{7.6}$$

The time course of the heat release rate is as follows:

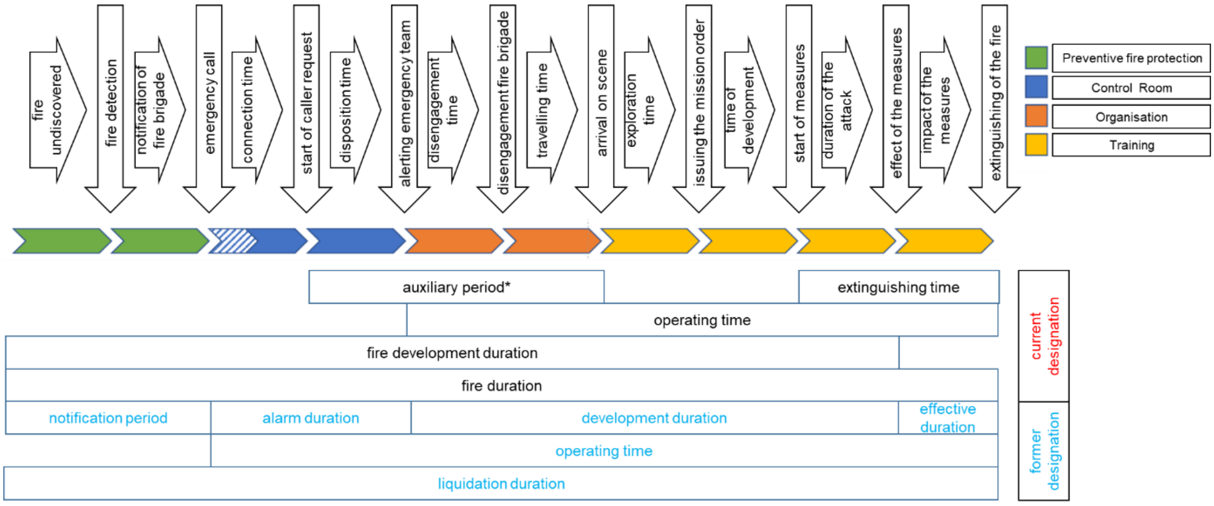
$$0 - t_{act}: \qquad \dot{Q}(t) = \left(\frac{t}{t_\alpha}\right)^2 \qquad [\text{MW}] \tag{7.7}$$

$$t_{act} - t_{con}: \qquad \dot{Q}(t) = \dot{Q}_{max}(t_{act}) \qquad [MW] \tag{7.8}$$

$$t_{con} - t_{sup}: \qquad \dot{Q}(t) = \frac{\dot{Q}_{max}(t_{act})}{t_{sup} - t_{con}} \cdot (t_{sup} - t) \qquad [MW] \tag{7.9}$$

For public fire brigades, different planning parameters are applied, whereby the time of 8 minutes recommended by the AGBF is regularly used as the so-called auxiliary period for the time from the beginning of the submission of a notification of a loss event to the fire brigade, the disposition time, the alert time, the disengagement time and the travel time until the arrival of the first emergency services at the scene of the operation, the disengagement and the travel of the fire brigade [7.23]. Figure 7.15 shows the deployment of the public fire brigade from the beginning of the fire to the completion of the extinguishing work in the form of a flow chart.

A quantification of the effect of public fire brigades on the fire scenario within the framework of engineering proofs is currently not possible due to a lack of valid data or only after consultation with the responsible fire protection authority.



* The auxiliary period is defined differently. The definition of the AGBF is used here. The extended assistance period is the time that a second emergency team requires to arrive on the scene.

Figure 7.15 Flowchart with time periods for firefighting operations [7.35]

7.6.1.2 Auxiliary period

According to DIN 14011 [7.23] the auxiliary periodis defined as the period of time from the beginning of the submission of a notification until the first emergency services arrive at the scene of the incident. It is made up of the disposition time, the alerting time, the disengagement time of the emergency forces and the travel time to the site of operation.

7.6.1.3 Intervention time

In order to be able to quantify the effect of extinguishing measures by a fire brigade on the fire scenario, the time span from the outbreak of the fire to the start of firefighting should be known. This corresponds approximately to the intervention time, which is defined according to DIN 14011 [7.23] as the time span between the discovery of a fire and the effectiveness of the ordered measures after the exploration and development time at the site of action. The intervention time is composed of the reporting time, disposition time, alarm time, disengagement time, travel time, investigation time and development time (see Figure 7.15). It depends essentially on

- the discovery of the source of the fire,
- the distance of the fire site from the alarmed fire station,
- the average traffic density on the approach route and special time delay points (e.g. level crossings),
- the type and use of the property (the time required for exploration and development is, for example, much greater in the case of tunnels than in the case of single-family homes),
- the emergency forces available, in particular those who able to use respiratory protection,
- the training level of the firefighters, and
- the accessibility of the object.

The training level of the firefighters can be simplified and assumed to be uniform across the country and does not depend on whether they are professional or volunteer firefighters. If a fire alarm system is present, accessibility is usually secured by a fire brigade key depot. Significant delays should then only be expected in exceptional cases. The exploration and development time can also be assessed for the different types of structures. The most difficult variable to predict is the time required to travel between the location of the fire brigade (fire station, fire equipment house) and the fire scene, which depends on the first two points mentioned: the distance travelled and the traffic density.

A statistical evaluation of fire brigade data sheets was used to determine p-quantiles (p % fractiles) of the time span between the alarm and the start of extinguishing measures as a function of the effective distance between fire station and fire site [7.3]. This time span corresponds approximately to the intervention time defined above. The results are presented in Figure 7.16.

The data is an example of a large city with about 260,000 inhabitants. In individual cases it must be taken into account that simultaneous fire events, traffic jams, traffic developments and road replanning can have a significant influence on the intervention times.

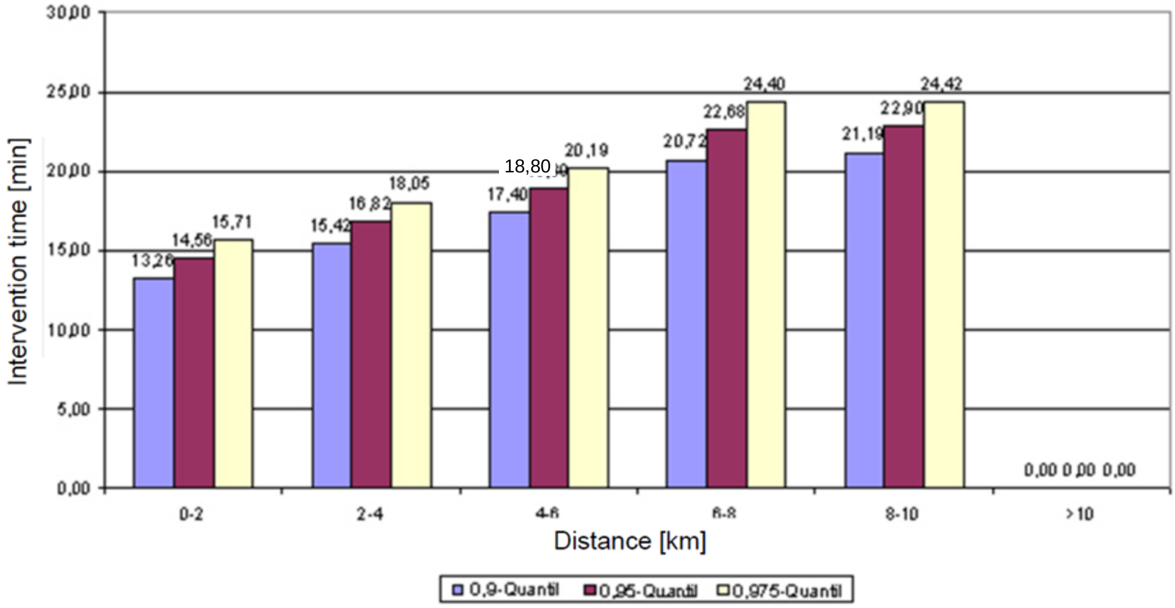


Figure 7.16 Quantiles of the intervention time depending on the distance from the fire station to the fire site

Depending on the boundary conditions regarding the fire alarm, the fire development time can be determined. A generally valid use of the p-quantiles in the safety concept requires comprehensive fire statistics.

If the speed at which the fire spreads is approximately known, the fire area reached at the time of the fire brigade's intervention can be estimated from the information on alarm times and auxiliary periods.

7.6.1.4 Simplified extinguishing model

If, in individual cases and in coordination with the competent authority, the extinguishing effect of firefighting by the fire brigade is to be taken into account in fire simulations, the simplified extinguishing model described below can be used.

It assumes that the fire spreads mathematically undisturbed until the time tact (start of the extinguishing measure) and reaches the fire area $A_F(t_{act})$. For certain fire models (such as the t^2 fire model) an "equivalent fire area" is determined and used.

The acting extinguishing agent immediately stops the further spread of the fire and limits the fire area to the value $A_F(t_{act})$. A defined limit value for the controllability of the fire scenario should not be exceeded. The "maximum controllable fire area" $A_{F,max}$.

The following limit condition can then be formulated for the effectiveness of the extinguishing measure:

$$A_F(t_{act}) < A_{F,max} \tag{7.10}$$

The controllable fire area $A_{F,max}$ depends in particular on the choice and design or on the characteristic performance features of the firefighting measure, i.e. essentially on the following parameters:

- the quantity and suitability of the extinguishing agent which can be effectively introduced into the fire, and
- availability and reliability of this measure.

It is assumed that on the fire surface $A_F(t_{act})$ the burning continues to take place with the $\dot{Q}_{max}(t_{act})$ heat release rate achieved at the time tact. In this phase until the fire is controlled at time tcon, a reduction of the heat release rate due to the extinguishing effect of the firefighting system (being on the safe side) is neglected.

However, it is assumed that due to the extinguishing effect, the proportion of the fire load burning on the fire surface $A_F(t_{act})$ is reduced to $Q_{F,red.}$

The extinguishing effect LW decreases when the fire area $A_F(t_{act})$ approaches the maximum controllable fire area $A_{extinguish,max:}$

$$LW = 1 - A_F(t_{act}) / A_{F,max} \tag{7.11}$$

The reduced fire load $Q_{F,red}$ can be estimated with equation (7.12):

$$Q_{F,red} = (1 - LW^2) \cdot Q_F(A_F) \quad \text{in kWh} \tag{7.12}$$

The reduced fire load increases with increasing activation time tact and consequently with increasing fire area $A_F(t_{act})$. Conversely, firefighting measures that reliably develop their full effect even in small fire areas can greatly reduce the amount of fire load that can be transferred and, accordingly, the design fire (Figure 7.17).

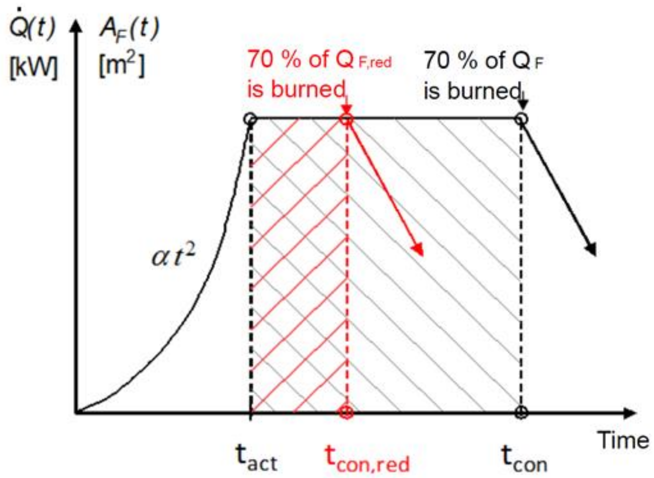


Figure 7.17 The extinguishing effect of firefighting when determining the design fire

In mathematical investigations, conservative assumptions are generally made in order not to underestimate the actual fire hazards. The assumptions and approaches of the model described apply to fires that preferably spread in the area and can be characterized by the fire surface $A_F(t)$. Other fires should be convertible to "equivalent surface fires" because of the "failure criteria" of the extinguishing measures. These assumptions do not apply to shelf or high-bay fires, which preferably develop at height and require special firefighting measures.

The time for the start of the extinguishing measure (the extinguishing agent reaches the burning material) is known as tact (it has been calculated or determined or agreed).

For the scenario of a quantified "critical" housing fire, the following values, among others, are given today by evaluating damage experience [7.35], [7.36]:

- 80% of all domestic fires can be extinguished with up to 1,000 l (min. 800 l) and up to 90% with approx. 2,300 l of water.
- 25% of all fires are extinguished by developing additional water supply points with sufficient water supply (DVGW 405 - 300m radius).
- The average duration of firefighting without additional water supply is 5 to 6 minutes.

7.6.2 Reliability of extinguishing measures

The model described below is used to determine the probability of failure of extinguishing measures by fire brigades as a function of the fire area.

The model is based on a simple limit state equation, in which the fire surface $A_{F,\text{ which}}$ increases with the fire duration, is compared with the maximum controllable fire surface $A_{F,max}$ (equation 7.13).

$$Z = A_{F,max} - A_F(t_{act}) = A_{F,max} - \pi \cdot (v_{aus} \cdot t_{act})^2 \tag{7.13}$$

In order to determine the fire surface $A_{F,}$ the internationally accepted approach to fire development ($\alpha \cdot t^2$ approach) is transformed by assigning α a numerical value for the rate of fire development v_{aus} to the characteristic value for fire development. In the example calculations, the rate of fire development (v_{aus}) was assumed to be v_{aus} = 0.4 m/min for an average fire spread and v_{aus} = 1.0 m/min for a rapid fire spread. t_{act} is the time until the start of extinguishing work.

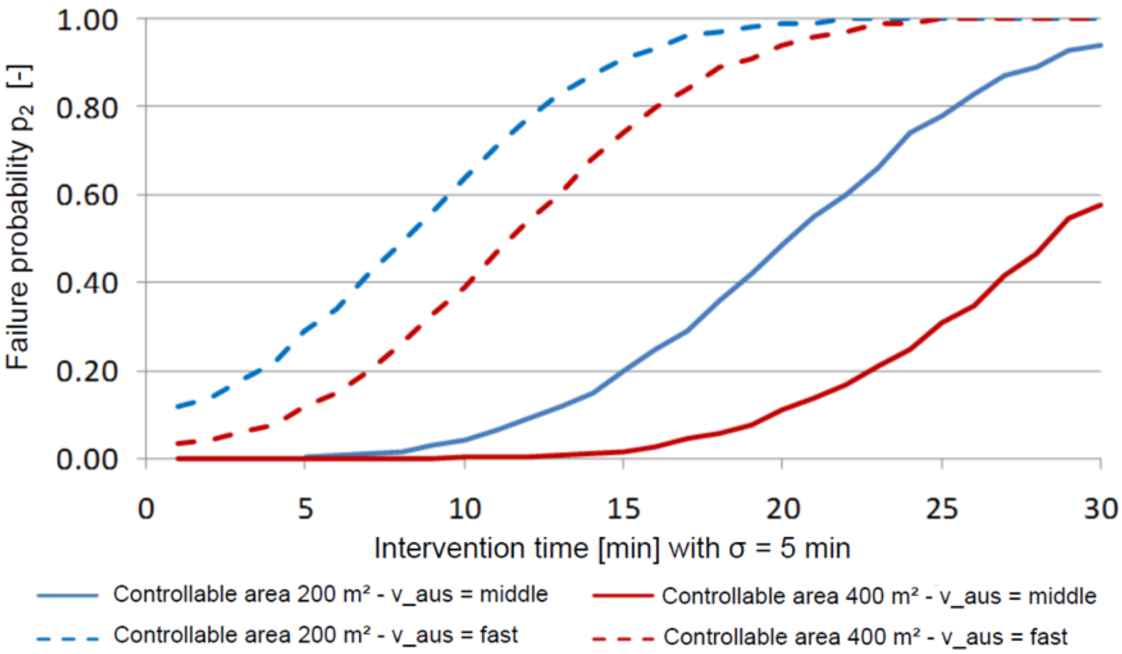


Figure 7.18 Probability of failure of firefighting by the fire brigade as a function of the intervention time and the maximum controllable fire area

Information on the maximum fire areas which can be controlled by the fire brigade under the respective boundary conditions cannot to be found in the literature. Figure 7.18 shows the failure probabilities for extinguishing measures depending on the intervention time of the fire brigade for two different maximum controllable fire areas $A_{F,max}$ (200 m² / 400 m²). This size offers the possibility to take into account fire brigades with different capacities, for example due to a larger number of available squadrons (number of emergency services and associated equipment, such as in particular the number of pumps and hose material).

Table 7.10 Model of input variables

Parameters	Symbol	Unit	Distribution	Mean value	Standard deviation	Coefficient of variation	Source
Fire propagation speed	from	m/min	Gauss standard	0.4/1.0	0.06 / 0.15	0.15	elected
Critical fire area	$A_{F,max}$	m²	Gauss standard	400/200	60 / 30	0.15	elected
Intervention time	t_{act}	min	Gauss standard	10.30	5	0.17 – 0.50	elected

The results, which were calculated using FORM/SORM or a Monte Carlo simulation, are based on a standard deviation σ= 5 min for the intervention time of the fire brigade, while a coefficient of variation V = 0.15 was taken into account for the fire propagation speed and the controllable fire area.

The values for p22 contained in the safety concept of Annex BB of DIN EN 1991-1-2/NA were determined on the basis of the model described here with the specified intervention times. For the critical fire area, the average value from Table 7.10 ($A_{f,grenz}$ = 200 m²) was used.

7.6.3 Effectiveness of firefighting operations

The effectiveness of operative firefighting by a fire brigade can be demonstrated on the basis of the vfdb fire damage statistics (see e.g. [7.37], [7.38], [7.39], [7.40], [7.41], [7.61]). The evaluation of 5,016 mission reports of 28 fire brigades with a total of 1,216 real fire incidents (Phases I and II) shows that there are differences between professional fire brigades (BF), voluntary fire brigades (FF) and industrial fire brigades (WF). On the basis of the vfdb fire damage statistics, information is available on real building fires, from fire emergence and propagation, alarming the fire brigade and the fire protection measures initiated (in terms of plant engineering) to the recording of fire damage (see Chapter 7.2.5, 7.3.5 and 7.4.5). In the present data set, the volunteer fire brigades are underrepresented with regard to the reported case numbers.

Table 7.11 provides the data basis for quantifying the effectiveness of the firefighting method. This proof can be included in the safety concept of an object. The results show, for example, that in 91% of cases the property damage amounts to less than EUR 1,000 for industrial fire brigades, 60% for volunteer fire brigades and 56% for professional fire brigades. In contrast, for professional fire brigades the property damage amounts to more than EUR 10,000 and less than EUR 100,000 in 10% of cases, while this value is 8% for volunteer fire brigades and 2% for fire brigades. In almost all recorded fires (96 %) in which a industrial fire brigade was alerted, the fire was limited to one object. This proportion was significantly lower in the fire cases of the voluntary fire brigades (71 %) and the professional fire brigades (67 %). The professional and voluntary fire brigades thus show the same tendencies with regard to the spread of fire. Smoke spread is also negligible in 91% of cases of fires in which an industrial fire brigade was alerted, in 36% of cases of volunteer fire brigades and in 29% of cases of professional fire brigades. The smoke spread over one or more storeys shows similar values for professional and volunteer fire brigades with respectively 7 and 5% respectively, whereas here the smoke spread is strongly limited for site fire brigades with only one case (one storey) or 1% (several storeys). Here it can be seen that, comparable to the extent of the fire, the spread of smoke during operations of the professional fire brigade and the volunteer fire brigade is similar and proportionately greater than for fires recorded by site fire brigades. The results mentioned above also correlate with the shorter period of time a industrial fire brigade requires to arrive on site compared to a public fire brigade.

No further conclusions regarding the extinguishing agent water used (e.g. effectiveness of water as extinguishing agent or effectiveness of water, depending on use by works or public fire brigades) can be derived from the evaluation for the recording criterion "Use of extinguishing water", because the use of water was only queried singly in the underlying recording sheet, but not, for example, the use of alternative extinguishing agents or the addition of wetting agents or foaming agents.

Table 7.11 Evaluation of fire damage criteria depending on the type of fire brigade (BF: professional fire brigade, FF: volunteer fire brigade, WF: industrial fire brigade; source: vfdb fire damage statistics[7.61]; Phase I and II with 5,016 building fire operations by 28 fire brigades, including 1,216 actual fires; cf. [7.37], [7.38] and [7.40])

Acquisition criterion		Fire cases			Share		
		BF [ANZ.]	FF [ANZ.]	WF [ANZ.]	BF [%]	FF [%]	WF [%]
Property damage	< EUR 1,000	383	125	220	56	60	91
	< EUR 10,000	125	57	6	18	28	2
	< EUR 100,000	69	16	4	10	8	2
	< EUR 500,000	11	1	0	2	0	0
	< 1.000.000 EUR	1	1	0	0	0	0
	> 1.000.000 EUR	0	2	0	0	1	0
	No specification possible	98	5	12	14	2	5
	Total	687	207	242	100	100	100
Extent of fire	Subject	485	156	238	67	71	96
	Room	163	35	5	22	16	2
	Several rooms	23	9	3	3	4	1
	Apartment	14	1	0	2	0	0
	Floor	11	4	1	2	2	0
	Several floors	7	4	0	1	2	0
	Fire compartment	7	3	0	1	1	0
	Several fire compartments	1	2	0	0	1	0
	Stairwell	3	2	1	0	1	0
	Overall building	14	3	0	2	1	0
	Further buildings	1	1	0	0	0	0
	Total	729	220	248	100	100	100
Smoke Spreading	Not significant	228	86	222	29	36	91
	Room, Shaft	160	56	12	20	24	5
	Apartment	192	39	1	25	17	0
	Floor	57	16	1	7	7	0
	Stairwell	72	15	2	9	6	1
	Corridor	31	12	4	4	5	2
	Several floors	41	12	2	5	5	1
	Total	781	236	244	100	100	100
	Smoke stratification visible	107	114	5	--	--	--
	Escape route usable?	460	165	164	--	--	--
LW insert	No fire water	326	85	66	45	40	28
	< 500 L	270	72	163	38	34	68
	< 2500 L	85	39	7	12	19	3
	> 2500 L	39	14	4	5	7	2
	Total	720	210	240	100	100	100

Overall, the results from the

Table 7.11 show that the loss distributions of industrial fire brigades differ from those of professional and volunteer fire brigades, while the distributions between professional and volunteer fire brigades show high similarities. In this context, differences arise from the different structural deployment spectra of professional and volunteer fire brigades (e.g. the emergence of high-rise buildings and apartment blocks). As the municipalities are required to maintain an efficient public fire brigade in accordance with the country-specific regulations and the fire protection requirement plan, no significant differences are to be expected in the

Table 7.11 between professional and voluntary fire brigades.

7.6.4 Compensation of structural fire protection measures through particularly effective extinguishing measures

The possibility of compensating for building authority requirements by means of particularly effective measures for early firefighting can be examined more closely with a time-dependent system reliability calculation (see Chapter 10). For this purpose, however, reliable data on the effectiveness and reliability in case of requirements would have to be available. Since this is only the case to a very limited extent, an explicit consideration of firefighting by the fire brigade in the fire scenario is generally not taken into account. Instead, based on an evaluation of fire statistics of different fire brigades, it can be assumed that only 10 % of the incipient fires develop into a major fire with extensive damage [7.23].

A differentiation of this general "failure probability" of manual firefighting according to the performance of the responsible fire brigade is hardly possible in the absence of fire statistics. Therefore, the "compensation" is limited to a general reduction of the probability of occurrence of a damaging fire in the semi-probabilistic safety concept for fire protection design with a natural fire model according to DIN EN 1991-1-2/NA [7.25].

On the other hand, it is undisputed that the more effective firefighting is carried out by a recognized industrial fire brigade in the area of industrial construction [7.26]. For many years, it has been taken into account in the fire protection design according to DIN 18230-1 [7.1] by means of the coefficient α_L for the fire protection infrastructure and can lead to a reduction of the required fire resistance duration comparable to that of an automatic fire extinguishing system (see Chapter 7.3.6).

7.7 Literature

[7.1] Muster-Richtlinie über den baulichen Brandschutz im Industriebau (M IndBauRL), Fassung Mai 2019.

[7.2] DIN 18230-1: Baulicher Brandschutz im Industriebau; Teil 1: Rechnerisch erforderliche Feuerwiderstandsdauer. Ausgabe September 2010.

[7.3] *DEHNE, M.*: Probabilistisches Sicherheitskonzept für die brandschutztechnische Bemessung, Institut für Baustoffe, Massivbau und Brandschutz, iBMB, TU Braunschweig, Heft 169 (2003).

[7.4] *DEHNE, M.*: Ein übergreifendes Sicherheitskonzept für den vorbeugenden Brandschutz, Institut für Baustoffe, Massivbau und Brandschutz, iBMB, TU Braunschweig, Heft 168 (2003), S. 11 - 40.

[7.5] *DEHNE, M.;* VAN LIER, M.: Zusammenwirken von baulichen und anlagentechnischen Brandschutzmaßnahmen. vfdb-Jahresfachtagung 2004, Essen, 2004.

[7.6] VFDB: Risikoangepasste Reaktion der Feuerwehren auf automatische Meldungen aus Brandmelde- und Sprinkleranlagen. Entwurf einer vfdb-Richtlinie, Fassung März 2002.

[7.7] *BRENIG, H. W.; RIOTTE, H. G.*: Statistische Auswertungen zur Brandeintrittshäufigkeit und Ausfallwahrscheinlichkeit aktiver Brandschutzmaßnahmen. Gesellschaft für Reaktorsicherheit (GRS) mbH. Abschlussbericht zur Studie – Optimierung von Brandschutzmaßnahmen und Qualitätskontrollen in Kernkraftwerken. Fachband 1. Teil B, Köln, September 1985.

[7.8] VdS Schadenverhütung: Jahresbericht 1979, Köln, 1979.

[7.9] *REINTSEMA, J.*: Brandschutz im Krankenhaus. Dissertation, Medizinische Hochschule Hannover, 2000.

[7.10] Vereinigung Kantonaler Versicherungen: Alarmstatistik BMA. Übersicht der echten und unechten Alarme. Bern. Auswertung 1996 - 2000, Bern, Ausgabe Dezember 2001

[7.11] *REINTSEMA, J.; STAIMER, A.;* Bedeutung komplexer Brandmeldesysteme im Rahmen von Brandschutzkonzepten; Praxisseminar Brandschutz in Sonderbauten, Braunschweig 2006.

[7.12] VdS CEA 4001: Richtlinien für Sprinkleranlagen. Planung und Einbau.

[7.13] *HOSSER, D.; DOBBERNACK, R.; SIEGFRIED, W.*: Rauchabzug in ausgedehnten Räumen ohne und mit Sprinkleranlage – am Beispiel des Industriebaus. vfdb, 46. Jahrgang, 4 / 97, S. 147 - 152.

[7.14] VdS Schadenverhütung: Jahresbericht 1990 / 91, Köln, 1991.

[7.15] *NASH, P.; YOUNG, R. A.:* Automatic Sprinkler Systems for Fire Protection. 2nd Edition, Paramount Publishing, 1991.

[7.16] *SCHUBERT, K.-H.:* Problemanalyse zur Berechnung von Löschflächen unter Berücksichtigung der im Industriebau vor allem bei eingeschossigen Hallen anzutreffenden

Gegebenheiten in Abhängigkeit der Kräfte und Mittel der Feuerwehren. Dissertation, Berlin, Juli 1979.

[7.17] Fire Engineering Guidelines. Australian Building Codes Board (ABCB), Australian Fire Authorities Council (AFAC), The Institution of Engineers, Australia (IEAust), 1996.

[7.18] *STAIMER, A.; KLEIN,W.; MONTRONE, F.*: Hochwertige Systeme als Voraussetzung für höchste Verfügbarkeit; vfdb-Zeitschrift 1/2007.

[7.19] *MADRZYKOWSKI, D.; VETTORI, R.:* A Sprinkler Fire Suppression Algorithm for the GSA Engineering Fire Assessment System. NISTIR 4833, U.S. Department of Commerce, 1992, USA.

[7.20] *EVANS, D.:* Sprinkler Fire Suppression Algorithm for Hazard. NISTIR 5254, 1993, U.S. Department of Commerce, Technology Administration, USA.

[7.21] The SFPE Handbook of Fire Protection Engineering. Fourth Edition, Quincy, Massachusetts (USA), 2008.'
FLEMING, R.: Automatic Sprinkler System Calculations.

[7.22] NFPA 13: Standard for the Installation of Sprinkler Systems. NFPA, 1994, Quincy MA (USA).

[7.23] DIN 14011:2010-06, Begriffe aus dem Feuerwehrwesen.

[7.24] *SCHNEIDER, U.; HOSSER, D:* Statistical determination of fire frequency in multi-storey residential buildings. Final report commissioned by the Institute for Structural Engineering (Ref. IV/1-5-383/83). Kassel Comprehensive University, Department of Building Materials, 1984.

[7.25] DIN EN 1991-1-2/NA:2015-09, National Annex - Nationally determined parameters - Eurocode 1: Actions on structures - Part 1-2: General actions - Fire actions on structures.

[7.26] *SCHNEIDER, U.; HOSSER, D*: Statistische Ermittlung der Brandhäufigkeit in mehrgeschossigen Wohngebäuden. Abschlussbericht im Auftrag des Instituts für Bautechnik (Az. IV/1-5-383/83). Gesamthochschule Kassel, Fachgebiet Baustoff-kunde, 1984.

[7.27] *FESTAG, S.* (1/2016). False Alarm ratio of Fire Detection and Fire Alarm Systems in Germany – A meta Analysis. Fire Safety Journal, 79, 119-126. doi:10.1016/j.firesaf.2015.11.010)

[7.28] *FESTAG, S.* et al. (2018). False Alarm Study: False Alarm Data Collection and Analysis from Fire Detection and Fire Alarm Systems in Selected European Countries. Berlin: Erich Schmidt Verlag.

[7.29] *STAIMER, A., FESTAG, S. , MÜNZ, F.* (8/2012). Verfügbarkeit von Brandmeldeanlagen. Wie sicher sind Brandmeldeanlagen? (Technischer Bericht, ZVEI-Merkblatt 33009:2012-08), Frankfurt am Main: Zentralverband Elektrotechnik- und Elektronikindustrie.

[7.30] *FESTAG, S., LIPSCH, C.* (03/2019). Empirische Untersuchung der statistischen Verfügbarkeit von automatischen Brandmeldeanlagen. Vortrag, 5th. Magdeburg Day of Fire and Explosion Safety, 25.-26.03.2019. Magdeburg: Universität Magdeburg.

[7.31] *BIROLINI, A.* (1997). Zuverlässigkeit von Geräten und Systemen. Heidelberg: Springer Verlag.

[7.32] FACHARBEITSKREIS PROBABILISTISCHE SAFETY ANALYSIS FOR NUCLEAR POWER PLANTS (eds.): Daten zur probabilistischen Sicherheitsanalyse für Kernkraftwerke, Schriften / Bundesamt für Strahlenschutz. Status: August 2005. Bremerhaven: Wirtschaftsverl. NW, Verl. für Neue Wiss, 2005 - ISBN 978-3-86509-415-5.

[7.33] *SCHLOSSER, I., STAHL, K.-H.* (26. August 1997). Ermittlung von Sicherheitsfaktoren bei Gaslöschanlagen mittels analytischer Methoden. (VdS, Hrsg.) Köln, NRW, Deutschland.

[7.34] *HIMMELBAUER, H.,TREYLT, A*. (Sommer 1996). Fehlerbaumanalyse; Fault Tree Analysis (FTA). Wien, Österreich.

[7.35] *FÖHL, A. C*.: „Untersuchungen der Wechselwirkungen zwischen gleichzeitig betriebenen Sprinkler- und Rauch/Wärme-Abfuhr-Systemen – Versuche“, Forschungsstelle für Brandschutztechnik an der Universität Karlsruhe (TH), Februar 2005.

[7.36] *TRETTER, L*.: „Leistungsorientierte Ermittlung von Kräften und Mitteln als Grundlage für Einsatzunterlagen im abwehrenden Brandschutz“, Masterarbeit an der TH Köln, Studiengang Rettungsingenieurwesen und Gefahrenabwehr – Studienrichtung Brandschutzingenieurwesen, Köln, 19. März 2019.

[7.37] *HOFFMANN, M*.: „Effektivität einer Feuerwehr - Zur Beschreibung der Leistungsfähigkeit einer Feuerwehr mittels quantitativer Kenngrößen“, Masterarbeit an der TH Köln, Studiengang Rettungsingenieurwesen und Gefahrenabwehr – Studienrichtung Brandschutzingenieurwesen, Köln, 06. September 2016.

[7.38] *FESTAG, S. , HEGGER, T.* (7/2017). vfdb-Brandschadenstatistik. URL: http://www.ref14.vfdb.de/brandstatistik (Erstellungsdatum: 28.07.2017).

[7.39] *HEGGER, T.* (9/2014). Entwicklung einer nationalen Brandschadenstatistik. In: Zehfuß, J. (Hrsg.): Braunschweiger Brandschutz-Tage 2014. 28. Fachtagung Brandschutz und Sonderbauten (S. 261-272), 16.-17. September 2014, Heft 224.

[7.40] *FESTAG, S.* (09/2015). Ergebnisse zur Erhebung der Brandschadenstatistik. In: Zehfuß, J. (Hrsg.): Braunschweiger Brandschutz-Tage 2015. 29. Fachtagung Brandschutz bei Sonderbauten (S. 227-248), Heft 227.

[7.41] *FESTAG, S*. (2018). Exemplarische Ergebnisse für einen Überblick und Sachstand zur Untersuchung der Wirksamkeit von anlagentechnischen Brandschutzmaßnahmen. Technische Sicherheit, Düsseldorf, Springer-VDI-Verlag.

[7.42] *FESTAG, S.* (9/2017). Statistical analysis of the effectiveness of fire protection system technologies – Extract from the project survey phases I of the German fire loss statistic.

In Thorsten Schultze (Hrsg.), Proceedings, 16th International Conference on Automatic Fire Detection, 12.-14. September 2016, Maryland (S. I-51-I-62), Duisburg: Universität Duisburg-Essen.

[7.43] VDI 6019 Ingenieurverfahren zur Bemessung der Rauchableitung aus Gebäuden, Blatt 1 und Blatt 2.2006.

[7.44] VdS Schadenverhütung (2019) – Prüfprotokolle punktförmiger Rauchmeldern nach dem Streulichtprinzip zu Normbränden TF2 (Holz) und TF5 (n-Heptan) nach DIN EN 54-7:2006-09, Anhang ZA, Köln, unveröffentlicht.

[7.45] *EVANS, D. D.:* Ceiling Jet Flows in SFPE Handbook of Fire Protection Engineering, 2nd Edition, Section 2/Chapter 4, National Fire Protection Association, Quincy, Massachusetts, 1995.

[7.46] Forschungsprojekt „Innovative Sicherheitsarchitektur der nichtpolizeilichen Gefahrenabwehr (TIBRO)“, 04/2012-06/2015, https://www.sifo.de/files/Projektumriss_TIBRO.pdf, Zugriff 10.06.2019.

[7.47] *FAMERS, G., MESSERER, J.*:„Rettung von Personen“ und „wirksame Löscharbeiten“ - bauordnungsrechtliche Schutzziele mit Blick auf die Entrauchung - Ein Grundsatzpapier der Fachkommission Bauaufsicht, 2008, https://www.bauministerkonferenz.de/Dokumente/42311831.pdf, Zugriff 10.06.2019.

[7.48] DIN 14675 Brandmeldeanlagen, Teile 1 und 2.

[7.49] DIN VDE 0833 Gefahrenmeldeanlagen für Brand, Einbruch und Überfall, Teile 1 – 4.

[7.50] DIN EN 54 Brandmeldeanlagen, Teile 1 – 32.

[7.51] DIN EN 12101-2 Rauch- und Wärmefreihaltung – Teil 2: Natürliche Rauch- und Wärmeabzugsgeräte.

[7.52] DIN 18232-2 Rauch- und Wärmefreihaltung – Teil 2: Natürliche Rauchabzugsanlagen (NRA); Bemessung, Anforderungen und Einbau.

[7.53] VdS 2098 VdS-Richtlinien für natürliche Rauch- und Wärmeabzugsanlagen (NRA), Planung und Einbau.

[7.54] DIN EN 12101-3 Rauch- und Wärmefreihaltung – Teil 3: Bestimmungen für maschinelle Rauch- und Wärmeabzugsgeräte.

[7.55] DIN 18232-5 Rauch- und Wärmefreihaltung – Teil 5: Maschinelle Rauchabzugsanlagen (MRA); Anforderungen, Bemessung.

[7.56] DIN EN 12101-6 Rauch- und Wärmefreihaltung – Teil 6: Festlegungen für Differenzdrucksysteme, Bausätze.

[7.57] DIN EN 12101-13 Rauch- und Wärmefreihaltung – Teil 13: Projektierung, Einbau, Abnahmen und Instandhaltung von RDA.

[7.58] VDMA 24188 Rauchschutzmaßnahmen in Treppenräumen – Rauchableitung, Rauchverdünnung, Rauchfreihaltung.

[7.59] DIN 18232-4 Rauch- und Wärmefreihaltung - Teil 4: Wärmeabzüge (WA); Prüfverfahren.

[7.60] DIN 18232-7 Rauch- und Wärmefreihaltung – Teil 7: Wärmeabzüge aus schmelzbaren Stoffen; Bewertungsverfahren und Einbau.

[7.61] Verband der TÜV e. V., Baurechtsreport 2016.

[7.62] *FESTTAG, S.; DÖBBELING, E.-P.:* vfdb-Brandschadenstatistik – Untersuchung der Wirksamkeit von (anlagentechnischen) Brandschutzmaßnahmen. Technischer Bericht 14-01, Vereinigung zur Förderung des Deutschen Brandschutzes e. V. (vfdb), Technisch-Wissenschaftlicher Beirat (TWB), Referat 14, Münster (in Bearbeitung zur Veröffentlichung 2020).

8 LIFE SAFETY IN ESCAPE ROUTES

8.1 Verification criteria for life safety

The available verification criteria for life safety are:

1) The height of the low-smoke layer,
2) The quality of the low-smoke layer, in particular:
   2.1 The optical density per path length or the visibility (Chapter 8.2 and 8.3),
   2.2 The effects of toxic gases (Chapter 8.4), and
3) Thermal impact from thermal radiation and convection (Chapter 8.5).

1) Height of the low-smoke layer

The most obvious and easiest to understand criterion is the height of the low-smoke layer. For self-rescue, layer heights of at least 2.5 m are typically required [8.31] depending on the strength of the stratification, room height and required safety margins, and only in exceptional cases less. The height of the low smoke layer is an essential output parameter of zone models. For CFD simulations, this parameter is based on evaluations of layer formation across the vertical coordinate axis, and the influence of gas flow inside the room may also be considered. In general, the height of the low-smoke layer is a conservative, early-stage criterion for life safety [8.32], which is based solely on physical phenomena and not on considerations of (individual) hazardous effects.

2) Quality of the low smoke layer

In order to demonstrate the extent of a low-smoke layer, evidence of the quality of the low-smoke layer may be required. This applies in particular to a surrounding with stratification, in which smoke gas components enter the low-smoke cold gas layer, in smoke extraction concepts based on smoke dilution (e.g., in garages or tunnels) or in very conservative fire scenarios. The evaluation of the optical density per path length or visibility includes physical aspects as well as photometric and chemical considerations. Depending on the height of the objects to be detected in the room, the visibility criterion may take precedence over the height of the low-smoke layer [8.32]. Physical, chemical and physiological aspects are included in the evaluation of fire gas toxicity. Performance criteria based on toxicity are not conservative. They may only be used in well-founded cases or in very conservative scenarios. The simple replacement of conservative criteria such as low smoke layer height by toxicity verifications would lead to a reduction of the safety level. The advantage of using toxicity assessments is that, in principle, they are best suited for risk quantification due to the consideration of chemical and physiological aspects.

3) Thermal effects

The thermal effects of heat radiation and convection should be considered especially in the vicinity of the flame and below a hot gas layer. Physical aspects are mainly considered in the calculation methods.

Since the impacts of the performance criteria 2 and 3 vary strongly locally, the computational verification of these criteria generally requires the use of CFD models. In the case of criteria 2 and 3, the harmful effect on humans depends on the duration of exposure. Since the effects typically increase with the development of the fire, the harmful effect (dose) on humans increases disproportionately (see Figure A2.3). The use of dose models such as FED (eq. (8.11)) or $FED_{thermal}$ (eq. (8.17)) therefore forms the basis for the definition of quantitative performance criteria and corresponding limits (as e.g., in Table 8.2) and is therefore preferable for risk assessments.

8.2 Obscuration by smoke

The extent of smoke and the associated reduction in visibility plays a significant role in the assessment of the hazards posed by a fire. Simplifying the complex processes involved in the generation and spread of smoke, it can be described as a medium which is initially generated in the area of the combustion zone and transported by the buoyancy-driven convective flow, possibly influenced by ventilation flows caused by building openings or mechanical ventilation systems. In the following, the term "smoke" is to be understood as the aerosol consisting of solid particles, low-volatile substances attached to them and gaseous products.

Obscuration by smoke is quantified by the optical density per path length D_L or the extinction coefficient K. Both quantities describe the same physical facts, but differ in their mathematical formulation (negative decimal or natural logarithm of the relative light transmission divided by the path length), which results in a conversion factor

$$D_L = \frac{K}{ln(10)} \approx 0.43 \cdot K \tag{8.1}$$

Since both quantities have the same physical units (m^{-1}), the underlying definition should be carefully considered when applying corresponding data. Sometimes the smoke density per path length is also given in the unit db/m, called obscura (Ob), where D_L [Ob] = 10 x D_L [m^{-1}]. In the following, the term "smoke density" means the optical density per path length D_L of the smoke.

Important for the application in the verification process is the relationship between smoke density and mass concentration of the smoke (smoke particle load) c_{soot}.

$$D_L = D_m \cdot c_{soot} / Y_{soot} \tag{8.2}$$

The quantity D_m is referred to as smoke potential (in relation to optical density per meter), or mass optical density (MOD) in accordance with DIN EN ISO 5659-1. Y_{soot} is the smoke yield, sometimes also referred as soot yield or smoke mass conversion factor.

The yield Y of a combustion product is given in the form [g/g] (ratio of the mass of the combustion product to the mass of the burned fuel) as the portion of the overall mass released due to combustion.

If the smoke potential is related to the extinction coefficient, the smoke potential should be multiplied by the factor ln(10) accordingly.

As an alternative to the smoke potential, D_L or K can also be calculated from the mass-specific extinction coefficient K_m and the smoke particle density, the latter including the smoke yield Y_{soot},

$$D_m = K_m \cdot Y_{soot} / \ln(10) \tag{8.3}$$

with a typical value for the flaming combustion of mixed fire loads (wood, plastic) for K_m of 8.7 ± 1.1 m^2/g [8.5]. The advantage of using the smoke potential D_m compared to K_m is that D_m directly contains the dependence of smoke opacity on the fuel, whereas in K_m this is only expressed by the combination with Y_{soot}. Furthermore, the smoke opacity also depends on the combustion process (air supply, flame formation). Fire stages without flame formation usually show a significantly higher smoke potential. It should be noted, however, that in this case the rate of combustion - and thus also the smoke generation - is considerably lower than in fires with flames and correspondingly high heat release rates.

8.3 Visibility of emergency signs

The visibility – defined as the distance between the observer and the emergency sign where the sign can be seen and recognised – is a complex quantity dependent on many influencing factors (properties and density of smoke particles, illumination of the area, properties of the object being perceived, perspective, individual characteristics of the person, eye irritation due to fire gases etc.).

The evaluation of smoke tests shows that there is a basically reciprocal relationship between smoke density and visibility. Studies on the effects of smoke on people [8.1], [8.2], [8.3] led to the following relationships:

$$S = \frac{C}{K} \text{ for non-irritant smoke or irritant smoke with } K < 0.25\ m^{-1} \qquad (8.4)$$

and

$$S = \frac{C}{K} \cdot [0.133 - 1.47 \cdot log(K)] \text{ for irritant smoke with } K \geq 0.25\ m^{-1} \text{ and } S > 0. \qquad (8.5)$$

The measured data in Jin's experiments are given for a distance between 5 m and 15 m from the observer to the object being detected. The values for the constant C for light-emitting (illuminated by an internal light source) signs depend strongly on the luminance in addition to the smoke composition, with values between 5 and 10 being observed. For reflecting signs (illuminated by an external light source), values between 2 and 4 were observed, depending on the reflectivity of the signs. In practice, the mean values already provided by Jin for the parameter C of 8 (light-emitting sign) and 3 (reflecting sign) are frequently used [8.4], [8.5].

Figure 8.1 shows the relationship between visibility and optical density per path length for different smoke compositions. For this purpose, the respective mean value was used in equation (8.4) and (8.5) for the proportionality constant C and the extinction coefficient K was converted into D_L. It can be seen that eye-irritating smoke components from a smoke density D_L above about 0.1 m^{-1} lead to an increased reduction of the visibility compared to non-irritating smoke. As early as the 1960s, Rasbash determined a similar correlation between recognition distance and optical density per path length on the basis of his own investigations and external data [8.6], which is close to the correlation determined by Jin for light-reflecting signs.

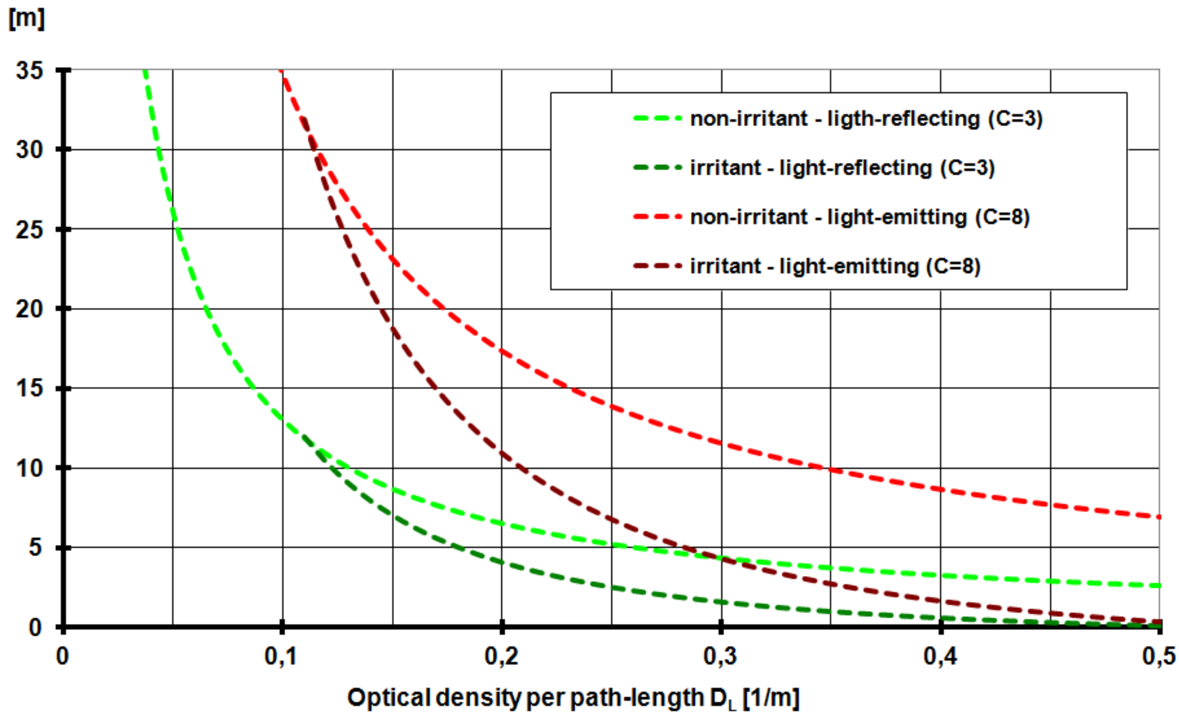


Figure 8.1 Visibility S as a function of D_L

The best-fit curves can also be extrapolated to lower [8.4] visibility - down to about 0.5 m (arm's length). However, in the range of smoke density D_L less than 0.2 m^{-1} the visibility is systematically overestimated due to simplifications and approximations in (8.4) or (8.5). For the smoke-free case K = 0, these relationships are not applicable. However, since the transition from the smoke-free to the low-smoke (as defined in Chapter 8.5) situation is essential for the proof of life safety in the self-rescue phase, approaches that are also valid for the low smoke case should be used in these cases for a more detailed analysis. Such detailed information on the calculation of visibility for emergency signs based on corresponding smoke tests can be found in [8.23], [8.24], [8.25]. In general, the visibility S is obtained by equating the contrast c_v with a contrast threshold c_{min},

$$c_v = c_{v,0} \cdot F_{\text{scatter}} \cdot e^{-KS} = c_{\text{min}} \tag{8.6}$$

c_v is dependent upon the contrast (ratio of luminance of the characters or pictogram to that of the sign's background) on the surface of the sign $c_{v,0}$, scattering on smoke particles and the exponential attenuation of light in the smoke. The contrast threshold is not a constant but rather is influenced by a whole range of factors. Thus, in addition to smoke density, the illuminance, properties of the sign (size, contrast), scattering properties of the smoke (light or dark smoke) and criteria for defining the visibility (perception or identification) are also incorporated into the general approach (8.6).

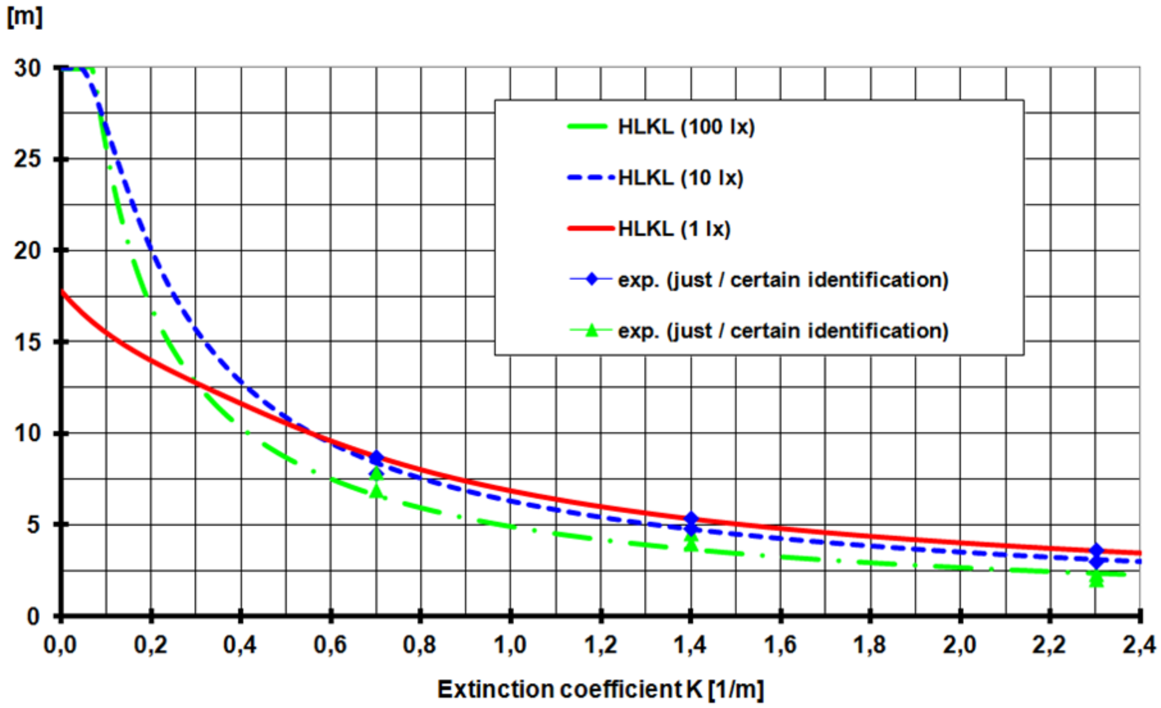


Figure 8.2 Recognition range S of a backlit escape route sign as a function of D_L for different illuminance levels [8.25]

Figure 8.2 shows an example of the influence of illuminance for a light-emitting sign of the size 10 cm x 20 cm, with an average luminance of the pictogram (white arrow) of 450 cd/m^2 and of the (green) sign background of 137 cd/m^2 for smoke with a scattering ratio of 80% ("white" smoke). The corresponding experimental data are taken from the study [8.23]. The visibility calculation according to (8.6) requires an iterative solution procedure. Further information on this method can be found in [8.25], the complete set of necessary equations of determination can be found in [8.30].

Furthermore, the angle of view between the observer and the sign is also important for determining the recognition range. The methods presented here for calculating the visibility refer to the optimal case of a direct line of sight. In reality, however, especially in complex and large-scale installations, one will be able to approach a sign at very different angles, which can be taken into account by suitable methods [8.25].

The equations (8.4) - (8.6) apply to homogeneous conditions over the distance of the light beam. If relevant spatial differences in the smoke density occur, an appropriate local treatment of the light attenuation (integral decomposition) must be calculated [8.29].

Two effects of reduced detection range due to smoke formation that are important for self-rescue are the associated slowing down of escaping persons and difficulties in orientation or, in general, trying to avoid smoky areas [8.10]. With a smoke density D_L of approx. 0.1 m^{-1} and above it can be seen in empirical studies [8.1] that people who are unfamiliar with the surroundings will slow down. These aspects can be considered in advanced simulation models which take individual aspects of movement and behaviour into account [8.7], [8.8].

8.4 The toxic effect of fire effluents

A direct impairment of an individual's ability to act is often due to the narcotic or suffocating effect of the gases produced during a fire, and possibly also to a lack of oxygen (hypoxia). The toxic effect consists in an undersupply of oxygen to the tissue, especially to the brain cells, which can lead to unconsciousness within a very short time and subsequently to death (through toxic reaction or heat exposure). The most common asphyxiant gases found in fire victims are carbon monoxide (CO) and hydrogen cyanide (HCN), possibly reinforced by carbon dioxide (CO2) [8.10], [8.11].

A procedure to determine the duration of exposure up to incapacitation, suitable for quantitative safety considerations, is the "Fractional Effective Dose" (FED) method [8.4], [8.10], [8.12]. In this method, the quotient F of the partial dose absorbed in a time interval Δt and the total dose leading to incapacitation is added up for a series of time intervals. Incapacitation strikes as soon as this sum reaches the value F = 1. The time to incapacitation then results from the sum of these time intervals. F depends on the corresponding quotients F_j of the individual components CO, HCN, CO_2 and O_2 (oxygen deficiency):

$$F_{CO} = \frac{3.317 \cdot 10^{-5} \cdot RMV \cdot c_{CO}^{1.036} \cdot \Delta t}{D} \tag{8.7}$$

$$F_{HCN} = \frac{c_{HCN}^{2.36} \cdot RMV \cdot \Delta t}{2.43 \cdot 10^{7}} \tag{8.8}$$

$$F_{CO_2} = \frac{\Delta t}{exp\left(6.1623 - 0.5189 \cdot c_{CO_2}\right)} \tag{8.9}$$

$$F_{O_2} = \frac{\Delta t}{exp\left(8.13 - 0.54 \cdot \left(20.9 - c_{O_2}\right)\right)} \tag{8.10}$$

Concentrations of c_{CO} and c_{HCN} shall be expressed in ppm units and concentrations of c_{CO2} and c_{O2} in volume percent units. RMV is the respiratory minute volume in l/min. D is the critical quantity of carboxyhemoglobin (COHb) in the blood, expressed in volume percent units, which causes unconsciousness. RMV and D are dependent on individual physical characteristics and level of activity. Typical values, based on a 70 kg adult under light physical strain, are D = 30 % and RMV = 25 l/min. For an adult at rest, D = 40 % and RMV = 8.5 l/min. Death occurs at D ≈ 50 %. For smaller children, the time to incapacitation is about two times shorter than for adults.

It should be noted that these ratios were developed for short-term heavy loads (duration up to a maximum of about one hour and CO concentrations of around 2000 ppm). At lower concentrations of volatile substances, saturation effects and the proportion of exhaled pollutants play an increasingly important role, which leads to a reduction of the effective dose. More detailed procedures for determining the effect of carbon monoxide even at lower concentrations and longer exposure times are described in [8.10].

The equations (8.7) - (8.10) follow the representation in [8.10]. In ISO 13571 [8.4] slightly simplified formulations of these relationships can be found, which refer to a typical adult under light physical stress.

The F_j of the relations (8.7) to (8.10) must now be linked by an approach that takes into account the interaction of the individual components in a suitable approximation, in particular the effect of the increased respiration rate caused by the presence of CO_2 (hyperventilation). This increases the absorption of the much more toxic gases CO or HCN, if they are present. For this reason, an amplification factor V_{Hyp} is introduced which makes it possible to estimate the effect of hyperventilation. This results in the following approach for calculating the quotient F:

$$F = \max\left((F_{\text{CO}} + F_{\text{HCN}}) \cdot V_{\text{Hyp}} + F_{O_2}, F_{\text{CO}_2}\right) \tag{8.11}$$

with

$$V_{Hyp} = exp(0.2 \cdot c_{CO_2}) \tag{8.12}$$

In [8.4] the application of (8.11) is limited to CO and HCN, as these are assumed to be the dominant active substances in fire smoke. However, it is pointed out in a note that oxygen deficiency must be considered from an O_2 concentration below 13 %. Following [8.4], hyperventilation according to equation (8.12) should be included in the calculation for a CO_2 concentration of 2% by volume or more.

Toxic effects, in particular those of oxygen deficiency and carbon dioxide, are often not only dose-dependent but also concentration-dependent [8.10]. In addition, long-term effects may also have to be taken into account when determining acceptable limits [8.13]. If in (8.11) reference values are used for a typical adult with light physical demands, a maximum F of 0.1 to 0.3 should be taken as a basis for determining the available evacuation time, with the lower value applying to particularly sensitive groups of persons [8.4], [8.10], [8.20], [8.26].

Regarding the various effects, it is usually more difficult to assess the large number of irritant gases that can be released during a fire. These often impair the sensory area and can therefore reduce the individual visibility (see Figure 8.1 and relation (8.5)) and make orientation more difficult. Methods for estimating the effects of irritant gases on persons (ability to act, obstruction of escape) and the associated concentration limits are given in [8.4], [8.10], [8.14].

In order to take into account, the combined effect of different irritants, the concept of fractional irritant concentration FIC [8.10] (or fractional effective concentration (FEC) in the terminology of ISO 13571 [8.4]) was developed. Similar to the FED model, the quotients of the present concentration and a critical reference value for the irritant in question are formed. Depending on the reference value selected, the total value $FIC_{irr} = 1$ corresponds either to an irritant effect which significantly restricts the possibilities of escape or to the occurrence of incapacitation (see Table 8.1). In contrast to the FED model, the duration of exposure is not important in this model approach, but the current effective concentration value is determined for each point in time. Assuming the effect of the irritant gases being approximately additive, the total FIC_{irr} value is the sum of the FIC of the individual components. Reference values for irritants frequently occurring in fire gases are given in the Table 8.1. The values of Purser [8.10] refer to concentrations which cause obstruction to escape or incapacitation in 50 % of the persons affected. The definition of incapacitation in ISO 13571 refers to a person of average sensitivity. It is noticeable that there are significant differences between [8.10] and [8.4], especially for hydrogen fluoride HF and formaldehyde, although the respective definitions of the term "incapacitation" are similar. In the case of individual substances (especially HCl), there are also clear differences to the effects of pollutants in fires [8.14] listed in Annex 5 of vfdb guideline 10/03 [8.14]. For particularly sensitive population groups, a safety factor of 0.3 is proposed in [8.10] for establishing the reference values according to the Table 8.1.

Table 8.1 Reference values for determining FIC values

Irritant gas	Incapacitation [8.4]	Incapacitation [8.10]	Impair escape [8.10]
HCl	1000 ppm	900 ppm	200 ppm
HBr	1000 ppm	900 ppm	200 ppm
HF	500 ppm	900 ppm	200 ppm
SO_2	150 ppm	120 ppm	24 ppm
NO_2	250 ppm	350 ppm	70 ppm
Acrolein	30 ppm	20 ppm	4 ppm
Formaldehyde	250 ppm	30 ppm	6 ppm

Since the production rates for the release of irritant gases are often not known, a mathematical evaluation of the irritant gas effect using engineering methods is currently only possible to a limited extent. For mixed fire loads, with an optical density per path length of between 0.1 m^{-1} and 0.2 m^{-1} irritant gas components may be present in the fire smoke, but in a concentration that is acceptable for short distances. At an optical smoke density of 0.1 m^{-1} and below, it can generally be assumed within the framework of an engineering verification that the smoke gas components (especially the irritant gases) do not impair successful escape (see Figure 8.3 and [8.7], [8.9], [8.10], [8.19], [8.20], [8.33]).

For the assessment of the effects of toxic substances that are not explicitly dealt with in the procedures listed so far and the corresponding literature references, other proven methods of consequence analysis, such as those described in [8.21], can be used. In addition, there are alternative definitions of assessment values for life safety in hazardous situations, such as the Emergency Response Planning Guidelines of the American Industrial Hygiene Association (particularly the category ERPG-2 which describes the limit values below which, for an exposure time of up to one hour, no serious or irreversible health problems can be expected and the capacity for self-rescue is not impaired) or the international AEGL values (Acute Exposure Guideline Levels) developed under the leadership of the USA (dealt with by the Commission on Process Safety in Germany). Vfdb guideline 10/01 also refers to the AEGL values for the assessment of dangerous substance concentrations for firefighting. In the guideline, the tolerable concentration values (German: Einsatztoleranzwerte (ETW)), which are designed for an exposure time of up to 4 hours, are determined. The associated basic information paper [8.22] provides a comprehensive overview of the methods for the assessment of health consequences of major fires. Yields of the most significant acutely toxic fire gases depending on fire loads and ventilation conditions are compiled in [8.28].

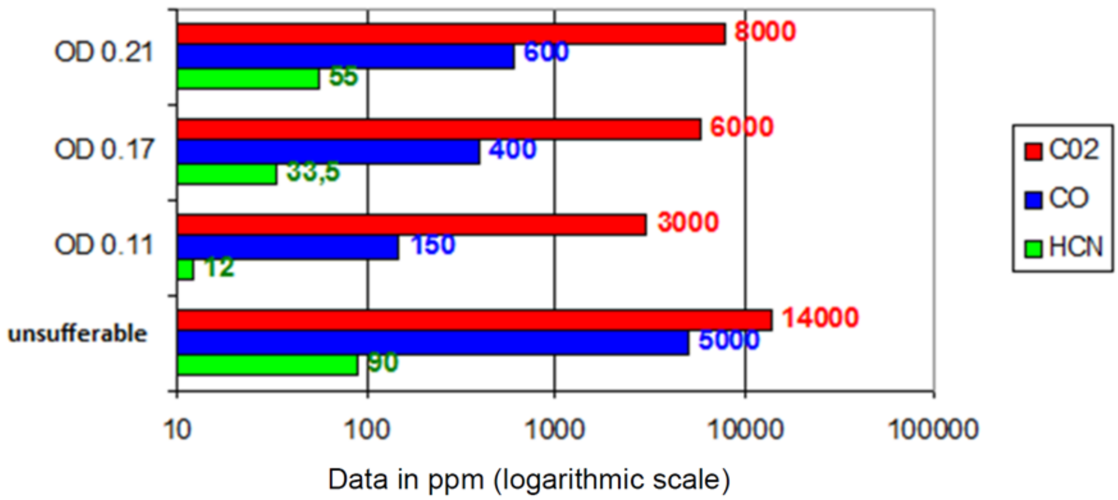


Figure 8.3 Measured distributions of toxic gas components in fire smoke [8.9]

8.5 The thermal impact of hot fire gases

In addition to the toxic effects of the fire effluents, possible heat effects also have a decisive influence on individual exposure and thus the time available for self-rescue. There are mainly three basic mechanisms of thermal impact that can lead to incapacitation and - in the last consequence - to severe physical damage or even death: thermal shock, skin burns and burns of the respiratory system. Details on this topic can be found, for example, in [8.4], [8.10], [8.15], [8.16].

Damage caused by hot gases can occur if persons are exposed to an increased ambient temperature for a longer period of time, which does not yet lead to direct burns. Corresponding critical temperatures depend on the humidity and the duration of exposure and range from 120 °C in dry air to about 80 °C. The cause of thermal shock is an increase in body heat, with values above 40 °C body temperature leading to impaired consciousness and physical damage, while body temperatures above 42.5 °C untreated can even lead to death within a few minutes.

Skin burns depend on the heat flow reaching the skin surface and are largely independent of the mechanism of heat transfer. Convection and heat radiation are particularly important in the case of self-rescue. In addition to air temperature, air humidity and the duration of exposure, air flow and the type of clothing play an important role. While the tolerance time in the range of the limit temperature between heat shock and burns is 15 - 25 minutes, it drops to 3 - 4 minutes at temperatures of approx. 200 °C (dry air). With heat radiation, the tolerance threshold is about 2.5 kW/m^2. In addition to the pain directly caused by the burns, burns of the skin surface can also lead to a state of shock caused by the loss of body fluid. This leads to a circulatory dysfunction and can even result in collapse or unconsciousness.

Humidity plays an even greater role in respiratory tract burns than in other types of exposure. In principle, the previously stated tenability limits for skin burns (critical air temperature or critical heat flow) are also sufficient for protection against respiratory tract burns. Temperatures above 180 °C may cause a sudden inhalation heat shock.

Thus, on an empirical basis, the time τ until the onset of the individual incapacitation can be estimated as a function of the local ambient temperature. It is important to note which definition underlies the term incapacitation in connection with heat exposure. Purser [8.10] uses the following definition, depending on the temperature range concerned, to determine incapacity: (1) Time at which painful skin irritation occurs immediately before the threshold to burning or (2) time at which a heat shock leads to disorientation and collapse. On this basis, the following relations were determined to determine the time τ for achieving incapacitation by convective heat transfer at medium humidity. The following applies:

$$\tau_{conv}\,[min] = \frac{2\cdot 10^{31}}{(T[°C])^{16.963}} + \frac{4\cdot 10^{8}}{(T[°C])^{3.7561}} \tag{8.13}$$

In the case of high humidity (in the range of 100%), it should be checked whether conditions for the occurrence of a thermal shock may not already exist at lower temperatures.

Critical irradiances q can also be specified, especially for the immediate vicinity of large flames and below hot gas layers. Below a threshold value of 2.5 kW/m^2, heat radiation is tolerable for at least a few minutes, but above this value, the range which is tolerable for only a few seconds is reached very quickly, as the tenability limits given in the Table 8.2 illustrate. According to [8.17], the limit value of irradiance for long-term effects is 1.7 kW/m^2.

For irradiances q > 2.5 kW/m^2, the time until second-degree burns are reached can be determined by the relation

$$\tau_{rad}\,[min] = \frac{6.9}{(q[kW/m^2])^{1.56}} \tag{8.14}$$

The time until the pain threshold is reached, which does not necessarily have to affect the escape, can be estimated with the help of [8.4].

$$\tau_{rad}[min] = \frac{4.2}{(q[kW/m^2])^{1.9}} \tag{8.15}$$

Purser [8.10] quotes

$$\tau_{rad}\,[min] = \frac{1.33}{(q[kW/m^2])^{1.33}} \tag{8.16}$$

for reaching the pain threshold.

Table 8.2 Tenability limits of heat radiation and convection [8.18].

Action	Intensity or temperature	Tolerable exposure time
Heat radiation	10 kW/m^2	Pain after 4 s
(Exposure to skin)	4 kW/m^2	Pain after 10 - 20 s
	2.5 kW/m^2	Pain after 30 s
Convection	< 40 °C (at H_2O saturation)	> 30 min
(Airways, skin)	160 °C (< 10 % H_2O)	2 min
	120 °C (< 10 % H_2O)	7 min
	100 °C (< 10 % H_2O)	12 min

For the combined effect of heat radiation and convection, it is also possible to specify a model depending on the duration of exposure [8.4], [8.10]

$$FED_{thermisch} = \sum \left(\frac{\Delta t}{\tau_{conv}} + \frac{\Delta t}{\tau_{rad}} \right) \tag{8.17}$$

with $FED_{thermisch}$= 1, the limit of incapacitation is reached.

8.6 Reference values for the assessment of life safety

Reference values should be specified as an alternative to the complex toxic or thermal dose models described in the previous sections. These values can help evaluate the possible risk posed by various fire characteristics. The reference values for the quantitative verification of the fire-safety objectives are shown in Table 8.3. Typical mixed fire loads were assumed here, such as those found in an office, housing, or shopping store environment.

The ratio of concentrations CO : HCN for fire loads with a low proportion of nitrogen (< 2 % of the fuel mass – e.g. office fires) is typically CO : HCN > 50 : 1, which means that the main impact comes from CO. For fires with a significant proportion of nitrogen (> 2 % of the fuel mass) the ratio is assumed to be 12.5 : 1 [8.26], [8.33]. This relatively high HCN yield was taken as the basis for the reference values in Table 8.3.

It should also be noted that in the event of a fire, the local concentrations of fire effluents and oxygen are thermodynamically related. Since for this reason the oxygen concentration - if the limits given in the Table 8.3 are observed - is well above 15 vol.% (a value which, taken alone, does not lead to serious damage during the exposure times in question here), the oxygen concentration is not explicitly listed as a performance criterion.

In the course of smoke propagation hot fire effluents are mixed into the cold gas zone. The result is an increase in temperature in the cold gas layer and an accumulation of smoke particles and pollutants. If this growth does not exceed the reference values given in the Table 8.3, the associated increase in gas temperature remains correspondingly low. In [8.24], a maximum temperature increase in the order of 10 K was determined on the basis of measurements in fire tests and a parameter study with fire simulation models. This value is clearly below the acceptance values for the gas phase given in the Table 8.3, so that if acceptable smoke densities are detected, the temperature criterion is usually also fulfilled.

The subdivision of the Table 8.3 into short (up to approx. 5 minutes), medium (approx. 5 - 15 minutes) and longer (approx. 15 - 30 minutes) exposure time describes typical categories of egress times. The fire safety objective is fulfilled if none of the listed reference values is exceeded during the corresponding exposure time.

In the following cases, detailed analyses using the methods described above may be required, taking into account the individual dose-dependent effect:

- The fire smoke composition deviates significantly from the relative pollutant concentrations assumed in the Table 8.3 or toxic combustion products other than CO, CO_2 and HCN are released in quantities relevant to life safety.

- The exposure times deviate significantly from the three categories of residence time chosen (very short or very long exposure times) or the concentration curves are subject to strong temporal fluctuations.
- Particularly vulnerable groups of people are affected (e.g., in hospitals or nursing homes).
- The exposure of people who cannot move themselves away from the hazardous area (e.g., passengers in travelling rail vehicles) or are reliant on third-party rescue should be evaluated.

Table 8.3 Performance criteria and reference values for quantitative fire-safety objectives

Assessment criterion	large exposure time (< 30 min)	medium exposure time (approx. 15 min)	short exposure time (< 5 min)
CO concentration	100 ppm	200 ppm	500 ppm
CO_2 concentration	1 Vol.-%	2 Vol.-%	3 Vol.-%
HCN concentration (1)	8 ppm	16 ppm	40 ppm
Heat radiation	1.7 kW/m^2	2.0 kW/m^2	< 2.5 kW/m^2
Gas temperature (2)	45 °C	50 °C	50 °C
Smoke density D_L (3)	0.1 m^{-1}	0.1 m^{-1} / 0.15 m^{-1} (4)	0.1 m^{-1} / 0.2 m^{-1} (4)
Visibility (5), (6)	10 m - 20 m	10 m - 20 m	10 m - 20 m

(1) The HCN concentrations are subject to wide variations. For typical fires there is a correlation with the CO/CO_2 concentrations, whereby a conservative CO:HCN ratio of 12.5:1 is assumed.
(2) The gas temperature refers to air with a water vapour content of less than 10 % by volume. The gas temperature shall not be used in isolation without simultaneous evaluation of the smoke propagation (in particular the smoke density) as an assessment parameter for the safety of persons.
(3) On the basis of a mass-specific extinction coefficient K_m = 8.7 m^2/g, a soot concentration of 25 mg/m^3 results (rounded) for D_L = 0.1 m^{-1} and 50 mg/m^3 for D_L = 0.2 m^{-1} (see Chapter 8.2).
(4) The respective higher reference value can be used for assessment if the area concerned is clearly structured or the persons are familiar with the premises.
(5) The visibility is subject to large variations. For typical fires there is a correlation with the smoke density D_L. For more details, see Chapter 8.3.
(6) The visibility criterion is usually verified by demonstrating the smoke density D_L in conjunction with the recognition of emergency signs (see Chapter 8.3). It is therefore assumed that emergency signs indicating exits (illuminated or backlit) are installed within the low-smoke layer.

With an optical density per path length $D_L \leq 0.1$ m^{-1}, it can generally be assumed in a fire safety engineering design that at the same time the acceptance values for toxic fire effluents are not exceeded and that other components (in particular irritant gases which influence the visibility) and the gas temperature are not critical [8.7], [8.9], [8.19], [8.20], [8.33]. Therefore, this can be considered a performance criterion to identify a low-smoke layer in the escape routes.

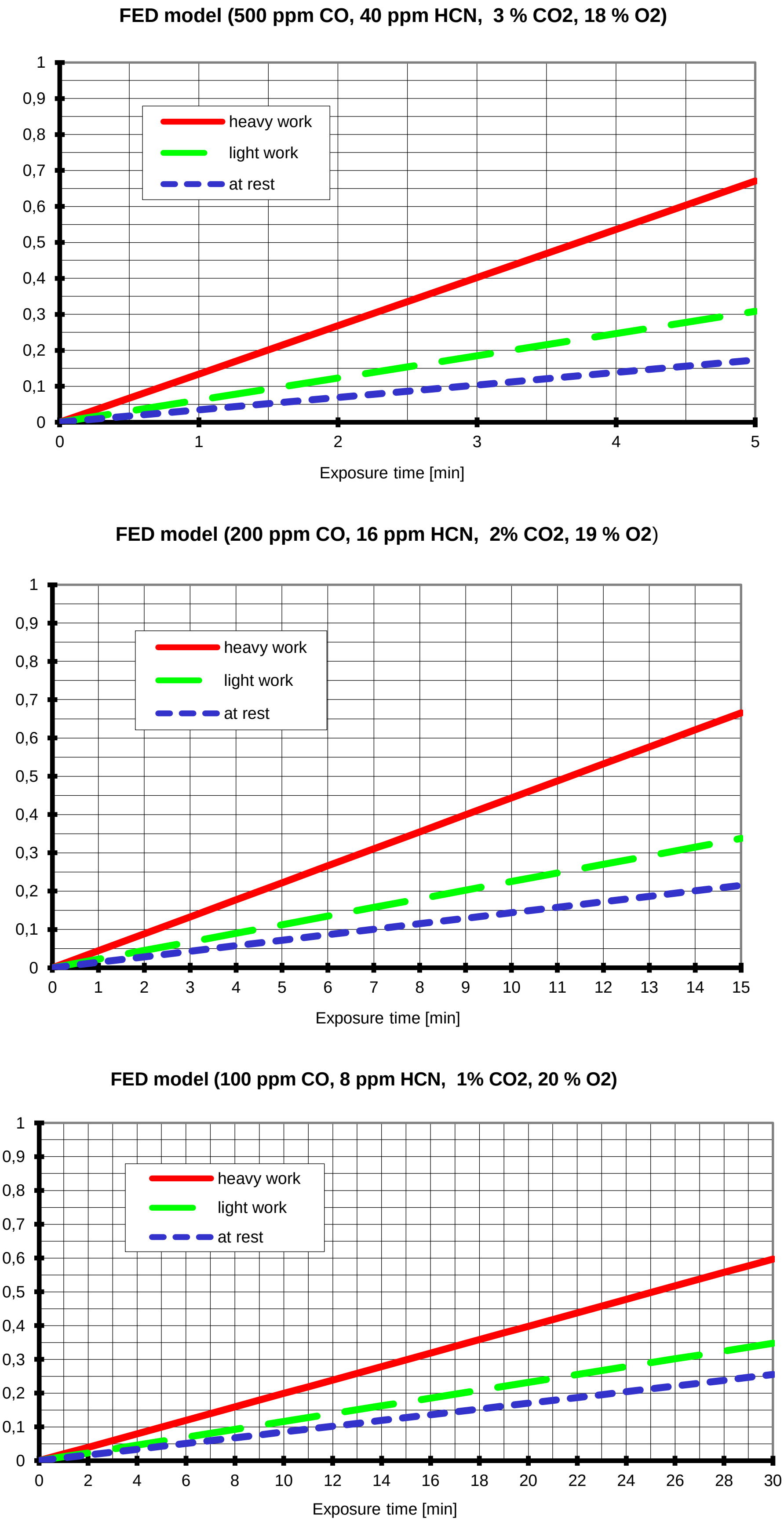


Figure 8.4 FED ratios for the reference values from Table 8.3

Figure 8.4 shows the development of the FED ratio, normalised to 1 (see relation (8.11)), for the reference values from Table 8.3 for heavy work or particularly vulnerable people respectively (D = 20 %, RMV = 50 l/min), light work (D = 30 %, RMV = 25 l/min) and people at rest (D = 40 %, RMV = 8.5 l/min). For light work with the maximum exposure time of each underlying subdivision, the reference values from Table 8.3 reach a value of around 0.3, and even with heavy work they remain clearly below the limit for incapacitation of 1.

8.7 Smoke yields

The design fires described in Chapter 4 are used to quantify fire scenarios with regard to the release of heat and smoke. Here, in addition to the heat release rate as a function of time (dynamic fire development), the yields of the main combustion products (so-called smoke yields) as well as the smoke potential D_m or the mass-specific extinction coefficients K_m (see Section 8.2) should be specified.

The smoke yields Y_i [g/g] indicate the ratio between the mass of the combustion product released (indicated by the index i) and the total mass loss of the fire load. The yields of the narcotic pollutants carbon monoxide (CO) Y_{CO}, hydrogen cyanide (HCN) Y_{HCN} and carbon dioxide (CO_2) Y_{CO2} as well as the yield of the obscuring smoke particles (soot) $Y_{Ruß}$ are of particular importance for the application of fire model calculations to evaluate life safety. As an alternative to the soot yield $Y_{Ruß}$ [g/g], the smoke potential D_m [m²/g] can also be specified, whereby both values are linked to one another by the equation (8.3). The release of hydrogen cyanide shall only be taken into account in the case of nitrogen-containing fire loads, such as polyurethane, nylon or acrylonitrile-butadiene-styrene (ABS).

By multiplying the smoke yields by the combustion rate, the release rate of the respective combustion product is determined. For this reason, it is necessary to specify the effective heat of combustion $h_{u,eff}$ (product of heat of combustion h_u and combustion efficiency χ with $\chi < 1$) of the specific fuel or the mixed fire load, since this is used to determine the rate of combustion as a function of the heat release rate:

$$\dot{m}_i = Y_i \cdot \dot{m}_{\mathrm{ab}} = Y_i \cdot \frac{\dot{Q}}{h_{\mathrm{u,eff}}} \tag{8.18}$$

As the verification of life safety generally takes place for self-rescue in an early stage of the fire, it is necessary to specify the smoke yields of the primary fire material at the ignition point.

Basically, there are two ways to determine the smoke yields:

1) Use of empirical data for specific fuels (as referenced from literature)

For the quantification of a fire scenario with regard to the release of combustion products, the smoke yields and smoke potentials of the main fire materials are determined on the basis of literature values (e.g., [8.5], [8.22], [8.27], [8.28]). The effective heat of combustion of the main fire substances must also be determined. In case of mixed fire loads, a weighted averaging is performed taking into account the respective burning rates.

Based on published reference values, the smoke yields and smoke potentials can be directly assigned to substances or objects. For example, in the event of a fire in an entrance hall, ignition can take place at a seating group whose upholstery is made of polyurethane foam. For this substance, the corresponding smoke yields can be taken from the literature.

The smoke yields provided in the literature mainly apply to fuel controlled fire conditions only. For ventilation controlled fires there is an increase in the formation of products from incomplete combustion and therefore an increase in the yields of CO and soot and a decrease in the CO_2 yield. Accordingly, the smoke yields and, in some cases, the mass optical density should be corrected for under-ventilated fire conditions. Calculation methods for this are found in [8.27] and [8.28].

2) Use of conservative smoke yields

For conservative fire scenarios, the yields of combustion products can be estimated taking into account the type of the relevant fuel and the prevailing ventilation conditions. With regard to the type of fuel, a distinction is made between cellulose, two groups of synthetics and halogenated plastics. It should be noted that conservative smoke yields were chosen due to the high diversity of different plastics. For this reason, it is advisable to determine the smoke yields as far as possible in accordance with point 1. Similarly, when calculating the smoke density D_L, empirical data for the mass optical density D_m or the mass-specific extinction coefficient K_m should be used explicitly, since the associated measurement process is based directly on the obscuring properties of fire smoke.

The smoke yields listed below are from reference [8.27]. The following substances were used for the substance groups cellulose, synthetics A and B and halogenated plastics.

Cellulose:	Wood or paper
Synthetics A:	Polyethylene (PE)
Synthetics B:	Polystyrene (PS)
Halogenated plastics:	Polyvinyl chloride (PVC)

For mixed fire loads, mean values can be calculated from the above-mentioned substance groups.

Table 8.4 contains the yields of carbon dioxide (CO_2), carbon monoxide (CO) as well as the yield of smoke particles (soot) and the effective heat of combustion for the above-mentioned categories of substances. A distinction is made between fuel controlled and ventilation controlled fire conditions.

Flammable liquids can be classified either as cellulose-containing fire products (e.g., alcohols), synthetics A (e.g., alkanes) or synthetics B (e.g., aromatics), depending on the respective category.

Table 8.4 Yields and effective heat of combustion for representative substance categories

Ventilation conditions	Substance group	$h_{u,eff}$ [kJ/g][1]	Y_{CO2} [g/g]	Y_{CO} [g/g]	$Y_{Ruß}$ [g/g]
fuel controlled	cellulose	12.0	1.30	0.004	0.015
	synthetics A	30.5	2.76	0.024	0.060
	synthetics B	27.4	2.33	0.060	0.164
	halogenated plastics	11.5	0.46	0.063	0.172
ventilation-controlled[2]	cellulose	12.0	0.91	0.145	0.028
	synthetics A	30.5	1.78	0.459	0.098
	synthetics B	27.4	1.50	0.137	0.331
	halogenated plastics	11.5	0.32	0.500	0.237

Smoke yields for the narcotic smoke component hydrogen cyanide (HCN) must be taken into account in the presence of nitrogen-containing fire loads, such as polyurethane, nylon or acrylonitrile-butadiene-styrene (ABS). These smoke yields can be taken from the literature, e.g. [8.22], [8.27], [8.28], or estimated on the basis of the following relationship:

Fire loads with < 2 % nitrogen content: $Y_{HCN} / Y_{CO} = 1 / 52$

Fire loads with > 2 % nitrogen content: $Y_{HCN} / Y_{CO} = 1 / 13$

For fire loads with > 2 % nitrogen content, the main contribution of toxicity is made by hydrogen cyanide. At mass fractions significantly above 2 % nitrogen, even higher HCN yields are sometimes observed, so that the ratio $Y_{HCN} / Y_{CO} = 1 / 13$ is no longer conservative [8.28].

With the help of the relationship (8.3) and $K_m = 8.7$ m²/g (reference value for mixed fire loads), the smoke potentials D_m in the table 8.4 are between 0.06 m^2/g and 0.65 m^2/g (fuel controlled) or between 0.11 m^2/g and 1.25 m^2/g (ventilation controlled). These values are predominantly consistent with empirical data [8.5], and in the case of PVC even clearly conservative.

[1] A combustion efficiency of $\chi = 0.7$ was selected to determine the effective calorific value.

[2] A global equivalence ratio of $\Phi = 2$ was chosen for the application of the calculation methods for determining the smoke yields in ventilation-controlled fires according to [8.27]. For fuel controlled fires, $\Phi << 1$ applies.

8.8 Literature

[8.1] *YAMADA, T.; AKIZUKI, Y.*: Visibility and Human Behavior in Fire Smoke. in: SFPE Handbook of Fire Protection Engineering, Springer New York, 5th Ed. 2016.

[8.2] *JOHN, R.*: Ermittlung der erforderlichen Luftvolumenströme zur Verdünnung von Brandrauch auf ein die Gesundheit und Sichtbarkeit in Rettungswegen gewährleistendes Maß. Teil 2. AG der Innenminister der Bundesländer. Forschungsbericht Nr. 50, Forschungsstelle für Brandschutztechnik der Universität Karlsruhe, 1983.

[8.3] *JOHN, R.*: Ermittlung der erforderlichen Luftvolumenströme zur Verdünnung von Brandrauch auf ein die Gesundheit und Sichtbarkeit in Rettungswegen gewährleistendes Maß. Teil 4: Brandrauch und Sichtbarkeit von Hinweiszeichen in Rettungswegen. AG der Innenminister der Bundesländer. Forschungsbericht Nr. 66, Forschungsstelle für Brandschutztechnik der Universität Karlsruhe, 1988.

[8.4] ISO 13571:2012-09 Life-threatening components of fire – Guidelines for the estimation of time to compromised tenability in fires. 2012.

[8.5] *MULHOLLAND, G. W.*: Smoke Production and Properties. in: SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, Massachusetts, 4th Ed. 2008.

[8.6] *BROWN, S. K.; MARTIN, K. G.*: A Review of the Visibility Hazard from Smoke in Building Fires, Commonwealth Scientific and Industrial Research Organization CSIRO, Division of Building Research, 1981.

[8.7] Fire Code Reform Centre. Fire Engineering Guidelines, New South Wales, Australia, 2000.

[8.8] *SCHNEIDER, V.; KÖNNECKE, R.*: Simulation der Personenevakuierung unter Berücksichtigung individueller Einflussfaktoren und der Ausbreitung von Rauch. vfdb-Zeitschrift 3 (1996) 98.

[8.9] *WILK, E.; LESSING, R.*: Untersuchungen zur Sichtweite im Rauch und zu Brandgaswirkungen auf den Menschen, vfdb-Zeitschrift 3 (2004) 168.

[8.10] *PURSER, D. A.; McALLISTER, J.L.*: Assessment of Hazards to Occupants from Smoke, Toxic Gases and Heat. In: SFPE Handbook of Fire Protection Engineering, Springer New York, 5th Ed. 2016.

[8.11] *EINHORN, I. N.; GRUNNET, M. L.; PETAJAN, J. H.*; BALDWIN, R. C.: The Physiological and Toxicological Aspects of Combustion. 5. Int. Brandschutzseminar, vfdb, Nachträge S. 23, 1976.

[8.12] ISO Technical Report TR 9122 - 5 Toxicity testing of fire effluents – Prediction of toxic effects of fire effluents. First edition, 15.04.1993.

[8.13] *CHRISTIAN, S. D.*: Safe tolerability limits for carbon monoxide? A review of the clinical and fire engineering implications of a single, acute sub-lethal exposure. Proceedings Interflam ’99, Fire Science & Engineering Conference, Edinburgh, 1999.

[8.14] vfdb-Richtlinie 10 / 03 – Schadstoffe bei Bränden. vfdb-Zeitschrift für Forschung, Technik und Management im Brandschutz, 3 (1997) 102 – aktualisiert August 2014.

[8.15] *STENSAAS, J. P.*: Toxicity, visibility and heat stress of fire effluents – human tenability limits. SINTEF Report STF25 A91022, Trondheim, 1991.

[8.16] *WILK, E.; LINDNER, D.; VOCK, R.*: Untersuchungen zum Inhalations-Hitzeschock, Archiv für Kriminologie Band 203, Seite 159-169, 1999.

[8.17] *SCHÖNBUCHER, A.*: Berechnung von Sicherheitsabständen bei Störfällen mit brennbaren Stoffen. in: Hartwig, S.: Schwere Gase und Sicherheitsanalyse – IV. Proc. IV. Symp. Bonn. Sept. 1991, Batelle-Eigenverlag, Frankfurt am Main, 1992.

[8.18] *BREIN, D.*: Evakuierungskonzepte – Anforderungen, Komponenten, Bewertungen. vfdb-Jahresfachtagung, Hamburg, 1997.

[8.19] *SIEGFRIED, W.; WILL, J.*: Die Verwendung des Verdünnungsverhältnisses zur Bewertung von Ergebnissen bei der Modellierung der Rauchableitung. vfdb-Zeitschrift 3 (2002) 101.

[8.20] *PURSER, D. A.*: Toxicity assessment of combustion products and human behaviour in fires. 10. Int. Brandschutzseminar, vfdb, 2005.

[8.21] TNO: Methods for the determination of possible damage to people and objects resulting from releases of hazardous materials – Green Book, 1992.

[8.22] *BUFF, K.; GREIM, H.*: Abschätzung der gesundheitlichen Folgen von Großbränden, Zivilschutzforschung Band 25, Bundesamt für Zivilschutz 1997.

[8.23] *BIESKE, K.; GALL, D.*: Evaluierung von Sicherheitsleitsystemen in Rauchsituationen, Forschungsbericht im Auftrag des Hauptverbandes der gewerblichen Berufsgenossenschaften Sankt Augustin, Technische Universität Ilmenau, Fachgebiet Lichttechnik, März 2003.

[8.24] *WILK, E.*; *WESKAMP, F.; LESSIG, R.*: Rauchbelastung in Rettungswegen und im Angriffsweg der Feuerwehr - Betrachtungen aus experimenteller und praktischer Sicht, vfdb-Zeitschrift 2 (2008) 73.

[8.25] *SCHNEIDER, V.*: Erkennungsweite von Sicherheitszeichen in Rauch, vfdb-Zeitschrift 4 (2009) 188.

[8.26] BSI British Standards: The application of fire safety engineering principles to fire safety design of buildings, Part 6: Human factors: Life safety strategies - Occupant evacuation, behaviour and condition, PD 7974-6:2004.

[8.27] *KHAN, M. M.*; *TEWARSON, A.; CHAOS, M.*: Combustion Characteristics of Materials and Generation of Fire Products i. V. m. Appendix 3, Table A.39. in: SFPE Handbook of Fire Protection Engineering, 5th Ed. 2016.

[8.28] *FORELL, B.*: Bewertung der akuten Toxizität von Brandrauch. TÜ Bd. 51 (2010), Nr. 3, S. 20-29.

[8.29] *ZHANG, Q.; RUBINI, P.*: Simulation of perceived visibility in smoke laden environment, 4. Int. Symposium on Human Behaviour in Fire, Cambridge, Juli 2009.

[8.30] *SCHNEIDER, V.*: Modelling the visibility of emergency signs in smoke and smoke-free conditions, 4. Int. Symposium on Human Behaviour in Fire, Cambridge, Juli 2009.

[8.31] *FORELL, B.*: Stand der Brandschutzingenieurmethoden zum Nachweis der Personensicherheit Teil 1: Gesamtkonzept und Bestimmung der verfügbaren Räumungszeit. S+S Report, Heft 3, S. 23-27, Juni 2010.

[8.32] *FORELL, B.*: Niveau der Personensicherheit von Versammlungsstätten - Nachweis nach vfdb-Leitfaden. Tagungsband zur 56. vfdb Jahresfachtagung 2007, 21. bis 23. Mai, Leipzig. S. 294-317.

[8.33] *WIEZOREK, M.; BÖTTGER, A.; FRANKE, E.*: Personensicherheit in rauchbelasteten Rettungswegen. Artikel aus: vfdb-Zeitschrift für Forschung, Technik und Management im Brandschutz, Jg. 63, Nr. 4, 2014, S. 188-197.

9 COMPUTATIONAL CROWD FLOW ANALYSIS

9.1 Introduction

Life safety is the main priority of fire protection and firefighting. In order to reliably optimise the necessary structural, technical and organisational measures, the search for performance-based solutions is increasing in practice. Thus, not only the spread of smoke and heat, but also the respective type of use, number of occupants, individual characteristics and behavioural options should be considered in order to determine the necessary fire protection measures.

Evacuation is understood to be the abandoning of an endangered area. In case of a fire, it includes the phase of self-rescue and assisted rescue. As the corresponding evacuation models are not usually limited to the evacuation process but can also deal with everyday scenarios (e.g., the admission situations at an event), the terms “crowd flow model” and “crowd flow analysis” are generally used.

An essential requirement for the planning of fire protection measures is that the time required for successful self-rescue of the persons (required egress time) is less than the time during which the exposure to smoke and heat propagation remains within acceptable limits (available egress time). Furthermore, the crowd flow analysis should ensure that the other conditions of the evacuation process do not lead to situations that could increase the risk to persons (e.g., high density of persons). Corresponding crowd flow models are now available, in graded complexity, in the form of calculation methods and computer-supported simulation models for use in practice.

9.2 Calculation of egress times

For each section of a building, the basic principle applies that the required safe egress time (RSET) must be less than the available safe egress time (ASET):

$$\text{RSET} < \text{ASET} \tag{9.1}$$

Safety factors should be taken into account, which cover the uncertainties in the selection of suitable fire scenarios and performance criteria as well as appropriate evacuation scenarios. These can be considered implicitly by choosing sufficient conservative initial and boundary conditions for the scenarios to determine the required and available evacuation time. This includes the selection of fire scenarios according to Chapter 4 in connection with the performance criteria according to Chapter 8 as well as the boundary conditions of a crowd flow analysis as listed in this chapter, such as the determination of the population (number, distribution, mobility parameters) and the choice of escape routes.

Alternatively, an explicit safety factor for RSET can be introduced by the methods of the safety concept described in Chapter 10.

The required evacuation time RSET is composed of the time interval $t_{detection}$ from the beginning of the fire (usually the zero time of a time-dependent design fire) until the fire is detected, the time interval t_{alarm} from detection until the alarm is triggered, a pre-evacuation time t_{pre} from the triggering of the alarm until the beginning of the escape movement and the time t_{move} from the beginning of the escape movement until a safe area is reached,

$$RSET = t_{detection} + t_{alarm} + t_{pre} + t_{move} \qquad 9.2)$$

t_{move} may also include assisted rescue. Microscopic models are able to determine the movement time t_{move} or respectively the escape time $t_{escape} = t_{pre} + t_{move}$ consistently from the individual movement of all persons involved. Macroscopic models calculate t_{move} as a superposition of the time t_{path} required to cover the escape path and the time $t_{passage}$ required to pass through the bottlenecks of the egress path.

9.3 Pre-movement time

The pre-movement time (also called “delay time to start”) covers in an implicit way various effects and behavioural patterns, in particular

- The time until the alarm is perceived,
- the time to interpret the perception, and
- the time for actions that do not serve the immediate escape (examination of the surroundings, firefighting, warning or searching for persons, etc.).

The pre-evacuation time depends mainly depends on people’s alertness (awake / asleep), their familiarity with the building, the quality of the alarm system, the complexity of the building and the quality of the fire safety management. For a quantitative determination, verifiable empirical data (e.g., from unannounced evacuation exercises) for the object to be evaluated or comparable utilizations can be used. If no such explicit a general data is available, they can be determined on a general empirical basis using the categorization proposed by Purser [9.1].

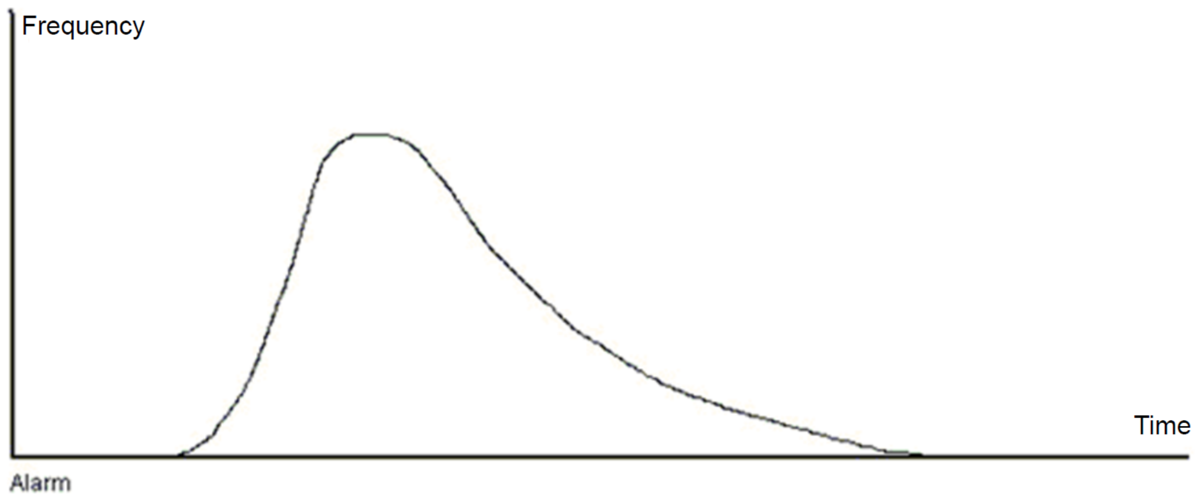


Figure 9.1 Schematic representation of a typical pre-movement time distribution

The individual pre-movement times within a group of people typically follow a distribution as shown schematically in the Figure 9.1.

Within a certain interval of time relative to the triggering of the alarm, the first people start to move. From this point on, the number of people who start to escape increases steeply, reaches a maximum and then slowly decreases. The distribution of the pre-evacuation time is thus made up of two components: the actual distribution function (approximately described by a logarithmic normal distribution) and a time offset of this distribution function relative to the time of the alarm. The time interval between the alarm and the beginning of the rise (the beginning of the individual pre-movement time) can be characterized by the 1 percentile t_1 of the pre-movement times of the escaping persons in a sample, the time interval from the beginning to the end of the pre-evacuation time by the 99 percentiles Δt_{99} of the distribution relative to t_1, so that the individual pre-evacuation time is between Δt_1 and $\Delta t_1 + \Delta t_{99}$.

t_1 and t_{99} depend on various influencing factors. The most important of these factors can be identified by categorising them according to the typical use of the building and some basic personal characteristics associated with it (Table 9.1). Other significant influencing factors such as the alarm system (Table 9.2), building complexity (Table 9.3) and fire safety management (Table 9.4) are considered through appropriate subcategories. These subcategories are each structured in three levels, with Level 1 representing the most favourable case (in terms of pre-evacuation time) and Level 3 the most unfavourable case.

Table 9.1 Categories for defining pre-evacuation times

Category	Alertness	Familiarity	Density	Type of uses
A	awake	familiar	low	Office, industrial
B	awake	unfamiliar	high	Shops, restaurants, assemblies
C(a)	asleep	familiar	low	Dwelling
C(b)	managed occupancy	managed occupancy	low	Residential (managed)
C(c)	asleep	unfamiliar	low	Hotels, hostels
D	medical care	unfamiliar	low	Residential (institutional)
E	transport	unfamiliar	high	Traffic facilities

Table 9.2 Alarm system

A1	Automatic detection system with immediate alerting of the affected areas
A2	Automatic detection system with immediate alarm of a control centre and subsequent alarm of the affected areas
A3	No or only local fire alarm

Table 9.3 Building complexity

B1	Simple, predominantly rectangular structure, single storey, few rooms or partitions, simple floor plan with exits in line of sight, short distances, suitable arrangements for exits leading directly to the outside (e.g., a simply structured supermarket)

B2	Simple floor plan with several rooms (also multi-storey), construction mainly corresponds to prescriptive specifications (e.g., standard office building)
B3	Large and complex building

Table 9.4 Fire protection management

M1	Staff and residents are well trained in fire safety. There are floor wardens, a well-developed emergency plan and regular drills. A high ratio of trained staff to visitors. An independent certification and regular audit of the system and procedures are necessary. A PA system is installed in areas used by the public.
M2	Similar to M1, but with a lower proportion of trained staff. Floor wardens are not required.
M3	Fire safety management in line with the basic minimum standard.

Pre-movement time Δt_1 (start time) and Δt_{99} (time spread of the individual pre-evacuation time) obtained from empirical data (evacuation exercises and real fire events) are compiled in Table 9.5 for categories A to C and the corresponding subcategories. Not all theoretically possible combinations of main category and subcategory are present in the Table 9.5, as some combinations are mutually exclusive. For example, an alarm system of Level A3 is not compatible with a fire safety management system of Level M1 or M2. Only a comparatively small amount of data was available for the determination of the time values quoted in brackets in the Table 9.5, so that these data are subject to a higher degree of uncertainty.

Table 9.5 Pre-evacuation times

Scenario (main and subcategories)	Δt_1 [min]	Δt_{99} [min]
Category A: awake and familiar		
M1 B1 - B2 A1 - A2	0.5	1
M2 B1 - B2 A1- A2	1	2
M3 B1- B2 A1- A3	(> 15)	(> 15)
B3: add 0.5 min to Δt_1 because of more difficult orientation		
Category B: awake and unfamiliar		
M1 B1 A1- A2	0.5	2
M2 B1 A1- A2	1	3
M3 B1 A1- A3	(> 15)	(> 15))
Scenario (main and subcategories)	Δt1 [min]	Δt99 [min]
B2: add 0.5 min to Δt1 because of more difficult orientation		

B3: add 1.0 min to Δt1 because of more difficult orientation		
Category C(a): sleeping and familiar		
M2 B1 A1	(5)	(5)
M3 B1 A3	(10)	(> 20)
Category C(b): Assisted living facilities		
M1 B2 A1- A2	(10)	(20)
M2 B2 A1- A2	(15)	(25)
M3 B2 A1- A3	(> 20)	(> 20)
Category C(c): sleeping and unfamiliar		
M1 B2 A1- A2	(15)	(15)
M2 B2 A1- A2	(20)	(20)
M3 B2 A1- A3	(> 20)	(> 20)
B3: add 1.0 min to Δt1 because of more difficult orientation		

9.4 Crowd flow models

9.4.1 General information

As in the case of the compartment fire models, very different methods modelling crowd flow exist - from simple hand formulas to complex computer-aided simulation models. Two main groups can be distinguished:

- Flow models (macroscopic flow models) - including network models, and
- Individual models (microscopic models).

The flow models (macroscopic models) essentially describe the directional movement of a crowd. They can be further subdivided into simplified calculation approaches for capacity analysis as well as procedures which also approximately take into account the dynamics of the movement of a larger crowd. These methods are limited to the elements of the escape route that are characteristic for the movement of a continuous crowd flow. The calculation steps are thus generally clear and easy to understand. Common to the flow models are the following basic assumptions [9.2]:

- As a rule, all persons within the crowd start the evacuation at the same time.
- There are no interruptions in the crowd flow that develops with the start of the evacuation (e.g., through individual decisions to act).

- Individual mobility parameters of the members of the crowd are not considered, they are only included via averaged values (e.g., speed of the flow).

These basic assumptions, together with the necessary simplifications, must be considered in an appropriate manner (e.g., by suitable safety margins or special boundary conditions [9.2]), especially for the simpler flow models (capacity analysis approaches).

The individual models (microscopic models) describe the movement along individual paths. According to the representation of building geometry or traffic area they can be divided into spatially discrete (cellular automata) and spatially continuous models. By simulating the movement of individual persons in an environment that is as close to reality as possible, individual influences on the efficiency of the evacuation are more strongly emphasized and restrictions of the flow models are removed.

9.4.2 Estimation of egress times through capacity analysis

These calculation approaches are based on relations that describe the capacity of a route element (exit, staircase or corridor) as a function of its width and, if necessary, other parameters (e.g., step dimensions).

Basic input variables for the application of capacity analyses are the path length L and escape route width B as well as the horizontal speed V and the specific flow F_s. The variables V and F_s characterize the coherent crowd flow for the type of route element (e.g., corridor, bottleneck, staircase). The crowd speed V is thus different to the unimpeded plane walking speed of an individual person, which plays an important role in individual models (see Chapter 9.4.4).

The crowd density D changes over time depending on the location. However, since the density cannot be calculated directly but can only be estimated by engineering expertise, the calculation of egress time by means of capacity analysis usually only refers to average crowd densities typical for a given scenario. The SFPE Handbook of Fire Protection Engineering [9.3], based on Fruin's "Level of Service" concept [9.4], distinguishes between four crowd conditions, each assigned to a certain density range: minimum ($D < 0.5$ P./m²), moderate ($D \approx 1$ P./m²), optimum ($D \approx 2$ P./m²), crush ($D \approx 3$ P./m²).

For the calculation of evacuation times, in which the escape route or exit widths are a significant design factor due to the possibility of congestion, only the options "moderate" (moderate) or "optimum" (optimum), which are also empirically best founded, are generally to be used. The "crush" option refers to special hazardous situations, e.g., necessary exits that cannot be used or emergency situations that are not related to a fire event (hooliganism, terrorist attacks) and is therefore generally not suitable for the design of escape routes. The "minimum" option describes person densities below 0.5 p./m², i.e., the situation of largely unimpeded movement.

In practice, at least two values should be used, both "moderate" (moderate) or "optimum" (optimum), to obtain a range of results. Table 9.6 shows values of the average horizontal velocity V and the specific flow F_s for moderate and optimum conditions. It should be noted that the underlying data show considerable fluctuations. Besides the values presented here, values from other sources (e.g., Weidmann [9.5] or Predtetschenski and Milinski [9.6]) can be derived for different densities (see Chapter 9.4.3).

Table 9.6 Horizontal speed and specific flow for certain route elements [9.3], converted into SI units

Route element	Speed V	Passenger flow F_s
Stairway (moderate density)	0.6 m/s	0.8 P./s·m
Stairway (optimal density)	0.5 m/s	1.0 P./s·m
Corridor, opening (moderate density)	1.0 m/s	1.1 P./s·m
Corridor, opening (optimal density)	0.6 m/s	1.3 P./s·m
Exit, doors (moderate density)	1.0 m/s	0.9 P./s·m
Exit, doors (optimal density)	0.6 m/s	1.4 P./s·m

For stairs, the Table 9.6 shows the effective horizontal component of the speed V, which is slowed down compared to the plane walking speed. Accordingly, the path length specifications for stairs refer to the horizontal path length (floor plan representation). The specific flow F_s indicates how many people can pass through a route element per unit of time and width. The type of the route element should be considered as a boundary condition. The movement time t_{move} now results from the larger of the time for covering the escape path t_{path} or the time for passing the way element with the lowest capacity for passage $t_{passage}$,

$$t_{\text{move}} = max\begin{cases} t_{\text{passage}} \\ t_{\text{path}} \end{cases} \tag{9.3}$$

for an element of the egress path characterized by index i, the time for traveling is given by

$$t_{path,i} = L_i \,/\, V_i, \tag{9.4}$$

and for the passage of this route element by a number of persons N

$$t_{passage,i} = N \,/\, (F_{s,i} \cdot B_i) \tag{9.5}$$

For the calculation of a movement time including several path elements, the path element with the minimum capacity (the minimum flow) should first be determined. The movement time then results either from the longer of the two times for covering the maximum distance or for the passage of the route element with the minimum capacity added to the time for travelling the minimum distance of this egress path element:

$$t_{move} = \max\,(\Sigma^{\text{max path}}\, L_i/V_i;\ \Sigma^{\text{min path}}\, L_i/V_i + N \,/\, \min\,(F_{s,i} \cdot B_i)) \tag{9.6}$$

Similar approaches based on crowd velocity and flow limits can be found in [9.30] and in guidelines for specific applications e.g., NFPA guideline 130 "Standard for Fixed Guideway Transit and Passenger Rail Systems".

A conservative estimation is obtained if in equation (9.6) the minimum distance is replaced by the sum of the times for the travel of all path elements, but for the passage time $\frac{N}{(F_S \cdot B)}$ only the one for the single route element with the longest passage time is used. This concept can be extended to divided and merging egress paths by assigning appropriate portions of the total occupant number N being part of the respective crowd flows. For more complex scenarios, however, the use of a dynamic flow model (see Chapter 9.4.3) or a microscopic analysis (see Chapter 9.4.4) is recommended so that changes in the density of persons and temporal superposition effects along the escape route can be detailed consistently.

Extending the basic case considerations, distributed pre-movement times can also be considered for estimating the escape time, whereby the equation (9.6) is extended as follows:

$$t_{move} = \Delta t_1 + \max\left(\Sigma^{max\ path} L_i/V_i;\ \Sigma^{min\ path} L_i/V_i + \max\left(N_i / (F_{s,i} \cdot B_i);\ \Delta t_{99}\right)\right) \tag{9.7}$$

9.4.3 Macroscopic dynamic flow models

Within the framework of the flow models, empirically derived correlations between velocity V and density D (fundamental diagrams) can be used to describe the effects of a crowd density changing locally and time-dependent. This leads to the group of dynamic flow models, which also permit the analysis of merging flows.

Different fundamental diagrams to be applied in evacuation analysis have been published from various research projects. With a few exceptions, these fundamental diagrams generally show a monotonically decreasing velocity V with increasing crowd density, based on various functional dependencies V(D) (see Figure 9.2).

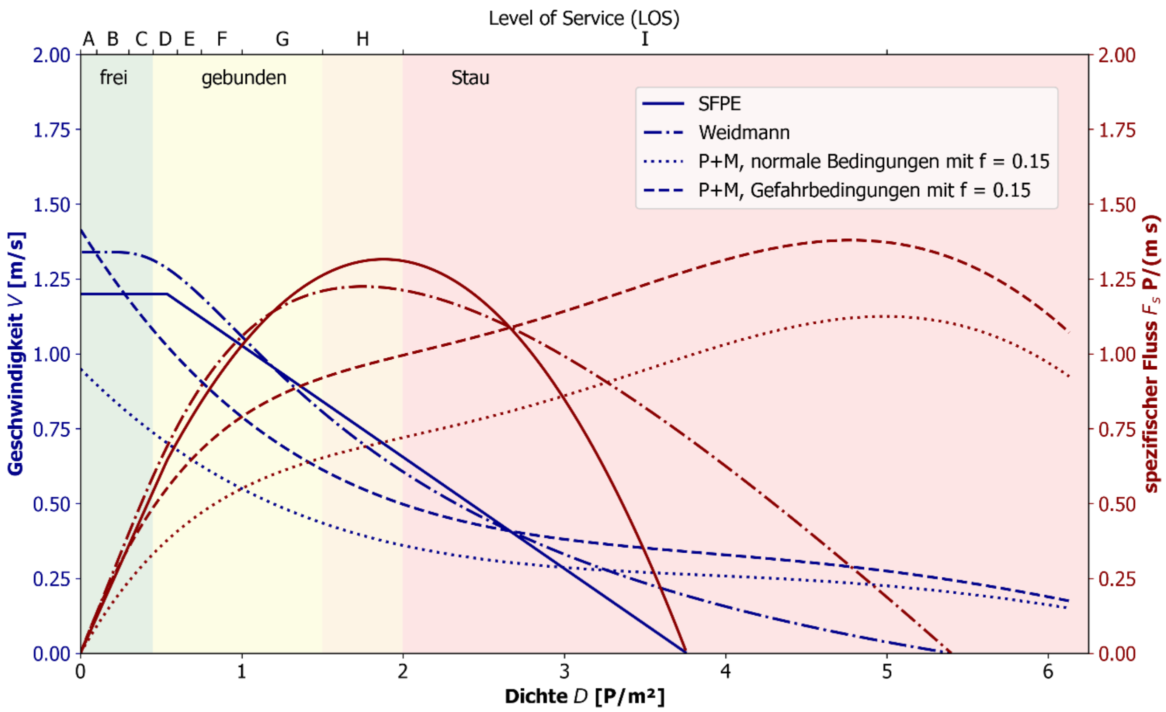


Figure 9.2 Exemplary presentation of fundamental diagrams for horizontal route elements ([9.2], [9.5] and [9.6])

In the Figure 9.2 above, the crowd density is assigned to the Levels of Service according to Weidmann [9.5] including the conditions free movement, restricted traffic and congestion. In terms of the definition of congestion (see chapter 9.6), this assignment is consistent with his fundamental diagram [9.5] and that published in the SFPE handbook [9.2]. Other fundamental diagrams such as Predtetschenski and Milinski [9.6] forecast congestion according to this definition at other crowd densities. The representation via the fundamental diagram thus illustrates the transition between free flow and congestion: At the turning point of the flow curve, the system is at maximum capacity. Higher densities lead to an overload and result in a reduced flow, and thus in a congestion. It should be noted that, in addition to the fundamental diagrams listed here, many other characteristics exist, depending on the composition of the population: They all have in common, however, that from a certain density onwards the turning point is reached and the system goes into a state of congestion.

Within the framework of the effective width model, the simplest version is derived on the basis of empirical data, i.e., a linear functional dependence of speed V and crowd density D [9.2],

$$V = k - a \cdot k \cdot D \ . \tag{9.7}$$

The specific passenger flow F_s is obtained by multiplying speed and density,

$$F_s = V \cdot D \ . \tag{9.8}$$

The constants a = 0.266 m^2/P. and k (see Table 9.7) are determined empirically. The range of validity of (9.7) is specified as 0.5 P./m^2 < D < 3.7 P./m^2. Most of the empirical data are relatively broadly scattered in a density range between 1 P./m^2 and 2 P./m^2. This means that the linear relationship postulated in relation (9.7) between V and D is not unique. A compilation of different correlation functions for the density dependence of V or F_s including non-linear dependencies can be found in [9.5]. When using (9.7) should be noted that the values given here for the constants a and k are assigned to a certain ("typical") composition of the population. If you want to describe a different population (especially those with other mobility parameters such as persons with luggage), the constants should be adapted. This requires the availability and analysis of corresponding data and thus sometimes causes considerable difficulties in practice.

Table 9.7 Speed constant k for specific route elements [9.2]

Route element	Constant k
Corridor, ramp, doorway	1.40 m/s
Stairs	
- Step height 19.1 cm / step width 25.4 cm	1.00 m/s
- Step height 17.8 cm / step width 27.9 cm	1.08 m/s
- Step height 16.5 cm / step width 30.5 cm	1.16 m/s
- Step height 16.5 cm / step width 33.0 cm	1.23 m/s

If one inserts (9.7) in (9.8), a quadratic dependence of D results for F_s, with a maximum at a crowd density of 1.9 P./m^2. This corresponds to the optimal load factor, which is often used in manual calculations.

With the help of the equations (9.3) to (9.8) and additional rules (partly derived directly from the flow model, partly based on additional assumptions regarding the distribution of persons and the splitting and merging of flows), systems of equations can be set up which in simple cases can still be solved by hand, but generally require the use of spreadsheet or special computer softwares.

Another example of a dynamic flow model is the method developed by Predtetschenski and Milinski [9.6]. An essential component of this calculation method is a collection of empirically derived correlation functions, which indicate the density dependence of the velocity V, separately for the individual route elements (horizontal path, doorway, staircase up, staircase down) and types of movement (danger, normal, comfort), in the density range from close to 0 up to an empirically founded maximum density D_{max} (see Figure A2.37 in the appendix). This makes it possible either to determine the velocity V (and thus at the same time the specific flow (here called intensity of movement q) for a known density D or, conversely, to determine a corresponding density and the associated velocity for a known value of q. By introducing the individual body surface f projected onto the walking plane in the definition of the density, a higher degree of flexibility is achieved compared to the hand calculations described above. The method is supplemented by equations describing escape routes other than the level ones and the process of congestion formation and decongestion.

The method of Predtetschenski and Milinski can be used if the characteristics of the escape routes allow the formation of a crowd flow of uniform density. In elongated geometries (e.g. escape routes in tunnels), the method can only be used in a modified form because it does not take into account the change in the density of persons over the length of the crowd [9.29].

Network models represent the next step in the expansion of the hydraulic approach. Here, the route elements critical for the flow are represented as nodes of a connected system, which contains the necessary information on the length and width of the escape routes. As the egress capacity of the bottlenecks and merging points is determined through empirical relations for the density dependence of the specific flow, these methods should be assigned to the hydraulic models. They provide the opportunity, however, to consider certain aspects of individual movement (e.g., mobility restrictions or egress route choice).

9.4.4 Individual models

When using individual models (microscopic models), in contrast to macroscopic flow models, it is generally not necessary to specify the density dependence of the walking speed. This fundamental correlation, which has a significant influence on egress time, is here rather a result of the modelling of elementary individual motion sequences.

The main input variables are the building or terrain model (either three-dimensional or in the form of two-dimensional walking surfaces that are spatially connected) and the individual characteristics. The latter are described by so-called populations. Populations are characterised by distribution functions for the individual mobility parameters and other parameters to describe individual behaviour (e.g., with regard to the choice of escape routes). The most important factors here include individual space requirements, individual pre-evacuation time and individual unimpeded walking speed.

There are two types of individual models: spatially discrete and spatially continuous models. In spatially discrete models, the accessible areas are covered by a grid of cells. The individuals then move from cell to cell, depending on their own goal and influenced by the movement of adjacent persons. The grid structure can lead to restrictions with respect to the representation of the individual mobility parameter (body size, walking speed) and in modelling individual movement. In principle, the maximum representable occupant density is limited by the cell size and fine-grained geometries can be represented less accurately.

In the room-continuous models, the accessible area is only limited by the actual enclosure components and obstacles. In addition, the persons are not limited in their body dimensions by a cell structure. In order to model individual collision avoidance, it is necessary to check for obstacles and other persons at a possible contact distance in each time step of the calculation. Continuous models therefore offer a high degree of flexibility, but usually require a higher computational effort. In addition to decision-based approaches that mimic the step behaviour of people (e.g., the Optimal Steps Model), continuous space models also include force-based social force models, in which the movement modelling is determined by the surrounding people and the pressure exerted by them.

Most individual models contain the possibility to randomly determine certain individual decisions in the course of the simulation in addition to the initial distribution of persons. Thus, if the same scenario is calculated several times, different results are obtained, the variance of which can provide information about hidden optimization potential. In addition, the most unfavourable results can be directly included in the safety analysis, thus avoiding otherwise necessary, but difficult to quantify, safety margins on average or optimistic egress times.

Typical representatives of spatially discrete individual models are buildingEXODUS [9.10], or PedGo [9.11]. The simulation softwares ASERI [9.12], SIMULEX [9.13], crowd:it [9.35], Pathfinder [9.36] and FDS+EVAC [9.37] follow a continuous approach. A comprehensive overview of currently available personal flow models can be found at www.firemodelsurvey.com.

9.4.5 Model selection and application principles

To be practicable for the elaboration or assessment of a safety concept, an efficient and profound evacuation model should contain the following properties:

- It should be possible to consider the building geometry in all details important for the evacuation process.
- Restrictions with regard to possible escape routes should be avoided as far as possible, so that the evacuation of areas with large open spaces (halls, assembly rooms without fixed seating, exhibition centres, distribution levels in stations, airports or stadiums, etc.) can also be dealt with in a workable manner.
- The individual characteristics directly influencing the evacuation process, in particular the mobility characterised by individual space requirements and unimpeded walking speed, should be taken into account.
- If necessary, the dynamic propagation of smoke, toxic combustion products (especially CO, CO_2 and HCN and, if applicable, oxygen depletion) and heat effects must be taken into account when calculating evacuation times (restricted visibility, critical concentration values, dose-effect relations). Possible effects may include disorientation, reduction of walking speed, turn-back behaviour, and complete blockade of building sections. A reduction in walking speed begins when visibility is reduced to about 5 m. In this range, an increasing turn-back behaviour in the presence of smoke is also to be expected [9.32].
- The determination of the individual escape route should allow the analysis of escape route alternatives.

An assessment of suitable egress times is obtained by an appropriately conservative choice of scenarios. This can be done within the framework of a risk assessment using the methods described in Chapter 10. In addition to the geometry of the building, the definition of scenarios requires at least information regarding the number of occupants and their distribution, as well as any individual mobility parameters. The calculation parameters (e.g., moderate instead of optimal density regime in the capacity analysis) must be varied to assess the robustness of the result.

Microscopic models are particularly suitable for escape route situations in which a certain direction of movement of persons is not predetermined by geometrical conditions or by the movement pattern of a crowd, so that individual decisions and movements will likely occur.

The use of computer-aided individual models requires great care in the selection of the variety of possible simulation parameters. Here, the model developers have to provide a detailed and comprehensive validation and documentation, so the user has access to all information required for a solid computational evidence. The advantages of the individual models lie in the better recording of the dynamics of an evacuation process, especially in the case of complex geometries with merging flows. Furthermore, even in a flow model such as that of Predtetschenski and Milinski, an inhomogeneous group of people is ultimately only described by averaged movement parameters, whereas in reality a homogeneous group of people moves faster than a heterogeneous group of people with the same average parameters. The slowing down of the flow of people due to overtaking processes that take place can only be detected with an individual model. When applying flow models, this must be taken into account in selecting appropriate fundamental diagrams. Curves or corners in the course of an escape route or the influence of the direction of the flow on doors or stairs can only be considered with flow models by means of empirical factors. With individual models, these influences are implicitly considered via the interaction of the individuals among each other and with the surrounding geometry. Finally, once the geometry has been created, parameter studies can be carried out and visualised more easily.

As an aid to model selection, the properties and possibilities of the model classes are given in the Table 9.8.

Table 9.8 Model properties to assist in model selection

	Macroscopic		Microscopic	
	Capacity analysis	Dynamic flow models	Spatially discrete models	Spatially continuous models
Significance:				
Escape time or movement time	Yes	Yes	Yes	Yes
Congestion (Where does a congestion occur)	Restricted	Yes	Yes	Yes
Density at congestion	No	No (set)	No (limited by cell size)	Restricted
Congestion size (number of people in the congestion)	No	Yes	Yes	Yes

Congestion time (duration of congestion)	Restricted	Yes	Yes	Yes
Individual waiting time	No	Restricted	Yes	Yes
Extent of congestion	No	Restricted (prescribed density)	Restricted (depending on cell size)	Restricted (depending on individual space requirements and density)
Representation:				
Escape routes	Sectionalized with constant properties	Sectionalized with constant properties	by fixed cell size	Continuous (exact)
Walking speed and individual characteristics	Homogeneous and averaged	Usually homogeneous and averaged	Individual	Individual
Merging of flows	No	Yes	Yes	Yes

9.4.6 Validation

When using a crowd flow model as a quantitative verification method within the scope of fire protection engineering, the same fundamental requirements apply with regard to validation and documentation as they do for the models for calculating the spread of smoke and heat. The following can be used for a validation

- Comparison with evacuation experiments,
- Comparison with evacuation exercises,
- Comparison with real evacuation events, or
- Comparison with other sufficiently validated calculation methods.

In order to be able to include certain aspects of individual behaviour (e.g., pre-movement time or choice of escape route) in the validation process, comparisons with unannounced evacuation drills or the evacuation of assemblies after major events are particularly qualified - due to the lack of suitable data from real fire events. For example, various macroscopic and microscopic models have been validated on the basis of several evacuation exercises in high-rise office buildings conducted by the Research Center for Fire Protection Technology [9.7], [9.16], [9.17] for this specific application area.

9.5 Behavioural aspects

9.5.1 General information

Individual behaviour in the event of a fire can have effects in all phases of evacuation which influence – and in certain circumstances considerably increase – the overall egress time. The behaviours and actions previously summarized under the term " pre-evacuation time" can usually be lumped together when calculating egress times (i.e., by an additive time interval as in relation Chapter 9.2 - on an individual or global level). Special cases that might require a more detailed analysis of this early phase of the evacuation are, for example, relevant changes in the initial distribution of people in the building within the pre-evacuation time (e.g., during the information search phase).

9.5.2 Choice of escape route

The calculation of egress times always requires information on the allocation of persons to the available escape routes within the framework of scenario definition. For the macroscopic models presented in Chapter 9.4.2 and 9.4.3, it is sufficient to specify the number of persons passing through a route element or exit. In the case of the microscopic methods (Chapter 9.4.4), the individual route must be determined, either by explicit specification or by implicit rules of movement or behaviour. Only with these individual models is it possible to explicitly consider individual behavioural aspects when choosing an escape route.

In a situation where evacuees have a choice between two or more routes at any given point along the way, the individual allocation of persons to these alternative escape routes should be made by evaluating the attraction of each option. It should be noted here that an optimized load distribution (in the sense of a minimum overall escape time) constitutes an ideal condition that can hardly been achieved in practice. The amount of information available for a route choice decision should be considered and how this information can be processed in the actual environment (familiarity with the building, experience of similar situations, social influencing factors etc.). There are four main criteria here for the selection of escape routes [9.15]: knowledge of each escape route, frequency in daily use, shortest distance to an exit and perception of smoke. In addition to general knowledge of surroundings (familiarity), knowledge of the route includes the existence and quality of escape route signs and where necessary an information system, as well as the influence of personnel and operational units, which is of special significance in actual practice. In addition to the length of the escape route, its subjectively perceived quality (width, evenness, complexity, and lighting) also plays an important role. A difference should also be made in each situation as to whether the evacuees are facing an unclear hazard situation or are fleeing from a specific, direct danger. In the former case, the length of the entire escape route until the building can be exited tends to be decisive (globally shortest route), and in the latter instance the length of the route until the next available exit from the endangered room or area (locally shortest route). Other influencing factors are the properties of the emergency exits (doors open or closed, direct access to outdoor areas) and the behaviour of other persons in the vicinity.

An additional aspect of escape route selection, which is particularly important for buildings occupied by a large number of people or a high density of people, is individual behaviour in the event of congestion. This leads to the question under which conditions alternative escape routes, if any, are accepted to avoid congestion or to reduce the respective waiting time.

Unfortunately, there is currently still too little empirical data available to comprehensively quantify these qualitative attractiveness criteria. It is therefore usually necessary to estimate possible variances in the utilisation of escape routes based on the above criteria and to investigate their effects by means of a sensitivity analysis. Basic questions of mathematical implementation as well as application limits of various computational methods were examined in more detail e.g., in [9.33].

9.5.3 Behaviour in case of immediate danger

With regard to the term "panic", which is often brought into the discussion, the following should be noted. "Panic" is used in very different meanings. Events that meet a strictly scientific definition of this phenomenon have no causal connection with the evacuation of buildings. On the other hand, the term "panic" is very often used, particularly in the media, without the necessary differentiation, to describe or explain incidents involving personal injury in congestions or moving crowds. Without a more detailed analysis of the actual course of events, however, such reports are not suitable for more far-reaching conclusions.

In fact, experts in the field of human behaviour repeatedly emphasise the predominantly hesitant or helpful behaviour towards the often claimed dominant selfish or irrational behaviour in the event of fire [9.8], [9.9], [9.20]. Often the local occurrence of extremely high occupant densities, in which serious injuries or even deaths can occur, is wrongly described by the term "panic". If we look at real events of this kind, they result either from situations in which a rapid spread of fire combined with inadequate design of escape routes (e.g., due to the illegal blocking of emergency exits or escape routes that were not adequately dimensioned at all) quickly creates an uncontrollable potential for danger, or from situations that are not related to a fire (e.g., escape from riot or inflow of people into already crowded areas). The first-mentioned situation is adequately dealt with by the basic requirement of a performance-based design of escape routes (RSET less than ASET and further criteria described in this chapter). The avoidance of situations with extremely high local densities shall be ensured by the appropriate planning of escape routes and evasion possibilities within the framework of a comprehensive safety concept, including, if necessary, appropriate organizational measures.

The application of crowd flow models should therefore make possible problem situations foreseeable and enable the investigation of alternatives. The publications [9.18] to [9.24] provide an overview of the current state of knowledge on the behaviour of people in fires.

9.6 Congestion

9.6.1 General information

In addition to the required egress time as a quantitative performance criterion, the quality of the evacuation process also plays an important role. “Quality" here in particular includes the development of the local crowd density on the escape routes and the resulting congestion situations. Congestion cannot be avoided in principle and does not necessarily lead to hazards or individual injury. Depending on the number of persons, the (geometric) boundary conditions and the pre-movement behaviour, congestion can form temporarily in the initial phase of an evacuation. An example of this is the evacuation process on a grandstand or in a cinema. In both cases, the flow of persons must merge at specific points in order to reach an exit. This results in very low speeds of movement and at times also in a standstill. Within the continuing escape routes however, congestion should be avoided if possible. Congestion in indistinct areas is usually unacceptable, since the persons in the congestion are at a significantly higher risk of being endangered by people moving along behind them (dynamic pressure). Criteria for a safe evacuation process are discussed in [9.31]. In order to further concretise these introductory considerations, it is first necessary to define the terms used to describe the process of congestion and to show the possibilities and limits of their mathematical implementation. Based on this, criteria for a definition and an evaluation of congestion can be developed.

9.6.2 Definition of congestion

A congestion always occurs when an incoming flow of people at a bottleneck exceeds the outgoing or maximum possible flow of people for this route element. The formation of congestion is always accompanied by a reduction in speed, possibly to a standstill, and usually by an increase in the density of people.

Due to its definition via the magnitude of the flow, a congestion is in principle a macroscopic phenomenon, which also has an impact on the movement parameters of individuals. It can also be deduced from this definition that a certain minimum number of people is required for a congestion to occur.

For people joining a congestion, there is an additional time requirement compared to a free or bound flow of people.

9.6.3 Identification of congestion in crowd flow models

Different criteria can be used to identify congestion. These criteria refer either to the congestion as a whole (macroscopic) or to the individuals within the congestion (microscopic).

Individual criteria (microscopic):

- Accessible area for individuals (results in occupant density),
- Speed reduction (local speed significantly lower than desired speed),
- Time loss,
- Dwell time in congestions,
- Distance travelled in congestions.

Criteria at congestion level (macroscopic):

- The duration of the congestion from its occurrence to its disbandment,
- The number of all persons simultaneously involved in the congestion,
- The location and extent (area) of the congestion,
- The total number of persons involved in the congestion.

The variables underlying these characteristic features each have specific advantages and disadvantages (see also Table 9.8). For macroscopic calculation models, the macroscopic criteria can be used to describe a congestion. Only the flow criterion from the above definition is to be used to identify a congestion.

The following criterion is recommended for microscopic calculations:

Speed

In principle, congestion identification based on speed as a characteristic variable can be implemented. The ratio to the desired speed or the absolute speed can be used as a relevant parameter. As a threshold value the speed V can be used, which is assigned to the maximum specific flow (see also Figure 9.2). As an alternative to a fixed threshold value, it is also possible to carry out a calibration for each model using defined scenarios to determine a suitable and comprehensible threshold value.

9.6.4 Local density

The local density of people as a criterion for assessing life safety, especially at events with a high visitor rate, is discussed in detail in [9.34]. At densities of 3 - 5 P./m^2, a temporary local standstill in the flow of people can be expected. At higher crowd densities, people can no longer escape the hazard area and the pressure waves caused by people pressing after cannot be compensated. In this case there is a great and immediate danger for the persons concerned.

In practical application, densities are therefore often used to assess critical situations (see comments in Chapter 9.5.3).

However, it is not advisable to use crowd density in calculation models for congestion identification. In macroscopic approaches, the density of people assigned to a congestion area is a prescribed value. In microscopic models, the local density of persons can be calculated, but there are significant, sometimes systematic, differences between the models with regard to the maximum local density of persons that can be represented. This is aggravated by the fact that there are different definitions for the density measurement. A consensus on standardization would therefore also have to be found here.

9.6.5 Assessment of congestion

In contrast to a jam as a traffic engineering phenomenon, congestion can cause personal injury when there is a high density of people. It is therefore relevant to assess the identified congestion. However, an assessment can only be made on the basis of available quantities.

Identifying a significant congestion is the basis for examining a scenario more closely. The classification of a significant congestion as critical can only be made under consideration of the specific boundary conditions resulting from the specific situation. Criteria for a significant congestion are both the prevention of discharge from a critical area and the individual queue time. The latter is relevant, since the psychology of the individual plays a role here. However, there is a lack of reliable empirical data that could provide a (possibly situation-dependent) threshold for the individual queue time.

9.7 Occupant number

The occupant number upon which a safety concept or crowd flow analysis is to be based depends on the building size (surface area of each storey) and the type of use. Either a crowd density adequate with utilization (usually representative of an empirically verifiable peak capacity) is multiplied by the related storey area here, or the maximum number of persons for which the building is designed (e.g., the maximum number of seats in a stadium) is used directly.

Table 9.9 shows a compilation of crowd densities depending on the type of use on the basis of the corresponding guidelines and/or regulations in the USA, UK, New Zealand and Switzerland [9.25] to [9.28]. The data collected here on crowd densities sometimes show considerable scattering for identical or similar types of use, with the highest value usually being adopted. As some additional differentiations not explicitly shown here (e.g., regarding the number of storeys) are also to be found in the original source documents, reference is made to the quoted sets of regulations for further details. A comparison of these guidance and regulations with the circumstances of real fires is to be found in [9.1]. The reference value is the usable net area (area within the inner circumference of the outer walls minus stairways, lift systems, sanitary facilities, interior walls etc.).

Table 9.9 Occupant load for various types of use *)

Utilization	Occupant density [P./m^2]
Stadium, grandstand, theatre, etc.	
- Standing room	5.0
- Free seating	2.0
- Fixed seating	Number of seats
- Lobby / Foyer	1.0
Passages, walkways (when used as place of assembly)	1.4
Art gallery, Museum	0.25
Library	
- Reading room	0.2
- Magazine	0.1
Exhibition, trade fair	0.6
Gaming casino	1.0
Training room, fitness centre	
- with equipment	0.2
- without equipment	0.7
Restaurant, pub	1.0
Bar, club, discotheque	4.0
School	
- Classroom	0.5
- Laboratory / practice room	0.2
Daycare facilities	0.3
Shops	
- Area (floor) with access at street level	0.5

Continued Table 9.9

- Other floors	0.3
Shopping market (for large appliances, furniture, etc.)	0.1
Showroom	0.2
Use	People density [P./m^2]
Office	0.2
Swimming pool	
- Water basin	0.2
- Rest and play area	0.35

*) Note: Since the underlying sources [9.25] to [9.28] tend to provide the highest specific person densities, the number of persons may be overestimated, especially in the case of large-scale use such as extensive retail outlets.

9.8 Literature

[9.1] *PURSER, D.*: Data Benefits. Fire Prevention Fire Engineers Journal, August 2003, pp. 21 - 24.

[9.2] *GWYNNE, S.M.V.; ROSENBAUM, E.R.*: Employing the Hydraulic Model in Assessing Emergency Movement. In: SFPE Handbook of Fire Protection Engineering, Springer New York, 5th Ed. 2016.

[9.3] *PAULS, J.*: Movement of People. In: SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, Massachusetts, 2nd Ed. 1995.

[9.4] *FRUIN, J.J.*: Pedestrian Planning and Design, Revised Ed., Elevator World Educational Services Division, Mobile, AL, 1987.

[9.5] *WEIDMANN, U.*: Transporttechnik der Fußgänger, Schriftenreihe des IVT (Literaturstudie Nr. 90). Zürich: Institut für Verkehrsplanung und Transporttechnik, Straßen- und Eisenbahnbau, ETH Zürich, 1993.

[9.6] *PREDTETSCHENSKI, W. M.; MILINSKI, A. I.*: Personenströme in Gebäuden – Berechnungsmethoden für die Projektierung, Staatsverlag der Deutschen Demokratischen Republik, Berlin, 1971.

[9.7] *KENDIK, E.*: Die baulichen Rechtsnormen in Bezug auf die Bemessung der Fluchtwege in Gebäuden. vfdb-Zeitschrift 2 / 86, S. 48 - 54.

[9.8] *FAHY, R.F.; PROULX, G*.: 'Panic' and human behaviour in fire, National Research Council Canada NRCC-51384, July 13, 2009.

[9.9] *KÜNZER, L*.: Myths of Evacuation, FeuerTRUTZ International 1.2016, Seite 8-11.

[9.10] *GWYNNE, S.; GALEA, E. R.; LAWRENCE, P. J.; FILIPPIDIS, L.*: Simulating Occupant Interaction with Smoke Using buildingEXODUS. 2nd International Symposium on Human Behaviour in Fire, Boston, MA, 26. - 28. März 2001.

[9.11] *KESSEL, A.; KLÜPFEL, H.; WAHLE, J.; SCHRECKENBERG, M.*: Microscopic Simulation of Pedestrian Crowd Motion. Tagungsband International Conference on Pedestrian Evacuation Dynamics (PED), 4. - 6. April 2001, Duisburg.

[9.12] *SCHNEIDER, V.; KÖNNECKE, R.*: Simulation der Personenevakuierung unter Berücksichtigung individueller Einflussfaktoren und der Ausbreitung von Rauch. vfdb-Zeitschrift 3 (1996), S. 98 - 109.

[9.13] *THOMPSON, P.A.; MARCHANT, E. W.*: A Computer Model for the Evacuation of Large Building Populations. Fire Safety Journal 24 (1995), S. 131 - 148.

[9.14] *BREIN, D.*: Evakuierungskonzepte – Anforderungen, Komponenten, Bewertungen. vfdb-Jahresfachtagung, Hamburg, 1997.

[9.15] *MÜLLER, K.*: Die Evakuierung von Personen aus Gebäuden – nach wie vor ein nationales und internationales Problem. vfdb-Zeitschrift 3 (1999) 131.

[9.16] *SCHNEIDER, V.*: Modelle für die Flucht und Rettung von Personen. 9. Internationales Brandschutz-Symposium der vfdb, 25. / 26. Mai 2001, München.

[9.17] *JOHN, R.; SEEGER, P.*: Untersuchung der Räumungsabläufe in Gebäuden als Grundlage für die Ausbildung von Rettungswegen – Teil III: Reale Räumungsversuche, Forschungsstelle für Brandschutztechnik an der Universität Karlsruhe im Auftrag des Bundesminister für Raumordnung, Bauwesen und Städtebau, 1978.

[9.18] *PHILLIPS, A. W.*: The Effects of Smoke on Human Behavior. Fire Journal. May 1978.

[9.19] *CANTER, D. (Hrsg.)*: Fires and Human Behaviour. 2. Ed., David Fulton Publishers Ltd, London, 1990.

[9.20] *SIME, J.*: "The concept of 'panic.'" In D. Canter (Ed.), Fires and human behaviour (2nd ed.), David Fulton Publishers, London, pp. 68, 1990.

[9.21] *SCHNEIDER, V.*: Verbundprojekt Simulation von Bränden, Lösch- und Notfallmaßnahmen – Teilprojekt Brand- und Rauchausbreitung, Evakuierungsmodell. BMFT-Abschlussbericht 13 RG 91141, 1994.

[9.22] *STEIN, J.*: Verhalten von Menschen bei Bränden, Brandschutz – Deutsche Feuerwehrzeitung 4 / 1999, S. 308 - 315.

[9.23] *HELBING, D. ET AL.*: Simulation of Pedestrian Crowds in Normal and Evacuation Situations. in: Schreckenberg, M.; Sharma, S. D. (Hrsg.): Pedestrian and Evacuation Dynamics, Springer, 2002.

[9.24] *BRYAN, J. L.*: Behavioral Response to Fire and Smoke. in: SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, Massachusetts, 3rd Ed. 2002.

[9.25] The Building Regulations 2000, Edition 2006 Fire Safety, Approved Document B, Volume 2 – Buildings other than Dwelling Houses, 2006 Edition, Department for Communities and Local Government.

[9.26] *BUCHANAN, A. H. (Hrsg.)*: Fire Engineering Design Guide, Centre of Advanced Engineering, Christchurch, New Zealand. 2001.

[9.27] NFPA 101 Life Safety Code, 2000 Edition.

[9.28] *HESS, E.*: Neue Kompetenzordnung und flexiblere Brandschutzkonzepte mit den neuen „Schweizerischen Brandschutzvorschriften“ VKF, Braunschweiger Brandschutz-Tage 2005.

[9.29] *STEGLICH, M.; WILK, E.*: Bestimmung der Zeiten für den Ausstieg von Personen aus Zugeinheiten und die Verteilung langgestreckter Personenströme im Ergebnis von Beobachtungen und Zeitmessungen, Brandschutz Consult - Ingenieurgesellschaft mbH, Leipzig, 2002.

[9.30] BSI British Standards: The application of fire safety engineering principles to fire safety design of buildings, Part 6: Human factors: Life safety strategies - Occupant evacuation, behaviour and condition, PD 7974-6:2004.

[9.31] *FORELL, B.; KLÜPFEL, H.; SCHNEIDER, V.; SCHELTER, S.:* Vergleichende Anwendung verschiedener Räumungsmodelle. Tagungsband zur 59. vfdb

Jahresfachtagung 2011, 30. Mai bis 1. Juni, Berlin, S. 465-493. Online verfügbar unter http://www.rimea.de/downloads.html.

[9.32] *PURSER, D. A.*: Toxicity Assessment of Combustion Products. in: SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, Massachusetts, 3rd Ed. 2002.

[9.33] *SCHNEIDER, V.*: Einfluss der Fluchtwegewahl auf Räumungszeiten und Evakuierungseffizienz, vfdb-Zeitschrift 2/2008, Seite 87 - 93.

[9.34] *OBERHAGEMANN, D. (Hrsg.)*: Statische und dynamische Personendichten bei Großveranstaltungen, vfdb Technischer Bericht TB 13-01, 2012.

[9.35] SEITZ, M. S.; KÖSTER, G.: Natural discretization of pedestrian movement in continuous space, American Physical Society, PHYSICAL REVIEW E, 2012, 86, 046108.

[9.36] *THORNTON, C.; O'KONSKI, R.; HARDEMAN, B.; SWENSON, D*.: Pathfinder: An Agent-Based Egress Simulator, Pedestrian and Evacuation Dynamics (R.D. Peacock, E.D. Kuligowski, J.D. Averill, Editors), Springer 2011, Seite 889 – 892.

[9.37] *KORHONEN, T.; HOSTIKKA, S.; HELIÖVAARA, S.; EHTAMO, H.; MATIKAINEN, K*.: FDS+Evac: Evacuation Module for Fire Dynamics Simulator, Proceedings of the Interflam2007: 11th International Conference on Fire Science and Engineering, Interscience Communications Limited, London, UK, 2007, Seite 1443–1448.

10 RISK METHODS AND SAFETY CONCEPT

10.1 General information

A prerequisite for the application of engineering methods in fire protection is the maintenance of the socially accepted fire safety level, which can be determined by the annual number of fire deaths and fire damage for a certain period of time. To ensure this, engineering methods should be applied in conjunction with a global safety concept. The essential requirements for the safety concept is the validity for all common methods and models:

- Dimensioning of Components,
- Design of smoke extraction systems,
- Calculation of evacuation times.

In general, the requirements for a global safety concept for preventive fire protection include the definition of rules and methods with which buildings can be designed, executed and used in a sufficiently safe and economical way. The objectives of the safety concept are:

- The provision of sufficient safety for
  - Building users, and
  - Fire brigade personnel,
- Dimensioning of the fire protection measures so that
  - Deaths and injuries are avoided, and
  - Consequences of construction failure can be minimized.

Naturally, a safety concept mediates between safety in the public interest on the one hand and the desired economic efficiency on the other hand. A sufficient level of safety exists if, for instance, the failure of a structure in case of fire within the planned service life only occurs with an acceptably small probability (target failure probability).

When designing the structural fire protection measures, the uncertainties and parameter variance in the engineering verifications used must be covered by selecting appropriate design values in order to avoid fire-induced failure with adequate reliability. These design values are defined by characteristic values and partial safety factors in accordance with the partial safety concept of the constructive Eurocodes. The reliability achieved in this way and/or the remaining risk cannot be recognised by the design engineer.

For a risk-oriented evaluation of fire protection, deterministic engineering methods for the realistic recording of fire impacts and the behaviour of the building structure or persons during the fire are required in addition to probabilistic methods to determine failure probabilities of fire protection measures due to uncertainties and scattering of the calculation models and the associated input variables and to calculate a failure probability of the fire protection from this. This can then be compared with specifications for the probability of failure accepted by society to date or the minimum required reliability.

In contrast to the English-speaking countries and Scandinavia, risk methods for the evaluation of preventive fire protection in buildings have so far only been used in Germany in exceptional cases, e.g., in nuclear power plants. To date, there is also no uniform statistical recording and evaluation of fire cases that could provide information on the effectiveness of preventive and averting fire protection. Therefore, reliable statistical data on the frequency of fire occurrence, the probability of fire propagation and the reliability of structural and plant-related fire protection measures are rare in Germany. Up to now, dependancy has been relied on international literature references whose transferability to German conditions is not assured. Currently, there are efforts to collect such data in a uniform way in Germany. If these data are not yet available, the following methods should be used to determine the suitability of the available data for the individual case.

To analyse the risk of fire and compare the risks between different buildings, occupancies and fire protection concepts, there are various techniques or procedures, which can roughly be categorized into qualitative and quantitative risk methods. The following methods are outlined in more detail here:

- Semi-quantitative index method [10.2].
- Quantitative event tree analysis [10.3].
- Quantitative system reliability analysis [10.3].

First, Chapter 10.2, sets out the semi-quantitative risk methods that appear suitable for practical engineering applications. Thereafter, a summary of the quantitative methods of event tree and system reliability analysis is intended for more precise examination and derivation of simplified methods are presented in Chapter 10.3.

10.2 Semi-quantitative risk methods

The index methods or ranking methods are procedures with which the fire risks in different buildings can be estimated and compared with each other. Over the last decades, index methods have been developed for different applications (Table 10.1).

The result of the evaluation is determined as a number, the risk index. In the event of changes in the building structure or changes to the technical measures of the plant, the risk index can be calculated again using this procedure and compared with the previous value. In this way it is possible to iteratively approach a limit value for the safety index, which is to be determined as a measure of the risk accepted by the company (or in individual cases). By comparing the numerical values for a specific building or for several comparable buildings, the most favourable or unfavourable conditions in terms of fire risk can be identified and measures optimised.

However, the method does not provide quantitative information on the actual fire risk, but only relative statements on how safe a building is in comparison to another or before and after an upgrade.

Some of the methods listed in the Table 10.1 are based on data dating back to the 1960s. For example, with the entry into force of the Swiss VKF (Association of Cantonal Fire Insurance) fire protection regulations 2015 [10.53], the calculation method according to SIA 81 in the form of fire protection declaration 115-03 was withdrawn.

Table 10.1 Examples of semi-quantitative risk methods

Method	Application	Developer
Fire Safety Evaluation System (FSES)	Buildings for offices, laboratories, apartments	NIST, USA [10.4]
ISO Specific Commercial Property Evaluation Schedule (SCOPES)	Commercial buildings	ISO Standard [10.5]
Dow Fire and Explosion Index (RDI)	Process planning, damage assessment	Dow Chemical [10.5]
Expert system Fire Insurance Risk Evaluation (XPS FIRE)	Industrial buildings	Munich Re insurance[10.6]
Hierarchical approach	Various buildings	University of Edinburgh, Scotland [10.7]
Fire risk assessment - calculation method (SIA 81)	Industrial buildings	Swiss Society of Engineers and Architects (SIA) [10.8]
Fire Risk Assessment Method for Engineering (FRAME)	Various buildings	De Smet, Belgium [10.9]
Fire Risk Index Method – Multi Storey Apartment Buildings (FRIM-MAB)	Multi-storey residential buildings	Lund University, Sweden [10.10], [10.11], [10.12]

Index or ranking methods are semi-quantitative methods, often developed with the aim of a simplified, schematic risk classification for certain types of buildings. The responsibility for the applicability of the method and its input variables lies with the user. During the development of the method, the input variables are determined by the creator, e.g., through expert interviews. The transferability of these specifications to the concrete problem should be ensured.

As a rule, a group of experts is involved, who discuss each individual factor that can influence the risk positively (increase in safety level) or negatively (decrease in safety level). The value of each factor is decided on the basis of the knowledge of the experts and their many years of experience in the fields of insurance, fire brigade, licensing authorities and science.

Because of their simple application, index methods are a cost-effective tool. The structured way of arriving at a decision facilitates understanding among users and makes it possible to introduce new findings and technology easily into the system.

Index methods have been used in fire protection for over 50 years. Methods are available for life safety in residential buildings [10.13], high-rise buildings [10.10], hotels [10.14] and for protecting industrial buildings [10.8].

10.3 Quantitative risk methods

10.3.1 Introduction

Quantitative risk methods can be used to establish the probability of the occurrence of individual events in buildings. There are various models (Table 10.2), which differ in their solution approaches.

One example is Event Tree Analysis (ETA), which can be used individually as a quantitative method for planning processes. Together with deterministic engineering methods, all necessary information that is to be used to evaluate a building can be presented quantitatively and checked for compliance with requirements, for instance, due to legal regulations.

When using ETA, it is often necessary to consider a large number of fire scenarios with different boundary conditions. A probability of occurrence can be assigned to each event, fire development or scenario. The ETA allows to evaluate and structure the time course of the investigated events starting from the beginning of a fire. When developing an event tree for the structure to be examined, human behaviour and the reliability of installed fire protection systems can also be taken into account.

Another advantage of the ETA is that it is easy to understand due to its binary system (yes / no) and its logical graphical representation with symbols. Internationally, the ETA is used as a recognized verification procedure for fire safety and risk assessments in different types of buildings [10.16] (see Table 10.2).

Table 10.2 Examples for the application of quantitative risk methods

Method	Utilization	Developer
Computation of Risk Indices by Simulation Procedures (CRISP)	Personal Risk	Fire Reseach Station (BRE), UK [10.17]
Fire Risk Evaluation and Cost Assessment Model (FiRECAM)	Office building	National Research Council, Canada [10.18]
Event Tree Analysis (ETA)	All building types	Various [10.19], [10.20]
Fire Risk analysis with Reliability Index ß	All building types Stage 3	Various [10.21], [10.22]

10.3.2 Event tree analysis (ETA)

For the application of an event tree analysis, first of all measures have to be identified which can have a great influence on the safety of persons or the building construction. These are, for instance, different fire locations (area, room, separation from the rest of the building, fire origin) and fire loads (fire growth, fire spread, ventilation conditions) as well as structural, plant-related and organizational protective measures.

The probability of failure of individual parts of the event tree may have to be determined on the basis of a computational analysis. This may, e.g., be a component calculation or a evacuation simulation, in each case taking into account the fire event to be associated with this branch and relevant failure criteria. These may be simpler calculation procedures such as manual equations or computer simulations (see Chapters 5, 6 and 8). The choice of the method depends on the complexity of the building to be investigated and the objectives of the analysis. In addition, the user may have recourse to databases or rely on literature references, empirical values and his own technical judgement.

Depending on the complexity and size of the investigated building, the following events, for instance, can be viewed with case distinctions in the event tree:

- Location of the fire, type of room
  - Office,
  - Corridor,
  - Atrium, etc.
- Fireproof enclosure,
  - Door open / door closed,
  - Walls,
  - Wall opening,
- Time of day (day / night),
- Fire alarm (yes / no),
- Smoke and heat extraction (yes / no),
- Attempts to extinguish by personnel (yes / no),
- Firefighting by means of extinguishing system (yes / no),
- Firefighting by fire brigade (yes / no).

The event tree analysis procedure can be divided into five steps:

- Collection of information on safety equipment and functions (both technical and organisational),
- Layout of the event tree,
- Quantification of the failure probability of the safety facilities and functions of all parts of the event tree,
- Capture the conditional probability of failure of each branch of the event tree,
- Quantification of the results (resulting probability of failure $P_{f,i}$ per branch or total $P_{f,sum}$).

The analysis is based on different fire scenarios, for each of which the fire development and measures are calculated within the scope of an evacuation process. The event tree is a logical diagram that is particularly suitable for displaying the sequence of events. Thus, the effects of the fire origin, the fire development, the control of the fire as well as the rescue process can be recorded.

The user of the procedure must ensure that he records all events relevant to the course of the fire in the event tree (e.g., closed or open door, blocked escape route, failure of the fire alarm system or sprinkler system), which results in further scenarios in each case.

Figure 10.1 shows a simple event tree for fire scenarios that can occur when a sprinkler system functions or fails and is separated by a door. The probability of occurrence of each scenario $P_{f,i}$ is calculated by multiplying the probability of a specific event, in this case of fire, by the probabilities of the subsequent events (function or failure) on that particular branch of the event tree. It is possible to calculate the probability of any damage occurring at all as a result of a fire event, and this is calculated from the sum of the probability of occurrence of the scenarios $P_{f,i}$. The extent of fire propagation should be taken into account when considering compliance with the safety objectives.

Depending on the definition of the protection objective, it would be possible, for instance, that a protection objective is met if the fire is confined to the area of origin. In this case, the branch with a functioning extinguishing system and a functioning fire protection closure would not have to be included in the total sum, although a fire has occurred in the room.

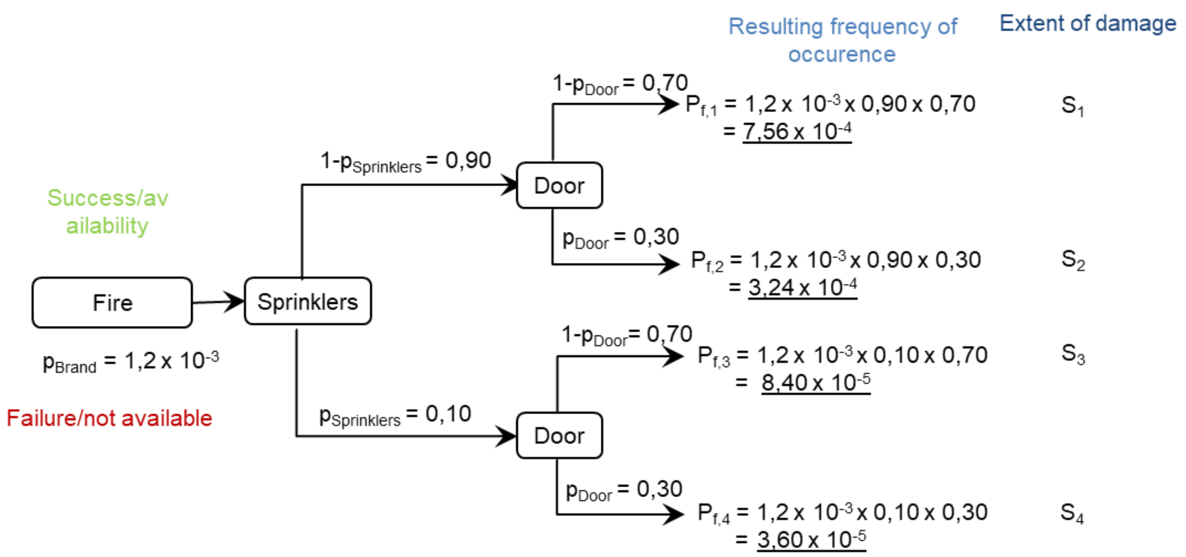


Figure 10.1 Example of part of a simple event tree

The methodology will be explained by means of a simple example. First of all, a safety objective is defined.

> Safety Objective Definition 1: A local damage is accepted, a fire transmission beyond the fire room does not occur. This is the case if either the extinguishing system or the fire protection closure is effective.
>
> Safety Objective Definition 2: Loss of building possible, fire leaves fire room. This is the case if the extinguishing system and the fire protection closure fail.

The probability of occurrence results from the evaluation of the event tree depending on the protection goal definition.

Safety Objective Definition 1: Damage occurs in scenarios 2 and 3.

$P_{f,sum} = P_{f,2} + P_{f,3} = 3.24 \times 10^{-4} + 8.4 \times 10^{-5} = 4.08 \times 10^{-4}$

Safety Objective Definition 2: Damage only occurs in scenario 4.

$P_{f,sum} = P_{f,4} = 3.6 \times 10^{-5}$

10.3.3 Implementation of a quantitative risk analysis

The methodology of the quantitative risk analysis is to be clarified by means of a more detailed consideration compared to Chapter 10.3.2.

This risk analysis is complex in real applications and depends on the particular, investigated problem. With regard to life safety, the extent of damage to be expected is high, for instance, if the determined available safe escape time until limit values is shorter than the required safe escape time from the building. Looking at the supporting structure, damage can occur if the temperature of the hot gas layer exceeds, for instance, 300 °C. The higher the temperature can become in a fire scenario, the higher the extent of damage, up to a certain limit, is usually expected. The product of the probability of occurrence p_i and the extent of damage S_i results in the risk contribution R_i for the respective scenario and a value for the overall risk by summing the individual contributions. The risk contributions of the scenarios can then be compared to show where risk-reducing measures are necessary or have the greatest influence with regard to the respective safety objective.

These connections are explained in an example. The spread of fire in a larger building will be investigated. The occurring damage S_i is given in simplified form as the area affected by the fire, depending on the rate of fire development and the duration of the fire. As a rule, measures such as

- the fire is extinguished by building users,
- the fire is suppressed by sprinkler systems, or
- the fire is controlled by the fire brigade,

limit the spread of fire and thus the extent of damage S_i in the respective scenario. The probability of occurrence p_i of the scenario resulting from the failure or success of the measures depends on the probability of failure or success of the respective (protective) measures.

The risk assessment can be carried out on the basis of the risk contributions R_i, the probabilities of occurrence p_i and the respective extent of damage S_i. The most common reason for the application of a risk assessment in fire protection is the efficient use of resources with an acceptable extent of damage.

In risk analysis, many influencing variables are to be regarded as stochastic variables. In a sensitivity analysis, the user should investigate how uncertainties affect the overall result, e.g.:

- Variation of the input data,
- Simplifications in models,

- Reliability of technical equipment, and
- Influence of open doors, unsuitable measures etc.

In a final evaluation of the affected protection measures, the fire effects determined by fire engineering methods and/or the respective extent of damage are compared with the fire safety objectives defined for this purpose. If the safety objectives are not achieved, additional measures for the upgrading of the building are required. By comparing different alternatives, optimal solutions can be found that provide the legally required protection for the occupants (possibly a higher level of protection) with the least possible effort. On the other hand, individual scenarios in the event tree or events in these scenarios can be singled out because they are not relevant for the risk assessment with regard to the fire safety objectives.

10.4 Safety concept for constructive fire protection

10.4.1 Requirements and principles

The safety concept for verifying structural fire protection using the Eurocode fire protection parts presented in the following was developed in [10.23]. It is intended for:

- Different construction methods (concrete, steel, composite, wood, masonry),
- Different types of use (standard and special occupancy buildings),
- Different fire actions (natural fire load),
- Different calculative verification methods (simplified and general calculation methods according to the Eurocode fire protection sections),

and takes into account the following boundary conditions:

- Frequency of fire outbreak (utilization-dependent),
- Probability of fire propagation (utilization-dependent),
- Availability and effectiveness of technical measures, and
- Availability and effectiveness of firefighting by the fire brigade.

The input variables for determining the fire actions contain random scatterings, statistical uncertainties and model uncertainties which are taken into account by a suitable choice of design values. This applies in particular to

- Fire load density,
- Heat release rates or mass loss rates, and
- Soot yield and contaminant yields.

The safety concept should be based on the specifications already outlined in the European standards - under higher level perspectives - and integrate them in a sensible manner. This affects the general requirements regarding the reliability of load-bearing structures, which are regulated for all construction types and materials in DIN EN 1990 - Eurocode [10.24]. Furthermore, the mechanical actions on buildings are standardized in the various sections of DIN EN 1991-1.

In the event of a fire, DIN EN 1991-1-2 (Eurocode 1 Part 1-2) [10.1] recommends, and the responsible DIN working committee for Germany also confirms in the National Annex, that the partial safety factors for the material characteristics are uniformly γ_M = 1.0 for all building materials and types of construction, which means that calculations are made with the characteristic values.

Thus, the required reliability of the fire safety design can only be ensured by defining a sufficiently conservative design fire. Incidentally, this corresponds to the previous practice of defining the fire exposure by means of the standard fire curve (ISO 834) for fires in normal building construction (residential and office buildings and buildings with comparable use), and a fire resistance duration that is on the safe side as required by building regulations.

Depending on the natural fire model and verification method used, different input variables are decisive for the fire exposures which show scattering and perhaps even model uncertainties and which should have partial safety coefficients added to them for this reason:

- The fire load, where the fire duration is decisive for the design (e.g., for structural components with a longer fire resistance period and for wooden components with a constant rate of combustion (this case is dealt with in Eurocode 1 Part 1-2, Annex E),
- The rate of fire propagation, if the fire exposure in the early phase of the fire becomes decisive (e.g., room temperature for unprotected steel components),
- The fire surface and/or mass loss rate, which determine the maximum heat release rate and temperature development in the stationary phase of a fire load controlled fire,
- The ventilation conditions which are decisive in ventilation-controlled fires for the maximum heat release rate and temperature development.

10.4.2 Probability of occurrence of a fire

The reliability required for the design of the structure and certifying life safety in the event of fire depends on the probability of a damaging fire occurring in a utilisation unit of a building and the related damage consequences (damage to components and/or persons).

The probability of occurrence p_{fi} of a destructive fire in a utilization unit with base area A, effectively separated in terms of fire protection in a reference period of 1 year, can be determined using equation (10.1):

$$p_{fi} = p_1 \cdot p_{21} \cdot p_{22} \cdot p_3 \tag{10.1}$$

with

p_1 Annual probability of occurrence of an initial fire in the unit of use,

p_{21} Probability of firefighting failure by users,

p_{22} Failure probability of firefighting by the fire brigade,

p_3 Failure probability of firefighting by an automatic extinguishing system.

The annual probability p_1 of at least one fire occurring in the utilisation unit can be determined according to equation (10.2) assuming an area-related fire outbreak rate λ_1 independent of the floor area, or alternatively according to equation (10.3) taking into account the fire outbreak frequency which increases (usually disproportionately) with the size of the utilisation unit:

$$p_1 = 1 - exp(\lambda_1 \cdot A) \approx \lambda_1 \cdot A \tag{10.2}$$

$$p_1 = 1 - exp(a \cdot A^b) \approx a \cdot A^b \tag{10.3}$$

with

A Floor area of the fire compartment [m^2],

λ_1 Mean rate of occurrence of incipient fires per square metre of floor area and year [$1/(m^2 \cdot a)$],

a Basic value of the related frequency of fire outbreak per square meter and year [$1/(m^2 \cdot a)$],

b Exponent, which depends on the type of use and the subdivision of the utilisation unit (room cells).

Simplified, an average annual probability of occurrence p_1 can be used for a typical variable (i.e., average floor area) of an area put to the appropriate use.

Numerical values for λ_1, a and b and p_1 can be taken from the Table 10.3. The data for various uses were compiled in [10.23] based on an evaluation of various international sources, in particular [10.25] and [10.26].

Table 10.3 Mean annual occurrence rate of fires λ_1 per square meter of floor area per storey or occurrence probability p_1 per utilization unit for various uses (according to [10.25], [10.26])

Utilization	Mean occurrence rate per m^2 and year	Probability of occurrence per utilization unit and year		
		$p_1 = a \cdot A^b$		p_1
	λ_1 [$1/(m^2 \cdot a)$]	a [$1/(m^2 \cdot a)$]	b	[1/a]
Residential building	4.7E-6	4.8E-5	0.9	3.0E-3
Office building	2.1E-6	5.9E-5	0.9	6.2E-3
Hospitals, nursing homes	5.6E-6	7.0E-4	0.75	3.0E-1
Public places of assembly, private places of assembly	3.8E-6	9.7E-5	0.75 1.0	2.0E-2 1.2E-1
Schools, educational institutions hotels, lodging facilities	1.9E-6 -	2.0E-4 8.0E-5	0.75 1.0	4.0E-2 3.7E-2
Commercial buildings	4.7E-6	6.6E-5	1.0	8.4E-3
Industrial buildings (production)	6.4E-6	1.7E-3	0.53	4.4E-2
Storage buildings	1.4E-5	6.7E-4	0.5	1.3E-2

The failure probability p_{21} takes into account the early fighting of the initial fire by the users, p_{22} applies analogously to the extinguishing measures of the fire brigade. Based on international experience and statistical studies, a flat-rate probability of failure of $p_2 = p_{21} \cdot p_{22} \approx 0.1$ can be calculated.

According to English fire statistics, an average of 50 - 70 % of initial fires are extinguished by the users [10.30] (conservatively $p_{21} = 0.5$), so that the fire brigade is either not alerted at all or only has to carry out supplementary extinguishing work.

The success of firefighting by the fire brigade depends on the one hand on the intervention time and efficiency of the fire brigade and on the other hand on the spread of the fire until the beginning of the extinguishing work. For public fire brigades, an average intervention time of approx. 15 minutes can be assumed. The intervention time of a plant fire brigade is usually significantly shorter than that of the public fire brigade and, if necessary, the strength and equipment is adapted to the specific object, so that the probability of failure p_{22} is lower.

Numerical values for p_{22} for firefighting by a public fire brigade or a works fire brigade are suggested in Table 10.4. Linear interpolation is permitted between the specified intervention times. Since the firefighting measures of the works fire department and the public fire department are not independent of each other, only one fire department, i.e., the one with the lower probability of failure, may be taken into account in equation (10.1).

Table 10.4 Probabilities of failure p_{21}, p_{22} and p_3 of fire fighting[1]

Firefighting by	Probability of failure		
	p_{21}	p_{22}	p_3
User	0.5		
Public fire brigade with intervention time < 15 min > 20 min		 0.2 0.5	
Works fire brigade with intervention time 1) < 10 min (four seasons) < 10 min (two seasons)		 0.020 0.05	
Automatic extinguishing system Sprinkler system according to VdS/CEA standard 2) in other cases Other water extinguishing system Gas extinguishing system			 0.020 0.050 0.1 0.1

1) Automatic fire detection and alarm are required
2) Planning, installation, operation and maintenance according to the recognized rules of technology

The failure probability p_3 of an automatic extinguishing system depends on the design standard. Sprinkler systems according to the VdS standard mentioned in Table 10.4 are

[1] Note: In the technical building regulations of the federal states, partly deviating specifications are made for the probabilities of default to be assumed.

systems that are planned, built, and operated according to VdS CEA 4001 and for which all quality assurance measures according to VdS CEA 4001 are applied. These include, in particular, the component and installer approvals, the maintenance measures to be carried out by the approved installer and operator, and the annual inspection by an inspection expert. The same applies to gas extinguishing systems according to the VdS standard in accordance with the VdS planning and installation guidelines for gas extinguishing systems (VdS 2093, VdS 2380, VdS 2381).

The extinguishing measures of the fire brigade and firefighting by means of an extinguishing system are approximately independent of each other, so that both p_{22} and p_3 may be used in equation (10.1). This does not apply if, due to the existing fire hazard, only a control of the fire development by the automatic fire extinguishing system in case of fire is to be expected and, therefore, an additional manual firefighting by the fire brigade is required. In this case, the failure of the automatic and the failure of the manual fire extinguishing system are no longer independent, so that, without a more detailed analysis, p_{22} = 1.0 can be conservatively assumed. A comparable interaction exists between automatic and non-automatic fire alarm systems and firefighting by the fire brigade. If a fire event occurs in a building equipped with a fire detection system, it can be assumed that the fire brigade can start fighting the fire at an earlier point in time than without a fire detection system, so that the probability of a successful extinguishing operation increases and the fire scenario under consideration is less intense. The probability of a successful firefighting operation is, however, like the interaction between the works fire brigade and the public fire brigade, a conditional probability. In this case, the failure probability p_2 to be specified for the safety concept for firefighting by the fire department would have to be specified in the form $p_{2|BMA}$ depending on the presence of a fire alarm system. Exemplary studies on the effects on the safety level were documented in [10.54]. The positive effect of the fire detection system on the fire event was approximately modelled over a shortened period of time until the beginning of the extinguishing work. However, there is hardly any statistical data available that proves how much time is saved between the outbreak of fire and firefighting in buildings with fire detection systems, compared to buildings without a fire detection system (see Chapter 7 and 7.2.3). The investigations therefore, examined the effects of a time gain of between 3 and 7 minutes. Furthermore, it was shown that the gain in safety depends on the type of fire brigade, the respective time of the extinguishing work and the failure probability of the fire detection system. It has been shown for the example that an additional factor $p_{2|BMA}$ for determining the required reliability in the event of fire can lie between $p_{2|BMA}$ = 0.15 and $p_{2|BMA}$ = 0.75, so that, for instance, a value of $p_{2|BMA}$ = 0.5 could be considered sufficiently conservative. In any case, further comparative calculations with different component types would be required for the fire safety design before the fire alarm system could be considered in the safety concept.

10.4.3 Required reliability of the construction in case of fire

In the informative Appendix B to DIN EN 1990 [10.24], the various structural systems are classified into damage consequence classes CC, which are assigned a required reliability index β or probability of failure p_f via reliability classes RC. These apply both to service load cases and to exceptional load cases such as fire. Table 10.5 shows the damage consequences as well as the values β and p_f for ultimate limit states and a reference period of 1 year. With Φ( ) as function of the standard normal distribution is

$$p_f = \Phi(-\beta) \quad (10.4)$$

Table 10.5 Classification of structural systems in damage consequences and assignment of reliability classes according to DIN EN 1990 [10.24], Annex B

Loss consequence classes CC Reliability classes RC	Characteristics	Examples in building construction
CC3 RC3	High impact on human life or very high economic, social or environmental impact β = 5.2 p_f = 1.0 E-7 (1/a)	Grandstands, public buildings with high failure rates (e.g. a concert hall)
CC2 RC2	Moderate impact on human life, significant economic, social or environmental damage β = 4.7 p_f = 1.3 E-6 (1/a)	Residential and office buildings, public buildings with medium failure consequences (e.g. an office building)
CC1 RC1	Low impact on human life and small or negligible economic, social or environmental impact β = 4.2 p_f = 1.3 E-5 (1/a)	Agricultural buildings without regular visit, (e.g. barns, greenhouses)

From the failure probability pf which applies to all load conditions and the annual probability of occurrence p_{fi} of at least one fire in the respective utilization unit according to equation (10.1), a conditional probability of failure $p_{f,fi}$ in case of fire or the reliability index β_{fi} can be determined as follows

$$p_{f,fi} = \frac{p_f}{p_{fi}} \quad (10.5)$$

$$\beta_{fi} = \Phi^{-1}(1 - p_{f,fi}) \quad (10.6)$$

Here ϕ^{-1} is the inverse function of the standard normal distribution.

For the assessment of possible economic and environmentally damaging consequences which according to Table 10.5, form the basis for the assignment of reliability classes according to DIN EN 1990, each case usually has to be viewed individually in the event of fire. Especially in the case of industrial buildings, a sweeping assessment of the economic consequences, which depend strongly on the individual operational processes and interactions of the company activities, is not appropriate.

10.4.4 Partial safety factors for the fire protection design of the structure

The temperature of the structural element is usually the decisive fire action for the fire protection design of structural elements and supporting structures. It results from the fire room temperature in the surrounding of the building components, which in turn depends on the type, quantity and distribution of the fire loads within the room, the ventilation conditions, the properties of the fire room and, where applicable, the effect of technical fire protection and firefighting systems.

There are only a limited number of data sources for fire loads in multiple-use buildings. In DIN EN 1991-1-2, Annex E [10.1] and in the National Annex DIN EN 1991-1-2/NA [10.35], mean values and standard deviations of fire load densities (mean fire loads per m^2 floor area) are given for typical building uses. Based on this, in [10.35] the 90% fractiles were recommended as characteristic values, which were calculated according to [10.1] assuming a Gumbel distribution with a coefficient of variation of 0.3 (see Table 10.6).

The fire load densities in Table 10.6 apply to areas that are typical for the respective use. Special rooms should be considered separately. Fire loads due to the building construction (supporting elements, claddings and coatings) should also be determined separately and added to the values in the Table 10.6.

In order to determine the time course of the room temperature with a natural fire model, a resulting course of the heat release rate is determined under specification of a design fire scenario, which contains a large part of the influencing variables. DIN EN 1991-1-2/NA [10.35] also specifies characteristic values for the heat release rate for the above-mentioned typical building uses.

Table 10.6 Fire load densities [MJ/m²] for various building uses (based on [10.1])

Utilization	Average value	Standard deviation	90 % quantile
Living	780	234	1085
Hospital (room)	230	69	320
Hotel (room)	310	93	431
Bookshop, Library	1500	450	2087
Office	420	126	584
School (classroom)	285	85,5	397
Shopping Centre	600	180	835
Theater (cinema)	300	90	417
Traffic (public area)	100	30	139
Industry - storage	1180	*)	2240
Industry - production	300	*)	590

*) The fire load densities in industrial buildings scatter widely. The values given are only a guide, they cannot usually replace a more precise determination.

In [10.23], extensive reliability analyses were performed for individual components made of different building materials (concrete, steel and wood) in buildings used for different purposes (residential/office buildings, sales/assembly areas, industrial buildings). For comparison, the reliability of the same components under standard fire load was calculated according to ISO 834, whereby the fire resistance required by the building authorities was specified deterministically. It turned out in all cases that during the fire, the reliability under realistic natural fire exposure taking into account scattering influencing variables is higher than under standard fire exposure at the end of the required fire resistance.

Furthermore, it was also shown that due to its wide scattering, the fire load density with concrete and steel elements has a decisive influence on reliability. In the case of wooden components, this applies to the mass burning rate of wood. The next most important factor is the maximum heat release rate in the phase of a fully-developed fire.

It is assumed that 90 % fractiles are defined as characteristic values for each of these decisive influencing variables of fire exposure. For the design, design values are used that are calculated from the characteristic values by multiplication with partial safety factors γ_{fi}. The partial safety factors are determined in such a way that the required reliability according to Table 10.5 is maintained on average and, in accordance with [10.23], is not exceeded or exceeded by a maximum of $\pm\Delta\beta_{fi}$ = 0.5.

A Gumbel distribution is usually assumed for both the fire load density and the heat release rate. The partial safety factors can be calculated using equation (10.7) as the quotient of the design value in the event of fire and the characteristic value:

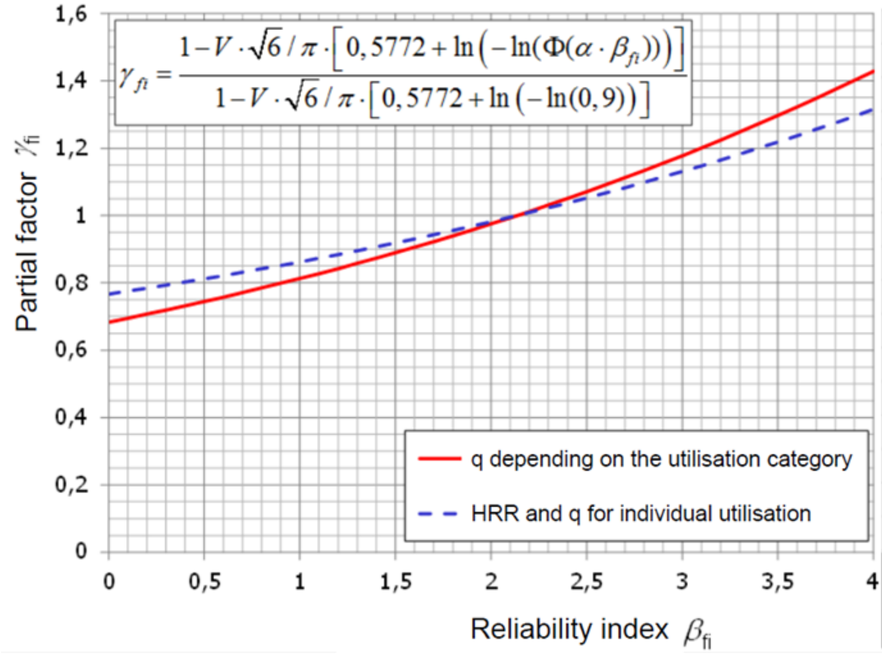
$$\gamma_{fi} = \frac{1-V\cdot\sqrt{6}/\pi\cdot\left[0.5772+ln\left(-ln(\Phi(\alpha\cdot\beta_{fi}))\right)\right]}{1-V\cdot\sqrt{6}/\pi\cdot[0.5772+ln(-ln(0.9))]} \tag{10.7}$$

Here $\Phi(\,)$ is the function of the standard normal distribution.

If the fire load density is taken from Table 10.6 as a wholesale value for utilization, the coefficient of variation is assumed to be V = 0.3 and the sensitivity factor for determining the design value is assumed to be α = 0.6. If the fire load density is determined on an individual basis (as is usual in industrial construction, for instance), the random scatter is smaller. Then the partial safety factor γ_{fi} can be calculated with the coefficient of variation V = 0.2 and the sensitivity factor α= 0.5.

Hardly any statistical data is available in the world on the area-specific heat release rate for different uses. However, the scattering is likely to be lower than for fire load densities. Analogous to the fire load density determined in individual cases, the coefficient of variation is assumed to be V = 0.2 and the sensitivity factor α = 0.5.

The partial safety factors γ_{fi} determined with these assumptions for the fire load density q and the heat release rate (HRR $\equiv\dot{Q}$) can be read off Figure 10.2 (from [10.35]) as a function of the required reliability index β_{fi}.



$p_{f,fi}$	β_{fi}
0,5	0
0,401	0,25
0,309	0,50
0,227	0,75
0,159	1,00
0,106	1,25
0,067	1,50
0,040	1,75
0,0228	2,00
0,0122	2,25
0,00621	2,50
0,00298	2,75
0,00135	3,00
0,000578	3,25
0,000233	3,50

$p_{f,fi} = p_f / p_{fi}$

$\beta_{fi} = -\Phi^{-1}(p_{f,fi})$

Figure 10.2 Partial safety factors for the influencing variables of a natural fire in relation to the defined characteristic values (90 % fractile); solid line: fire load density for uses according to the Table 10.6; dashed line: heat release rate and fire load density when determined exactly in individual cases

10.4.5 Consideration of different fire scenarios

In the presence of an automatic extinguishing system or a particularly powerful fire brigade, a destructive fire (fully-developed fire) is only to be expected with a significantly lower probability of occurrence than without these measures. When the special firefighting measures become effective, they extinguish or control the fire so that it no longer plays a role in the fire safety design of the construction.

The situation is different if the fire is influenced by technical measures such as smoke and heat extraction, but still reaches critical temperatures for the construction. Such scenarios can be considered in the event tree analysis (ETA) described in Chapter 10.3.2.

An event tree containing measures for fire detection and firefighting as well as measures for smoke and heat extraction (SHE) is shown in Figure 10.3. The individual event paths of the event tree can be assigned different fire courses a to f according to the Figure 10.4, which are described by the temporal course of the heat release rate. These fire courses are taken into account in the limit state equations for the verification of the structural elements, which are linked to each other within the framework of a system reliability analysis.

The conditional probability of failure of the system in the event of fire $p_{f,fi}$ is variable over the duration of the fire: on the one hand, the probability that a certain limit state (e.g. a failure temperature) is reached or exceeded increases with increasing fire exposure, on the other hand, the probability that extinguishing measures start and become effective also increases. Because of this opposite process, the probabilistic system reliability analysis should generally be performed in a time-step procedure. Therefore, it is very costly and not very suitable for practical applications. In [10.23], such analyses were performed to derive or calibrate safety requirements for simplified, practice-oriented verifications.

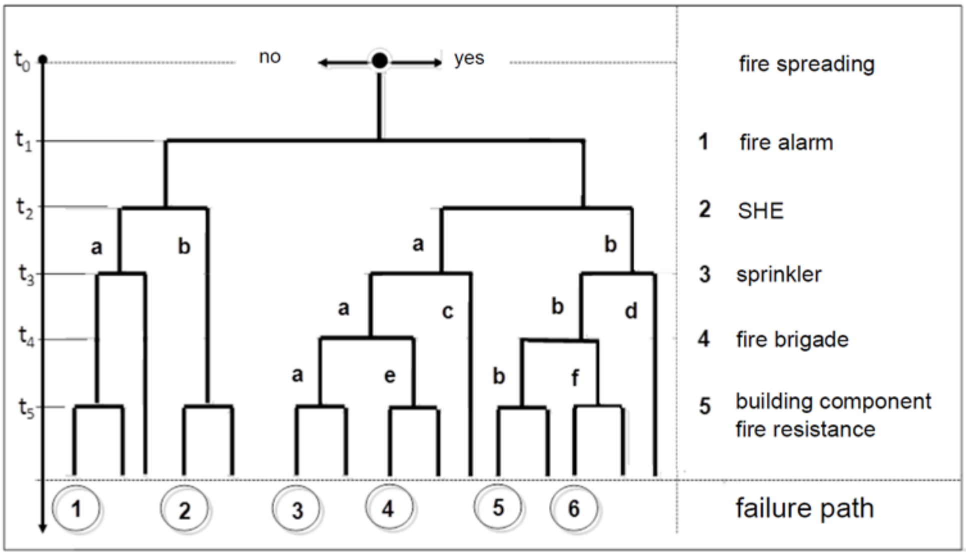


Figure 10.3 Event tree for determining possible failure paths (according to [10.3])

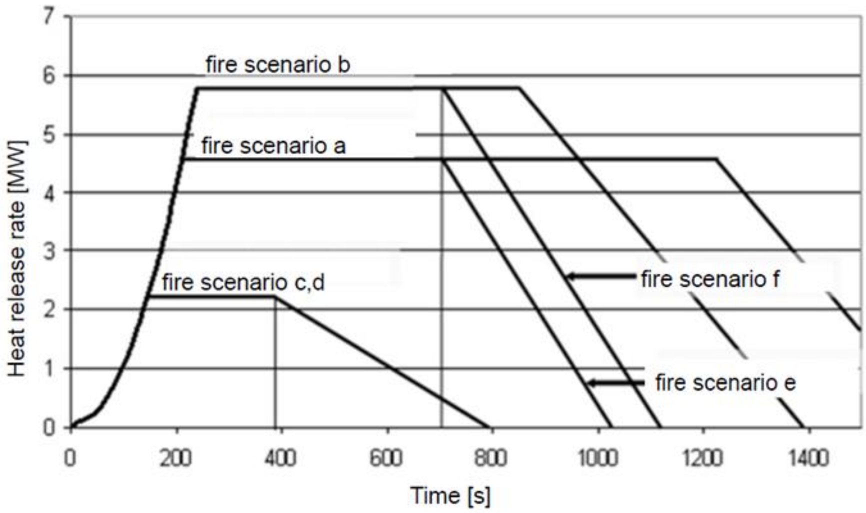


Figure 10.4 (Qualitative) fire characteristics as a function of function and failure of the technical and defence components

10.5 Safety concept for verification of evacuation in case of fire

10.5.1 Principles for performance-based certification

A quantitative safety concept for the verification of life safety analogous to the safety concept for structural fire protection (see Chapter 10.2), which quantifies and considers the existing uncertainties in the verification and ensures a constant safety level, is not yet available or has been yet developed. In practice, the boundary conditions for the application of the procedures are currently being defined between the designer and the approval authority or the test engineer. This results in individual case solutions that cannot be easily transferred to other buildings. The parties involved should ensure that the planning at least meets the generally accepted safety level. A certain degree of standardization and traceability for third parties can be guaranteed by the structured and objective derivation of decisive fire scenarios and the associated design fires, as described in DIN 18009 [10.51]. An example of a more extensive standardisation can be found in the Swiss VKF fire protection guideline 27-15 "Verification procedures in fire protection" [10.53]. This is mandatory in Switzerland for the application of fire safety engineering methods. In addition to the basic requirements for verification methods, comparable to DIN 18009-1, the performance criteria of the height of low-smoke layer together with the reference value for the extinction coefficient of 0.2 m^{-1} in combination with a heavily sooting fire material ensures that a constant safety level is achieved when performing the corresponding verifications.

The level of life safety of buildings planned according to prescriptive specifications or buildings proven on the basis of fire engineering methods is unknown and not easily quantifiable.

In the following, the status quo and the necessary work for the derivation of an appropriate safety concept are described. The preparatory work of the existing safety concept for the fire protection certification for components and structures according to the Eurocodes should be used.

The current international state of the art for the proof of life safety in case of fire is to compare the Available Safe Egress Time (ASET) with the Required Safe Egress Time (RSET). Evidence is provided if $t_{available}$ becomes greater than $t_{evacuation}$ [10.28].

$$t_{available} > t_{evacuating} \tag{10.8}$$

In most cases, an empirical safety factor is still selected to compensate for the existing uncertainties of the detection variables. With a global safety factor κ, equation (10.8) is then as follows:

$$t_{available} / t_{evacuation} \geq k \tag{10.9}$$

Although the level of safety cannot be quantified in this way, the choice of input variables and the limit values for the performance criteria, which are on the safe side, generally ensures sufficient safety. The documentation and verification of the corresponding proofs are of great importance.

The detection variables $t_{available}$ and $t_{evacuation}$ are obtained from fire or evacuation simulations of varying complexity and accuracy, taking into account different performance criteria (e.g., height of the low-smoke layer, detection distance, FED, see Chapter 10.5.3).

The very simple equation (10.9) describes a complex problem which requires a structured approach to achieve comparable results and a uniform level of safety. A possible approach is presented in the following sections.

10.5.2 Fire and evacuation simulation

There are various models in the field of fire protection engineering for the simulation of the course and effect of fires (see Chapter 5). With these models, the designer is able to calculate the available escape time $t_{available}$, depending on the performance criteria. The selection of the correct model for the problem under consideration (see Chapter 5) as well as experience in its application is of great importance.

Models of varying accuracy and complexity are available for the simulation of the evacuation (see Chapter 9). In addition to the duration of the pure evacuation movement, which can be calculated with the above-mentioned models, further time spans from the alarm to the beginning of the evacuation, the so-called pre-movement time, have to be considered (Figure 10.5). The approaches for the pre-movement time are mostly approximate and based on evaluations of evacuation exercises. The most well-known model is the Purser model (see Chapter 9, [9.1]).

Since various numerical models exist for fire and evacuation simulations, problems with the applicability and acceptance of the results may arise under certain circumstances. Nevertheless, no models should be laid down in a normative implementation of the evidence for life safety, because this would freeze the state of the art and leave no room for incorporation of the findings and outcomes of new research. Rather, a catalogue of validation examples should be provided, analogous to [10.36], in order to be able to check the suitability of the models and softwares for the respective area of application. Corresponding proposals are made, for example, in [10.37].

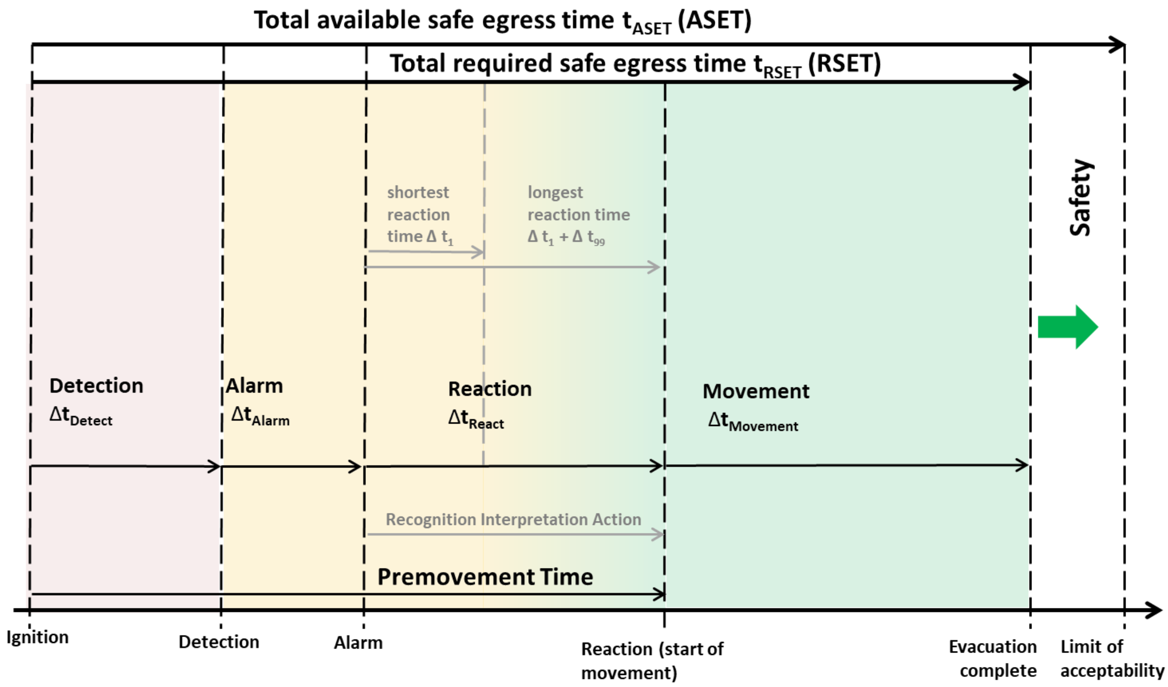


Figure 10.5 Schematic illustration of the different time spans for evacuation in the event of fire

10.5.3 Performance criteria

After selecting the models for the fire and evacuation simulation, the associated performance criteria must be defined, according to which the times for t_{ASET} and t_{RSET} can be derived from the simulation results. For the evacuation simulation this is usually quite simple: t_{RSET} describes the time until the escape process is completed, i.e., until the last person has reached a safe area.

The procedure for determining t_{ASET} is somewhat more complex, as the performance criteria implicitly lead to different levels of safety. For simplification, these are grouped into two categories:

- *Hindrance to escape*: escape can be impeded by people slowing down due to poor visibility or by changing the direction of escape due to excessive smoke density. The performance criteria used are, for instance, the height of the low-smoke layer, the recognition distance or the optical smoke (see Chapter 8).
- *Prevention of escape*: the criteria chosen here imply a greater risk for people who are unable to escape when the limit values are reached and who are no longer in a position to save themselves. In the literature [10.30], either assessment values or dose models (FED, fractional effective dose) can be found (see also Chapter 8).

Depending on the selected performance criteria, even with the same scenario and design fire with the same models leads to different t_{ASET}, so that the proof according to equation (10.9) can only be provided, taking into account the performance criteria for the category "prevention of escape" and not for the performance criteria of the category "hindrance to escape". As long as a safety concept for life safety is not yet available, performance criteria of "hindrance to escape" should be applied for corresponding proofs based on the implicit safety.

Furthermore, in addition to the different safety levels of the various performance criteria, the location of the evaluation also plays a major role, especially in the CFD models, which record the corresponding evaluation criteria in each cell. Local smoke gas concentrations can, for instance, cause the performance criteria "optical density" or "FED" to take effect earlier or later, although in reality the people are moving through the room. Since today's evacuation models are usually not directly coupled to the models for calculating the actions of fire, they cannot react to corresponding local effects. The determination of t_{-ASET} and, accordingly, the verification based on the location in the verification area that first no longer fulfils the performance criteria guarantees a verification on the safe side. Current research work in this area can be found, for instance, in [10.52].

10.5.4 Design fire scenarios and design fires

Considerable differences may arise in the individual derivation of the fire scenarios or design fires relevant for the verification and the determination of the performance criteria. Therefore, it is important to identify the relevant fire scenarios and to determine design fires. With regard to life safety, there is a tendency to develop fire scenarios that have a direct or indirect effect on the escape route and to derive design fires accordingly. A standardised procedure based on a safety concept should therefore at least provide appropriate qualitative specifications.

Principles and rules for the application of fire protection engineering methods are regulated in DIN 18009 [10.51]. The selection of relevant scenarios and their concretization (worst-credible) is carried out here on the basis of the probability of occurrence and the extent of damage.

A further approach for the definition of design fire scenarios is provided by the US-American guideline NFPA 101 "Life Safety Code" [10.37], which, in addition to prescriptive requirements, also provides performance-oriented proof. Eight different scenarios are specified for this purpose, which are listed in Table 10.7.

Table 10.7 Design fire scenarios based on NFPA 101 [10.39]

Scenario	Description
1	Typical use-dependent scenario (standard case)
2	Very fast developing fire in the main escape route (reduction of the number of escape routes)
3	Ignition in an unused room next to a room with a large number of people (undetected fire outbreak)
4	Ignition in an unused room without detection or sprinkler system next to the room with a high number of people (failure of fire protection barriers)
5	Slowly developing fire shielded from fire barriers near highly frequented rooms (low-energy fire)
6	Fire with the highest possible fire load of an intended use (large fire in normal use)
7	Fire entry from outside, which develops into the relevant section (fire propagation)
8	Standard fire taking into account the failure of active and passive fire protection systems (worst case scenario)

If one of the fire scenarios is not relevant or not possible, this must be justified. Furthermore, additional scenarios should be demonstrated, taking into account the characteristic features of the building structure and the safety objectives, if they become relevant in the individual case. This procedure ensures that the most important cases are covered. Fleischmann [10.38] assigns the performance criteria to the individual scenarios depending on their risk contribution. For instance, the FED criterion should be fulfilled for the worst-case scenario 8, while for the standard case scenario 1 the detection range is applied. In a further step, the design fires are derived from the defined fire scenarios.

For the design fires, which are usually specified in the simulation models, such as the time course of the heat release rate ($HRR_{(t)}$), the Life Safety Code does not make any concrete requirements [10.37]. Also, no specifications are made regarding the maximum heat release rate, the fire load and other parameters. In order to ensure comparable verifications, it is considered useful to completely define and document the fire scenarios depending on the type of use, size and/or other parameters in a holistic safety concept for the verification of life safety. Fleischmann [10.38] presents various scenarios based on the t^2 fire and defines the associated parameters such as calorific values, fire growth rates, rates of harmful gas formation.

With the publication of DIN 18009-1 [10.51], a standard has become available in Germany which specifies performance criteria for the verification by means of fire safety engineering methods for the specification of fire safety objectives and functional requirements. The basic principles are the identification of fire hazards and the assessment of the resulting risks, which can be used as an objective basis for the selection of fire and evacuation scenarios relevant for design.

In addition to the derivation of relevant scenarios, information on suitable models and principles for the determination of safety factors and surcharges is given.

10.5.5 Probabilistic quantification of the safety level

The above-mentioned specifications for the simulation models are only the first step towards a holistic approach for the development of a safety concept for the verification of life safety in the event of fire. Although the decisive influencing variables, models and performance criteria have been named, no quantitative analyses have yet been carried out which demonstrate the current safety level or prove that the required safety level is achieved by the performance-oriented verifications.

In contrast to the verifications for structural elements and load-bearing structures in the event of fire, no target failure probabilities are regulated for verifications of life safety in the event of fire. As described, this is problematic due to the different safety levels associated with the performance criteria (see Chapter 10.5.3).

In this case, analogous to GruSiBau [10.39] or EN 1990 [10.24], performance criterion-related probabilities of failure can be derived by examining representative buildings or relevant parts of buildings that comply with the applicable building code with regard to their probabilities of failure in relation to the respective performance criterion and the relevant scenario. A classification into risk classes could be carried out e.g., analogous to [10.35] according to building class and use. Representative target failure probabilities could then be derived from a sufficiently large number of comparative calculations (see Chapter 10.5.9).

In general, equation (10.8) can also be interpreted as a probabilistic limit state, where both t_{ASET} and t_{RSET} exhibit scattering and uncertainties. The failure range of the limit state function Z is then defined as

$$Z(x) = t_{ASET} – t_{RSET} \leq 0 \tag{10.10}$$

It is the totality of the combinations of values with which equation (10.10) results in less than or equal to zero, where x is a vector of the parameters with an uncertainty. If t_{ASET} and t_{RSET} with its stochastic parameters mean μ and standard deviation σ are known and can be assumed to be normally distributed, the conditional probability $p_{f,fi}$ of unsuccessful evacuation in the case of a dangerous fire can be calculated using equation (10.11):

$$p_{\mathrm{f,fi}} = \Phi\left[\frac{-(\mu_{t_{ASET}} - \mu_{t_{RSET}}}{\sqrt{\sigma^2_{t_{ASET}} + \sigma^2_{t_{RSET}}}}\right] = \Phi(-\beta_{\mathrm{fi}}) \tag{10.11}$$

Here μ is the mean and σ the standard deviation of the stochastic variables t_{ASET} and t_{RSET}. Where $\phi()$ is the function standard normal distribution and β_{fi} is the reliability index in case of fire.

Generally, neither the distribution parameters of t_{ASET} and t_{RSET} are known a priori, nor do they necessarily follow a normal distribution. In this case, the probability of failure has to be calculated with much more sophisticated methods like the First Order Reliability Method (FORM) or the (optimized) Monte Carlo Method for simulation-based approaches. These methods themselves require a large amount of computing time, which is why they currently cannot be easily coupled with fire simulation models, which are also computationally intensive. Further research is needed here. In the following, the procedure is therefore explained by means of two examples.

10.5.6 Example for probabilistic recalculations with simple models

As an example, for the standard scenario according to Table 10.7, the probability of an unsuccessful evacuation is calculated using simple models for a 200 m² large and 4 m high place of assembly. The models used - the zone model [10.41] and the evacuation model [10.33] - correspond to the typical case of simple engineering methods. In a first step, the necessary parameters were identified and described with stochastic models based on literature references (Table 10.8) (see also [10.43]).

Due to the limited sources, all parameters were assumed to be on the safe side as normally distributed with conservative mean values and standard deviations. Therefore, the result can also be assumed to be on the safe side.

Table 10.8 Stochastic parameters for the verification with simple models

Parameters	Mean value	Standard deviation
Max. heat release rate	2000 kW	500 kW
Fire growth duration up to 1 MW	300 s	80 s
Person density per m² at the beginning	2.0 P/m²	0.5 P/m²
Used area per person in the crowd flow	0.1 m²	0.0125 m²
Reaction time	60 s	15 s

The performance criterion used to determine t_{ASET} was a low-smoke layer height of 2.5 m (category: hindrance to escape). The optimized Monte Carlo method "Adaptive Importance Sampling" (AIS) according to [10.43] was used as calculation method. For the calculation of the failure probability about 1200 simulations were needed. The analyses resulted in a failure probability under the condition that a dangerous fire occurred of $p_{f,fi} = 6.28 \cdot 10^{-2}$, which corresponds to a reliability index $\beta_{fi} = 1.5$.

The sensitivity analyses showed that the fire growth duration with 77 % and the reaction time with 22 % have the greatest influence on the probability of failure and therefore together contribute 99 % to the overall variance (Figure 10.6).

If this tendency should be confirmed in future calculations, it appears reasonable to ensure the required reliability for simple verifications by appropriately selected characteristic values for the fire growth duration and the reaction time.

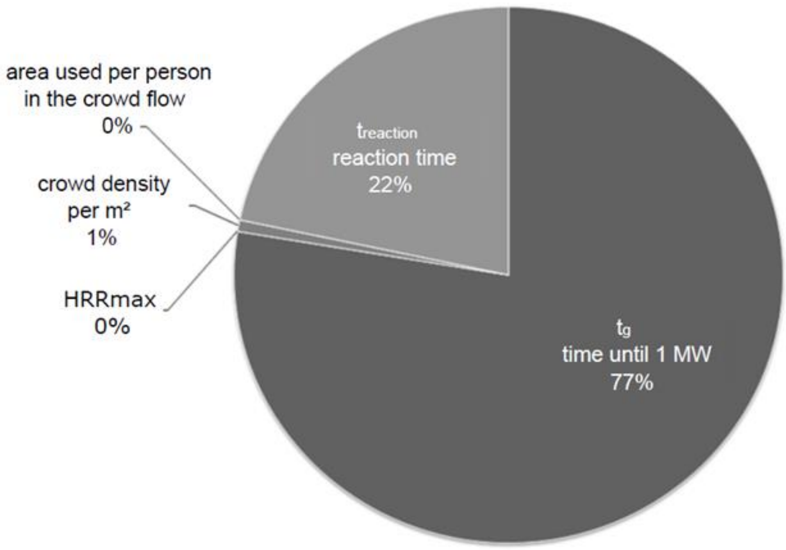


Figure 10.6 Sensitivities for the reliability calculation with a smoke layer height of 2.5 m as performance criteria (the fire development time until 1 MW is the clearly dominant parameter)

For the derivation of a maximum permissible target failure probability $p_{f,target}$, which should be compared to the calculated failure probability p_f, the procedure is analogous to the safety concept for the design of the components. This depends on the choice of the performance criterion. Since when using a performance criterion such as the low-smoke layer with a height of 2.5 m, unlike, for instance, the performance criterion FED, personal injury does not have to be expected immediately if the performance criterion is not met, it is possible to orientate oneself on the target reliability for the serviceability limit state checks for components. This target failure probability is thus $p_{f,target} = 1 \times 10^{-5}$ ($\beta = 2.9$).

Since the probability of failure $p_{f,fi}$ applies under the condition that a dangerous fire has occurred, the (low) probability p_{fi} of at least one fire in the unit of use can also be taken into account. In analogy to the safety concept for structural components according to Chapter 10.4 and [10.35], a reference period of one year is taken. For the example examined, Table 10.3 (last column) is used to select a general annual probability of occurrence $p_1 = 0.02$.

As a measure to prevent the spread of a fire, manual firefighting by the users can be considered with a failure probability $p_{21} = 0.5$ according to Table 10.4, since a fire fought by the users usually does not develop into a dangerous fire anymore. Firefighting by the fire brigade usually starts only after completion of the self-rescue, so that the failure probability of the fire brigade's extinguishing measures is not relevant here and is assumed with $p_{22} = 1.0$. Assuming that the occurrence of the fire, the manual firefighting by the users and the falling below the low-smoke layer height are independent of each other, the probability that a fire will result in a fall below the limit value for the low-smoke layer of 2.5 m before the last person has left the room is

$$p_f = p_1 \cdot p_{21} \cdot p_{22} \cdot p_{\mathrm{f,fi}} = 0.02 \cdot 0.5 \cdot 1.0 \cdot 0.0628 = 6.28 \cdot 10^{-4} \text{ 1/a} \quad (10.12)$$

The associated reliability index is $\beta = 3.22$ and is thus above the value $\beta = 2.9$ for verifications of the usability of supporting structures according to [10.24]. The conditional failure probability in of the event of fire ($p_{f,fi}$ = 6.28·10^{-2} or β_{fi} = 1.5) determined in the present example with conservative assumptions for the input variables is obviously sufficient because if the smoke-free layer height of 2.5 m is not reached, escape is impeded but not prevented. There is therefore no direct danger to persons.

To illustrate the conservative nature of the chosen performance criterion (low smoke layer with a height of 2.5 m), the reliability assessment was repeated again with identical models and input values, but this time a less conservative performance criterion of a low smoke layer height of 1.8 m was used. This results in a conditional probability $p_{f,fi}$ = 0.26 %, which is lower by a factor of 25, that the low-smoke layer height of 1.8 m is undercut in the event of a fire before all persons have left the room:

$$p_f = p_1 \cdot p_{21} \cdot p_{22} \cdot p_{\mathrm{f,fi}} = 0.02 \cdot 0.5 \cdot 1.0 \cdot 0.0026 = 2.6 \cdot 10^{-5}\ 1/a \tag{10.13}$$

This corresponds to a reliability index β = 4.0, which is almost in the range of the reliability (β = 4.7) to be aimed for according to [10.24] or [10.35] for ultimate limit states of load-bearing capacity.

10.5.7 Influence of fire protection systems using the example of a fire detection system

In order to be able to quantify the influence of fire protection systems, it is necessary to include them in the system taking into account their failure probability. For instance, the influence of a fire detection system with building-internal alarm will be considered here. Although it does not have a direct effect on the course of the fire like a sprinkler system, it can contribute to a significant reduction of the reaction time by early detection of the fire and subsequent alarming, as is already envisaged to some extent in Pursers model [9.1].

In order to maintain comparability, the previous example is taken over unchanged, but now a normal distribution with a mean value of 45 s at constant standard deviation (15 s) is assumed for the response time with a functioning fire detection system with alarm. The calculation of the conditional probability of failure for the performance criterion smoke layer height of 2.5 m for a fire and a functioning BMA with alarm chain yields $p_{f,fi,BMA}$ = 1.96·10^{-2}.

However, the fire detection system with alarm chain may fail on request. In Chapter 7, a probability of failure of $p_{f,BMA}$ = 0.00092 is given with reference to tests of fire alarm systems conforming to standards, which are installed and regularly maintained by certified service providers. In view of the fact that not all fire detection systems in use are designed, installed, operated and maintained in accordance with the recognized rules of technology, it is recommended to assume a value of $p_{f,BMA}$ = 0.05, which is on the safe side, for future safety concepts. If the fire detection or the alarm fails, the scenario already calculated above with the conditional probability of failure $p_{f,fi}$ = 6.28·10^{-2} will occur. The interrelationships are shown in the Figure 10.7 as a system (according to Albrecht [10.27]).

The probability of failure of the system is mathematically simplified to

$$p_f = p_1 \cdot p_{21} \cdot p_{22} \cdot \left[p_{f,BMA} \cdot p_{f,fi} + (1 - p_{f,BMA}) \cdot p_{f,fi,BMA}\right] \tag{10.14}$$

The annual probability that in the event of a fire, the smoke layer will fall below 2.5 m before all persons have left the room is calculated with the failure probability $p_{f,BMA}$ = 0.05 to p_f = 2.18·10^{-4} if a fire detection system with alarm is present, which corresponds to a reliability index β ≈ 3.5. In the presence of a fire detection system with a chain of alarms the failure probability for the rescue of persons reduces by a factor of 2.9.

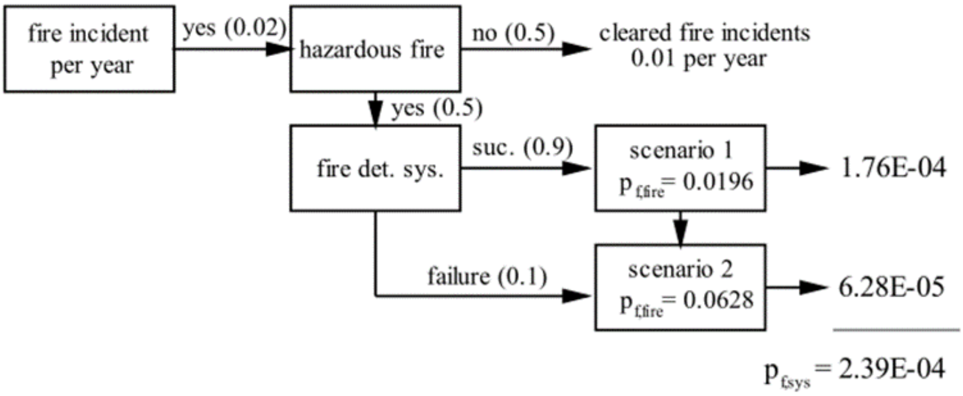


Figure 10.7 Representation of the fire protection system considering a fire detection system with a chain of alarm (approximate solution by multiplying and adding the components according to [10.27])

A comparison with other systems, taking into account the respective costs, could therefore provide an optimised cost-benefit solution without compromising the (required) safety level. The case presented here again represents only an exemplary application. In order to be able to generally evaluate the influence of equipment-related measures on the reliability of the rescue of persons in the event of fire, additional system analyses should be carried out with statistically proven failure probabilities. (see Chapters 7.2.4, 7.3.4, 7.4.4).

10.5.8 Example for probabilistic recalculations with complex models

The probabilistic calculation is more complex when using complex calculation models (e.g., numerical models of the flow and evacuation simulation), since these usually require significantly longer calculation times. For this purpose, a response surface method was developed in [10.45] with which such probabilistic analyses are possible with few calculation runs under certain boundary conditions.

For the analyses, the example shown above was adopted and the FED value determined during simulation calculations with the FDS software [10.46] near the exits from the fire room was selected as the performance criterion. The areas near the exits from the fire room represent the design case because this is where most fire fatalities are found during escape attempts [10.47] and because congestion can usually form here. The quadratically developing fire in the area of the bar was assumed as the design scenario. The available time t_{ASET} represents the period from the beginning of the fire until the point in time when an FED value of 0.3 is reached at one of the exits from the fire room.

A capacity analysis was chosen for the evacuation in order to simplify it. A slowing down of people by smoke was neglected, because the congestion in front of the doors causes a slowing down anyway. The stochastic models, whose parameters were assumed to be normally distributed, are shown in Table 10.9.

The conditional probability that in the event of a fire at one of the doors an FED value of 0.3 is reached or exceeded before all persons have left the fire room is now calculated as $p_{f,fi}$ =

$9.22 \cdot 10^{-7}$. This value for the performance criterion "Prevention of escape" with an FED value ≥ 0.3 is, as expected, far below the conditional failure probability for performance criterion "Hindrance to escape" with a low smoke layer height ≤ 2.5 m. The probability of failure of the rescue of persons in the event of fire in relation to a reference period of one year results analogously to the example in chapter 10.5.6 at $p_f = 9.22 \cdot 10^{-9}$, which corresponds to a reliability index β = 5.6 and is thus somewhat higher than the value of the target reliability for limit states of load-bearing capacity (β = 5.2 for high damage consequences CC3) which is used here as a comparative value. If instead of the performance criterion of the FED value (prevention of escape) the performance criterion of maintaining a low-smoke layer height of 2.5 m (performance criterion obstruction of escape) is chosen, greater failure probabilities should be expected. On the other hand, the value for the target reliability is then based on the serviceability limit state (β = 2.9).

This is an indication that the standard verification for compliance with a low-smoke layer height of 2.5 m guarantees conditions for the rescue of persons that are on the safe side.

Table 10.9 Stochastic parameters for verification with complex models

Parameters	Mean value	Standard deviation
Max. heat release	2500 kW	250 kW
Fire growth duration up to 1 MW	300 s	50 s
Carbon Monoxide Yield	0.1 g/g	0.02 g/g
Reaction time	60 s	12 s
Walking speed	1.2 m/s	0.12 m/s
Number of persons in the room at t=0	300 Pers	30
Capacity of the doors	1.39 Pers/m/s	0.139 Pers/m/s

An analysis of the sensitivities, as shown in the Figure 10.8, shows that the decisive influencing variables here are the duration of the fire (67 %) and the number of people (16 %). The door capacity (8 %), CO concentration (5 %) and reaction time (4 %) play only a minor role in this case.

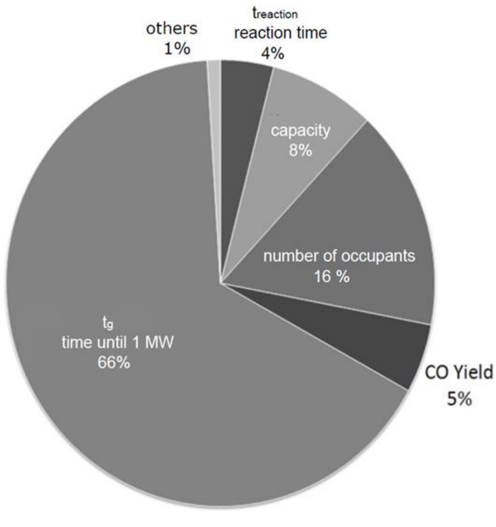


Figure 10.8 Sensitivities for the calculation of the reliability with the FED value as performance criterion

For parameters with a high sensitivity, a partial safety factor should be specified in addition to a suitably selected characteristic value when a suitable safety format is subsequently defined. For parameters with medium influence, the characteristic value may be sufficient.

It is becoming apparent that an additional partial safety factor is required for the corresponding verifications of life safety, above all for the duration of fire development, as was already recommended in principle in [10.48]. The other influencing variables could be used with conservatively chosen characteristic values (nominal values) without additional safety elements.

Also in this verification, fire protection systems with their respective failure probability can be included in the analyses and quantified with regard to their effectiveness analogously to Chapter 10.5.7. An example can be found in [10.45].

On the basis of the reliability analysis according to Chapter 10.5.6, a safety concept with a global safety factor κ according to equation (10.9) could also be calibrated in such a way that a target failure probability is complied with for the respective performance criterion with a certain tolerance.

10.5.9 Performance criteria and reliability requirements

Depending on the nature of the performance criterion, comparable criteria of proof should be created, which include the following information:

- The performance criterion itself,
- The permissible limit value,
- The place or method by which the value is recorded,
- The period of consideration, and
- The admissible probability.

A well-formulated probabilistic performance criterion could be, for instance:

"An optical density of 0.1 1/m measured at a height of 2.5 m at the exit from the room to be verified (t_{ASET}) may only be undercut with a maximum permissible probability of failure $p_{f,fi}$ in the event of a fire during the required evacuation time, i.e. the time until the last person has passed the exit (t_{RSET})."

For verifications with the performance criteria of the low-smoke layer height, which only describe a hindrance to escape, the maximum permissible failure probability is $p_f = 1.9 \cdot 10^{-3}$ [1/a], in accordance with the method described in DIN EN 1990 [10.24], Annex C for serviceability limit states with medium consequences $\beta = 2.9$. If a bandwidth of $\Delta\beta = \pm\ 0.5$ is allowed for smaller or larger consequences, the annual probability of failure p_f should lie between max $p_f = 8.2 \cdot 10^{-3}$ and min $p_f = 3.4 \cdot 10^{-4}$ [1/a].

If the verification is carried out with the performance criteria FED value, which considers the prevention of escape, the target failure probability should be chosen in the same order of magnitude as for verifications of load-bearing capacity. For average damage consequences this means pf = $1.3 \cdot 10^{-6}$ [1/a], corresponding to $\beta = 4.7$ with a range of $\Delta\beta = \pm 0.5$ for smaller or larger consequences (e.g., smaller or larger number of persons affected) between max p_f = $1.3 \cdot 10^{-5}$ and min p_f = $1.0 \cdot 10^{-7}$ [1/a].

Concrete definitions of the performance criteria and target failure probabilities should be developed in the framework of further research projects and should be based on comparative calculations with the reliability methods described above for different buildings that comply with the applicable prescriptive regulations and standards. Subsequently, a suitable safety format - with partial safety factors γ_i for individual parameters with a particularly large influence on reliability or with a global safety factor κ for the required evacuation time - can be developed and calibrated using reliability verifications for a representative selection of buildings.

Even in performance-oriented concepts, some elements must be defined prescriptively. Examples of this are the scenarios and performance criteria to ensure comparability and testability. Specifications should also be made for the approach of equipment-related fire protection measures. For instance, only a sprinkler system that is designed, approved and maintained in line with the relevant standards can have the high level of availability and effectiveness required in the safety concept.

In addition, there are also basic requirements that cannot be replaced by performance-oriented approaches, e.g., the requirement for two independent escape routes above a certain room size or number of persons. These elements should be identified, calibrated and specified.

10.6 Proof of effective firefighting operations

In recent years, the fire safety objective of "effective firefighting operations" as defined by the statutory authorities has also become the focus of attention and has led to controversial discussions in practice. These were triggered by a position paper of the expert commission for construction supervision of ARGEBAU (conference of German building ministers) [10.49]. In this paper it is clarified that the safety objective "Rescue of persons" is achieved in standard buildings solely by complying with the material requirements for the design and dimensioning of escape routes in accordance with regional building regulations. Particular measures for smoke extraction in the event of a fire are therefore not required for this fire safety objective. However, smoke extraction measures may be necessary in order to ensure sufficient visibility for the fire brigade and thus enable effective extinguishing work to be carried out. With this in mind, the expert commission for building supervision has reviewed and revised various special building regulations (regulations governing sales premises and places of assembly, guidelines for industrial buildings).

It is undisputed and qualitatively comprehensible that in the event of a fire, the fire brigade can find the source of the fire more quickly and fight the fire more effectively if visibility is sufficient. However, it remains unclear to what extent keeping an area free from smoke contributes to the success of firefighting operations, i.e., whether it influences the failure probability of the firefighting system according to Chapter 10.4.2.

In order to quantitatively evaluate this influence, a model is needed for the effectiveness of firefighting operations carried out by the fire brigade, as described in simplified form in Chapter 7.6.1.4 of the guideline. The model is based on the following limit state equation, in which the fire area A_F, which increases with the duration of the fire, is compared with a maximum controllable fire area $A_{F,max}$

$$Z = A_{F,max} - A_F(t_{act}) = A_{F,max} - \pi \cdot (v_{aus} \cdot t_{act})^2 \quad (10.15)$$

In order to determine the fire area A_F, the internationally accepted approach for the heat release rate in the fire growth phase ($\alpha \cdot t^2$ approach) is transformed by assigning a numerical value for the fire growth rate v_{aus} to the characteristic value for the fire growth α. In example calculations the rate of fire development was assumed as follows:

v_{aus}= 0.4 m/min for a medium fire growth

v_{aus} = 1.0 m/min for rapid fire propagation

Information about the fire areas $A_{F,max}$ which can be controlled by the fire brigade can hardly be found in the literature. Only with regard to ground floor industrial buildings, clear parameters can be found in [7.16]. Alternatively, in Chapter 7.6.2 probabilities of failure p_{22} for the firefighting work of the fire brigade as a function of the intervention time for two different controllable fire areas $A_{F,max}$ = 200 m² or 400 m² were determined in parameter calculations and compared with empirical values from practical application.

Theoretically, the size $A_{F,max}$ offers the possibility to consider the performance of the fire brigade, e.g. according to the number of firefighters and/or jet pipes, a better extinguishing water supply, a clearer building or better visibility conditions due to smoke extraction:

$$A_{F,max} = f(\text{fire brigade, extinguishing water, building, smoke extraction}) \quad (10.16)$$

To get reliable statements, however, statistical data is required which can only be provided by nationwide fire statistics. In Germany, it is well-known that there are large deficits in this area, which means that short-term results cannot be expected quickly. Since the last edition of this guideline, no significant changes have been recorded in this respect. However, in 2017 the Technical Committee Preventive Fire and Hazard Protection of the German Fire Brigades (FA VB/G) has published an evaluation sheet on measures of preventive fire and hazard protection [10.50], which can be used as a basis for a uniform data collection. If the application of the evaluation form is accepted by the German fire brigades, a reliable database can be expected until a further edition of this guideline is published, which will allow further investigations and the development of a safety concept for the fire safety objective "effective firefighting operations" analogous to the concepts described above for the safety objective "constructive fire protection" and "evacuation in case of fire".

10.7 Literature

[10.1] DIN EN 1991-1-2:2010-12, Eurocode 1 - Einwirkungen auf Tragwerke; Teil 1-2: Allgemeine Einwirkungen, Brandeinwirkungen auf Tragwerke.

[10.2] *RANTANTALO, T.; DOBBERNACK, R.*: State of the Art of Fire Risk Analysis; 10. Internationales Brandschutz-Symposium des vfdb, Ingenieurmethoden des Brandschutzes, Kurzreferate, Herausgeber D. Hosser; 6. und 7. Juni 2005, Hannover, 2005.

[10.3] *DEHNE, M.*: Probabilistisches Sicherheitskonzept für die brandschutztechnische Bemessung; Dissertation, Institut für Baustoffe, Massivbau und Brandschutz, Technische Universität Braunschweig, Braunschweig, September 2003.

[10.4] *NELSON, H. E.; SHIBE, A. J.*: A System for Fire Safety Evaluation of Health Care Facilities; NBSIR 78-1555, NIST, Washington DC, 1980.

[10.5] *WATTS, J. M.*: Fire Risk Indexing. The SFPE Handbook of Fire Protection Engineering; section five, chapter 10, 3rd edition, 2002.

[10.6] XPS FIRE, manual Version 3.0, Munich Re, 9/96.

[10.7] *BUDNICK, E. K.; MCKENNA, L. A. Jr., WATTS, J. M. Jr.*: Quantifying Fire Risk for Telecommunications Network Integrity; in: Fire Safety Science – Proceedings of the Fifth International Symposium, International Association for Fire Safety Science, pp. 691 – 700, 1997.

[10.8] *FONTANA, M.*: SIA 81 – A Swiss Risk Assessment Method; in: VTT Symposium 179, Institute of Structural Engineering, ETH, Zurich, Switzerland, pp 59-69.

[10.9] *DE SMET*: F.R.A.M.E: Fire Risk Assessment Method for Engineering; http://www.framemethod.net/index_5.html.

[10.10] *LARSSON, D.*: Developing the Structure of a Fire Risk Index Method for Timber-frame Multi-storey Apartment Buildings; Report 5062, Dept. of Fire Safety Engineering, Lund University, 2000.

[10.11] *HULTQUIST, H., KARLSSON, B.*: Evaluation of a Fire Risk Index Method for Multi Storey Apartment Buildings; Department of Fire Safety Engineering, Lund University, Sweden, Report 3088, Lund, 2000.

[10.12] *KARLSSON, B.*: Fire Risk Index Method-Multi Storey Apartment Buildings, FRIM-MAB, Version 1.2, Trätek Report I 0009025, Sweden, 2000.

[10.13] *WATTS, J. M. Jr.*: Fire Risk Ranking; Section 5, Chapter 2, SFPE Handbook of Fire Protection Engineering, 2nd Edition, USA, 1995.

[10.14] *FRANTZICH, H.*: Fire Safety Risk Analysis of a Hotel; Department of Fire Engineering, Lund University, Report 3091, Sweden, 1997.

[10.15] *LINSTONE; TUROFF*: The Delphi Method – Techniques and Applications; Addison-Wesley Publishing Company, 1975.

[10.16] *NYSTEDT, F.; RANTANTALO, T.; MICHEELSEN, Ch.*: Quantifying the Safety Level in the Danish Building Fire Regulations, National Agency for Enterprise and Construction, Copenhagen, 2000.

[10.17] ISO/TC92/SC4/WG10 N24 Rev: Draft Material submitted describing Fire Risk Assessment Methods, 2001.

[10.18] *MEACHAM, B. J.*: The SFPE Handbook, Fire Protection Engineering; section five, chapter 12, 3rd edition, 2002.

[10.19] ISO/TC/SC4/WG10 N34 Rev1: Fire Safety Engineering, WG10: Fire Risk Assessment; Draft document on fire risk Assessment guidance, 09/2001.

[10.20] *RANTANTALO, T.; NYSTEDT, F.*: Use of Fire Safety Engineering and Risk Analysis in Cultural Heritage Buildings; Fire Risk Evaluation To European Cultural Heritage (FIRE TECH), European study into the Fire Risk to European Cultural Heritage, WG6, Fire Risk Assessment Methods, Example of Application (Appendix 4), 2005.

[10.21] *MAGNUSSON, S. E.; FRANTZICH, H.; HARADA, K.*: Fire Safety Design Based on Calculations, Uncertainty Analysis and Safety Verification; Department of Fire Safety Engineering, Lund University, Report 3078, Sweden, 1995.

[10.22] *HOSSER, D.; SPREY, W.*: A Probabilistic Method for Optimisation of Fire Safety in Nuclear Power Plants; in: First International Symposium on Fire Safety Science, Gaithersburg, Maryland, USA, 1985.

[10.23] *HOSSER, D.; WEILERT, A.; KLINZMANN, C.; SCHNETGÖKE, R.; ALBRECHT, C.*: Erarbeitung eines Sicherheitskonzeptes für die brandschutztechnische Bemessung unter Anwendung von Ingenieurmethoden gemäß Eurocode 1 Teil 1-2 (Sicherheitskonzept zur Brandschutzbemessung). Abschlussbericht zum DIBt-Vorhaben ZP 52-5-4.168-1239/07; Institut für Baustoffe, Massivbau und Brandschutz, Technische Universität Braunschweig, Braunschweig, November 2008.

[10.24] DIN EN 1990: 2010-12, Eurocode – Grundlagen der Tragwerksplanung.

[10.25] *RAHIKAINEN, J.; KESKI-RAHKONEN, O.*; Statistical Determination of Ignition Frequency of Structural Fires in Different Premises in Finland; Fire Technology 40, 2004, pp 335-353.

[10.26] BSI, PD 7974-1:2003: Application of fire engineering principles to the design of buildings; Part 1: Initiation and development of fire within the enclosure of origin.MBO Musterbauordnung, IS-Argebau, Fassung November 2002 zuletzt geändert am Februar 2019.

[10.27] *ALBRECHT, C.*: Grundlagen und Sicherheitskonzept für den Nachweis der Räumung im Brandfall. In: Hosser, D. (Hrsg.): Braunschweiger Brandschutz-Tage 2011, Tagungsband. Institut für Baustoffe, Massivbau und Brandschutz, TU Braunschweig, Heft 214, 2011, S. 83-100.

[10.28] *TUBBS, J. S.; MEACHAM, B. J.*: Egress Design Solutions -- A guide to Evacuation and Crowd Management Planning, John Wiley & Sons, Inc., Hoboken, NJ, 2007

[10.29] ISO 13571: Life-threatening components of fire - Guidelines for the estimation of time available for escape using fire date International Standardization Organization (ISO), 2007.

[10.30] *PURSER, D. A.*: Toxicity Assessment of Combustion Products, In SFPE Handbook of Fire Protection Engineering, Section Two, Chapter 6 National Fire Protection Association (NFPA), 2002, 1, S. 2-83-2-171.

[10.31] *MEHL, F.*: Richtlinien für die Erstellung und Prüfung von Brandschutzkonzepten, Praxisseminar Brandschutz bei Sonderbauten, 2004, Institut für Baustoffe, Massivbau und Brandschutz, TU Braunschweig, Heft 178, 2004, S. 109-134.

[10.32] MVStättVO Versammlungsstättenverordnung, Fassung Juni 2005. www.is-argebau.de.

[10.33] *PREDTETSCHENSKI, W. M.; MILINSKI, A. I.*: Personenströme in Gebäuden – Berechnungsmethoden für die Projektierung, Staatsverlag der Deutschen Demokratischen Republik, Berlin, 1971.

[10.34] *HELBING, D. & MOLNAR: P*. Social force model for pedestrian dynamics Physical Review, 1995.

[10.35] DIN EN 1991-1-2/NA:2015-09, Nationaler Anhang – National festgelegte Parameter – Eurocode 1, Einwirkungen auf Tragwerke – Teil 1-2/NA: Allgemeine Einwirkungen – Brandeinwirkungen auf Tragwerke.

[10.36] RiMEA Richtlinie für Mikroskopische Räumungsanalysen, Version: 2.2.1, 2009

[10.37] NFPA 101: Life Safety Code National Fire Protection Association (NFPA), 2008.

[10.38] *FLEISCHMANN, C.*: Is Prescription the Future of Performance-based Design? Proceedings of the 10th International Symposium on Fire Safety Science (IAFSS), 2011.

[10.39] Normenausschuss Bauwesen im DIN: Grundlagen zur Festlegung von Sicherheitsanforderungen für bauliche Anlagen, Beuth Verlag, Berlin, 1981.

[10.40] *SCHNEIDER, J.*: Sicherheit und Zuverlässigkeit im Bauwesen - Grundwissen für Ingenieure, Verlag der Fachvereine (vdf), Zürich, 1994.

[10.41] *PEACOCK, R. ET AL*: CFAST 6.1 - Consolidated Model of Fire Growth and Smoke Transport (Version 6), Technical Reference Guide, 2009.

[10.42] *SIEMON, M.*: Zuverlässigkeitsorientierte Bewertung der sicheren Räumung im Brandfall mit Hilfe von Ingenieurmethoden, Diplomarbeit, Institut für Baustoffe, Massivbau und Brandschutz, TU Braunschweig, 2011.

[10.43] *BUCHER, C.*: Adaptive sampling-an iterative fast Monte Carlo procedure, Structural Safety, 1988, 5(2), 119-126.

[10.44] BS7974 Application of fire safety engineering principles to the design of buildings. Code of practice. British Standards Institution (BSI), 2001.

[10.45] *ALBRECHT, C.; HOSSER, D.*: A Response Surface Methodology for Probabilistic Life Safety Analysis using Advanced Fire Engineering Tools, Proceedings of the 10th International Symposium on Fire Safety Science (IAFSS10), 2011.

[10.46] *MC GRATTAN, K.* et al.: Fire Dynamics Simulator (Version 5) - Technical Reference Guide – Volume 1: Mathematical Model, 2009.

[10.47] *BRYNER, N. P.; MADRZYKOWSKI, D.; GROSSHANDLER, W. L.*: Reconstructing the Station Nightclub Fire: Computer Modeling of the Fire Growth and Spread, Proccedings of the 11th International Interflam Conference (INTERFLAM 2007), interScience Communications, 2007.

[10.48] *FORELL, B.* Niveau der Personensicherheit von Versammlungsstätten - Nachweis nach vfdb-Leitfaden. Tagungsband 56. Jahresfachtagung der vfdb, Leipzig, 20.-23. Mai 2007.

[10.49] Grundsatzpapier der Fachkommission Bauaufsicht der Bauministerkonferenz (ARGEBAU) „Grundsätze zur Auslegung des § 14 MBO"; u. a. veröffentlicht in: DIBt Mitteilungen, Heft 1/2009, S.11/12.

[10.50] Evaluierungsbogen zu Maßnahmen des Vorbeugenden Brand- und Gefahrenschutzes (Einsatzstellenbegehung). Fachausschuss Vorbeugender Brand- und Gefahrenschutz der deutschen Feuerwehren (FA VB/G).

[10.51] DIN 18009-1:2016-09, Brandschutzingenieurwesen – Teil 1: Grundsätze und Regeln für die Anwendung.

[10.52] *SCHRÖDER, B.*: Multivariate Methods for Life Safety Analysis in Case of Fire; Dissertation, Fakultät für Architektur und Bauingenieurwesen, Bergische Universität Wuppertal, Wuppertal, 2016.

[10.53] Brandschutzrichtlinie 27-15de Nachweisverfahren im Brandschutz. Brandschutzrichtlinie, Vereinigung Kantonaler Feuerversicherungen (VKF), 2015.

[10.54] *KLINZMANN, C., HOSSER, D.*: Berücksichtigung abwehrender und anlagentechnischer Maßnahmen beim brandschutztechnischen Nachweis von Bauteilen; vfdb-Zeitschrift 58 (2009) Heft 2.

Annex 1 Terms, symbols and units

A1.1 Explanation of terms

Terms/ characteristics	Symbols/Units	Explanation
Mass loss	[kg]	Burnt mass of the fire load after defined fire duration. Loss of mass measured in the fire test with a combustion balance.
Mass loss rate	$\dot{m}$ [kg/s]	Burnt mass of the fire load per unit of time. The rate of combustion is linked to the heat release rate via the effective calorific value: $\dot{Q} = \dot{m} \cdot H_{eff}$. It corresponds to the pyrolysis rate in the case of fire load controlled fire progress.
Mass loss rate, per unit surface area	$\dot{m}''$ [kg/(m²·s)]	When using "material parameters" for the area-related burnup rate, it should be noted that the reference area (m²) is the area of the burning surface and not the base area on which these objects are located [4.26].
Mass loss rate, per unit area	$\dot{m}''$ [kg/(m²·s)]	Mass of combustible material burned per unit of time and area, in relation to the base area
Decay phase	-	Phase of the fire, following the full fire phase with clearly decreasing fire performance.
Activation time	t [s]	Time interval between the response of a transmitter and the full operational readiness of an extinguishing system, smoke extraction system, alarm system or other fire protection system
Accepted probability of occurrence		The probability of occurrence of possible scenarios that can be regarded as generally accepted by society (e.g. because it cannot be further reduced with reasonable effort).
Generally accepted limits		Limit values can be regarded as generally accepted if they are generally applied and defined, for example, in technical rules or other pre-normative principles. Assessment values that are used as the basis of aaRdT or of building regulations are generally recognised.
equivalent time of fire exposure (according to DIN 18230)	t_{eqv} [min]	Time in minutes at which the same effect (e.g. temperature at or in the component) is achieved in the considered component in a standard fire according to ETK as in a natural damage fire.
Yield Y	[g/g]	Formation or release components for fire products such as soot and pollutants during combustion.

Terms/ characteristics	Symbols/Units	Explanation
Design fire	-	Quantitative description of a design relevant fire development by the (usually time-dependent) heat release rate or combustion rate as well as, if necessary, further fire characteristics such as e.g. the yield of combustion products or the smoke potential. In connection with a (calculative) verification method, one also speaks of the determination of a suitable source term.
Design fire scenario	-	A defined fire scenario with which a fire protection analysis or a fire protection design is carried out. It contains information on the fire location and details of the fire event, including the ignition sources and materials involved and the influences of persons, technical safety systems and other technical plant equipment.
Fire spread velocity	v_{aus} [m/min]	Rate of flame spread on the surface of the fire origin in horizontal or vertical direction [4.26].
Fire effects	-	Phenomena caused by the fire, such as a release of energy and substances with emissions of particles and harmful substances.
Fire actions	-	Phenomena of a fire affecting the environment (e.g. people, animals, components), such as heat exposure and particle and pollutant emissions.
Fire growthfactor	α [kJ/s³] or [kW/s²]	Parameter for determining the heat release rate during the fire growth phase: $\alpha = 1000\ kW / t_\alpha^2$
Characteristic fire growth time	t_α[s]	Duration of α-t^2 fire growth until a heat release rate of 1000 kW is reached.
Fire area	A_F [m²]	Area (here "floor area") on which combustion is currently taking place.
Fire origin	-	Location (see fire location) and size of the fire at the beginning of the design fire.
Fire load	Q [kJ]	Amount of heat that can be released during the complete combustion of all combustible materials in a (room) volume including the cladding of all adjacent surfaces.
Fire load density	q or q'' [kJ/m²] or [kWh/m²]	Fire load, related to the reference surface to be applied. Calculated value for the amount of heat released in case of fire; has an influence on the burning time and on the fire room temperature.
Fuel controlled	-	The fire performance is only determined by the burning rate and the combustion efficiency. There is sufficient oxygen available for combustion.
Heat release rate	$\dot{Q}$ [kW]	Synonym for heat release rate. It contains a radiative $\dot{Q}_{rad}$ and a convective component $\dot{Q}_{conv}$

Terms/ characteristics	Symbols/Units	Explanation
Heat release rate, per unit area	$\dot{q}$ or $\dot{q}''$ [kW/m^2].	Synonym for heat release rate, related to the area above which the burning materials are located.
Fire location	-	Location of the current fire event in a room.
Fire phases (stages)	-	Classification (often schematic) of the fire progess into specific time phases (stages), which have one or more characteristic common features.
Fire source	-	Term used to identify fire modelling in certain calculation models (see Chapter 5).
Fire room	-	Room in which the source of the fire is initially located and in which mass loss occurs in the further fire progess.
Fire regime	-	Dependence of the fire course on the oxygen supply: fuel controlled or ventilation controlled.
Fire risk	-	Product of the expected probability of occurrence of a fire and its extent of damage.
Fire protection report	-	Object-related fire protection planning with documentation.
Fire effluents	-	Decomposition products of the burning material released during combustion, such as smoke particles or carbon monoxide.
Combustibles, flammable	-	Flammable materials which may be ignited and may burn during the fire process.
Fire scenario	-	Description of the type and chronological sequence of events which influence the fire process and can also be influenced retrospectively by the fire process. These events are typically related to the building structure, ventilation conditions, fire protection facilities, extinguishing measures and/or the behaviour of persons. From a technical point of view, a fire scenario is understood to be the initial and boundary conditions necessary for the performance of a (mathematical) proof with a suitable model.
Fire progess curve	-	Representation of the temporal development of the heat release rate (initial, fully-developed fire, decay phase)
Gross heat of combustion (previously: upper calorific value H_o)	H_S [kJ/kg] or [kWh/kg]	Measure for the specific thermal energy per measurement unit. Testing in the bomb calorimeter according to DIN 4102-1 and DIN EN ISO 1716.
Deterministic	-	Quantitatively determinable, as the result of a fixed relationship between a certain starting position and a result. Opposite of probabilistic (considering the probability).

Terms/ characteristics	Symbols/Units	Explanation
Emissivity	ε [-]	Quotient of the radiation produced by a radiation source and the radiation that would be produced at the same temperature by a Planckian radiator.
Escape	-	Self-rescue. Leaving a potentially or actually endangered area with your own power. The escape ends as soon as the endangered area is left.
Initial fire	-	The fire is spatially localized (see fire origin). This means that it is limited to one object or a contiguous, spatially narrowly defined group of objects.
Required safety level		Specified safety level, expressed in terms of design values, that covers the specified design situations lying on the safe side.
Evacuation	-	Planned and organised transfer of persons from an area of indirect danger.
Expert judgement	-	Assessments by experts using their expert knowledge.
Flashover	-	Transition to a fire stage in which the entire surface of the combustible materials in a (closed) space is involved in the fire (fully-developed fire). The flashover is characterized by a very steep rise in the fire progess curve.
Flashover temperature	[°C]	Temperature of the hot gas layer at which the flashover is initiated.
Flashover time	[s]	Time at which the flashover occurs.
Fire growth rate at flashover	v_{fo} [kW/s]	Calculated value for the increase in the heat release rate from the onset of the flashover.
Escape route	-	Traffic routes which have to meet special requirements and which are used for escape from a potentially dangerous area and, as a rule, also for the rescue of persons. Escape routes lead to a safe area or directly into the open.
Fire resistance		Ability of a test specimen to withstand a certain (standard) fire for a defined period of time or to provide protection against a fire.
Endangerment		Potential source of damage. Danger specifically related to a certain situation or object.
Dangerous situation		A condition in which people, goods or the environment are exposed to one or more hazards.
Danger		Possibility of a hazardous situation.
Geometric fire model	-	Model for determining the fire progress curve using the development of the fire area, the mass burning rate, the calorific value and the combustion efficiency over time.
Glowing fire	-	Incomplete combustion with insufficient oxygen supply, without flame formation, but with the appearance of light.

Terms/ characteristics	Symbols/Units	Explanation
Limit values		Numerical values for the individual safety objective criteria, above which it is to be assumed that the safety objective is not achieved.
Calorific value (formerly lower calorific value H_u)	H_i [kJ/kg] or [kWh/kg]	Heat of combustion when completely burnt, describes primarily the heat release rate via the area-specific mass loss rate.
Effective calorific value	$H_{eff} = \chi \cdot H_i$ [kJ/kg]	Product of calorific value H_i and combustion efficiency χ
Incubation period of fire growth	[s]	Duration of a fire before the calculated start of the fire. (Before the start of the design fire.)
Performance criteria		Quantitative criteria that provide an acceptable basis for assessing the safety of a design proposal for a structural installation. Exceeding or falling short of the performance criteria may indicate that the safety objectives are not met.
Mass burning rate, per unit area	v_{ab} [kg/(m²-min)]	The mass burning rate allows the determination of the area-specific heat release rate in connection with H_i. These values refer to the projection of the fire loads on the base area. Synonym for area-specific mass loss rate $\dot{m}''$
Possible fire scenario	-	Fire scenario that can occur even under very unlikely boundary conditions.
Natural fire	-	Fire progress which deviates from the normatively defined fire progess. It is defined as a design fire on the basis of object-specific assumptions for model applications.
Normative design fires	-	Nominal temperature-time curves or natural fires calculated on the basis of design fires.
Opening condition	-	Criteria, how or under which conditions the opening areas and the volume flows change in the progress of the fire.
Personal safety		Persons can generally be considered safe if they are in a safe space (= in the context of fire protection in an area not affected by critical media or temperatures) or if they are in an area that is affected by critical media but does not exceed the generally accepted limits.
Plume	-	Above the fire origin, rising flow of smoke and heat with a variable temperature, speed and mass. Its modellability starts only from a certain height above the burning objects.
Pyrolysis products	-	Thermal decomposition products or vapours resulting from the action of heat on a combustible material.

Terms/ characteristics	Symbols/Units	Explanation
Pyrolysis rate	[kg/s]	Mass [kg] of pyrolysis products or vapours released from the combustible material per unit time. Corresponds to the mass loss rate in the case of fuel controlled fire progress.
Source term	-	The description of the heat release rate and the time release of fire products.
Smoke particle mass generation portion or smoke yield or yield	Y e.g. $Y_{Ruß}$ [$g_{Ruß}/g_{verbrannter\ Stoff}$]	Mass portion of the smoke particles released from the fuel mass by combustion, typical yields with relevance for detection methods the soot yield $Y_{Ruß}$ or Y_s as well as the yields for carbon monoxide and carbon dioxide Y_{CO} or Y_{CO2}.
Mass optical density	D_m [m²/kg]	Measure of the visual opacity of fire smoke (optical smoke density); essentially dependent on the material composition of the combustible material and the ventilation conditions (for further details see chapter 8).
Eviction		Emptying a building or part of a building due to a potential or real danger to the persons concerned. Evacuation in unforeseen cases with an acute need for action, which mainly leads to self-rescue.
Escape route		Rescue routes are traffic areas which are both intended for the escape of persons from acute danger situations and are also to be used as attack routes by emergency services.
Risk		Measure for the extent of a danger. Product of the probability of occurrence of a damage and its extent of damage [€; injured persons].
Risk analysis	-	Systematic use of available information to identify hazards (for individuals or population groups, property, plant and equipment or the environment) and assess risks.
Risk assessment	-	Procedure based on risk analysis to determine whether an acceptable risk has been exceeded. Weighing up advantages and disadvantages and determining which risks are acceptable or have to be accepted.
Oxygen supply	-	Oxygen available for combustion in the combustion chamber.
Damage	-	Injury or damage to human health or damage to goods or the environment.

Terms/ characteristics	Symbols/Units	Explanation
Extent of damage		To quantify the extent of damage resulting from a scenario that has occurred. Type and manner of determination not regulated. In the case of buildings, often the cost of restoration. The criteria of the extent of damage are the same as those used for the concretization of the safety objective, because the safety objective always aims at limiting the extent of damage.
Smouldering fire	-	Incomplete combustion with insufficient oxygen supply, without flame formation or apparence of light
Security		Absence of hazards of a condition that is unattainable. A condition is considered safe if it contains a comparably small or unaccepted risk.
Safety factor		Factor between a nominal value (in a technical rule e.g. fractile value) and the value to be used in the design.
Security format		Design equations (in terms of E(effect) < W(resistance)) for the respective verifications using nominal values and safety factor(s).
Safety concept		Definition of a safety format and of nominal and, via safety factors, design values to ensure a level of safety.
Safety level/ existing safety level		Level of safety provided by safety factors and nominal values (expressed, for example, by the reliability index β or a probability of failure p_f), which represents the majority of design situations by design values on the safe side. (used for policy compliance)
Special construction		Building of a special type or use that fulfils at least one of the elements of the facts in §2 Para. 4 MBO.
Thermal impulse		Product of heat flux density and exposure time (used as criterion for the ignition of materials by heat radiation).
Ventilation controlled fire		Fire growth at an oxygen supply which is not sufficient for complete combustion within the fire area. Synonym for an underventilated fire.
Combustion		Exothermic, complete or incomplete oxidation of pyrolysis products.
Combustion efficiency	χ [-]	Ratio of heat released in a fire to the maximum possible heat resulting from the calorific value H_i and the pyrolysis rate.
Fullydeveloped fire	-	All flammable materials present in a certain part of a room ("fully-developed fire" on a partial area) participate in the fire.

Terms/ characteristics	Symbols/Units	Explanation
Fully-developed fire	-	Fire stage in which the entire surface of the combustible materials in a (closed) room is involved in the fire. The fully-developed fire always requires openings for oxygen supply.
Fully probabilistic		Verification with probabilistic methods (e.g. reliability analysis) in which scattering variables with their distributions and corresponding parameters are used for all relevant (i.e. significantly influencing) parameters.
Full probabilistic projections		Forward calculation based on probabilistic methods and scattering input variables for the essential parameters using the reliability index β as a measure of the safety level.
Incubation period	[s]	See incubation time.
Forward calculation / principle of forward calculation		Calculation of the existing safety level (expressed by measures of any kind) using (probabilistic) methods, in which design situations are recalculated using generally accepted design methods. Calculations for quantifying design situations on the basis of deterministically determinable parameters in combination with scattering parameters, taking into account their distribution functions.
Heat release	Q [kJ]	Thermal energy generated by combustion (heat quantity).
Heat release rate	$\dot{Q}$ [kW]	Heat released per unit of time during the combustion of a material. For verification purposes, it is important to distinguish between the convective component (which is available as the source term for the buoyant convection flow of the combustion gases) and the radiation component.
Heat release rate, per unit area	$\dot{q}$ [kW/m²] or $\dot{q}''$ [kW/m²]	The area-specific heat release rate is the fire output related to the (horizontal) base area of the fire, see also DIN 18230-3. The area-specific fire output refers to the free surface of the combustible material, independent of the arrangement on the combustible object. see also ISO 5660-1.
Heat release area related		Synonym for (area-)related fire performance based on the floor space of the fire origin.
Heat release, specific		Heat release rate, related to the free surface of the combustibles.
Heat capacity, specific	c_p [J/(kg·K)]	Amount of heat required to raise the temperature of an object with a mass of 1 kg by 1 K.
Thermal conductivity	λ [W/(m·K)]	Characteristic quantity relating to the speed at which heat flows through a material.
Heat flow	$\dot{Q}$ [kW]	Quantity of heat emitted, transmitted or received per time unit.

Terms/ characteristics	Symbols/Units	Explanation
Heat flux	$\dot{q}$ or [$\dot{q}''$ kW/m^2].	Quantity of heat emitted, transmitted or received per unit of surface area and time.
Water admission	W [mm/s]	Area-related volume flow of water delivered by activated sprinklers.
Active area	[m^2]	Maximum area over which sprinklers are assumed to open in the event of fire for design purposes.
Relevant scenario	-	Fire scenario with sufficient probability of occurrence for the definition of design fire scenarios. According to DIN 18009-1, these are a larger number of "significant" scenarios whose probability of occurrence during the relevant period of time is also sufficiently high and which can cause damage / effects that must be included in the design. The design scenarios are selected or determined / developed taking such scenarios into account. It is important for design issues that special individual scenarios do not have to be applied here, but that suitable (covering) scenarios for the design are selected or defined / developed.
Available safe escape time; ASET		Calculated time between the moment of ignition and the moment when the conditions change in such a way that it can be assumed that the user is considered incapacitated and is therefore no longer able to escape or successfully complete the escape.
Initial source	-	Energy source used to initiate combustion in fire tests. The ignition source is also the subject of the design fire and the design fire scenario.
Ignition phase	-	The combustible material is thermally processed by supplying ignition energy in such a way that the necessary ignition temperature is reached and the additional minimum energy required for independent combustion is supplied.
Reliability	-	Ability of a technical system to meet the requirements of its intended use within given limits.

A1.2 Symbols and units

Symbol	Meaning	Unit	if applicable Value
α	Fire growth factor	kW/s^2	not applicable
α	Heat transfer coefficient	$W/(m^2 \cdot K)$	not applicable
α	constant	-	0,44
α_c	Heat transfer coefficient for convection	$W/(m^2 \cdot K)$	not applicable
α_{inst}	Unsteady heat transfer coefficient	$kW/(m^2 \cdot K)$	not applicable
α_L	Additional coefficient for fire protection infrastructure	-	not applicable
β	Reliability index	-	not applicable
β^2	Ratio of temperature to velocity in profile	-	0,913
χ	Combustion efficiency	-	not applicable
χ_{O_2}	Oxygen utilization factor	-	not applicable
χ_r	Radiative fraction of the heat release rate	-	not applicable
ε_m	Surface emissivity of the structural component	-	not applicable
ε_{res}	Resulting emissivity ($= \varepsilon_f \cdot \varepsilon_m$)	-	not applicable
ε_f	Emissivity of the flame	-	not applicable
γ	Partial factor	-	not applicable
γ_{GA}	Partial factor for permanent actions in combination with accidential actions	-	not applicable
$\gamma_{n,c}, \gamma_{n,r}$	Factor for taking into account national fire tests	-	not applicable
$\gamma_{M,fi}$	Partial factor for material characteristics under fire exposure	-	not applicable
γ_R, γ_S	Partial factors	-	not applicable

Symbol	Meaning	Unit	if applicable Value
η_{fi}	Reduction factor for mechanical effects in case of fire (depending on ratio $\xi = Q_{k,1}/G_k$)	-	not applicable
κ	Kármán constant	-	≈ 0,4
λ	Thermal conductivity	W/(m·K)	not applicable
λ_1	average rate of occurrence of initial fires per square metre of floor area and year	-	$1/(m^2 \cdot a)$
μ	Utilisation factor for structural components according to Eurocodes	-	not applicable
ν	Kinematic viscosity	m^2/s	not applicable
ρ	Density of the gas mixture	kg/m^3	not applicable
ρ	Density or bulk density	kg/m^3	not applicable
$\overline{\rho}$	Density	kg/m^3	not applicable
ρ_s	Density of the material	kg/m^3	not applicable
ρ_∞	Density of ambient air	kg/m^3	not applicable
ρ_∞	Gas density of the cold gas layer	kg/m^3	not applicable
σ	Stefan-Boltzmann-constant	$W/(m^2 \cdot K^4)$	$5{,}67 \cdot 10^{-8}$
ξ	Temperature ratio smoke gas layer (T_s) to cold gas layer (T_∞)	-	not applicable
$\psi_{1,1}, \psi_{2,i}$	Combination coefficients according to EC 1 part 1	-	not applicable
Φ	Configuration factor	-	not applicable
θ	Temperature	°C or K	not applicable
$\Delta\theta$	Temperature difference	K	not applicable
$\theta_{a,cr}$	Critical steel temperature	°C	not applicable

Symbol	Meaning	Unit	if applicable Value
θ_g	Hot gas temperature (in the area surrounding the structual component)	°C	not applicable
θ_m	Temperature of the structural component surface	°C	not applicable
θ_r	Radiation temperature of the environment Effective radiant temperature of the fire	°C	not applicable
τ	Action time	min	not applicable
a	Thermal conductivity $\left(\frac{\lambda}{\rho \cdot c_p}\right)$	m^2/s	not applicable
a	Basic value of the related fire occurrence frequency per square metre and year	$1/(m^2 \cdot a)$	not applicable
a	constant	m^2/P.	0,266
b	Exponent that depends on the type of use and the subdivision of the utilization unit (room cells)	-	not applicable
c	Concrete covering	mm	not applicable
c	Courant-Friedrichs-Lewy-number	-	not applicable
c	Conversion factor (in DIN 18230-1)	$m^2/(kW \cdot h)$	not applicable
c_p	Specific heat or specific heat capacity of the cold gas layer	$J/(kg \cdot K)$ $kJ/(kg \cdot K)$	not applicable
c_{Smoke}	Smoke concentration	g/m^3	not applicable
$c_{Ruß}$	Mass concentration of smoke	g/m^3	not applicable
c_v	Specific heat at constant volume	$kJ/(kg \cdot K)$	not applicable
d	Thickness of the smoke gas layer	m	not applicable
f	Similarity factor	-	not applicable
f_{ck}	Characteristic value of the cylinder compressive strength	N/mm^2	not applicable
f_{pk}	Characteristic value of strength (prestressing steel)	N/mm^2	not applicable

Symbol	Meaning	Unit	if applicable Value
f_{yk}, f_{ay}	Characteristic value of yield strength (reinforcing/structual steel)	N/mm²	not applicable
g	Gravitional acceleration	m/s²	9,81
h	Building height	m	not applicable
$h_{Fenster}$	Height of the ventilation openings (windows, doors, etc.) as air inlets	m	not applicable
$h_{u,eff}$	Effective calorific value	kJ/kg kWh/kg MJ/kg	not applicable
h_w	Averaged, clear height of the openings	m	not applicable
$\dot{h}_c$	The energy released per unit of time due to combustion and fire side effects in the fire room	J/s = W	not applicable
$\dot{h}_g$	The energy of the smoke gases stored in the fire room per unit of time, which determines the fire room temperature	J/s = W	not applicable
$\dot{h}_l$	The energy of the smoke gases (convection energy) released per unit of time by the gas exchange (convection through openings)	J/s = W	not applicable
$\dot{h}_o$	The energy extracted due to window radiation per unit of time	J/s = W	not applicable
$\dot{h}_s$	Other energy lost per unit of time (e.g. energy stored in installations)	J/s = W	not applicable
$\dot{h}_w$	The energy emitted to enclosing structural elements due to convection and radiation per unit of time	J/s = W	not applicable
$\dot{h}_{net}$	Heat flux (net heat flux)	W/m²	not applicable
$\dot{h}_{net,c}$	Convective part of the net heat flux	W/m²	not applicable
$\dot{h}_{net,r}$	Radiative part of net heat flux	W/m²	not applicable
k	Contant (Table 9.7)	m/s	not applicable
k_Θ	Temperature-dependent reduction factor for strength and modulus of elasticity	-	not applicable
k_{Verb}	Factor for describing combustion efficiency (≤ 1,0)	-	0,80

Symbol	Meaning	Unit	if applicable Value
l	Length	m	not applicable
m	Mass loss factor (storage type, density) for fire loads when determined according to DIN 18230	-	
m	Mass of the smoke gas inside the room	kg	not applicable
m_{in}	Mass of inflowing air	kg	not applicable
m_{out}	Mass of outflowing air	kg	not applicable
$\dot{m}''$	areal mass loss rate	kg/(m^{2}s)	not applicable
$\dot{m}_g$	Mass of smoke gas flowing out of the fire room per unit of time	kg/s	not applicable
$\dot{m}_l$	Mass of fresh air flowing into the fire room per unit of time	kg/s	not applicable
$\dot{m}_L$	Supply air mass flow	kg/s	not applicable
$\dot{m}_{O_2}$	Oxygen mass flow	kg/s	not applicable
$\dot{m}_P$	Plume mass flow	kg/s	not applicable
$\dot{m}_{Pl}$	Mass flow of the plume at height z	kg/s	not applicable
p	Pressure in the room	Pa	not applicable
p_1	Annual probability of occurrence of an incipient fire in the utilization unit	-	not applicable
P_{21}	Probability of failure of firefighting by the users	-	not applicable
P_{22}	Probability of failure of firefighting by the fire brigade	-	not applicable
p_3	Probability of failure of firefighting by an automatic extinguishing system	-	not applicable
p_f	Probability of failure	-	not applicable
$p_{f,fi}$	Conditional probability of failure in case of fire	-	not applicable
p_{fi}	Probability of occurrence of at least one fully-developed fire (destructive fire)	-	not applicable

Symbol	Meaning	Unit	if applicable Value
p_v	Partial vapour pressure	Pa	not applicable
Δp	Pressure differentail	Pa	not applicable
q	Fire load density	MJ/m^2	not applicable
q_m	Mean fire load density	MJ/m^2	not applicable
q_R	Evaluated fire load (according to DIN 18230-1)	kWh/m^2	not applicable
r	Horizontal distance of a sprinkler from the plume axis	m	not applicable
r	Radial distance from the plume axis	m	not applicable
r	Stoichiometric air demand	kg air/ kg fuel	not applicable
s	Stoichiometric coefficient	-	not applicable
t	Time	s min h	not applicable
t	Fire duration without consideration of the ignition phase / smouldering phase	s	not applicable
$t_{1,fo}$	Time of a possibly occurring flashover	s	not applicable
t_α	Characteristic fire growth time; the numerical value corresponds to the fire duration until a fire intensity of 1 MW is reached	s	not applicable
t_{act}	Time until the activation of a technical fire protection measure (e.g. extinguishing system)	s	not applicable
t_{eqv}	Equivalent fire duration	min	not applicable
t_{con}	Time of fire control by the fire brigade	s	not applicable
t_{sup}	Time of fire suppression	s	not applicable
t_t	Mixing time	-	not applicable
Δt	Time interval	s	not applicable

Symbol	Meaning	Unit	if applicable Value
Δt	Discrete time step	s	not applicable
erf t_F	Calculated required fire resistance time	min	not applicable
u	Flow speed	m/s	not applicable
u*	Shear stress speed	m/s	not applicable
u or a	Axis distance of the reinforcement from the flamed concrete surface	mm	not applicable
u_m or a_m	Mean axis distance	mm	not applicable
v	Speed	m/s	not applicable
v_{ab}	Average specific mass loss rate of the substance or mixture of different substances (mean value over mass fractions)	kg/m² min	0.5 to 3.4
v_{ab}	Mass burning rate	kg/(m²·min)	not applicable
v_{aus}	Fire spread velocity in horizontal direction equally fast in all directions	m/min	0,25 to 0,50
$v_{jet,t}$	Velocity in ceiling jet	m/s	not applicable
w	Specific water exposure	mm/s	≥ 0,07
w	Heat extraction factor according to DIN 18230-1	-	not applicable
Δx	Spatial discretisation step	m	not applicable
x, y, z	Space coordinates	m	not applicable
z	Height of the plume above the fire origin area or vertical distance between fire origin area and the location of the calculation	m	not applicable
z_0	Roughness parameter	-	not applicable
z_0	Dynamic roughness length	m	not applicable

Symbol	Meaning	Unit	if applicable Value
z_s	Height of the lower boundary of the smoke layer	m	not applicable
$z_{I,1}$	Distance of the real fire origin to the boundary area between upper and lower layer	m	not applicable
$z_{I,2}$	Distance of the "virtual heat source" from the boundary area between the upper hot smoke gas layer and cold gas layer	m	not applicable
A	Surface	m^2	not applicable
A	Pre-exponential factor	m/s	not applicable
A	Floor area of the through fire protection separated utilization unit	m^2	not applicable
$A_d(t)$	Design value of indirect actions	-	not applicable
A_f	Floor space of the fire room	m^2	not applicable
$A_F(t)$	Fire area (increasing with fire duration)	m^2	not applicable
A_i	Inner perimeter	m^2	not applicable
A_F	Fire area at the beginning of firefighting process at time t_{act}	m^2	not applicable
$A_{F,max}$	Maximum controllable fire area	m^2	not applicable
A_T	Total interior surfaces of the room	m^2	not applicable
A_t	Inner surface of the fire room	m^2	not applicable
AW	Opening area	m^2	not applicable
$\widetilde{B}$	Mean molecular fraction of the combustible	-	not applicable
C	Locally measured concentration	-	not applicable
C	Empirical parameter in relation to visibility	-	2 to 10
C	Material-dependent constant	-	not applicable
C_0	Initial concentration		not applicable
C_R	Model parameters dependent on mixing time, kinetic viscosity and turbulent kinetic energy	-	not applicable

Symbol	Meaning	Unit	if applicable Value
C_T	Constant	-	9,115
D	Fire origin diameter	m	not applicable
D	Critical amount of carboyhemoglobin (COHb) in the blood, which leads to unconsciousness	Vol. %	not applicable
D_f	Fire diameter	m	not applicable
D_m	Mass optical density (related to D_L)	m^2/g	not applicable
D_L	Optical smoke density per path length	1/m	not applicable
E	Activation Energy	J/mol	not applicable
E	Internal energy of the smoke gas in the room	kJ	not applicable
E_a	Activation Energy	J/mol	not applicable
$E_{d,fi}$	Design value of internal forces in case of fire	-	not applicable
$E_{d,fi,t}$	Design value of the actions according to Eurocode 1 part 1-2	-	not applicable
E_i	internal energy at constant volume	kJ	not applicable
E_L	Heat release per converted mass of fresh air	MJ/kg_L	not applicable
E_{O_2}	Heat release per converted mass of oxygen	MJ/kg_{O2}	not applicable
F	Standardized ratio in the FED model	-	not applicable
F_s	Specific crowd flow	P./(s·m)	not applicable
G_k	Characteristic value of permanent action	-	not applicable
H	Room height or distance between fire origin and ceiling	m	not applicable
H_{hi}	Average calorific value of the substance or mixture of different substances (average value over the mass fractions)	kWh/kg	See DIN 18230-3

Symbol	Meaning	Unit	if applicable Value
H_i	Calorific value of combustible materials 1kWh = 3,600 kJ	kJ/kgk Wh/kg MJ/kg	not applicable
Je	Jensen number	-	not applicable
K	Extinction coefficient	1/m	not applicable
K_m	Extinction coefficient per mass unit of combustible materials	m^2/g	not applicable
L	Luminance	cd/m^2	not applicable
L	Path length	m	not applicable
L_v	Temperature independent evaporation enthalpy	J/kg	not applicable
LW	Extinguishing effect	-	not applicable
M	Quantity / Mass	kg	not applicable
N	Number of persons	-	not applicable
P	Number of users	-	not applicable
$\tilde{P}$	Mean molecular fraction of the reaction product	-	not applicable
$\dot{Q}$	Heat release rate	kW or MW	not applicable
$\dot{Q}_s$	Heat release rate at time t_0, at which the initial fire passes from an object fire to a fire spreading over the object (start of design fire)	kW	not applicable
$\dot{Q}(t)$	Heat release rate at time t	kW or MW	not applicable
$\dot{Q}(t)$	Heat release rate under sprinkler protection	kW	not applicable
$\dot{Q}(t_{act})$	Heat release rate upon opening the first sprinkler head (t_{act})	kW	not applicable
$Q_{k,1}$	Characteristic value of the principle variable load	-	not applicable
$Q_{k,i}$	Characteristic value of further variable loads	-	not applicable

Symbol	Meaning	Unit	if applicable Value
$\dot{Q}_{LK}$	Maximum heat release rate during fire control by extinguishing system	MW	not applicable
$\dot{Q}_{FO}$	Fire performance at which a flash-over occurs	kW	not applicable
$\dot{Q}_{max,v}$	Maximum heat release rate of the ventilation-controlled fire	kW	not applicable
$\dot{Q}_{max,f}$	Maximum heat release rate of the fire load controlled fire	kW	not applicable
$\dot{Q}_R$	Energy loss due to radiation	kW	not applicable
$\max\dot{Q}_{vent}$	Maximum fire performance in small rooms with limited air supply	kW	not applicable
$\dot{Q}_c$	Convective heat output	kW	not applicable
$\dot{Q}^*$	Dimensionless heat release rate	-	not applicable
$\dot{Q}^*_{I,1}$	Dimensionless heat release rate of the real fire origin	-	not applicable
$\dot{Q}^*_{I,2}$	Dimensionless heat release rate of the "virtual heat origin”	-	not applicable
R	State variable describing the resistance	-	not applicable
R	General gas constant	J/(K·mol)	8,314
R	Risk Index	-	not applicable
$R_{fi,d,0}$	Component resistance at time t = 0	-	not applicable
$R_{d,t,fi}$	Design value of resistance in case of fire	-	not applicable
RHR_f	Heat release rate per unit area	MW/m^2	not applicable
RTI	Response Time Index, measure of the response sensitivity of the sprinkler	$\sqrt{m \cdot s}$	not applicable
RMV	Respiratory rate	l/min	not applicable
$\dot{R}$	The fire load converted per unit of time, which causes the release of heat	kg/s	not applicable
S	Visibility	m	not applicable

Symbol	Meaning	Unit	if applicable Value
$\tilde{S}$	Average molecular fraction of oxygen	-	not applicable
T	Temperature	K	not applicable
T	Fire room temperature	K	not applicable
T	Temperature of the surface of the substance	K	not applicable
T_0	Temperature of the test specimen at the start of the test	K	not applicable
T_∞	Temperature of the ambient air or cold gas layer	°C or K	not applicable
T_{jet}	Ceiling jet temperature	°C	not applicable
$T_{jet,t}$	Temperature in the ceiling jet at time t	°C	not applicable
T_p	Plume temperature	K	not applicable
T_s	Smoke gas temperature	°C	not applicable
$T_{D,t}$	Sprinkler temperature at time t	°C	not applicable
$T_{Heißgas}$	Smoke gas temperature	°C	not applicable
ΔT	Temperature difference	K	not applicable
ΔT_{jet}	Temperature difference between ceiling jet and hot gas layer	°C	not applicable
V	Volume of the room (constant)	m^3	not applicable
V	Walking speed	m/s	not applicable
V	Dilution ratio ($= C_0/C$)	-	not applicable
V_{is}	Minimum visibility	m	not applicable
V_l	Volume of the air layer	m^3	not applicable
V_s	Volume of the smoke gas layer	m^3	not applicable
V_{Hyp}	Factor for estimating the effect of hyperventilation	-	not applicable

Symbol	Meaning	Unit	if applicable Value
X_k	Characteristic value of a scattering value	-	not applicable
Y_{Rauch}	Smoke yield rate	g/g	not applicable
$Y_{Ruß}$	Soot yield rate	g/g	not applicable
Y_i	Smoke yield	g/g	not applicable
Z	Limit state function, safety distance between acting and resisting variable	-	not applicable
Z_f	Average flame height	m	not applicable
Z_n	Position of the neutral plane	m	not applicable
Z_s	Position of the smoke gas layer	m	not applicable

ANNEX 2 **Application example**

A2.1 Introduction

An example will be used to illustrate the processing of a fire protection task using this guide. It is based on a lecture hall with an adjacent atrium-like office building. Figure A2.1 shows a perspective exterior view of the two buildings.

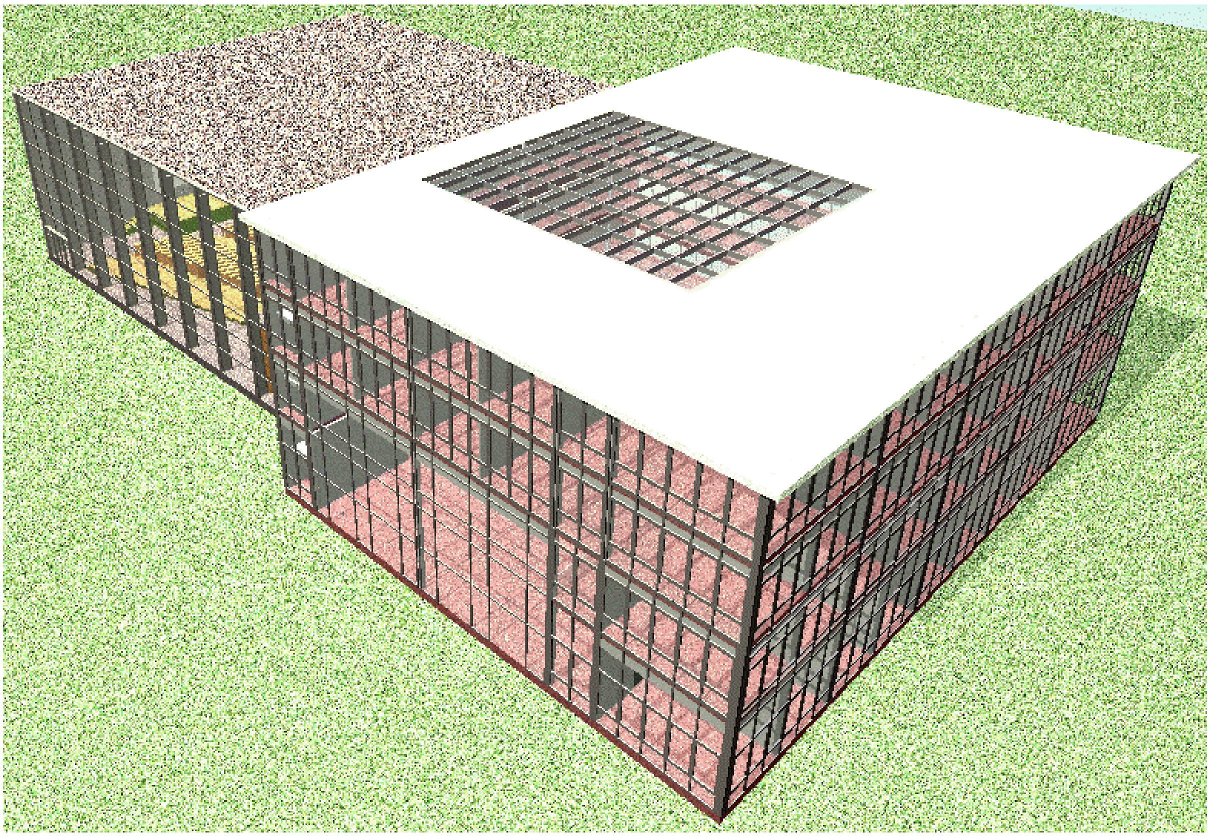


Figure A2.1 General view of lecture hall and office building

The auditorium building with the dimensions 34 m x 29 m x 12 m (L x W x H) is a place of assembly with about 650 seats. During special events, up to 1,000 people can be accommodated in the building by additional standing room or seats on steps. The wooden seating area, which slopes gently upwards, is divided by aisles (Figure A2.2). At the rear of the seating is a wall panel with opening areas through which one can reach the entrance to the lecture hall. The lecture hall is accessed via a wide staircase from the atrium of the office building with its dimensions of 36 m x 27 m x 15 m (L x W x H), the entrance is located on the first floor (Figure A2.3). Open galleries surround the inner atrium. Escape doors are located in the façade on both sides of the building in the area of the stage.

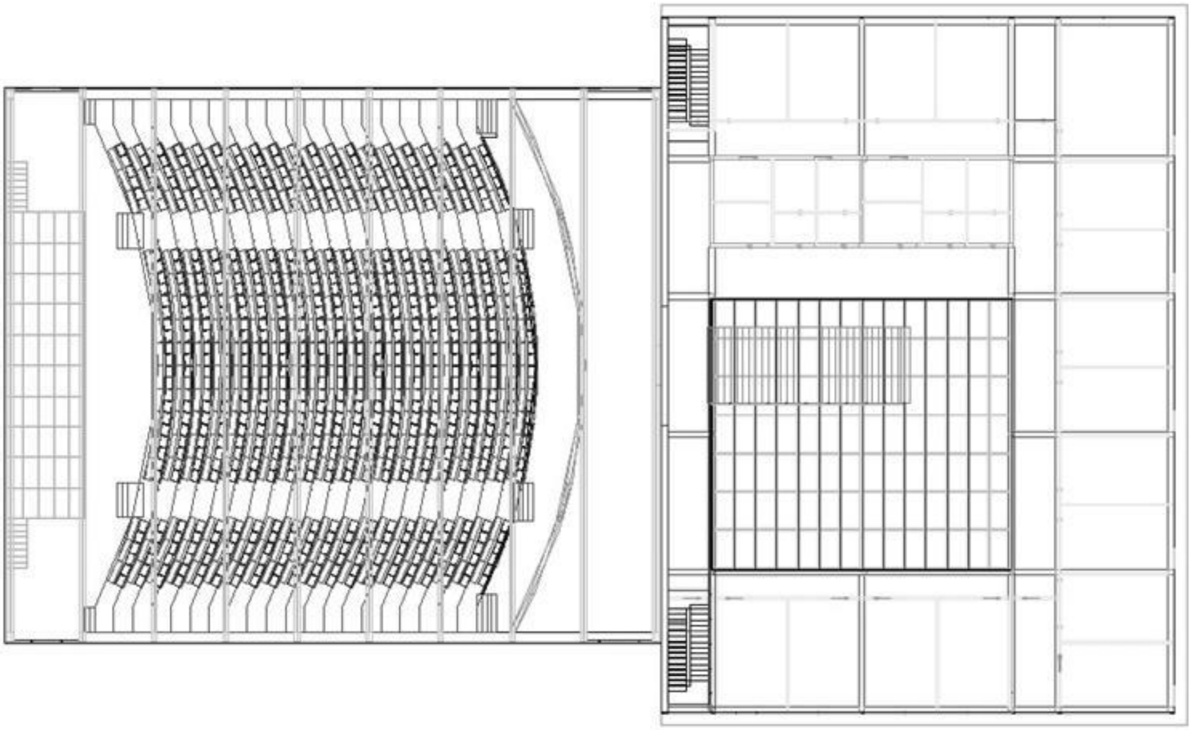


Figure A2.2 Floor plan of the lecture hall and office building

The auditorium building consists of a steel frame construction (columns and beams), the rear wall as transition to the atrium is designed as a fire wall (Figure A2.4). The side walls are designed as a steel-glass façade. The roof consists of a non-combustible sandwich panel ceiling. For smoke removal in case of fire, openable windows for supply and exhaust air are available on both sides of the building.

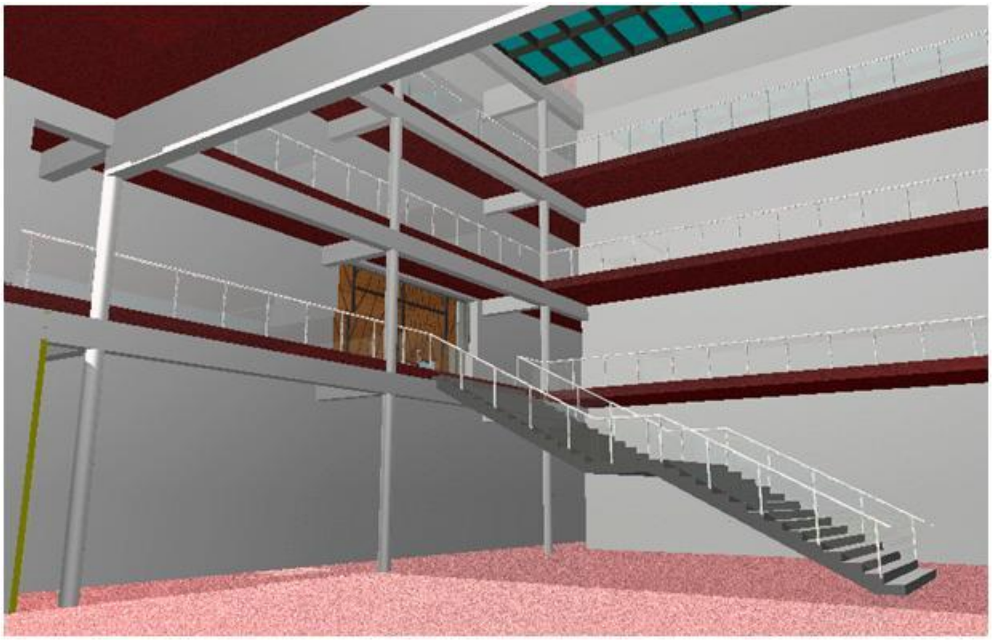


Figure A2.3 Access to the lecture hall from the atrium of the office building

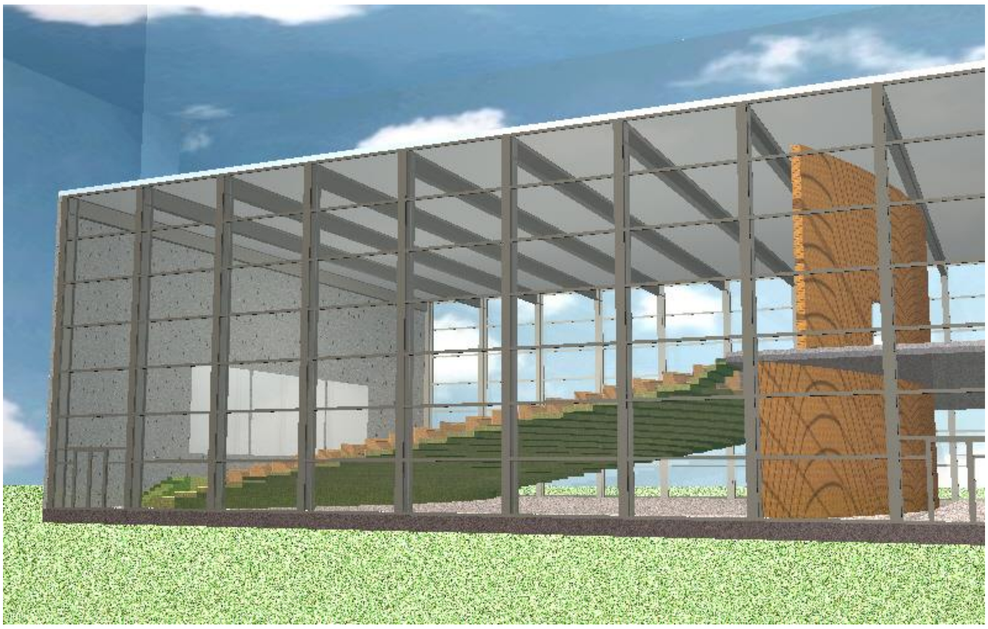


Figure A2.4 Steel frame construction of the lecture hall building with columns and beams

Open galleries surround the inner atrium of the administration building, the access to the lecture hall is located on the first floor.

In the following chapters of this Annex, the individual verification steps are described in a use-related manner with the aim of an objective-oriented fire protection concept.

In A2.2, the safety objectives and their implementation on the example project is discussed, whereby the public law protection interests in accordance with the MBO [A2.1] and MVStättV [A2.1] regard to the number, length and width of the escape routes are in the foreground. Subsequently, the relevant fire scenarios are determined and the associated design fires are specified. Accordingly, two scenarios are to be examined:

- A fully developed fire without the effect of extinguishing measures with a heat release rate of max. 224 MW is to be used as the design fire for the fire resistance specifications of the supporting structure of the lecture hall.
- A growing fire reaches a heat release rate of 38 MW in the short term after intervention by the fire brigade and then subsides. This scenario is used in the evaluation of personal safety in the lecture hall.

In A2.3 a covering temperature-time curve is derived for the evaluation of the construction of the lecture hall building, which is further used in A2.4 investigations are based on the specifications from A2.2 regarding the fully-developed fire. In A2.4 the fire protection verifications of building components and supporting structure (steel frame construction) are carried out. Using the temperature-time curve for the hot gas temperature determined in accordance with A2.3 into account the temperature-dependent material properties, the load-bearing capacity of the steel frame structure is determined and evaluated by the following alternative verification procedures in accordance with Eurocode 3 Part 1-2:

- Verification of the individual components using the simplified design method,
- Determination of the component temperatures and verification of the load-bearing capacity with the extended design method.

Finally, A2.5 provides evidence of personal safety with the proviso that the previously defined safety objectives are achieved or the associated criteria are met, in particular

- Height of the low-smoke layer,
- Optical smoke density / detection distance, and
- Flue gas toxicity / gas concentrations.

In addition to the fire scenario, the evacuation processes from the lecture hall are evaluated by using different models such as the capacity analysis, the dynamic flow model and various individual models. The results will be compared with the data in the MVStättV.

A2.2 Protection interests and protection objectives

The basic public law interests to be protected by appropriate measures in the present example of application can be found in the Model Building Regulations (MBO) [A2.1]. According to these, structural facilities are to be arranged, erected, modified and maintained in such a way that the development of a fire and the spread of fire and smoke (fire spread) is prevented and, in the event of a fire, the rescue of people and animals as well as effective firefighting activities are possible.

In addition, the application example falls within the scope of the Ordinance on Places of Assembly of the respective German federal state or, as shown here, the Model Ordinance on Places of Assembly (MVStättV) [A2.1] due to its dimensioning for a number of visitors well in excess of 200. This results in special requirements for escape routes (number, length and width) with regard to the protection goal of personal safety under building law. On the other hand, relief is provided if a greater room height is available and sufficient smoke removal can be ensured so that the escape routes are available for a sufficiently long time, i.e. they can be kept low in smoke. The protection objective of a sufficiently high, low-smoke layer that is available for a long time should be considered that important because the conditions in the hot gas layer pose a great danger to the health and life of persons even at a great distance from the fire. In addition, the low-smoke layer is necessary to enable the fire brigade to operate safely and effectively. According to [A2.2] the number of visitors and the size of the meeting rooms are the most important factors when considering the risk.

In the present example, the requirements according to § 7 MVStättV are deviated from in such a way that the maximum escape route length is moderately exceeded and therefore a mathematical verification using engineering methods, as shown in A2.5 required. In order to be able to assess the fire effects with regard to personal safety, specific acceptance values must be formulated, such as a height of the low-smoke layer of h = 2.5 m. This is composed of the average height of a person and a safety factor [A2.2]. The values given in Tables 8.2 and 8.3 are reference values that can be used to assess the safety of persons. In addition, the FED model can be used to derive an assessment variable from the concentrations of the harmful gases which is not graded but provides a value that increases continuously over time.

According to [A2.2] the MVStättV is based on a fire protection concept that differs from the MBO, in which a classification of building classes according to the size of the utilization units would not be appropriate. Rather, the places of assembly require that the building components are to be treated in the same way as building class 5 of the MBO with regard to fire protection. That means that they are subject to the same fire protection requirements as buildings with a height of more than 13 m and units of use of more than 400 m^2 each. This takes into account the increased risks for fire spread and firefighting by the fire brigade. In [A2.1] a fire-retardant design - i.e., F 30-B under ETK fire - is therefore required for load-bearing and bracing components of ground floor assembly areas. According to [A2.2] this requirement can be fulfilled in the steel structure provided in the application example, for example, by a suitable protective coating. Whether this measure can be omitted in the underlying fire scenario of a natural fire and thus ultimately be allowed to deviate from the requirement "fire-retardant" is investigated with the help of the engineering methods in [A2.4]. Furthermore, the MVStättV stipulates that the multi-storey office building must be fire-resistant in order to achieve the fire safety objectives for the present example. As a boundary condition, the partition wall between the lecture hall building and the office building must also be fire-resistant.

A2.3 Fire scenarios and design fires

A2.3.1 General information

From Chapter 4 of the guideline, numerous information and possibilities for the development of design fires for the individual fire phases can be taken. In the following, design fires, as shown schematically in Figure 4.5, will be developed for the application example with the help of the guidelines. The developed time courses of the heat release rate are the basis for the calculation of the smoke and temperature development with a CFD model. The results of this calculation are in turn used as input variables for the evaluation of the stability of the auditorium roof and for the proof of evacuation.

A2.3.2 Design fire scenario 1 - Assessment of the supporting structure

A2.3.2.1 Procedure

The underlying design fire scenario excludes a smouldering phase and the effectiveness of extinguishing measures and no longer represents a small fire.

In the application example it is assumed that the source of the fire is located in the middle of the room in the rows of chairs and the fire spreads evenly and unhindered to all sides. This assumption is justified by the fact that the spatial distance between the rows is too small to limit the spread of the fire. Chairs and tables made of wood represent the fire load. Detailed information on the type, storage density and quantity of combustible materials will be provided later.

Due to the size of the room and the presumed destruction of window surfaces as a result of thermal stress, it can be assumed that sufficient combustion air / atmospheric oxygen is available and that a fuel controlled fire is therefore present. A fire alarm is not (initially) reported to the responsible fire brigade, since a fire alarm system is not provided and the fire breaks out at a time when there are no people in the building. This might be the case at night or on weekends. The latter also leads to all doors and windows of the lecture hall being closed. In this fire scenario, a fire brigade deployment with the effectiveness of extinguishing measures should be deliberately excluded. On the one hand, there is no guarantee that the responsible fire brigade will be informed in time without a fire alarm system and without the presence of people, and on the other hand, it cannot be ruled out that the fire brigade's intervention will be unsuccessful under certain circumstances and that a fully-developed fire will nevertheless develop. However, Chapter 4 the guidelines contains information on how the effectiveness of extinguishing measures affects a design fire scenario and how this can be described in the form of a changed course of the design fire.

The end of the fire propagation stage and, in this example, the transition to the fully-developed fire stage occurs when all combustible materials, i.e. the entire fire load in the lecture hall, are involved in the fire and an increase in fire is therefore no longer possible.

The time course of the heat release rate for the fire propagation phase can be developed with the help of normative approaches with low certainty of the fire conditions. In this example there is a low degree of certainty because no reliable data can be given on the combustion properties (especially the combustion rate). The only reason for this is the missing or insufficiently described data material on burning rows of chairs and tables. It is therefore necessary to make general assumptions, on the safe side, for which the American approach used in international standardization (t^2 approach) is very well suited. In the application example, the heat release time curve for the fire propagation stage can be determined as shown below.

A2.3.2.2 Probability of occurrence of a damaging fire

The reliability required for the design of the structure and for the proof of personal safety in the event of fire depends on the probability of a damaging fire occurring in a unit of a building and the associated damage (damage to components or persons).

The probability of occurrence p_{fi} of a damaging fire in a unit of use with base area A effectively separated in terms of fire protection in a reference period of 1 year can be determined using equation (A2.1):

$$p_{fi} = p_1 \cdot p_{21} \cdot p_{22} \cdot p_3 \tag{A2.1}$$

with

- p_1 Annual probability of an incipient fire in the unit of use,
- p_{21} Probability of firefighting failure by users,
- p_{22} Failure probability of firefighting by the fire service,
- p_3 Probability of failure of firefighting by an automatic extinguishing system.

The annual probability p_1 of at least one fire occurring in the unit of use can be determined alternatively according to equation (A2.2) assuming a fire frequency λ_1 independent of the floor area or according to equation (A2.3) taking into account the (usually disproportionately low) increase of the fire frequency with the size of the utilization unit.

$$p_1 = 1 - \exp\left(\lambda_1 \cdot A\right) \approx \lambda_1 \cdot A \tag{A2.2}$$

$$p_1 = 1 - \exp\left(a \cdot A^b\right) \approx a \cdot A^b \tag{A2.3}$$

with

- A Floor area of the fire protection-separated usage unit [m^2],
- λ_1 Average incidence rate of incipient fires per square meter of floor area and year [$1/(m^2 \cdot a)$],

a Basic value of the related frequency of fire occurrence per square meter and year [1/(m^2·a)],

b Exponent that depends on the type of use and the subdivision of the utilization unit (room module).

As a third alternative, a simplified average annual probability of occurrence p_1 can be used for a typical size (i.e., average floor area) of the area used.

The second and third alternatives are included in the National Annex to Eurocode 1 Part 1-2 [A2.3], in Annex BB, with the numerical values shown in Table A2.1.

For the present assembly center, in accordance with Table A2.1, line 7 p_1 is replaced by

$$p_1 = 2.0 \cdot 10^{-2} \tag{A2.4}$$

The probability of failure p_{21} takes into account the initial fighting of the fire in which the user is responsible for the fire, p_{22} applies analogously to the extinguishing measures of the alarmed fire brigade. According to English fire statistics, an average of 50 - 70 % of initial fires are extinguished by the users (conservatively p_{21} = 0.5), so that the fire brigade is either not alerted at all or only has to carry out supplementary extinguishing measures.

Table A2.1 Probability of occurrence p_1 of at least one initial fire per utilization unit and year depending on use (according to [A2.3])

Line	Use	Probability of occurrence per utilization unit and year $p_1 \approx a \cdot A^b$		p_1
		a [1/(m^2 - a)]	b	[1/a]
		1	2	3
1	Residential building	$4.8 \cdot 10^{-5}$	0.9	$3.0 \cdot 10^{-3}$
2	Office building	$5.9 \cdot 10^{-5}$	0.9	$6.2 \cdot 10^{-3}$
3	Hospital, nursing home	$7.0 \cdot 10^{-4}$	0.75	3.0E-1
4	hotel, lodging establishment	$8.0 \cdot 10^{-5}$	1.0	$3.7 \cdot 10^{-2}$
5	School, educational institution	$2.0 \cdot 10^{-4}$	0.75	$4.0 \cdot 10^{-2}$
6	Salesroom, office building	$6.6 \cdot 10^{-5}$	1.0	$8.4 \cdot 10^{-3}$
7	public place of assembly (theatre, cinema)	$9.7 \cdot 10^{-5}$	0.75	$2.0 \cdot 10^{-2}$
	other place of assembly (e.g. discotheque)		1.0	$1.2 \cdot 10^{-1}$

The failure probability p_{22} of firefighting by the fire brigade depends on the one hand on the intervention time and efficiency of the fire brigade and on the other hand on the spread of the fire until the beginning of the extinguishing work. For public fire brigades, an average intervention time of approx. 15 minutes can be assumed. The intervention time of a private or works fire brigade is usually significantly shorter than that of the public fire brigade and, if necessary, the strength and equipment is adapted to the specific object, so that the probability of failure p_{22} is lower. Numerical values p_{22} for firefighting by a public fire brigade or plant fire department are given in Table A2.2 (based on [A2.3]). Linear interpolation is permitted between the intervention times.

For the present example, initial firefighting by the users is assumed with p_{21} = 0.5 and firefighting by the public fire brigade with an intervention time of 15 min with p_{22} = 0.2. Altogether, the failure probability of firefighting results in

$$p_2 = p_{21} \cdot p_{22} = 0.1, \tag{A2.5}$$

which is consistent with earlier assumptions in [A2.4], [A2.5].

The failure probability p_3 of an automatic extinguishing system depends on the design standard. Recommended numerical values p_3 for different extinguishing systems can also be taken from Table A2.2.

Table A2.2 Failure probabilities p_{21}, p_{22} and p_3 of firefighting (based on [A2.4])

Firefighting by	Probability of failure		
	p_{21}	p_{22}	p_3
User	0.5		
public fire brigade with intervention time < 15 min > 20 min		 0.2 0.5	
Works fire brigade with intervention time 1) < 10 min (four seasons) < 10 min (two seasons)		 0.02 0.05	
Automatic extinguishing system Sprinkler system according to VdS/CEA standard 2) in other cases Other water extinguishing system Gas extinguishing system			 0.02 0.05 0.1 0.1

1) Automatic fire detection and alarm are required.
2) Planning, installation, operation and maintenance in accordance with recognized rules of technology.

An automatic extinguishing system is not available in the lecture hall building, therefore

$$p_3 = 1.0\,. \tag{A2.6}$$

This results in the probability of occurrence of a damaging fire according to equation (A2.1) to

$$p_{fi} = p_1 \cdot p_{21} \cdot p_{22} \cdot p_3 = 0.02 \cdot 0.5 \cdot 0.2 \cdot 1.0 = 0.002 \tag{A2.7}$$

A2.3.2.3 Reliability required for the fire protection design of the construction

According to DIN EN 1990 [A2.6] the various structures are classified into damage sequence-classes CC, which are assigned a required reliability index β and a probability of failure p_f via reliability classes RC, each with reference to one year. These values are generally valid for all load cases, including the exceptional load cases such as fire. The reliability index β and the probability of failure p_f are linked by the function $\Phi(\,)$ of the standard normal distribution

$$p_f = \Phi(-\beta) \tag{A2.8}$$

For the exceptional situation of a fire, a conditional probability of failure $p_{f,fi}$ in case of fire and the associated reliability index β_{fi} can be determined from the probability of failure p_f and the annual probability of occurrence p_{fi} of at least one fire in the unit of use concerned, as follows

$$p_{f,fi} = \frac{p_f}{p_{fi}} \tag{A2.9}$$

$$\beta_{fi} = \Phi^{-1}\left(1 - p_{f,fi}\right) \tag{A2.10}$$

Here Φ^{-1} is the inverse function of the standard normal distribution.

In the National Annex [A2.3], Annex BB, the reliability indices β and failure probabilities p_f for limit states of load-bearing capacity in the event of fire are specified for specific uses depending on the expected damage consequences according to Table A2.3.

Table A2.3 Guidelines for the reliability index β and the associated probability of failure p_f (reference period one year) for the fire design of the structure for different utilizations (according to [A2.3])

Line	Use	Consequences of damage					
		high		medium		Low	
		β	p_f	β	p_f	β	p_f
		1a	1b	2a	2b	3a	3b
1	Residential buildings, office buildings and similar uses Building classes according to MBO	4.7	$1.3 \cdot 10^{-6}$	4.2	$1.3 \cdot 10^{-5}$ 4 + 5	3.7	$1.1 \cdot 10^{-4}$ 2 + 3
2 3 4 5 6 7	Hospital, nursing home Accommodation facility, Hotel School Point of sale Meeting place High-rise	5.2	$1.0 \cdot 10^{-7}$	4,7	$1.3 \cdot 10^{-6}$	4.2	$1.3 \cdot 10^{-5}$
8	Buildings used for agricultural purposes	--	--	4.2	$1.3 \cdot 10^{-5}$	3.7	$1.1 \cdot 10^{-4}$

For the lecture building as a place of assembly, the following applies to the main supporting structure, assuming average values (safety index β = 4.7)

$$p_f = 1.3 \cdot 10^{-6} \tag{A2.11}$$

The conditional probability of failure $p_{f,fi}$ and the reliability index β_{fi} for the design in case of fire are calculated as follows

$$p_{f,fi} = \frac{p_f}{p_{fi}} = \frac{1.3 \cdot 10^{-6}}{2.0 \cdot 10^{-3}} = 6.5 \cdot 10^{-4} \tag{A2.12}$$

$$\beta_{fi} = \Phi^{-1}\left(1 - p_{f,fi}\right) = \Phi^{-1}\left(1 - 6.5 \cdot 10^{-4}\right) = 3.22 \tag{A2.13}$$

A2.3.2.4 Partial safety factors for the fire protection design of the construction

Extensive probability-theoretical investigations in [A2.7] have shown that the fire load density q has a decisive influence on the reliability in case of fire due to its large scattering. The next most important factor is the maximum heat release rate $\dot{Q}_{max}$ (HRR) in the phase of a fully-developed fire.

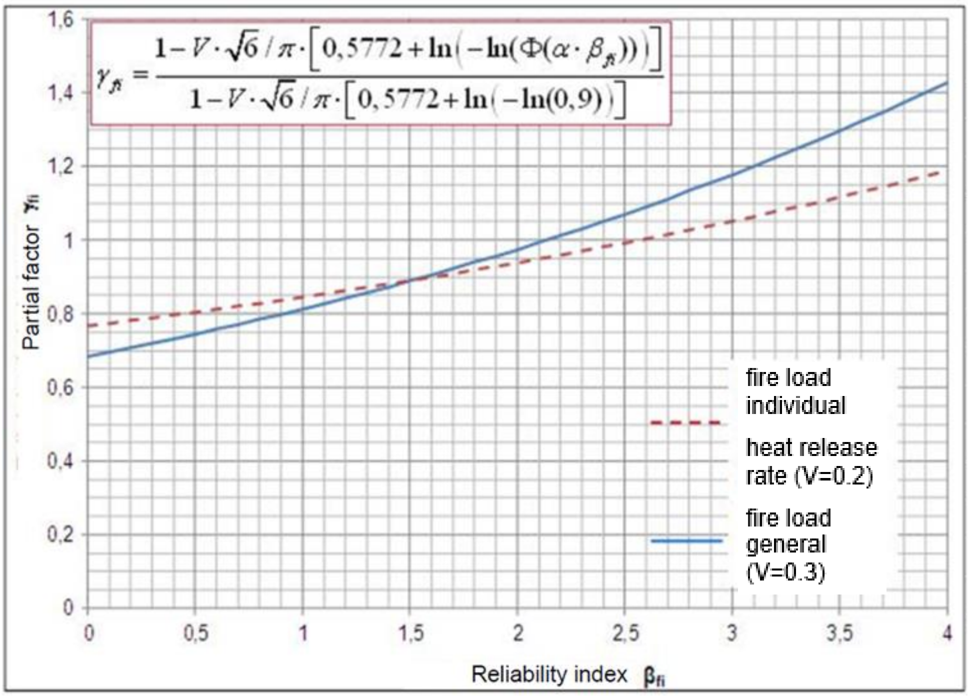
It is assumed that for each of these two influencing variables of fire exposure, 90 % quantiles are defined as characteristic values or determined individually. For the design, design values are used which are calculated from the characteristic values by multiplication with partial safety factors γ_{fi}. The partial safety factors are specified such that the required reliability according to Table A2.3 is met on average for all components and design situations and that the values are usually not exceeded or undercut by more than $\pm\Delta\beta_{fi}$ = 0.5[A2.6].

If a Gumbel distribution is assumed (according to international statistics) for the fire load density and the heat release rate, then the partial safety factors can be calculated using equation (A2.14) as the quotient of the design value in case of fire and the characteristic value:

$$\gamma_{fi} = \frac{1 - V \cdot \sqrt{6} / \pi \cdot \left[0.5772 + \ln\left(-\ln\left(\Phi\left(\alpha \cdot \beta_{fi}\right)\right)\right)\right]}{1 - V \cdot \sqrt{6} / \pi \cdot \left[0.5572 + \ln\left(-\ln\left(0.9\right)\right)\right]} \qquad \text{(A2.14)}$$

If the fire load density q is taken from the corresponding table in [A2.3] for a single use, the coefficient of variation V_q = 0.3 and the sensitivity factor α= 0.6. For the maximum heat release rate, $\dot{Q}_{max}$ the coefficient of variation V_Q = 0.2 and the sensitivity factor α= 0.5. If the fire load density is determined in an individual case (as is common in industrial construction, for example), the random scatter is smaller. Then the partial safety factor γ_{fi} can be calculated with the coefficient of variation V_q = 0.2 and the sensitivity factor α= 0.5.

The partial safety factors γ_{fi} determined in this way for the fire load density and the heat release rate can be read from Figure A2.5 as a function of the required reliability index β_{fi}.



$p_{f,fi}$	β_{fi}
0.5	0
0.401	0.25
0.309	0.50
0.227	0.75
0.159	1.00
0.106	1.25
0.067	1.50
0.040	1.75
0.0228	2.00
0.0122	2.25
0.00621	2.50
0.00298	2.75
0.00135	3.00
0.000578	3.25
0.000233	3.50

$p_{f,fi} = p_f / p_{fi}$

Figure A2.5 Partial safety factors for the influencing variables of a natural fire in relation to the defined characteristic values (90 % quantile)

With β_{fi} = 3.22 according to equation (A2.13), Figure A2.5 gives

$\gamma_{fi,g} = 1.24$ for q when determined by service class (A2.15a)

$\gamma_{fi,HRR} = 1.19$ for HRR and for q for individual determination (A2.15b)

The value for the heat release rate $\dot{Q}_{max}$ (HRR) also applies to the fire load density q, which is to be determined individually for the auditorium building.

A2.3.2.5 Design fire for structural design

According to Chapter 4 of the Guide, the following information is relevant:

- A $\alpha \cdot t^2$ approach is chosen for the fire growth stage to cover the most critical case.
- The source of the fire is located in the middle seating area of the lecture hall (see Figure A2.6).
- The fire spreads rapidly ($\alpha = 0.04689$) over the entire rows of wooden chairs and tables.
- Partial areas of the window panes fail above 300 °C.

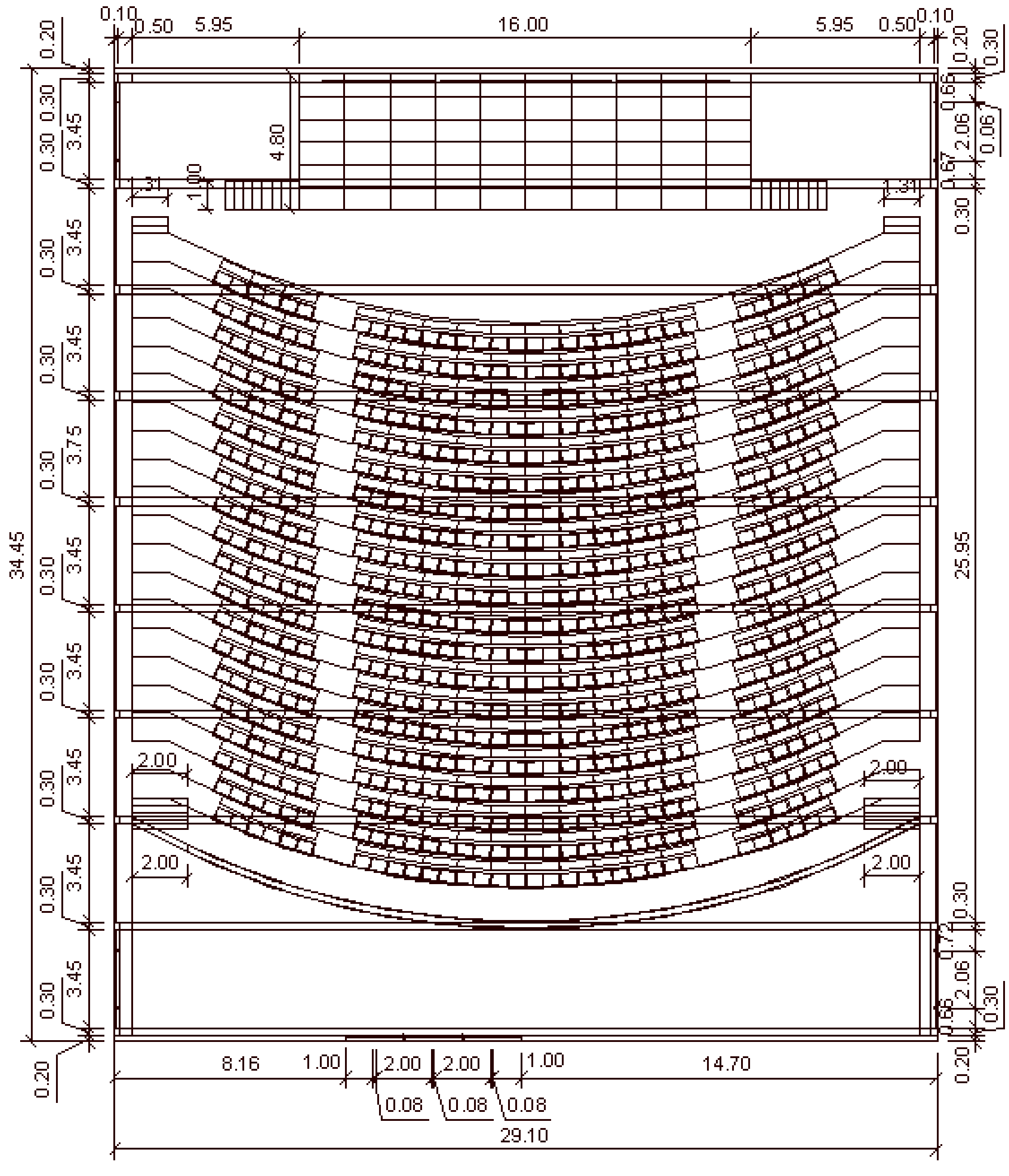


Figure A2.6 Floor plan of the lecture hall building

The following considerations are used to determine the relevant design values of the fire load density q and the maximum area-specific heat release rate. The rows of chairs and tables made of wood represent the fire load to be taken into account, which are arranged on an area of approximately 20.0 m x 20.0 m = 400 m² (see Figure A2.6). If about 30 % of this is subtracted for the existing gaps between chair and table or between the individual rows of seats, the total fire area A_F is

$$A_F = 0.70 \cdot 400\,\text{m}^2 = 280\,\text{m}^2 \tag{A2.16}$$

The floor area A of the lecture hall is calculated as follows

$$A = 28.9\,\text{m} \cdot 34.0\,\text{m} \approx 1.000\,\text{m}^2 \tag{A2.17}$$

With a density of the wood of about 500 kg/m³ and an assumed total thickness of all wooden parts (seat, table surface, backrest, etc.) of 12.5 cm, the combustible mass is therefore

$$M_F = 500\,\text{kg/m}^3 \cdot 0.125\,\text{m} \cdot 280\,\text{m}^2 = 17500\,\text{kg} \tag{A2.18}$$

The net calorific value of wood (furniture) can be assumed (according to Table A4.1 of the School/Classroom Guidelines) to be H_i = 18.2 MJ/kg. The total fire load results in

$$Q_{max} = 17500\,\text{kg} \cdot 18.2\,\text{MJ/kg} = 318500\,\text{MJ} \approx 319\,\text{GJ} \tag{A2.19}$$

The characteristic value of the average fire load density in relation to the base area is therefore

$$q_{f,k} = Q_{max} \,/\, A = 319000\,\text{MJ} \,/\, 1000\,\text{m}^2 = 319\,\text{MJ/m}^2 \tag{A2.20}$$

The design value of the fire load density is defined as:

$$q_{f,d} = q_{f,k} \cdot \chi \cdot \gamma_{fi,g} \qquad \text{in MJ/m}^2 \tag{A2.21}$$

Where:

$q_{f,k}$ the characteristic fire load density in relation to the base area in MJ/m²,

γ_{fi} a partial safety factor which takes into account the probability of occurrence of a fully-developed fire in the utilization unit and the required reliability of the components,

χ the combustion efficiency, which generally takes incomplete combustion into account on a flat-rate basis; for solid fire loads χ = 0.8 may be assumed.

With the corresponding values and taking into account the partial safety factor of $\gamma_{fi,HRR} \approx 1.19$ from equation (A2.15b) mentioned above, (A2.21) gives the design value of the average fire load density related to the floor area of the lecture hall for the application example of

$$q_{f,d} = 319 \cdot 0.8 \cdot 1.19 = 304\,\text{MJ/m}^2 \tag{A2.22}$$

or the design value of the total fire load to

$$Q_{f,d} = 304 \cdot 1000 = 304\,\text{GJ} \tag{A2.23}$$

If one compares this value with the 90 % fractiles of the fire load densities for different uses, the partial safety factor would have to be applied γ_{fi} = 1.24 for the flat-rate assumption of the fire load density.

It can thus be seen that the individually determined value $q_{f,k,}$ assuming an identical distribution with an identical coefficient of variation, lies between the values given in Table A4.1 of the Guide for the theatre/cinema and for lecture halls:

$$1.24 \cdot 0.8 \cdot 417\,\text{MJ/m²} = 413\,\text{MJ/m²} > q_{f,d} > 1.24 \cdot 0.8 \cdot 195\,\text{MJ/m²} = 193\,\text{MJ/m²}$$

This can be considered a good agreement and confirmation.

To determine the maximum heat release rate and the rate at which the fire develops, stacked wooden pallets are used as the equivalent fire load. Table A4.2 of the guide contains the information required for this. A stacking of a maximum of two wooden pallets is considered a realistic assumption of the equivalent fire load. In conjunction with the partial safety factor according to equation (A2.15b) $\gamma_{fi,HRR} \approx 1.19$, the maximum area-specific heat release rate is

$$\dot{q} = (2 \cdot 0.14\,\text{m}) / 0.5\,\text{m} \cdot 1249\,\text{kW/m²} \cdot 1.19 = 832\,\text{kW/m²} \tag{A2.24}$$

This value can in turn be compared with table values for the maximum area-specific heat release rate for different fire load arrangements. According to this, for horizontally stored wood / PMMA, where the top surface of the stack burns, one obtains

$$\dot{q} = 0.720\,\text{MW/m²} \cdot 1.19 = 0.8576\,\text{MW/m²}\,,$$

so that here too the realistic assumption corresponds with empirical values on an experimental basis.

In order to finally determine the maximum heat release rate on the fire surface, the area-specific value $\dot{q}$ should be multiplied by the fire surface $A_{F.}$ The maximum heat release rate is calculated as follows

$$\dot{Q}_{max} = 0.832\,\text{MW/m²} \cdot 280\,\text{m²} = 233\,\text{MW}. \tag{A2.25}$$

For comparison: Table A4.1, for example, gives an area-specific heat release rate of 250 kW/m² for an office use (without sprinkler system). This results in a maximum use-related heat release rate of

$$\dot{Q}_{max} = 1.19 \cdot 250\,\text{MW} = 297.5\,\text{MW}.$$

Figure A2.7 shows the course of the heat release rate of the design fire as a result of the investigation, as evaluated according to the data.

In addition, different inflowing and outflowing air situations are controlled and estimated on the basis of the model, which result when the failure of window panes due to the effects of fire is taken into account.

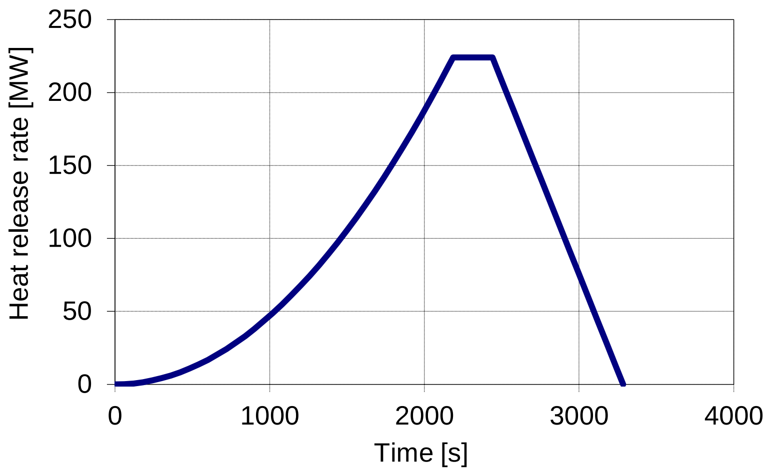


Figure A2.7 Rated fire load-bearing structure of lecture hall, heat release rate [MW]

A2.3.3 Design fire scenario 2 - Assessment of the evacuation of the lecture hall

A2.3.3.1 Procedure

For the assessment of the personal safety or rescue of visitors in the lecture hall, a scenario different from the previous design fire scenario has to be chosen, since it was assumed that there were no people in the building at the time of the fire. Furthermore, it is to be assumed that at least one fire alarm to the fire brigade will be triggered when people are present in the building, so that extinguishing measures are likely to become effective. As the time of the fire brigade's intervention cannot be exactly determined, a conservative estimate of 15 minutes after the start of the fire is assumed for evacuation. Within this period of time, the fire will develop according to the previous design fire due to the otherwise unchanged general conditions. It is further assumed that the fire breaks out during a major event, when there are about 1,000 visitors in the auditorium, which is actually only designed for 640 visitors.

A2.3.3.2 Reliability required for the proof of evacuation in case of fire

Analogous to the proof of the load-bearing capacity of the construction in the event of fire, the required reliability must also be maintained when it is proven that the escape of persons from the utilization unit affected by the fire can be completed before the limit values of the fire effects are exceeded. This results from a probability of failure p_f, which is valid for all load cases and depends on the consequences of the damage, and the probability of occurrence p_{fi} of the fire scenario according to equation (A2.1) that is decisive for evacuation.

With the failure probability p_f, a distinction should be made between whether escape from the affected unit of use is prevented or "only" impeded by the effects of the fire.

Preventing escape, e.g., through the toxic effect of the fire gases, means a specific danger for the users, which is comparable to that in the case of a fire-related failure of structural fire protection measures. Therefore, p_f can be taken in principle from Table A2.3. For the lecture hall as a place of assembly, the average damage consequences are given as in equation (A2.11) $p_f = 1.3 \cdot 10^{-6}$ [1/a]. In the present case, in view of the very conservative specification of the performance criterion FED ≤ 0.3, relatively low damage consequences are to be expected, so that $p_f = 1.3 \cdot 10^{-5}$ appears acceptable.

This allows the conditional probability of failure $p_{f,fi}$ and the reliability index β_{fi} for the proof of evacuation in the event of fire to be calculated in the same way as equation (A2.12) and (A2.13).

With the probability of occurrence p_{fi} of the decisive fire scenario for evacuation in the early phase of the fire according to equation (A2.1), however, as a rule only the initial fighting of the fire by the users may be taken into account, while extinguishing measures of the fire brigade are not yet effective at this point in time (p_{22} = 1.0). This results in the following for the lecture hall:

$$p_{fi} = p_1 \cdot p_{21} \cdot p_{22} \cdot p_3 = 0.02 \cdot 0.5 \cdot 1.0 \cdot 1.0 = 0.01 \tag{A2.26}$$

$$p_{f,fi} = \frac{p_f}{p_{fi}} = \frac{1.3 \cdot 10^{-5}}{1.0 \cdot 10^{-2}} = 1.3 \cdot 10^{-3} \tag{A2.27}$$

$$\beta_{fi} = \Phi^{-1}\left(1 - p_{f,fi}\right) = \Phi^{-1}\left(1 - 1.3 \cdot 10^{-3}\right) = 3.01 \tag{A2.28}$$

If escape is only expected to be hindered, e.g., by falling below a required minimum height of the low-smoke layer or a minimum detection range due to smoke, a higher probability of failure can be accepted because of the significantly lower damage consequences. In Chapter 10 of the guideline, a maximum permissible probability of failure of $p_f = 1.9 \cdot 10^{-3}$ [1/a] is recommended for this case with a range of max. $p_f = 8.2 \cdot 10^{-3}$ to min. $p_f = 3.4 \cdot 10^{-4}$.

With the probability of occurrence of the relevant fire scenario according to equation (A2.27), this results in

$$p_{f,fi} = \frac{p_f}{p_{fi}} = \frac{1.9 \cdot 10^{-3}}{1.0 \cdot 10^{-2}} = 1.9 \cdot 10^{-1} \tag{A2.29}$$

$$\beta_{fi} = \Phi^{-1}\left(1 - p_{f,fi}\right) = \Phi^{-1}\left(1 - 1.9 \cdot 10^{-1}\right) = 0.88 \tag{A2.30}$$

A2.3.3.3 Safety factors for the proof of evacuation in case of fire

Chapter 10 of the guideline examines exemplary evidence for evacuation in the event of fire on the basis of the performance criteria "low smoke layer height ≥ 2.5 m" or "optical density ≤ 0.1 1/m" (representing an obstruction to escape) and evidence for Basis of the performance criterion "FED value ≤ 0.3" (for prevention of escape). A reliability analysis provided the shares of the influencing variables in the resulting variance of the limit state equation $Z = t_{available} - t_{clearing}$ as shown in Figure 10.6 and Figure 10.8 in Chapter 10. In both cases the fire growth time t_α (= time until a heat release rate of 1 MW is reached) is dominant. For this purpose, a design value or, alternatively, a characteristic value in combination with a partial safety factor shall be determined such that the required reliability in accordance with equation (A2.28) or (A2.30) is met.

If the fire growth time is assumed to be log-normal with a coefficient of variation V_{tg} = 0.2 and the characteristic value $t_{\alpha,k}$ (e.g. 150 s for the place of assembly) is defined about 50 s lower than the mean value, no additional partial safety factor is required with a conservative specification of the pre-movement time in order to ensure the required reliability according to equation (A2.30) when proving the low-smoke layer or the detection range. For the verification of the FED value, the characteristic value $t_{\alpha,k}$ should then be divided by a partial safety factor

γ_{fi} = 1.4 in order to achieve the higher reliability according to equation (A2.28). In this case, the maximum number of persons in the place of assembly should also be specified conservatively (in the lecture hall example with max. 1000 persons).

A2.3.3.4 Design fire for the proof of evacuation

For the performance criteria "low-smoke layer height ≥ 2.5 m" or "optical density ≤ 0.1 1/m", the heat release time curve for the first 900 s (15 min) corresponds to a α-t^2 curve, with 1 MW heat release after 150 s. After the 15-minute unimpeded fire growth, i.e., when the extinguishing measures begin, the heat release rate runs at a constant level, which corresponds to control of the fire as shown in Figure 4.9, and decays after a fire duration of about 26 minutes until the fire is completely extinguished. Figure A2.8 shows the course of this design fire for the evaluation of the evacuation of the lecture hall over all fire stages.

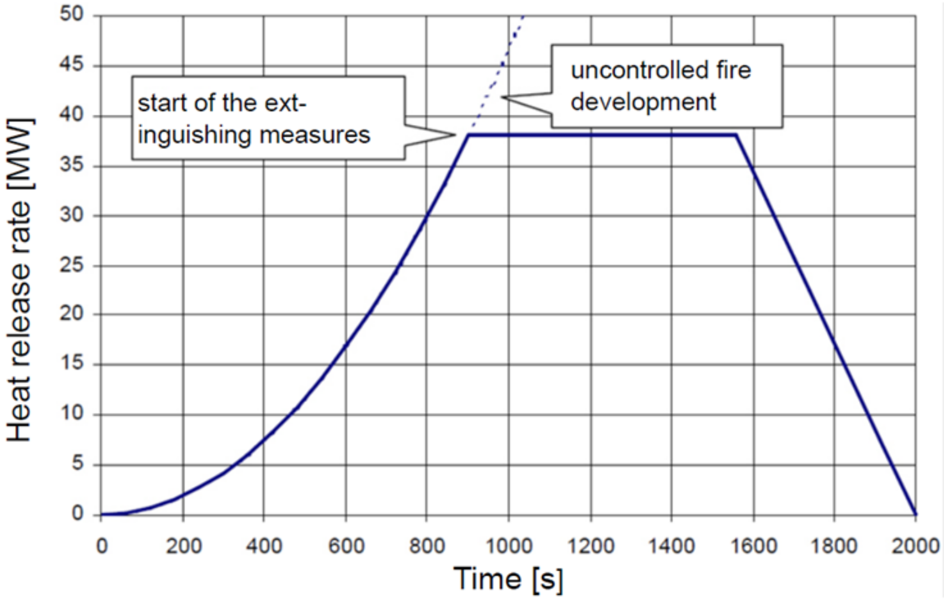


Figure A2.8 Rated fire for the assessment of auditorium evacuation

For the performance criterion "FED ≤ 0.3", the heat release rate for the first 900 s (15 min) corresponds to a α-t^2 curve, whereby after 150 s / 1.4 = 107 s a heat release of 1 MW is reached.

The front row of seats was chosen as a conservative location for the fire because here supply air can be mixed into the smoke plume from all sides and maximum climbing heights are achieved, so that the smoke mass flow and the resulting smoke is at a maximum.

A2.4 Determination of the fire effects for the structural design

A2.4.1 Issues

The previously determined fire scenario is given for the assessment of the roof support structure of the lecture hall. The corresponding fire effects are to be used for the fire protection design of the steel structure.

With regard to the component dimensioning, eight frames in steel construction consisting of columns and transoms are considered in the lecture hall. The following considerations should be taken into account in the parameter studies for the component design:

- Smoke extraction areas in the upper area of the window front on the long sides of the auditorium: 3.4% of the floor space (requirement according to MVStättV [A2.1]: at least 2%),
- Corresponding supply air areas in the lower area of the hall, each arranged below the smoke extraction areas,
- The smoke extraction and supply air areas are opened 2 minutes after the start of the fire,
- The connecting door to the atrium building (fire compartment) in the upper part of the lecture hall is closed in any case when the component design is considered, which also corresponds to the more critical case for the development of temperatures in the event of a fire in the lecture hall, and
- Firefighting activities take place after 10 minutes and lead to the opening of one of the lower escape route doors. However, firefighitng proceedures with extinguishing water is not taken into account in the course of the specified heat release rate, which can be regarded as a worst case scenario.

A2.4.2 Selecting the model type

The selection of the model type is directly linked to the research question. Whenever results with high spatial accuracy are required (e.g., for further component design) and especially when the results depend on the flow conditions in space, CFD models are preferable to zone models, even if their use involves greater effort.

The Fire Dynamics Simulator in Version 6 [A2.10] was selected for the calculation of the flue gas temperatures present at the component. The FDS model is regularly validated by the NIST (National Institute of Standards and Technology) [A2.11].

The model is also suitable for further questions, e.g., for the calculation of smoke propagation and for the calculation of the height of the low smoke layer, as they are considered for the rescue of persons or evacuation.

When creating the model for the calculation with FDS, the following general assumptions were made for the geometry and the enclosure components:

For the component calculation, a closed connecting door to the adjoining atrium was assumed. Figure A2.9 shows the model of the auditorium for the calculation with FDS Version 6.

- All geometric specifications were considered in a grid with an accuracy of 50 cm. The trusses have cross-sections of 50/100 cm, the columns cross-sections of 50/50 cm.
- The walls at the upper and lower front side, the ceiling and the floor were calculated with thermophysical data corresponding to an insulated normal concrete.
- For the front sides of the lecture hall (window fronts), a thermally "thin" material with the properties of glass was assumed.

- The rows of seats were approximated by 5 steps of 4 m width each, the upper platform (access via atrium) has a height of 3.5 m, the fire load was assumed on an area of 280 m², which is evenly distributed over these 5 steps.
- The exterior space of the lecture hall is taken into account all around.
- To exclude calculation errors at grid boundaries, only one (global) calculation grid is used in FDS (see Figure A2.9).

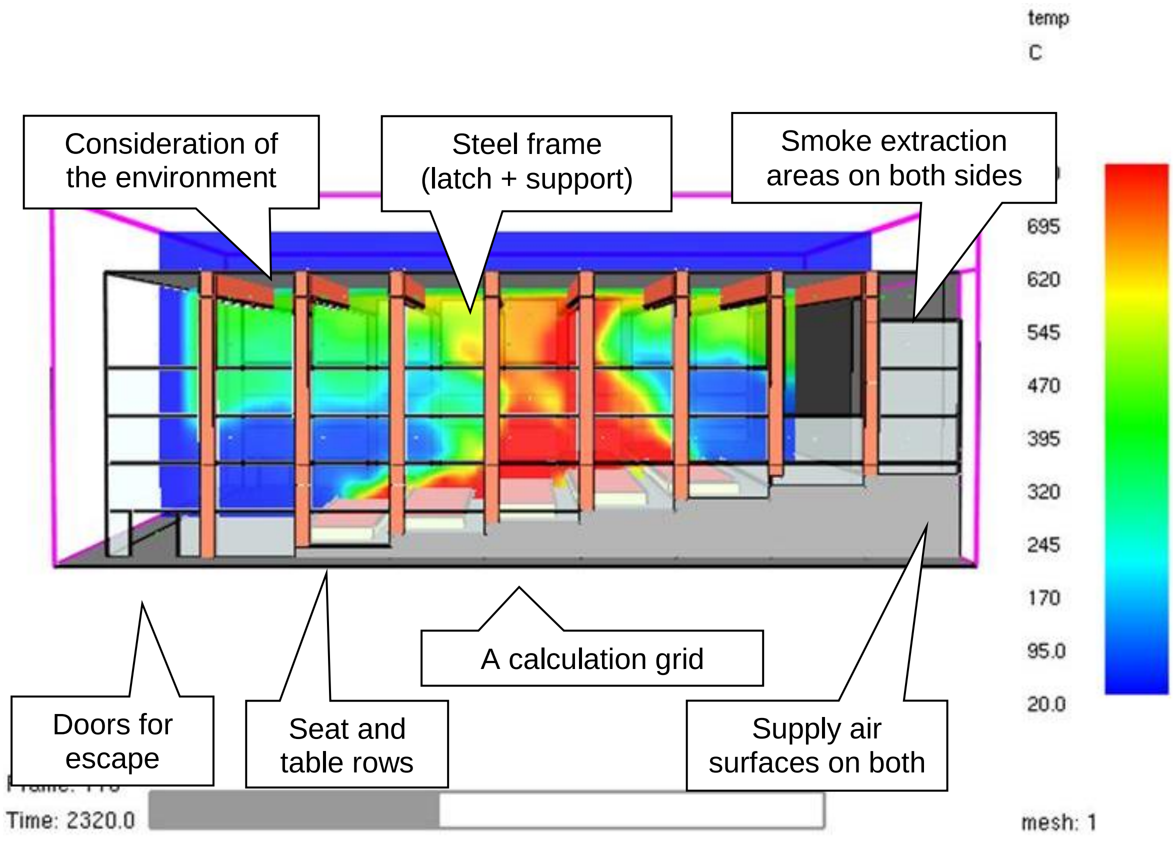
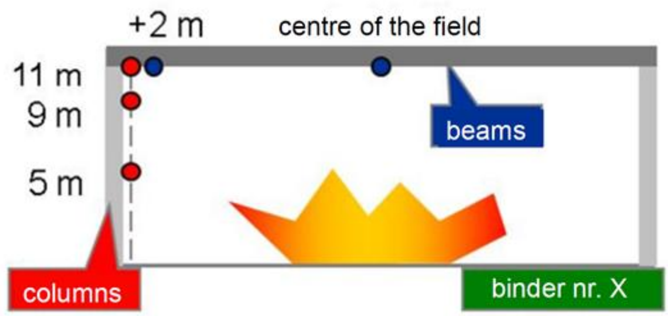


Figure A2.9 Model of the lecture hall for the calculation with FDS Version 6, displayed with Smokeview, representation with exterior space outside the lecture hall

With a view to further component design, relevant measuring points were defined at which the gas temperatures in the area of the binders were saved to a file every 10 seconds.



shows these measuring points as an example for one of the 8 roof trusses.

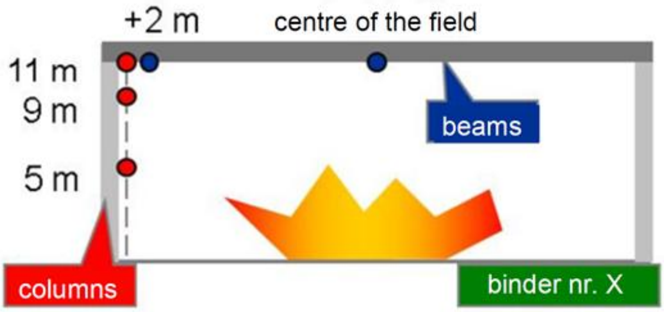


Figure A2.10 System sketch, designation of the measuring points for the gas temperatures of the truss system (support and beam)

A2.4.3 Performed calculations

The following investigations were carried out:

Type A: $\alpha \cdot t^2$ approach, no consideration of window failure

Type B: Fire spread over rows of chairs

Type C: same as Type A, but taking into account the failure of windows

A rapid fire spread of 100 cm/min was assumed for Type B (see Table 4.2). A spreading over the center axis of the lower seat row (20 m) upwards therefore takes 20 minutes.

Based on the considerations in 5.6.2 "Choice of grid resolution", a grid resolution in the range of 25 cm is already comparatively very good for a fire with 233 MW. It is a fact, however, that the heat release rate only increases from smaller values at the beginning of the fire and therefore the grid resolution would have to be continuously adjusted. This is not possible with the FDS model, so that the grid resolution should also be suitable for smaller heat release rates. For smaller heat release rates, finer resolutions are also required to adequately resolve a fire. For a characteristic grating resolution of at least R*=4, fires with at least 1 MW power are already sufficiently resolved for grids with 25 cm.

The calculation runs with different parameters are summarized in Table A2.4 according to [A2.12] basis was an analysis of the dependence of the results on the cell fineness, which leads to good results when using grid cells with 50 cm edge length. Overall, a cell fineness of up to 25 cm is considered reasonable.

Table A2.4 Overview of modelling parameter study, selected parameters

Designation Model run	A_50	A_25_50	A_25	B_50	C_50	C_50_T
Cell size, fineness [cm]	50*50*50	25*25*50	25*25*25	50*50*50	50*50*50	50*50*50
Number of cells	77,792	311,168	622,336	77,792	77,792	77,792
Fire source and spread in the area of the seat rows	Center, square. Approach, alpha= fast	Center, square. Approach, alpha= fast	Center, square. Approach, alpha= fast	Bottom, 1m/min over 5 areas of 4 m	Center, square. Approach, alpha= fast	Center, square. Approach, alpha= fast
Windows fail at 300 °C	no	no	no	no	yes	yes

Supply and exhaust air	2 minutes	2 minutes	2 minutes	2 minutes	2 minutes	2 minutes
Lower escape door open	no	no	no	no	no	10th minute

*) Font in italics: Changes compared to basic variant A_50

A2.4.4 Selected results

As a result of the calculations, Figure A2.11 shows an excerpt of the gas temperature curve in the area of bar 4 (R_4) in the middle of the field.

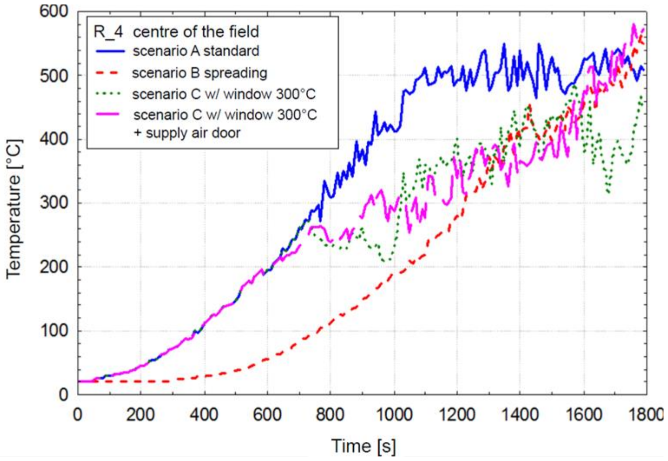


Figure A2.11 Temperature curve at bar 4 in the middle of the field for 4 different fire scenarios

If the lower escape door remains closed, the highest temperatures are in the area of the bolts 2 and 3; if the escape door is open (due to intervention of the fire brigade after 10 minutes), the temperatures are highest in the area of the binders 4 and 5.

The influence of the additional inflowing air surfaces due to "falling out" window panes from the 800th second is clearly visible, it first leads to a plateau in temperature development. From the 1000th second on, however, the temperatures rise again significantly, as the rate of heat release continues to increase significantly.

Figure A2.12 shows the course of the temperatures in the area of transom 3 and at the supports 3 for case C with a cell size of 25 * 25 * 25 cm³ for 90 minutes calculation time. In the middle of the field, temperatures up to just over 800 °C are calculated at ledger 3. The temperatures at the columns are below the values calculated in the middle of the field below the slab for the entire period under consideration.

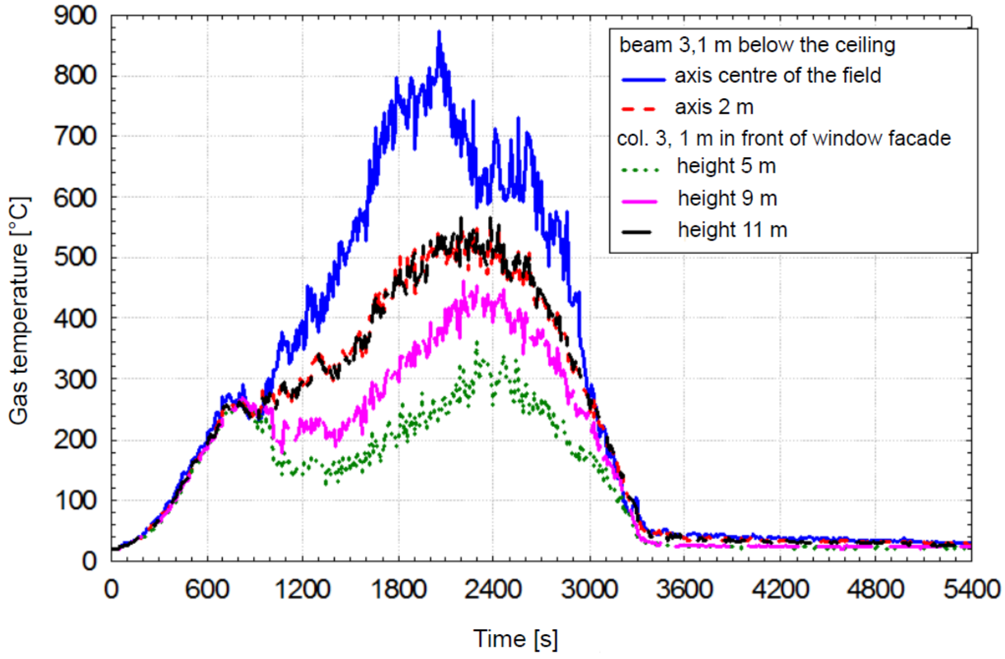


Figure A2.12 Temperature curve at the ledger and the supports 3 at different measuring points (see Figure A2.11) for case C_25), 1 m below the slab, central axis for 90 minutes calculation time

A2.4.5 Conclusion on the determination of the effects of fire

The CFD model Fire Dynamics Simulator (FDS) was used to investigate the effect of a fire on the gas temperatures in a lecture hall building. For the design of a steel frame structure, a fire scenario was defined as the "worst case scenario", in which the entire area of the rows of chairs in the auditorium area is considered as the fire load.

Additional assumptions regarding the smoke extraction system and inflowing air were made in accordance with the requirements of the MVStättV [A2.1], and a fire-related failure of the panes on the long sides of the auditorium at 300 °C was assumed. The necessary steps for calculating the time course of the required temperatures with FDS were described. For this purpose it is necessary,

- to check the model for a convergence of the solution at the selected fineness (size) of the cells and
- to vary the parameters and compare the solutions to determine the most critical scenario.

A grid with 25 cm edge length of the cells has proven to be sufficient for the simulation with the field model with regard to the convergence of the results. It could be shown that flows through additionally opened doors lead to very different temperature distributions in the room and that the highest temperatures do not always have to be reached directly above the source of the fire.

The steel beams should therefore be designed for the same temperature range. The maximum temperature at beam 3 was calculated to be more than 800 °C. The temperature-time curve calculated on this beam and the associated columns serves as the basis for the subsequent structural analyses.

A2.5 Fire protection dimensioning of the construction

A2.5.1 Structure and actions

The supporting structure of the auditorium consists of 10 steel frames with the dimensions b = 29.10 m and h = 12 m (Figure A2.13). The frames are to be designed as two-joint frames with the joints in the base points. The center distance of the frames is 3.75 m.

The uprights of the frames are made of HEA 500 profiles, the transoms of HEA 700 profiles. Bolt and post are rigidly connected to each other by bolted end plate joints (Figure A2.14). The end plates have a thickness of 25 mm. In the corner of the frame there are two braces in the post with a thickness of 25 mm in extension of the beam flanges. The base plate has a thickness of 20 mm.

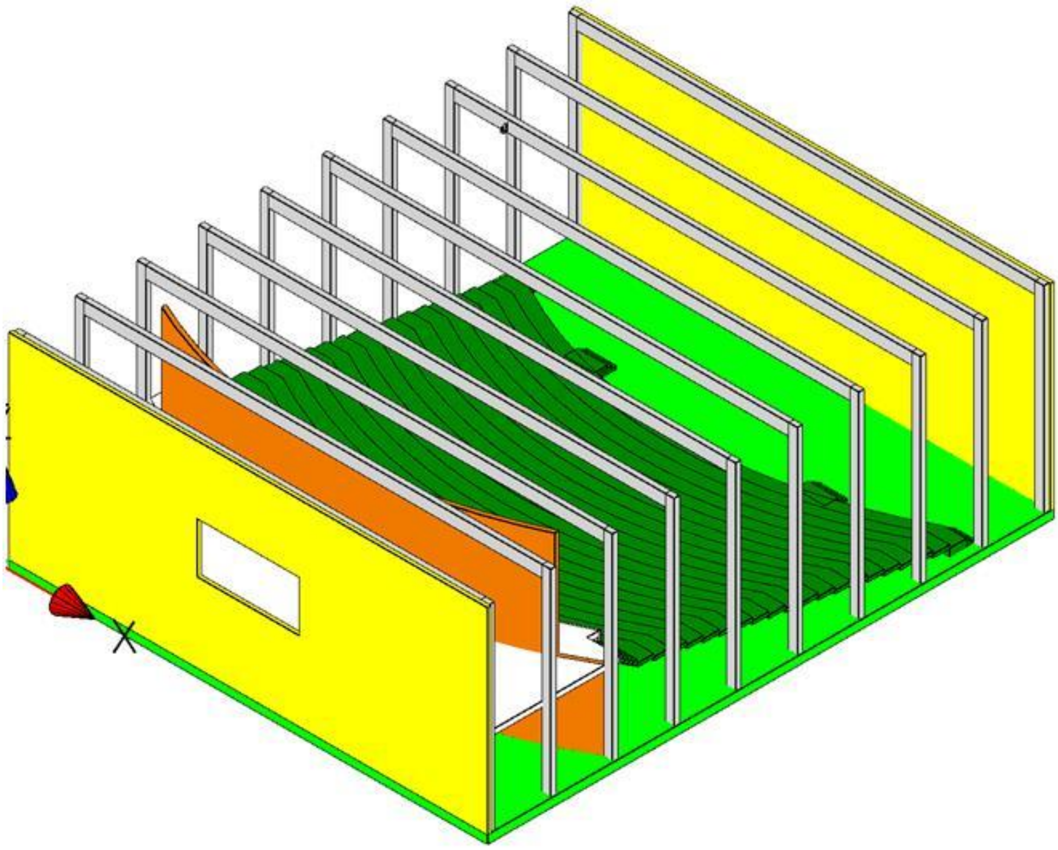


Figure A2.13 Supporting structure of the auditorium with steel frame

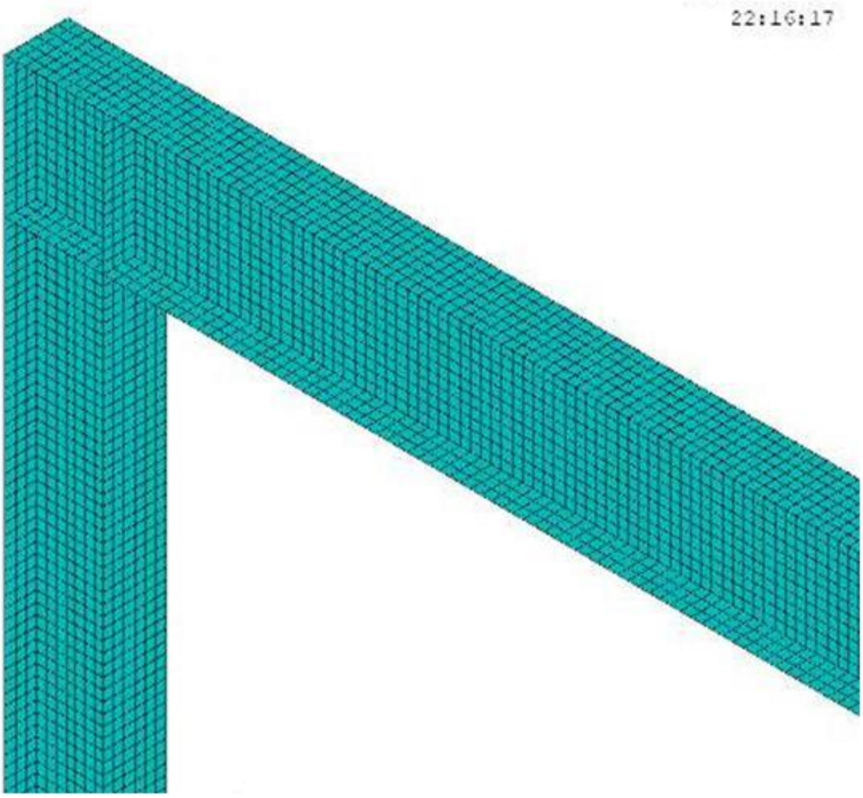


Figure A2.14 Corner design of the steel frames in the lecture hall building

Compilation of the actions according to DIN EN 1991

Table A2.5 Composition of the dead weight of the roof

Sandwich elements with 100 mm mineral wool insulation	0.20	kN/m²
Acoustic ceiling of A2 building material	0.09	kN/m²
Technical extension load	0.30	kN/m²
Sum of the roof own weight	0.59	kN/m²

Line load due to dead weight of roof: $g_{k,1}$ 2.21 kN/m

Dead weight steel-glass façade: $g_{k,2}$ 1.88 kN/m

Snow load:
$s_k = \mu_i \cdot C_e \cdot C_t \cdot s_k \cdot b = 0.8 \cdot 1.0 \cdot 1.0 \cdot 0.95$ kN/m² $\cdot$ 3,75 m = 2.85 kN/m

Wind facing side:
$w_{k,z} = q_p\ (z_e) \cdot c_{pe} \cdot b = 0.8 \cdot 0.72 \cdot 3.75 =$ 2.16 kN/m

Side facing away from the wind:
$w_{k,a} = q_p\ (z_e) \cdot c_{pe} \cdot b = 0.8 \cdot (-0.35) \cdot 3.75 =$ -1.05 kN/m

Wind load on flat roof
$w_{k,F} = q_p\ (z_e) \cdot c_{pe} \cdot b = 0.8 \cdot (-1.8) \cdot 3.75 =$ -5.4 kN/m
$w_{k,H} = q_p\ (z_e) \cdot c_{pe} \cdot b = 0.8 \cdot (-0.7) \cdot 3.75 =$ -2.1 kN/m
$w_{k,I} = q_p\ (z_e) \cdot c_{pe} \cdot b = 0.8 \cdot 0.2 \cdot 3.75 =$ 0.6 kN/m

Load case combination for "cold" assessment: Basic combination

$$E_d = E\ [\sum \gamma_{G,j} \cdot G_{k,j} + \gamma_{Q,1} \cdot Q_{k,1} + \sum \gamma_{Q,i} \cdot \psi_{0,i} \cdot Q_{k,i}] \quad \text{(A2.31)}$$

Load case combination for "hot" assessment: Exceptional situation

$$E_d = E\ [\sum \gamma_{Gi} \cdot G_{ki} + A_d + \psi_{2,1} \cdot Q_{k,1} + \sum \psi_{2,i} \cdot Q_{k,i}] \quad \text{(A2.32)}$$

(Note: In general, the quasi-permanent size $\psi_{2,1} \cdot Q_{k,1}$ may be used. This does not apply to components where the wind is the guiding force. In this case, the frequent size $\psi_{1,1} \cdot Q_{k,1}$ should be used for wind action).

According to DIN EN 1991-1-1 [A2.14] following partial safety factors as well as the combination coefficients according to Table A2.6 are to be applied for the ultimate limit state of the load-bearing structure or load-bearing components:

Permanent actions (favourable): $\gamma_{G,sup} = 1.35$

Permanent actions (unfavourable): $\gamma_{G,inf} = 1.00$

Variable actions (unfavourable): $\gamma_Q = 1.50$

Exceptional actions (unfavourable): $\gamma_A = 1.00$

Table A2.6 Combination coefficients according to Table A.1.1 of DIN EN 1990 [A2.6]

	ψ	ψ	ψ
Payloads in assembly rooms	0.7	0.7	0.6
Snow loads for buildings < 1000 m above sea level	0.5	0.2	0.0
Wind loads for buildings	0.6	0.2	0.0

This results in the load in Figure A2.15. It is assumed that the loads from the ledger are introduced into the two standards without a planned center.

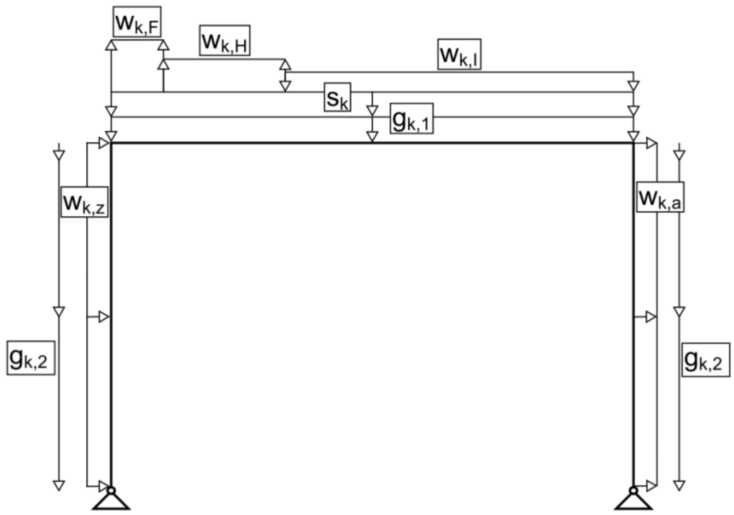


Figure A2.15 Characteristic load on the frame

According to [A2.14] a sinusoidal initial imperfection of h/1000 is applied to the vertical components in the center of the component.

For the calculation at normal temperature, the frame transoms are held by the roof panels at right angles to the frame axis. In case of application, this proof should be carried out specifically or other measures should be taken to prevent torsional flexural buckling. For the calculation in case of fire, the lateral support of the frame transoms by the roof panels is still assumed, since the roof panels practically do not lose their stiffness due to the thermal insulation of the upper sheet level. In the model, the frame beam is held in the middle of the upper chord on the entire outer side of the flange against displacement transversely to the frame axis. A lateral support is missing on the frame transoms, so that the proof of torsional flexural buckling should be carried out here.

For the design of the steel frames, the course with the highest fire room temperatures is selected as the decisive temperature load (see Figure A2.16 and Table A2.7). On the safe side, these fire room temperatures are applied unchanged over the height of the frame standards and over the length of the frame transom. It is neglected that the lower part of the frame leg is partially shielded from direct fire attack by the supporting structure for the rows of chairs.

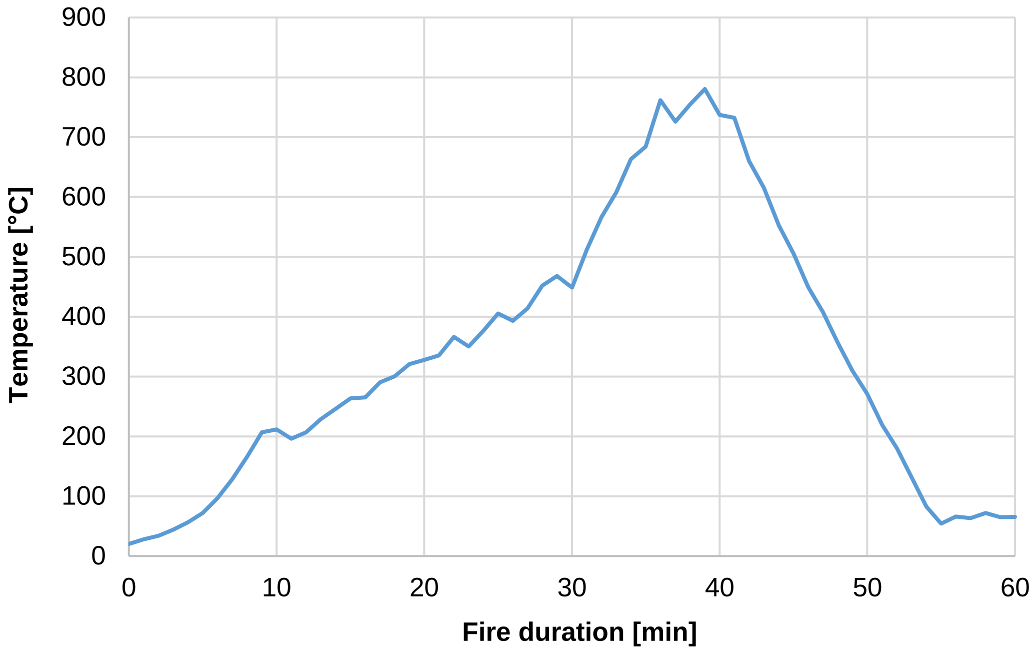


Figure A2.16 Time-dependent temperature effect on the construction in the beam 3

Table A2.7 Time-dependent temperature effect on the construction in the beam 3

Time [min]	Temperature [°C]	Time [min]	Temperature [°C]	Time [min]	Temperature [°C]
0	20.2	20	327.6	40	737.1
1	28.2	21	335.2	41	732.6
2	34.1	22	366.1	42	660.4
3	44.3	23	350.1	43	615.7
4	56.4	24	376.4	44	552.5
5	71.7	25	405.2	45	505.7
6	96.5	26	392.9	46	449.0
7	128.3	27	413.9	47	407.2
8	166.3	28	451.8	48	356.6
9	206.8	29	467.7	49	309.4
10	211.1	30	448.8	50	271.2
11	196.2	31	511.9	51	219.0
12	206.6	32	566.5	52	179.8
13	228.8	33	607.8	53	131.2
14	245.7	34	663.2	54	82.7
15	263.5	35	684.1	55	54.1
16	265.3	36	762.1	56	66.0
17	290.3	37	725.9	57	63.5
18	300.4	38	755.0	58	72.2
19	320.6	39	780.5	59	65.1

A2.5.2 Material properties

The heating of a component depends on the heat transfer at the edge of the component and the heat flow inside the component. The heat flow caused by a temperature gradient in the component is influenced in its velocity by the temperature and material-dependent material properties thermal conductivity λ [W/(m·K)], specific heat c_p [J/(kg·K)] and bulk density ρ [kg/m³]. The heat transfer conditions for the convective heat transfer coefficients on the flamed surface α_c = 35 W/(m²K) and on the surface facing away from the fire α_c = 9 W/(m²K) and a resulting emissivity of ε_{res} = 0.7 are assumed [A2.15].

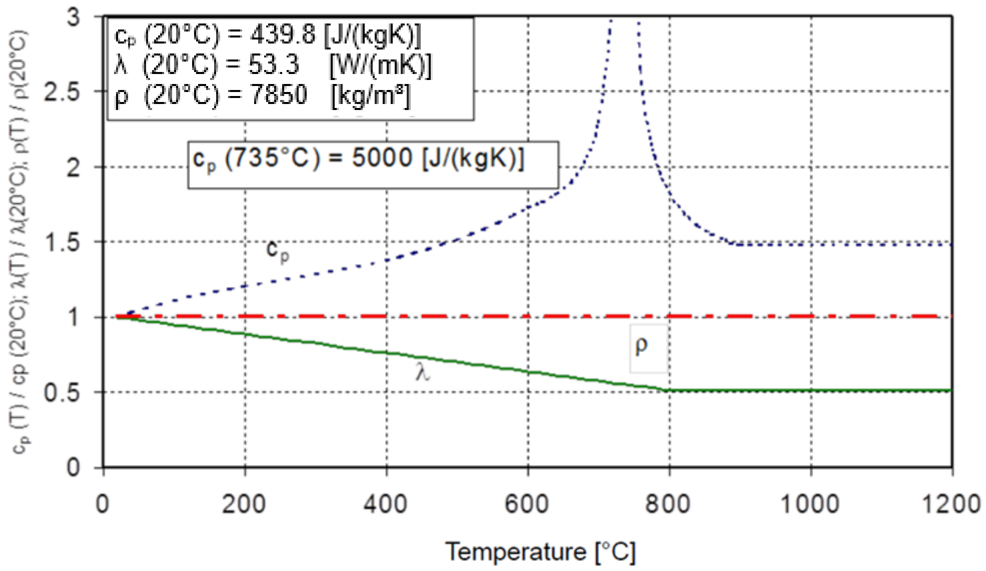


Figure A2.17 Temperature-dependent curve of thermal material properties of structural steel

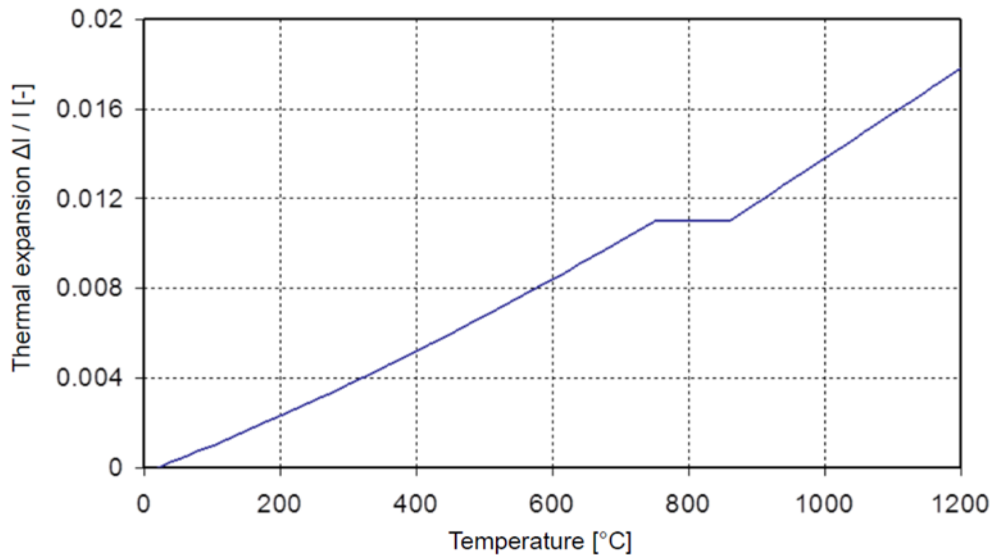


Figure A2.18 Thermal expansion of structural steel

The temperature-dependent thermal material properties for structural steel are given in Eurocode 3 Part 1-2 [A2.14] as temperature-dependent calculation functions. Figure A2.17 shows the temperature-dependent thermal conductivity (λ), specific heat (c_p) and bulk density of structural steel and Figure A2.18 the thermal strain. Figure A2.21 shows temperature-dependent stress-strain curves for structural steel S235 according to [A2.14]. Figure A2.20

shows the temperature-dependent course of thermal conductivity (λ), specific heat (c_p) and bulk density (ρ) of mineral wool.

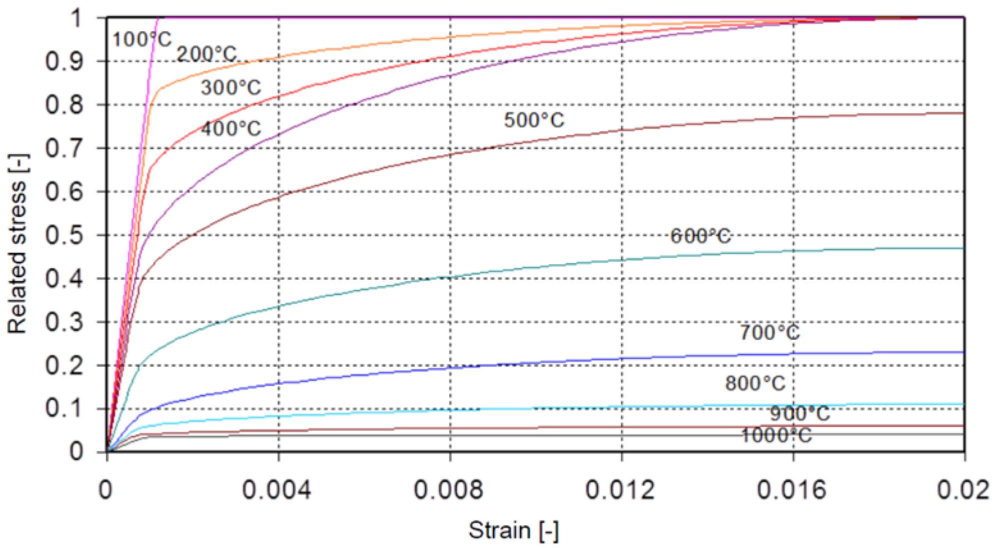


Figure A2.19 Temperature-dependent stress-strain curves for structural steel S235

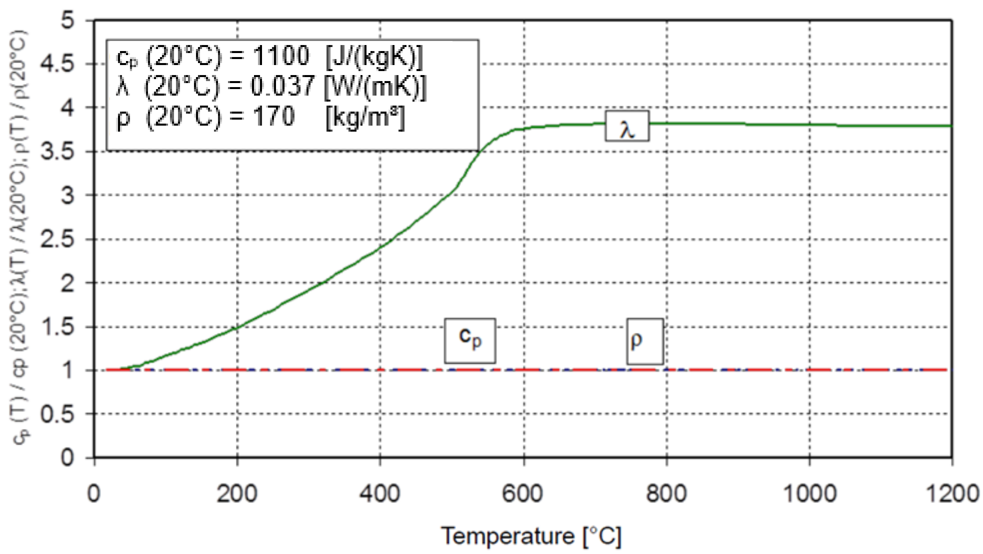


Figure A2.20 Temperature-dependent curve of thermal material properties of mineral wool [A2.20]

A2.5.3 Design of the structure using the simplified design method according to Eurocode 3 Part 1-2

A2.5.3.1 Dimensioning at temperature level

The simplified design procedure according to Eurocode 3 Part 1-2 [A2.14], Chapter 4.2.4 sets out the determination of the critical temperature as a function of the component load μ_0 unless deformation criteria or influences from stability problems have to be considered. For this reason, only the beam may be designed on the temperature level since lateral supports are provided here to prevent torsional flexural buckling.

The utilization of the frames $\mu_0 = E_{fi,d} / R_{fi,d,0}$ is 0.59 for the beam. This results in a critical steel temperature for the beams of 557 °C.

To determine the component temperature, Eurocode 3 Part 1-2 [A2.14], Chapter 4.2.5.1 offers a method with which the temperature rise $\Delta\theta_{a,t}$ of an unprotected steel component during a time interval Δt can be calculated.

$$\Delta\theta_{a,t} = k_{sh} \frac{A_m / V}{c_a \rho_a} \cdot \dot{h}_{net,d} \Delta t \tag{A2.33}$$

Where:

$\dot{h}_{net,d}$	The design value of the net heat flux per unit area,
k_{sh}	Correction factor for the shadow effect,
A_m/V	The section factor of the unprotected steel component,
A	The surface of the structural element exposed to fire per unit length,
V	The volume of the structural element per unit of length,
c_a	The specific heat of steel,
Δt	The time interval,
ρ_a	The density of steel.

For I-sections under other than the nominal fire exposure, the shadow effect should be determined with:

$$k_{sh} = [A_m/V]_b / [A_m/V]$$

Where $[A_m/V]_b$ is the section factor for the box enclosing the profile. Conservative results are obtained when the shadow effect is not taken into account (i.e. $k_{sh} = 1$).

A_m and V are profile-dependent constant values. ρ_a may also be assumed to be constant at 7,850 kg/m^3 . The specific heat c_a is a temperature-dependent quantity that is calculated in accordance with DIN EN 1993-1-2, Section 3.4.1.2 using the equations (A2.37) to (A2.40). The steel temperature θ_a is specified in °C:

For 20 °C ⩽ θ_a < 600 °C

$$c_a = 425 + 7.73 \cdot 10^{-1} \cdot \theta_a - 1.69 \cdot 10^{-3} \cdot \theta_a^2 + 2.22 \cdot 10^{-6} \cdot \theta_a^3 \quad \text{[J/kg·K]} \tag{A2.34}$$

For 600 °C ⩽ θ_a < 735 °C

$$c_a = 666 + \frac{13002}{738 - \theta_a} \quad \text{[J/kg·K]} \tag{A2.35}$$

For 735 °C ⩽ θ_a < 900 °C

$$c_a = 545 + \frac{17820}{\theta_a - 731} \quad \text{[J/kg·K]} \tag{A2.36}$$

For 900 °C ⩽ θ_a < 1200 °C

$$c_a = 650 \quad [\text{J/kg·K}] \tag{A2.37}$$

The net heat flow $\dot{h}_{net,d}$ on the surface exposed to fire can be calculated according to DIN EN 1991-1-2, taking into account heat transfer by convection and radiation according to equation (3.1). The convective part of the net heat flow is obtained from equation (3.2), the net heat flow by radiation from equation (3.3), where ε_m = 0.7 and ε_f = 1.0 [A2.16], [A2.14] and ϕ= 1.0.

The calculation of the component temperature according to equation (A2.33) can be done with a spreadsheet or mathematics program. The radiation temperature of the fire is assumed to be equal to the gas temperature which is derived from the CFD calculation. The chosen time steps Δt should not be too large; in Eurocode 3 Part 1-2 [A2.14] 5 s are recommended. Here, the time steps of 10 s from the CFD calculation are used for the fire room temperature. In an additional calculation, the development of the component temperature was checked in 5 s steps and only a very small deviation of less than 2 °C was found. For the initially unknown component temperature, the value from the previous calculation step is used and the temperature difference $\Delta\theta_{a,t}$ is calculated according to equation (A2.33).

The result of the simplified design method is shown in Figure A2.21 . The component temperatures in the cross-section of the frame beam is compared with the critical temperature determined according to equation (6.1). It can be seen that the component temperature in the beam clearly exceeds the critical steel temperature. Therefore, the frame beam cannot be designed unprotected according to the critical temperature verification method.

Here it should be taken into account that, in the case of statically indeterminate stored components, the proof may be very much on the safe side with the help of the critical temperature. In the event of fire, the corner moments in the frame increase until the plastic moment is reached. As a result, the field moment is reduced and the critical temperature actually increases. This effect is not taken into account in the check according to [A2.14] because the action and resistance are determined at minute 0.

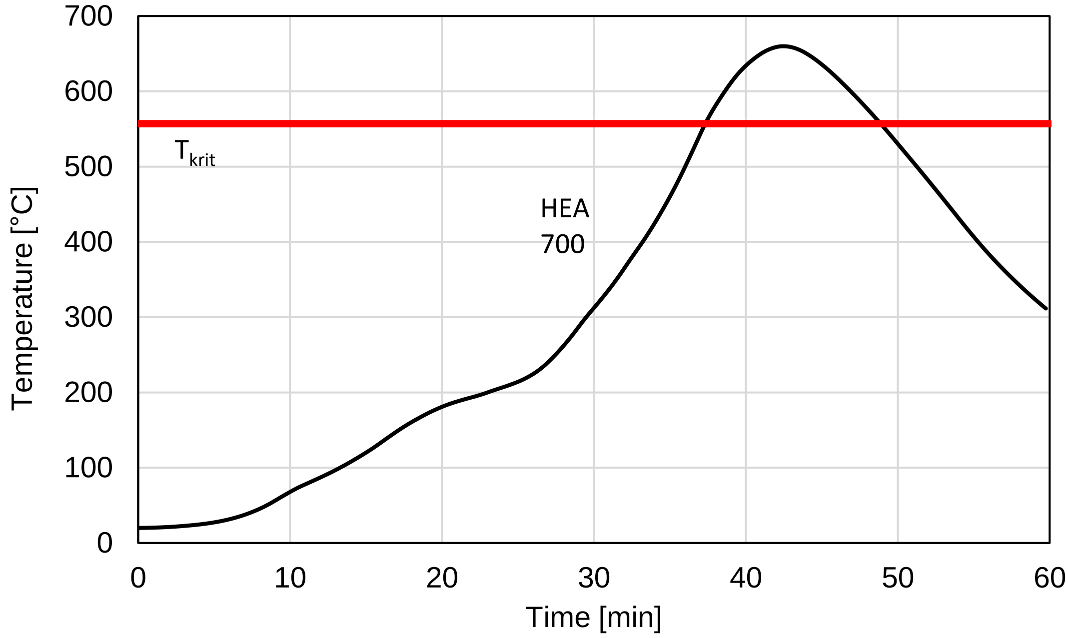


Figure A2.21 Temperature-time curve in the frame beam (HEA 700) according to the simplified design method according to DIN EN 1993-1-2 [A2.14]

A2.5.3.2 Assessment of structural elements at risk of instability (struts in this case)

The verification of stability in case of fire is carried out according to the simplified design method on the load-bearing capacity level according to Chapter 4.2 [A2.14]. The verification is performed using the decisive load combination.

The buckling stability for the present example is verified by means of the equivalent member method. According to paragraph 5.2.2 (8) [A2.16] when using the equivalent member method, neither imperfections of the strut nor internal forces due to second-order theory must be taken into account when using the equivalent member method.

The material used is steel grade S235 with a yield strength of f_y= 235 N/mm². The modulus of elasticity is 210000 N/mm². According to [A2.16] the HEA 500 profile is classified in Class 1 cross-section.

The cross-sectional values, steel grade and section properties for the profile used are shown in Table A2.8. The thermal analysis according to equation A2.36 results in a maximum temperature of approx. 672°C in the strut.

Table A2.8 Profile characteristics of the strut

Column / cross-section value	Frame strut
Profile	HEA 500
Steel grade	S235
Profile area A [cm²]	198
I_y / I_z [cm⁴]	86970/10370
$W_{el,y}$ / $W_{el,z}$ [cm³]	3550/691
$W_{pl,y}$ / $W_{pl,z}$ [cm³]	3949/1059
I_T [cm⁴]	309
I_w [cm⁶]	5643000

When determining the reduced mechanical characteristics as a function of the irregular cross-sectional temperature, the maximum temperature in the cross-section is taken as the decisive temperature, being on the safe side.

Table A2.9 shows the reduced mechanical properties (according to Table 3.1 [A2.14]) of various decisive supports at the design temperature.

Table A2.9 Decreased mechanical characteristics at design temperature for the supports

Column/section value	Frame strut
Rated temperature	672°C
$k_{y,\theta}$ [-]	0.297
$k_{E,\theta}$ [-]	0.18

In the following, it is to be demonstrated that the load-bearing capacity is ensured in case of fire. For this purpose, the verifications for the components loaded by bending and axial pressure are performed in accordance with Section 4.2.3.5 [A2.14] (buckling safety check, lateral torsional buckling check). The decisive load combination consists of the loads due to dead weight and wind:

$E_d = E\,[\sum 1.0 \cdot G_{ki} + 0.2 \cdot w_k]$

This results in the following loads for the struts according to the actions in Table A2.5:

From the self-weight of the roof, the facade and the steel girders:

$N_{Ed,fi}$ = 1.0 · ($G_{k,1}$ + $G_{k,2}$) = 1.0 · ((-2.21 kN/m) · 29.1 m · 0.5 + (-1.88 kN/m) · 12 m + (-1.55 kN/m) · 12 m + (-2.04 kN/m) · 29.1 m · 0.5)

= -102.9 kN

From wind:

E_d = 0.2 · ($w_{k,z}$ + $w_{k,a}$ + $w_{k,F}$ + $w_{k,H}$ + $w_{k,I}$)

This results in the following maximum compression force in the strut:

$N_{Ed,fi}$ = -1.91 kN

The wind is the only stress that systematically causes a moment in the strut. The clamping moment at the connection between frame and strut is decisive for the design. When calculating the moment load, the load-bearing effect of the entire frame must be taken into account, as wind suction occurs at one leg and wind pressure occurs at the other leg (see Figure A2.23 Characteristic loading of frame).

This stress results in the decisive moments at the connection between frame and strut:

M_{wk} = -49.28 kNm

M_{wd} = 0.2 · (-49.28) kNm = -9.86 kNm

In addition, the horizontal wind load creates a vertical supporting force, which is neglected here due to its small size.

The moment due to the wind load acts in the direction of the strong axis of the HEA 500 profile, so that the stability verification is performed for the strong axis. In addition, the stability verification is carried out for the weak axis. Since the moment due to the wind only acts in the direction of the strong axis, the verification for the weak axis is carried out without stress due to the wind.

In the following, the verification of flexural buckling is performed according to Chapter 4.2.3.5, equation 4.21a [A2.14] both for the weak and strong axis and the torsional flexural buckling check according to Chaper 4.2.3.5, equation 4.21b [A2.14] only for the strong axis.

Bending crease check:

The buckling length is determined according to [A2.16] for a frame with hinged foot points. The buckling load factor and the resulting buckling lengths of the frame struts are determined depending on the stiffness of the strut and beam. This results in the buckling length as:

$s_{k,z}$ = 27.82 m

For the verification of flexural buckling, the following formulas and characteristic values are used according to [A2.14]:

- Partial factor in the event of a fire: $\gamma_{M,fi}$ = 1.0
- Radius of gyration: $i_z = \sqrt{(I_z / A)}$
- Slenderness ratio: $\lambda_{k,z} = s_{ki,z} / i_z$

- $$\lambda_1 = 93.6 \cdot \sqrt{(235 / f_y)}$$

- Relative slenderness: $\bar{\lambda} = \dfrac{\lambda_{k,z}}{\lambda_1}$
- Relative slenderness in the event of a fire : $\bar{\lambda}_{k,z} = \bar{\lambda} \cdot \sqrt{k_{y,\theta} / k_{E,\theta}}$
- Reduction factor $\chi_{fi,z}$ for flexural buckling: $\chi_{fi,z} = \dfrac{1}{\phi_\theta + \sqrt{\phi_\theta^2 - \overline{\lambda_{\theta,z}}^2}}$

with: $\alpha = 0.65 \cdot \sqrt{235 / 235} = 0.65$

$$\phi_\theta = \frac{1}{2} \cdot \left(1 + \alpha\overline{\lambda_\theta} + \overline{\lambda_\theta}^2\right)$$

Coefficient for taking into account the moment curve in the event of fire k_y or k_z

$$k_y = 1 - \frac{\mu_y \cdot N_{fi,Ed}}{\chi_{y,fi} \cdot A \cdot k_{y,\theta} \cdot f_y / \gamma_{m,fi}} \leq 3.0$$

$$k_z = 1 - \frac{\mu_z \cdot N_{fi,Ed}}{\chi_{z,fi} \cdot A \cdot k_{y,\theta} \cdot f_y / \gamma_{m,fi}} \leq 3.0$$

with: Adjustment factor for consideration of the torque β_m=1.1 (Figure 4.2, [A2.35] most unfavourable value)

$$\mu_y = (2 \cdot \beta_{M,y} - 5) \cdot \bar{\lambda}_{y,\theta} + 0.44 \cdot \beta_{M,y} - 0.29 < 0.8$$

$$\mu_z = (1.2 \cdot \beta_{M,z} - 3) \cdot \bar{\lambda}_{z,\theta} + 0.44 \cdot \beta_{M,z} - 0.29 < 0.8$$

The characteristic values and reduction factors are determined in tabular form in Table A2.10.

Check for flexural buckling according to Chapter 4.2.3.5, equation 4.21a [A2.14]:

$$\frac{N_{fi,Ed}}{\chi_{min,fi} \cdot A \cdot k_{y,\theta} \cdot f_{y,k} / \gamma_{M,fi}} + \frac{k_y \cdot M_{y,fi,Ed}}{W_{pl,y} \cdot k_{y,\theta} \cdot f_{y,k} / \gamma_{M,fi}} \leq 1.0$$

Flexural buckling verification (strong axis):

$$\frac{104.8}{0.032 \cdot 198 \cdot 0.297 \cdot 235 / 10} + \frac{1.93 \cdot 9.86 \cdot 100}{3949 \cdot 0.297 \cdot 235 / 10} = 2.37 + 0.1 = 2.47 > 1.0$$

Table A2.10 Characteristic values for the buckling safety check

Column / Calculated value	Frame strut
i_y / i_z [cm]	20.96 / 7.24
$\bar{\lambda}_y / \bar{\lambda}_z$	1.4 / 4.1
$\bar{\lambda}_{\Theta,y} / \bar{\lambda}_{\Theta,z}$	1.82 / 5.26
φ_Θ	2.74/ 16.0
μ_y / μ_z	-4.89/ -8.34
k_y / k_z	2.74 / 3
$\chi_{fi,y} / \chi_{fi,z}$	0.21 / 0.032

Flexural buckling verification (weak axis):

$$\frac{104.8}{0.032 \cdot 198 \cdot 0.297 \cdot 235 / 10} = 2.37 > 1.0$$

The proof in case of fire could not be provided.

For the sake of completeness, the next step is to perform the torsional flexural buckling verification for the strut. This is only to be carried out for the strong axis, since only here is there a moment load in addition to the normal force. In case of fire, the verification is performed according to Chapter 4.2.3.5, equation 4.21b [A2.14].

The stresses are identical to those determined for the flexural buckling verification.

The determination of the characteristic values and reduction factors is calculated using the following formulas:

- Ideal lateral torsional buckling moment: $M_{cr} = \zeta \cdot N_{cr,z} \cdot \left[\sqrt{(c^2 + 0.25 \cdot z_p^2)} + 0.5 \cdot z_p \right]$

with: $c^2 = (I_w + 0.039 \cdot l^2 \cdot I_T) / I_z$

$$N_{cr,z} = \frac{\pi^2 \cdot E \cdot I_z}{l^2}$$

- Relative slenderness for lateral torsional buckling: $\bar{\lambda}_{lt} = \sqrt{W_{pl,y} \cdot f_y / M_{cr}}$

- General reduction factor for lateral torsional buckling in case of fire:

$$\chi_{LT,fi} = \frac{1}{\Phi_{LT,\Theta,com} + \sqrt{\left[\Phi_{LT,\Theta,com}\right]^2 - \left[\bar{\lambda}_{LT,\Theta,com}\right]^2}}$$

with:

$$\Phi_{LT,\Theta,com} = 0.5 \cdot \left[1 + \alpha \bar{\lambda}_{LT,\Theta,com} + \left(\bar{\lambda}_{LT,\Theta,com}\right)^2 \right]$$

$$\lambda_{LT,\Theta,com} = \bar{\lambda}_{lt} \cdot \sqrt{k_{y,\Theta} / k_{E,\Theta}}$$

$$\alpha = 0.65\sqrt{235 / f_y}$$

The lateral torsional buckling verification in case of fire under additional compressive stress is verified for a Class 1 cross-section according to equation 4.21b [A2.14] in Table A2.11.

Table A2.11 Characteristic values for the buckling safety verification

Calculated value	Frame strut
ζ	2.25
c^2 [cm²]	2217.59
z_p [cm]	24.5
M_{cr} [kNm]	1993
$\bar{\lambda}_{LT}$	0.647
$\bar{\lambda}_{LT,\Theta,com}$	0.83
α	0.65
$\Phi_{LT,\Theta,com}$	1.12
$\chi_{LT,fi}$	0.54

$$\frac{N_{fi,Ed}}{\chi_{z,fi} \cdot A \cdot k_{y,\theta} \cdot \frac{f_{y,k}}{\gamma_{M,fi}}} + \frac{k_{LT} \cdot M_{y,fi,Ed}}{\chi_{LT,fi} \cdot W_{pl,y} \cdot k_{y,\theta} \cdot \frac{f_{y,k}}{\gamma_{M,fi}}} \leq 1.0$$

where $\gamma_{M,fi} = 1.00$

$$k_{LT} = 1 - \frac{\mu_{LT} \cdot N_{fi,Ed}}{\chi_{z,fi} \cdot A \cdot k_{y,\Theta} \cdot \frac{f_{y,k}}{\gamma_{M,fi}}} \leq 1$$

$k_{LT} = 1$ is set conservatively. The lateral torsional buckling verification is as follows:

$$\frac{104.8}{0.032 \cdot 198 \cdot 0.297 \cdot 235 / 10} + \frac{1.0 \cdot 986}{0.54 \cdot 3949 \cdot 0.297 \cdot 235 / 10} = 2.37 + 0.066 = 2.4 > 1.0$$

The proof against lateral torsional buckling in case of fire is also not fulfilled.

The possible solution to the problem could consist in fire protection (lining, painting) of the structural elements.

In the following section, the verification is carried out using the extended design method. For this purpose, first the temperature distribution within the cross-section is determined (thermal analysis) and then the load-bearing capacity of the entire frame is calculated in a mechanical analysis.

A2.5.4 Design of the structure using the general design method according to Eurocode 3 Part 1-2

A2.5.4.1 Determination of the component temperatures

A 2D finite element model is generated to calculate the component temperatures. The FE software ANSYS [A2.21] is used. The temperature distributions are determined separately for the frame struts and the frame beams. To clarify the application of the guide, the determination of the component temperatures and the calculation of the load-bearing capacity of the heated steel frame are considered separately.

The structure of the 2D temperature model is shown as an example for the cross-section of the frame beam (Figure A2.22). For the FE model, a section of the frame beam with the roof panel on top was selected. The consideration of the roof panel is important in order to capture the delayed heat flow upwards or outwards in the thermal analysis. A roof panel overhang of 50 cm on both sides was considered. Temperature is applied to the beams profile from three sides. Since a 2D temperature calculation takes only a short time, even on an average PC, the elementation can be selected almost as finely as required.

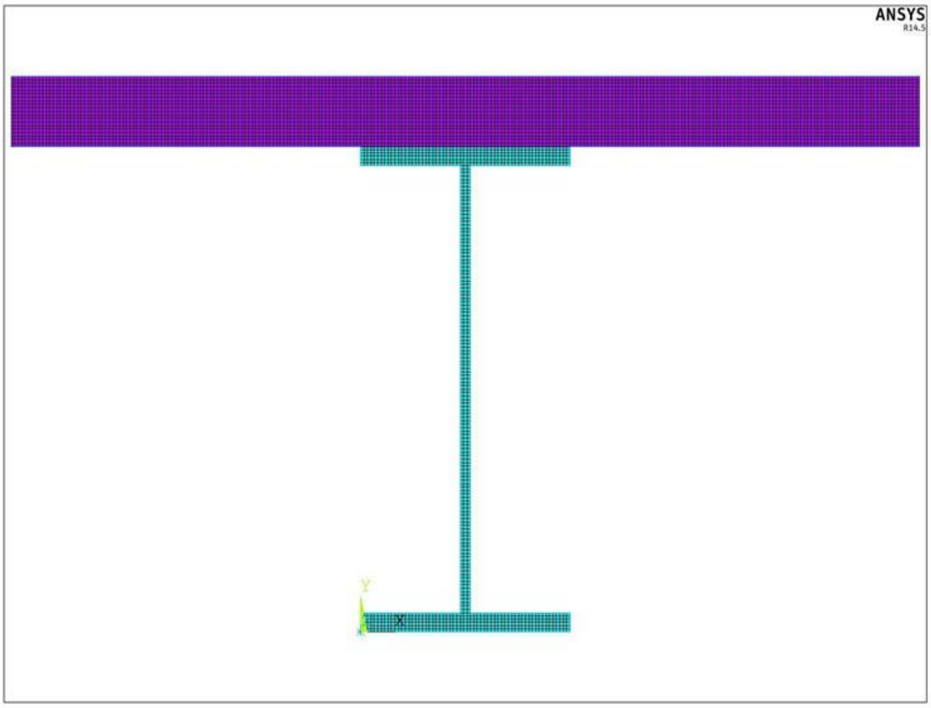
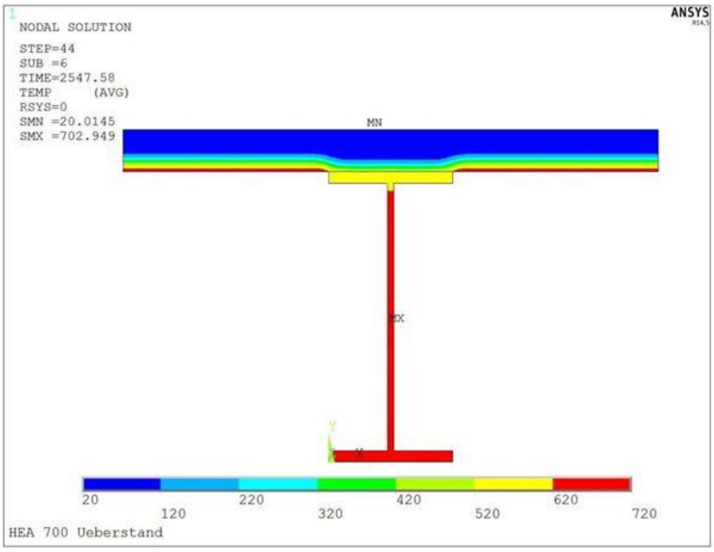


Figure A2.22 FE model for the temperature calculation of the frame beam

The thermal material properties of steel and insulation material are assigned to the elements. A point outside the cross-section is selected as the radiation source. The surface of the cross section that absorbs the thermal radiation should be defined for this point. This is the surface of the steel profile (with the exception of the side of the upper flange that is turned away from the fire) and the underside of the roof construction. For these surfaces the heat transfer conditions are defined, which are represented by the Stefan-Boltzmann constant σ= 5.67-10^{-8}.

The results of the heating calculation in Figure A2.23 show that a maximum temperature of 703°C in the web and 664°C in the flange is achieved.

The heating of the profiles in the web is shown in Figure A2.24. The maximum temperature in the web is reached approx. 200 s after the fire room temperature has exceeded its maximum.



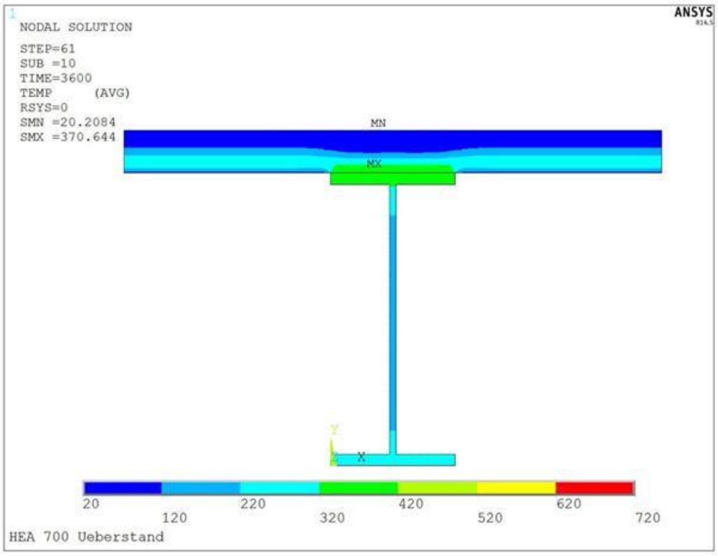


Figure A2.23 Heating of the frame transom HEA 700, top: at maximum temperature in the web after 2540 s, bottom: at the end of heat release after 3600 s

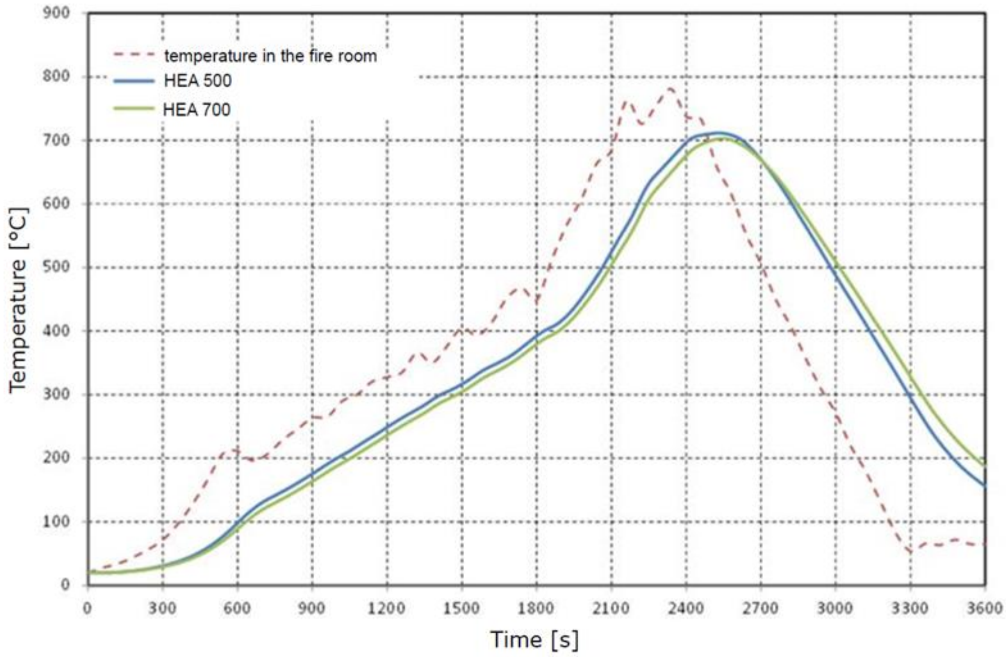


Figure A2.24 Temperature curve in the web of HEA 500 and HEA 700 sections

A2.5.4.2 Structural analysis

The temperatures for the HEA 500 and HEA 700 profiles differ only insignificantly, so that the temperature curve in the web of the HEA 500 column profile with a maximum temperature of 711 °C for all webs in the frame is taken as the effect for the structural analysis. The temperature curve in the lower flange of the HEA 500 with a maximum temperature of 679 °C is the decisive curve for all other components (flanges, braces, end and base plate).

The support of the frame struts is made by a base plate. The central node of the base plate is held in the direction of the frame standards (y-axis). The base plate is held at the nodes of the flanges, i.e. transverse to the frame axis (z-axis) and the web is held in the direction of the frame axis (x-axis). This simulates a minimum clamping as it occurs in real frames due to the fixing of the base plate by plugs or anchors.

The frame corners are supported on the outside between the support and the beam perpendicular to the frame axis. The upper flange of the beam in the middle of the frame is also held at right angles to the frame axis (in the Z-direction) over the entire profile width.

The element size is approx. 5 cm.

The results of the structural analysis show that due to the high temperatures and the dimensions of the components - especially the length of the frame transom - large thermally induced deformations occur (Figure A2.27).

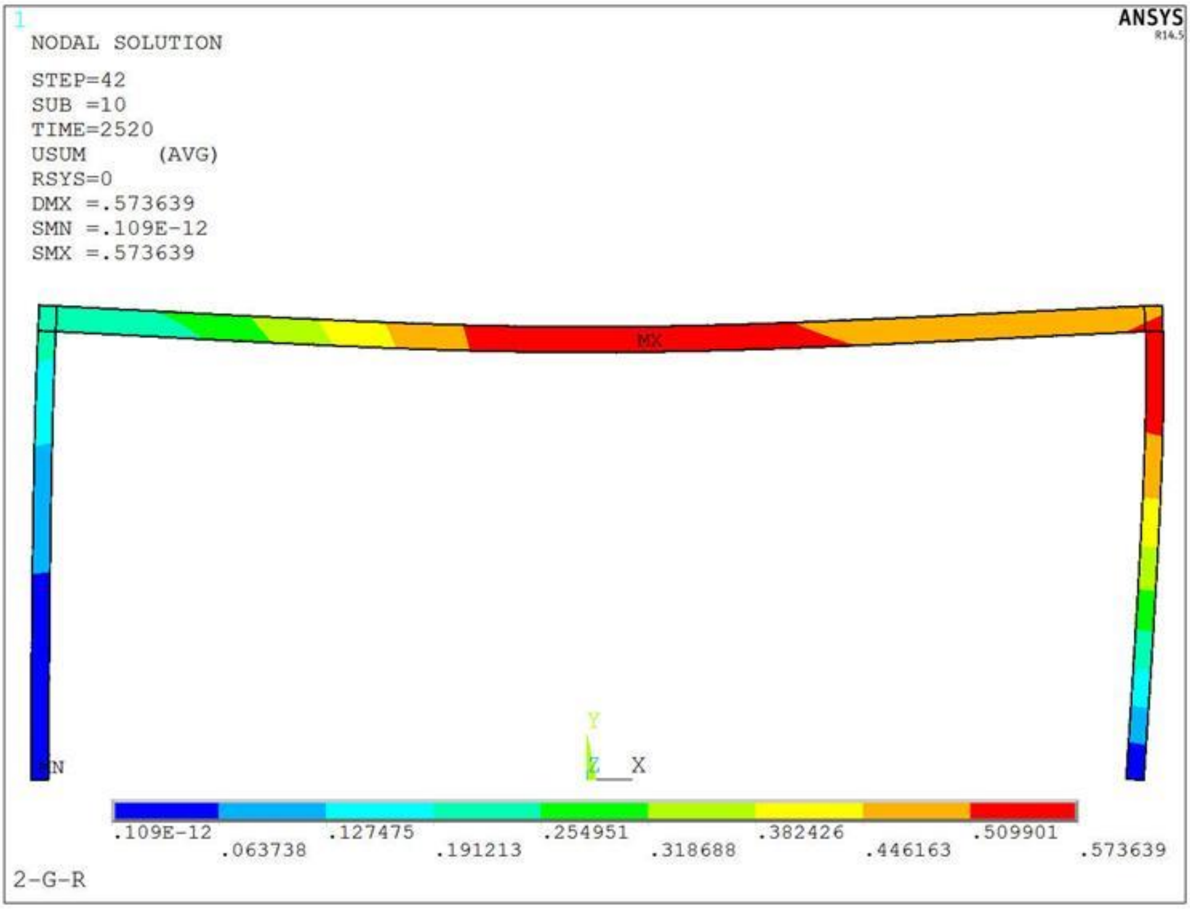


Figure A2.25 Total deformation of the frame (True Scale) at deformation maximum. The scale shows the summed deformations of the nodes in all directions in [m].

Plastic expansion occurs in the area of the frame corner (Figure A2.28). This makes it clear that, with the help of precise computational analysis, the load-bearing capacity is recorded up to the area of large deformations. When using the extended design procedure with the FE method, structural reserves can be mobilized that cannot be considered in the tabular verification or in the simplified design procedure.

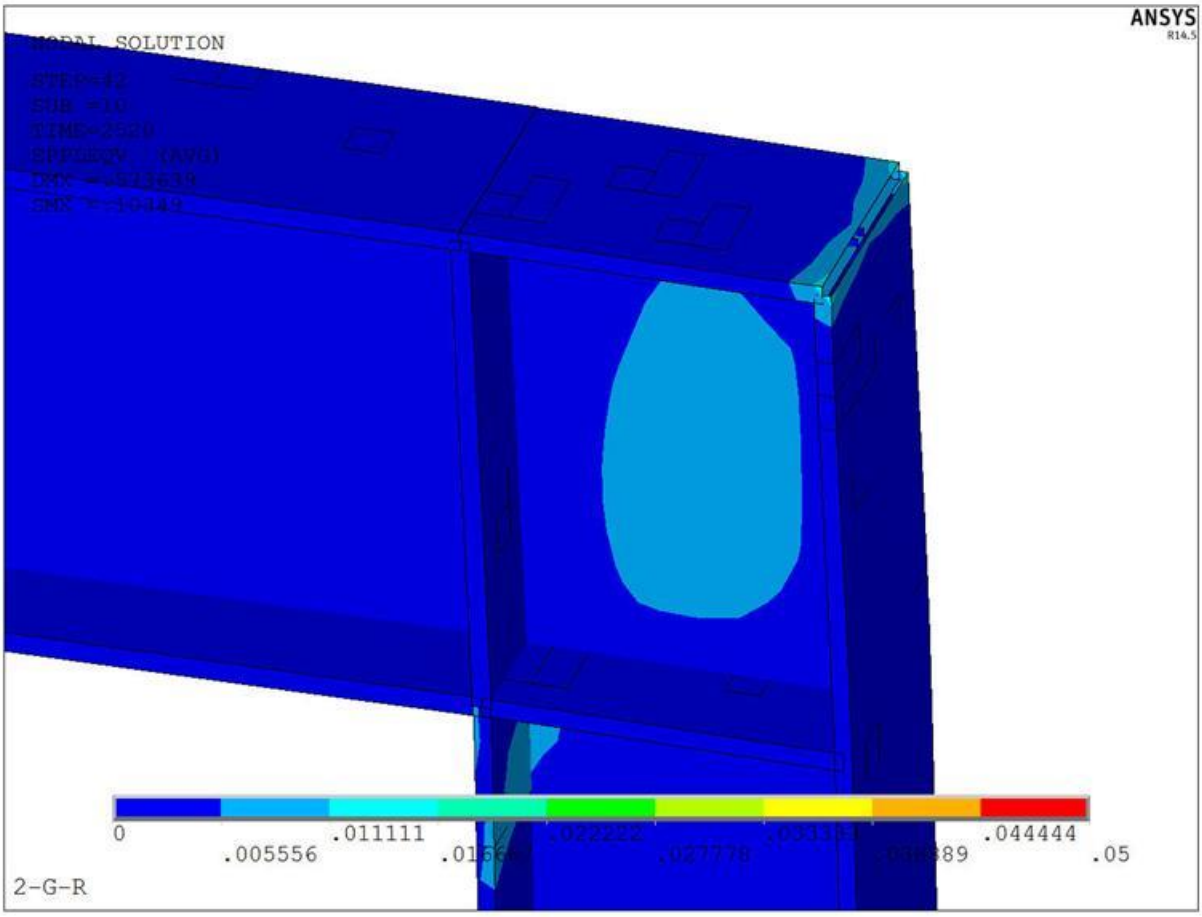


Figure A2.26 Plastic strains

Figure A2.27 and Figure A2.30 show the horizontal and vertical displacement of the left frame corner. Due to the heating of the frame, a strong extension of the frame beam occurs. This causes the frame corners to move apart. This displacement is so large on the windward side of the frame that the displacement due to wind action is cancelled and the displacement of the frame knot takes place in the opposite direction after approx. 700 s. After approx. 2100 s, the deflection of the frame beam increases significantly, so that the frame corner shows a strong increase in deformation at this point.

If one looks at the vertical displacement of the bottom chord of the frame beam in the middle of the field in Figure A2.31 , the deflection from the load application can be seen first. With increasing temperature influence the beam seems to bend upwards. In reality, however, two effects overlap here, as can be seen by comparing Figure A2.31 and Figure A2.30 . On the one hand, the deflection of the frame increases as a result of the load effects, since the stiffness decreases due to the temperature effect. On the other hand, the thermal expansion of the supports raises the entire beam. The difference between the deformation of Figure A2.31 and Figure A2.30 corresponds to the actual deflection of the frame beam (Figure A2.32). Figure A2.30 shows that there is no upward deflection.

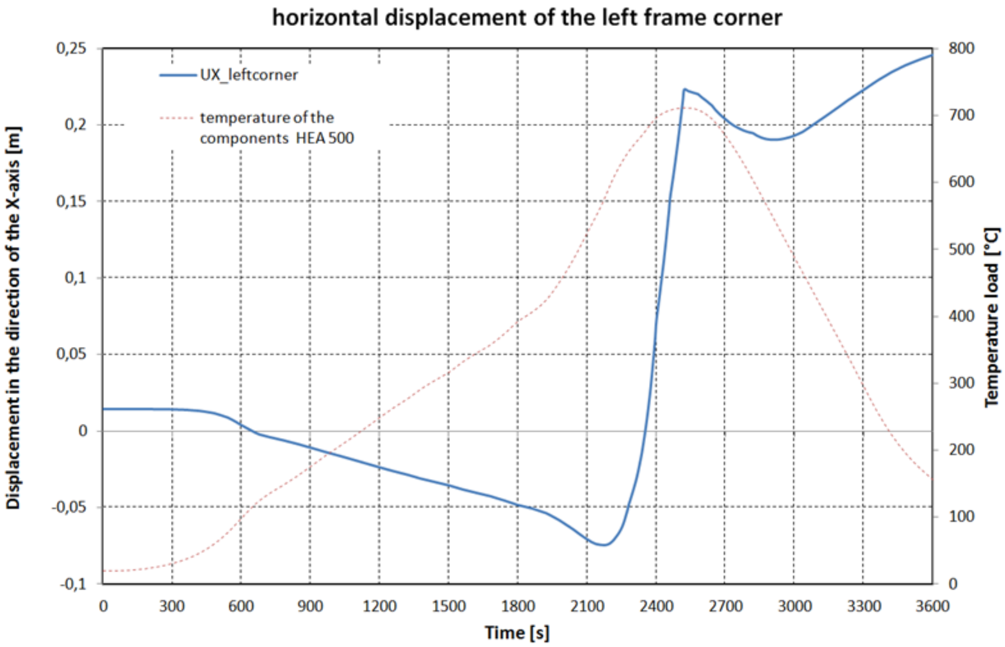


Figure A2.27 Horizontal displacement of the left (windward) frame corner

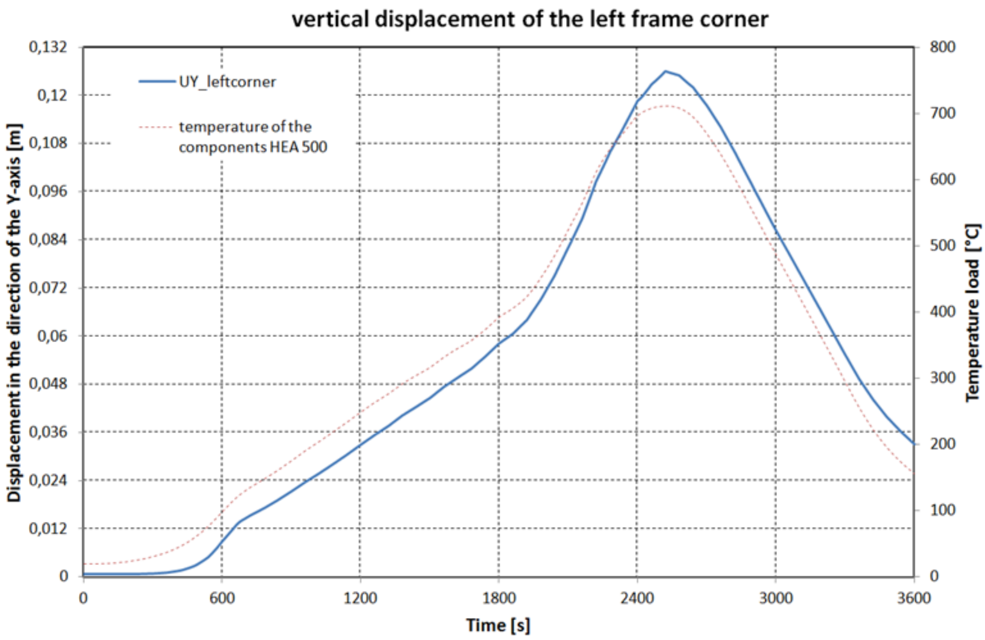


Figure A2.28 Vertical displacement of the left frame corner

Figure A2.29 Vertical displacement of the bottom chord of the frame beam in the center of the field

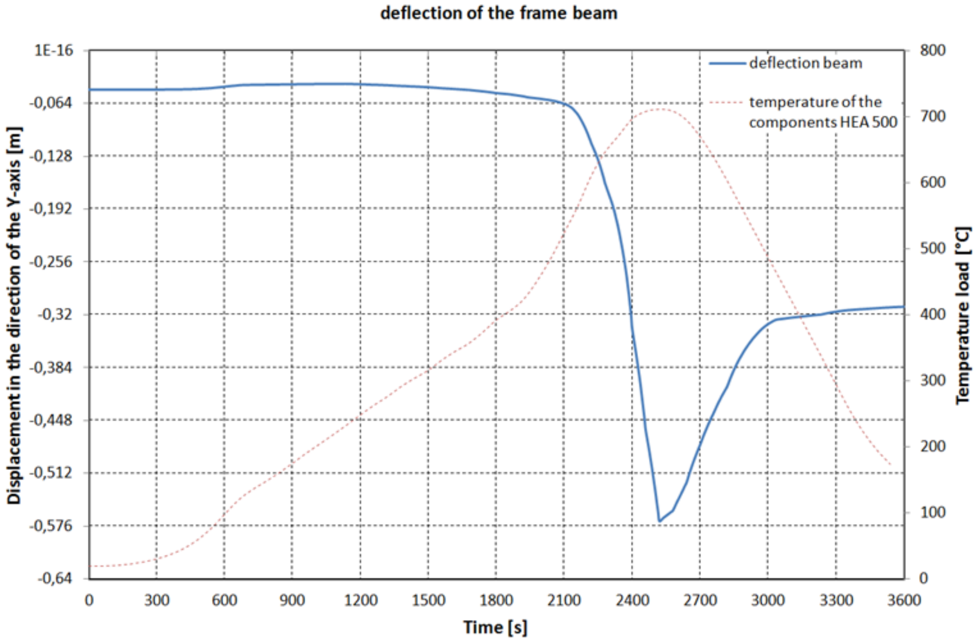


Figure A2.30 Actual deflection of the frame beam in the center of the field

The failure conditions shall be specified by an engineer when applying the extended design method. In this context, the load-bearing and deformation behavior of adjoining structural members (partitions and partition walls, suspended ceilings) shall also be considered. The load-bearing capacity of the structural element, the magnitude of the deformations and the failure rate can be defined as failure criteria (see Chapter 6).

The following applies to the load capacity:

$$E_{d,fi} \leq R_{d,t,fi}$$

When determining the maximum permissible deformation, the area-enclosing function of the structural elements should be taken into account. The roof consists of sandwich panels where the deformations do not have a great influence on adjacent solid components. Since the finite elements do not fail by definition due to temperature effects, one possible failure criterion is the tearing off of the fasteners from the frame beam due to much elongation of the elements. On the other hand, joints between the sandwich panels may open laterally due to elongation of the frame beam. However, this would not cause the elements to fall down, so that no deformation limit needs to be observed for this type of damage.

According to Chapter 6, the criterion chosen as the failure criterion is the one provided in DIN 4102- 2 or DIN EN 13501-2 for statically determinate mounted components that are stressed wholly or predominantly by bending in the component tests. It specifies a critical deflection and critical deflection rate according to equation (A2.38 and A2.39)

(a) Deflection: D = L2/(400 d) [mm] (A2.38)

(b) Deflection rate: dD/dt = L2/(9000 d) [mm/min] (A2.39)

Where

L The clear span, in mm;

d The distance, in mm, from the outermost edge of the compression zone to the outermost edge of the tension zone of the supporting section, in each case for cold design.

The criterion of the deflection speed only applies after a deflection of L/30 is exceeded.

The maximum deflection of the frame beam is 570 mm.

The critical deflection is

$L^2/(400\ d) = 28300^2 / (400 \cdot 690) = 2900\ mm > 570\ mm$

The maximum deflection speed occurs shortly before the maximum temperature is reached. In the center of the field the largest difference in displacements in y-direction between two time steps of 60 s is $\Delta s = 126$ mm, as shown in Figure A2.30 . This should only be considered from a deflection of L/30:

$L/30 = 28300 / 30 = 943\ mm > 570\ mm$

For completeness, the verification of the critical deflection speed is nevertheless shown here. The critical deflection speed is

$L^2 / (9000\ d) = 28300^2 / (9000 \cdot 690) = 129\ mm/min > 126\ mm/min.$

The critical deflection speed is not reached during the calculation. The verification of the load-bearing capacity in case of fire could therefore be carried out using the extended design method.

Connections

The load-bearing capacity of the connections of beams and struts shall be verified in accordance with DIN EN 1993-1-2 [A2.14], Annex D, in which the temperature-dependent reduction factors of the load-bearing capacity of screws and weld seams are specified.

A2.6 Verification of personal safety

A2.6.1 Objective

The auditorium building has 20 rows of seats with 32 seats each, so that there are 640 seats available. For certain events, up to 360 additional people can be expected to sit or stand in front of the first row of seats or on the steps. Proof should be provided that in the event of a fire, safe self-rescue of all persons from the auditorium is possible. This includes the proof that the time required to leave the lecture hall ($t_{evacuation}$) is considerably less than the time ($t_{available}$) until significant loads from the spread of smoke and heat occur. Furthermore, it should be ensured that the other conditions of the evacuation process do not lead to any danger to persons. The main escape route from the auditorium is a 35 m long path through the atrium to the outside, whereas § 7 (3) MVStättV [A2.1] only provides for a maximum length of 30 m. Since all other personal protection requirements are in accordance with the MVStättV, the safety level achieved by the MVStättV is determined at this point using the specified fire scenarios and engineering methods.

A2.6.2 Criteria for demonstrating that the safety objectives are fulfilled

The criteria "height of the smoke layer", "optical density" and the "Fractional Effective Dose" (FED) are relevant for the fire scenarios to be investigated (Table A2.12). The evaluation value for the low-smoke layer is 2.5 m above the floor. An optical density of 0.2 1/m corresponds to a detection distance of 10 to 20 m (see Table 8.3).

Table A2.12 Selected criteria for demonstrating that the protection goal has been achieved

Measured variable	Evaluation value	Comment
low smoke layer height	2.5 m	according to [A2.3]
Optical density	0.2 1/m	according to Chapter 8, Table 8.3 10 m to 20 m
Fractional Effective Dose (FED)	0.3	0.1 – 0.3 according to [A2.20].

The FED is used to determine the direct impairment of a person until the inability to escape due to toxic gases and lack of oxygen and is therefore far less conservative than the criteria mentioned above. According to Chapter 8 the integral effect of CO, if present HCN, O_2 deficiency and CO_2 is considered. When using the FED, primary literature, such as Purser [A2.21] should be consulted in any case, in which, for example, an extension of the FED to include irritant gases is also suggested. The FED is defined as a dimensionless number, which reaches the value 1.0, if the damaging effects of fire smoke cause escape inability of persons. However, since different population groups react more sensitively, an FED of 0.1 to 0.3 should be used as a measure of the inability to escape [A2.20], [A2.21]. Since time- and location-dependent gas concentrations are calculated by CFD models, the coupling of the FED calculation with the CFD output data is in principle suitable.

A2.6.3 Fire scenarios and simulation

It is assumed that, depending on the performance criteria to be demonstrated, the fire characteristics described in A2.3.3.4 will occur in the lecture hall.

The fire simulation with the model Fire Dynamics Simulation (FDS) Version 6 followed basically as described in A2.4 for the determination of the fire effects for the structural analysis. The simulation was carried out differently with a node distance of 25 cm due to the significantly shorter observation periods. The measuring points of the performance criteria decisive for the evaluation were taken in the auditorium on the top level on the right and left staircase in front of the wall panel (Figure A2.18). Gas compositions for the optical density and the FED were recorded at a height of 1.75 m. In accordance with the assumed fire load, a simple combustion reaction of wood with a yield of soot of 0.015 g/g and carbon monoxide (CO) of 0.004 g/g was used in FDS (see Table 8.4 for the fire load-controlled combustion of cellulose-type fire loads). This results in an effective calorific value of 17247 kJ/kg. As the fire loads do not contain any relevant amounts of nitrogen, it is assumed that no HCN (hydrogen cyanide) is produced in the fire (see [A2.20]).

In order to exclude an unrealistic fire-induced pressure increase in the building, the emergency exit doors located at the bottom were considered as pressure relief openings.

The auditorium building has four SHE openings on both sides in the upper area, each 8 m^2 in size (calculated at 3.4 % of the floor area), which can be opened if necessary (Figure A2.33).

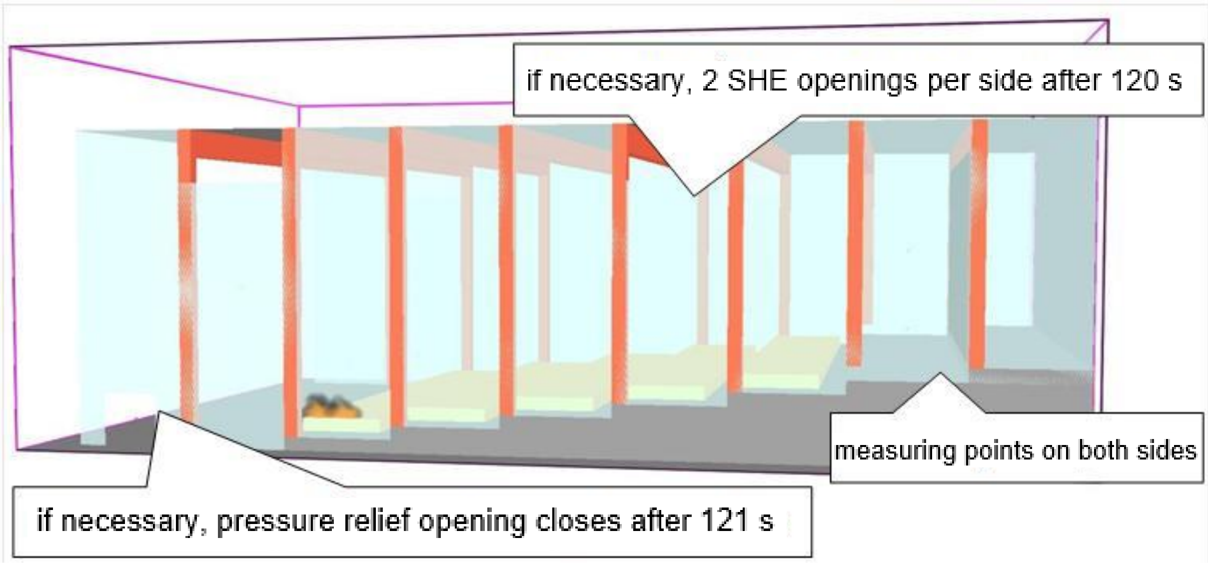


Figure A2.31 Lecture Hall model for the calculation with FDS Version 6 at the 121st second

A2.6.3.1 Fire in the lecture hall to prove the low-smoke layer height or optical density ("Hindrance to escape")

For this proof, a quadratic increase in the heat release rate with a time of 150 s until 1 MW is reached is assumed. It is assumed that equipment-related measures take effect according to the design. Preliminary studies have shown that, for the time course of the heat release rate according to figure A2.8 ceilings-installed smoke detectors trigger within 60 s even at a smoke yield of only 0.001 g/g. Due to a maximum opening time of SHEV devices of 60 s, it is assumed that after 120 s the extraction surfaces are available. Since no requirements are placed on air inlet openings in the case of a design in accordance with the MVStättV, these are not modelled and the emergency exit doors as pressure compensation openings close after the 121st second. Table A2.13 shows the times until the safety objective criteria (Table A2.13) are reached at the relevant measuring points (see Figure A2.33).

The criterion "low smoke layer-height" is exceeded after a relatively short time. However, the dilution of the fire smoke is relatively high due to the large quantities of air mixed in, so that the criterion "optical density" is only passed much later.

Table A2.13 Times in seconds until non-compliance with the assessment values for the scenario with opening of smoke extractor systems after 120 s

Measuring point	Optical density at 1.75 m height ≥ 0.2 1/m	low smoke layer height ≤ 2.5 m
in front of the wall panel left/right	380 s / 383 s	205 s / 207 s

A2.6.3.2 Fire in the lecture hall to prove the Fractional Effective Dose (FED) ("Prevention of escape")

For this proof, a quadratic increase in the heat release rate with a time of 150 s / 1.4 = 107 s until 1 MW is reached is assumed. It is conservatively assumed that equipment-related measures will not be effective. Table A2.14 presents the results for the relevant measuring point in front of the wall panel. The FED of 0.3 is exceeded for this very conservative scenario after 717 s and 730 s, respectively.

Table A2.14 Times in seconds to non-compliance with the safety objective criteria for the scenario without opening the smoke extractors

Measuring point	FED at 1.75 m height ≥ 0.3
in front of the wall panel left/right	730 s / 717 s

In contrast to the conventional, purely physical criteria, the FED reflects the acute fire gas toxicity. It is not suitable to replace the above mentioned criteria, but represents a meaningful supplement. If, for example, seats with PU upholstery and PVC construction elements catch fire instead of the wooden auditorium seating, that has practically no effect on the height of the low-smoke layer and only little influence on the detection range, so that the actual increase in danger is not reflected. Only the FED is noticeably affected by this, as higher and additional pollutant yields are produced. Figure A2.32 shows the course of the FED at the measuring point on the left step in front of the wall panel for the scenario without SHEV.

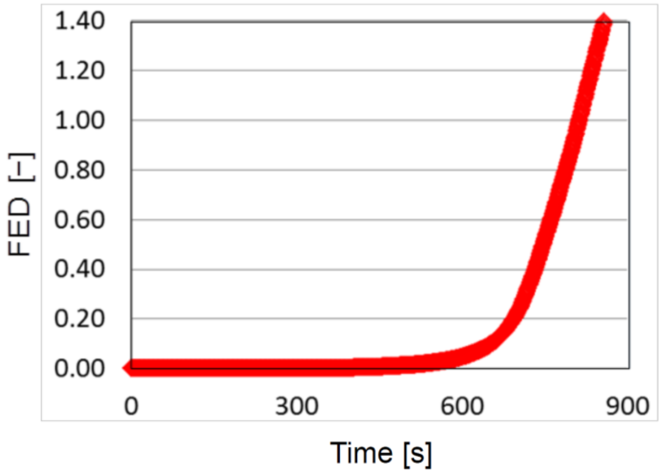


Figure A2.32 Course of the FED at the measuring point on the left step in front of the wall plate

A2.6.4 Modelling of the evacuation

A2.6.4.1 Design fundamentals

The auditorium building with the dimensions 34 m x 29 m x 12 m (L x W x H) is equipped with 20 rows of seats, each with 32 seats. For special events, in addition to the 640 people seated in the seats, further visitors can be seated on the stairways or in front of the rows of seats, so that a total of 1000 people can be accommodated in the lecture hall as a basis for assessment. The slightly rising rows of seats are accessed by two side and two middle aisles. Behind the rows of seats there is a wall panel with four passages, through which one can reach the two main access doors of the lecture hall, which are located next to each other, from the staircases via a front surface. The doors lead to the first level of an adjacent foyer building. There a staircase leads down to the ground floor with exits to the outside (Figure A2.33). The second escape route is provided by two exit doors located at the front to the left and right of the podium (Figure A2.34).

The escape routes from the lecture hall are designed in accordance with MVStättV [A2.1]. According to the MVStättV, the number of visitors of almost 1000 persons requires an escape route width of ten modules of 0.60 m each, corresponding to a total free width of 6.00 m. These requirements are covered by the two main entrances and the emergency exits, each 2 m wide (12 modules, 8 m total width). The openings in the wall panel and the four stairways also cover the width of the escape route. The maximum length of the escape routes until a safe area is reached (the foyer or the open air) is also maintained.

Evacuation via the main exits (escape route 1) and emergency exits (escape route 2) is considered. In order to highlight the similarities and differences that result from the use of different models frequently used in practice, the models listed in Table A2.15 were used in the basic settings given. The default values of the respective computer softwares were used for the basic settings, provided they were compatible with the definition of the scenarios.

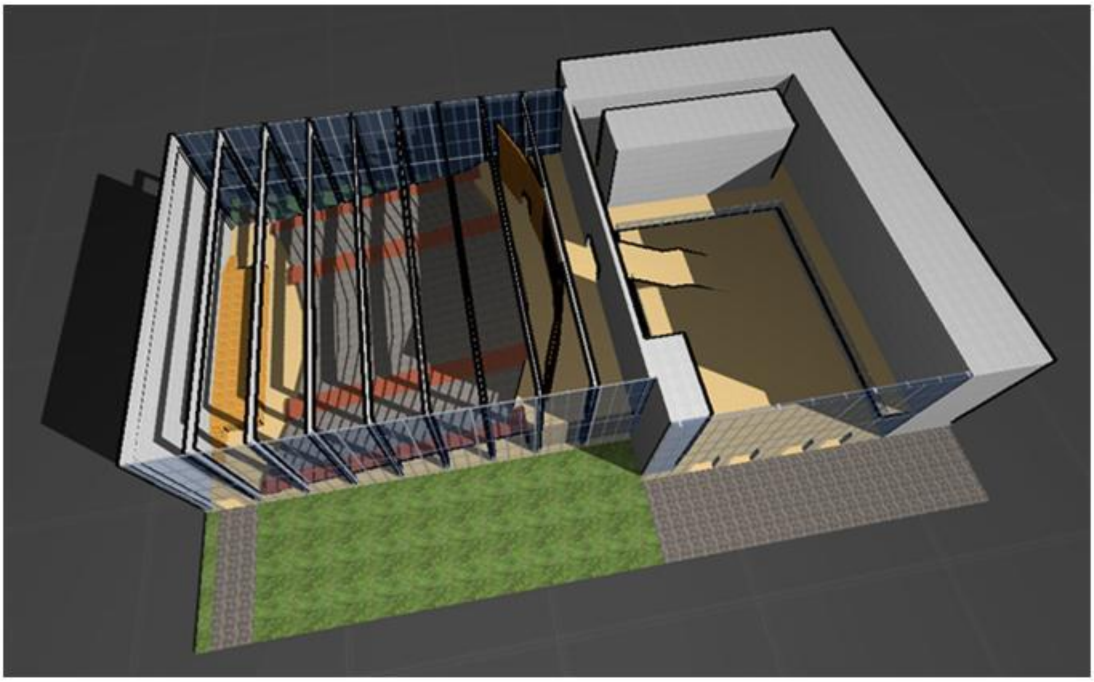


Figure A2.33 View of the lecture hall and foyer

Table A2.15 Overview of models used

Type	Model
Capacity analysis	Capacity analysis according to vfdb guidelines "moderate" capacity utilization
Dynamic flow model	Predtetschenski and Milinski [A2.22] ("transitional street clothes", "normal conditions")
Discrete individual model	buildingEXODUS (Version 4.00) [A2.22] (Standard population)
Discrete individual model	PedGo (Version 2.5) [A2.24](Standard population)
Continuous individual model	FDS+Evac (Vers.: FDS 5.5.3, Evac 2.3.1) [A2.24] (Standard population "adult")
Continuous individual model	ASERI (Version 4.8) [A2.26] ("Evacuation", inhomogeneous population according to basic settings)

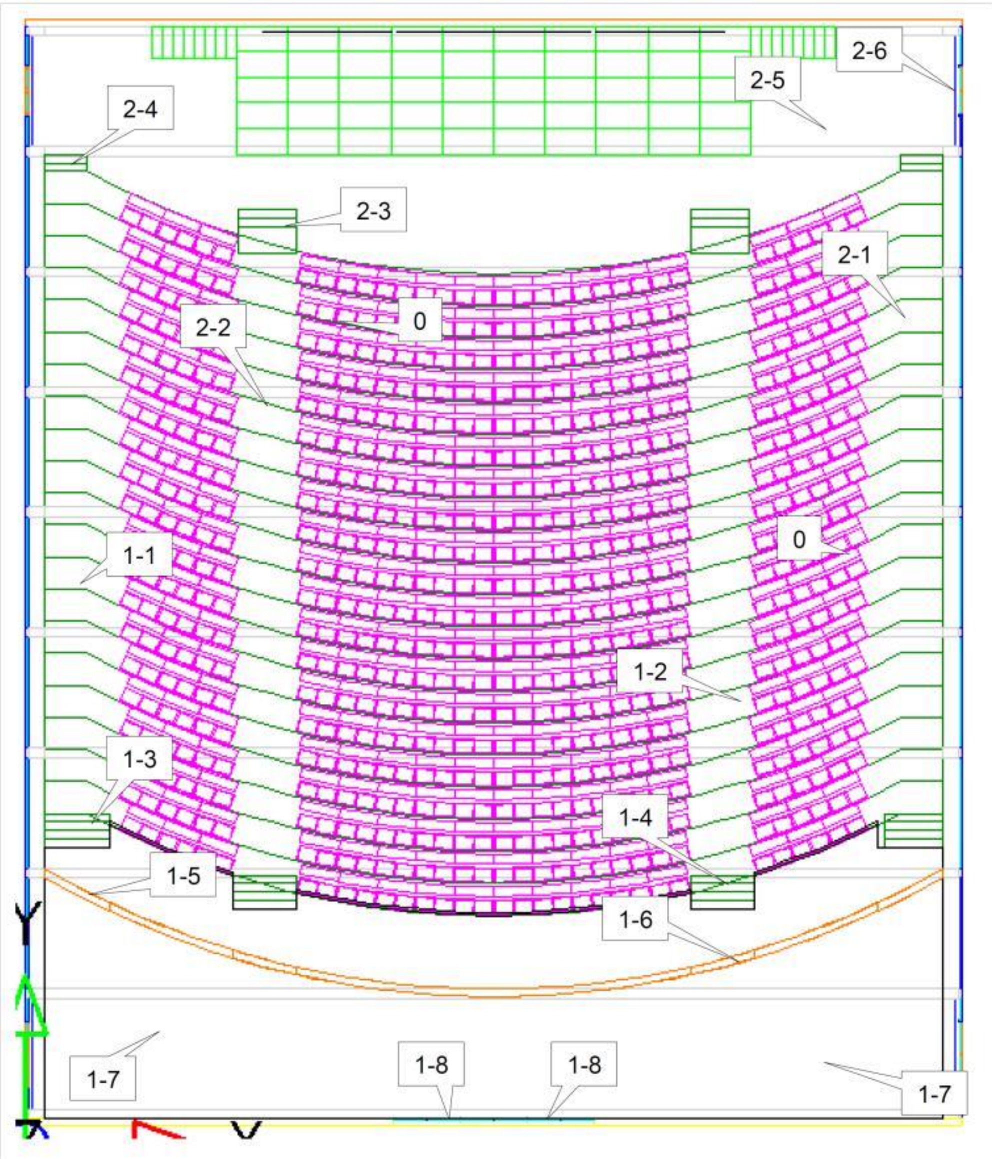


Figure A2.34 Plan view of the lecture hall with designation of the path elements of both escape routes (0) and the first and second escape routes (1-i and 2-i respectively)

A2.6.4.2 Procedure

For this application example, a fire outbreak in the lecture hall will be investigated.

According to equation (9.2), the evacuation time $t_{evacuation}$ is defined as the sum of the time spans $t_{detection}$, t_{alarm}, $t_{reaction}$ and t_{escape}.

The time periods $t_{detection}$ and t_{alarm} depend on the speed of fire development and the location where the fire started. When a fire breaks out in the lecture hall, $t_{detection}$ and t_{alarm} become $t_{reaction}$.

For the reaction times $t_{reaction}$ of the persons, who may have a significant share in the total duration $t_{evacuation}$, the procedure developed by Purser [A2.20] is proposed in Chapter 9, in which a distribution of the individual reaction times is assumed. The lecture hall falls under building category B (users are *awake*, *unfamiliar* with the building and there is a *high density of people*). Because of the easily recognizable location of the exits in the lecture hall, the building complexity is classified in category B2 as a *"simple floor plan with several rooms (also multi-storey), construction predominantly corresponds to prescriptive specifications".* An alarm system corresponding to category A2 *"two-stage automatic fire alarm system with immediate alarm of a control center and subsequent time-delayed alarm of the affected areas"* is present and effective. In addition, it can be assumed that the fire will cause a direct alarm to those present. The last parameter M for fire protection management according to Table 9.4 has a significant influence on the resulting reaction time. Reliable response times can only be determined for categories M1 or M2 that go beyond the required minimum standard, for which a loudspeaker system and, if necessary, trained personnel are required. For example, Table 9.5 shows that for category M1 Δt_1 = 1 min and Δt_{99} = 2 min and thus a reaction time interval of 1 min to 3 min.

Since in this example the comparison of the models is in the foreground and macroscopic models cannot consider individual reaction time, an average reaction time of 2 min is assumed in the following. This is consistent with the fire scenario in A2.3.2, 2 min after ignition the fire burns there on 3.1 m^2 with a power of 675 KW. It can be assumed that under these circumstances the escape movement has started for all those present. Due to the reference to the fire scenario, this period includes the times $t_{detection}$ and t_{alarm}. Consequently, in order to determine the evacuation time, a reaction time of 2 minutes must be added to the movement time, the calculation of which is described below.

A2.7 Calculation of the escape times

The last summand of equation (9.2) is the duration of the escape movement until a safe area $t_{movement}$ is reached. In the following, the models used are briefly explained with their specific application possibilities and limits for this scenario and the results achieved are compared. Further details on the model calculations can be found in [A2.28].

Capacity analysis

The escape of people from the lecture hall takes place via various path elements for which empirical studies have provided data on the specific passage capacity (flow, usually in P/(m*s)) as a function of person density (P/m^2) [A2.30]. For the scenarios considered here, the path elements (Figure A2.34) to be considered are the aisles between the rows of seats, the stairways, the stairs up and down, the narrow places of different widths and the horizontal paths. By assuming a homogeneous behavior of the persons and a stationary flow of people, the movement times for the last persons to escape via one of the respective escape routes are obtained together with the specifications for the choice of escape route.

Table A2.16 lists the path elements located in the escape route according to their position in the first (1-i) or second escape route (2-i) and provides their corresponding free passage widths (column 4) and maximum path lengths (column 8). Due to the use of the building as a lecture hall, moderate personal behavior is assumed and the specific flows (column 5) and walking speeds (column 9) of Table 9.6 for "moderate occupancy" ($D \approx 1$ P/m^2) are assigned to the path elements. This density is conservative compared to the alternative "optimal utilization" ($D \approx 2$ P/m^2) in Table 9.6 due to the lower flow of people.

The flow rate (column 6) is the product of free passage width (column 4) and specific flow (column 5). The total flow (column 7) is the product of the flow rate and the number of parallel route elements in the escape route (column. 3) The time taken (column 10) is the quotient of maximum length (column 8) and walking speed (column 9).

For the first escape route, the elapsed time for the head of the slow of people via the lateral staircases (route element no. 1-1, approx. 8.3 s for the upper 5 m), the stairs (no. 1-3, 2.5 s), the narrow passage (no. 1-5, 0.3 s), the horizontal passage (no. 1-7, 15 s) and finally through an entrance door (no. 1-8, 0.5 s) into the secured foyer is $t_{time\ taken\text{-}1}$ = 26.6 s The main part of the flow of people must pass through the path element with the lowest total flow (column 7) and requires the time $t_{Barrier\text{-}1}$. Since the elements 1-1 and 1-2, 1-3 and 1-4 as well as 1-5 and 1-6 are each passed through in parallel, the two doors (nos. 1-8) with a total flow of 3.60 P/s are the bottleneck. The 1000 persons need $t_{bottleneck}$ = 1000 P / 3.60 P/s = 277.8 s to flow through. The movement time as the sum of $t_{time\ taken}$ and $t_{bottleneck}$ is $t_{movement\text{-}1}$ = 304 s.

For the second escape route, the time taken for the head of the flow of people over the lateral staircases (no. 2-1, approx. 8.3 s for the lower 5 m), the stairs (no. 2-4, 1.2 s), the horizontal path (no. 2-6, 10 s) and finally through an emergency exit door (no. 2-6, 0.5 s) is $_{time\ taken\text{-}2}$ = 20.0 s. The emergency exit doors have the lowest total flow rate of 3.6 P/s (col. 7). The 1000 persons need again the time $t_{bottleneck\text{-}2}$ = 277,8 s for passage. The movement time as the sum of $t_{time\ taken}$ and $t_{bottleneck}$ is $t_{movement\text{-}2}$ = 298 s.

Table A2.16 Characteristics of the route elements to be passed when the auditorium is cleared. Movement parameters for "moderate utilization" from Chapter 9

1	2	3	4	5	6	7	8	9	10
No.	Route element	Number in escape route	free passage width [m]	Spec. flow capacity [P/(m*s)].	Flow capacity [P/(s)]	Overall flow capacity [P/(s)]	max. length [m]	Walking speed [m/s]	Time taken [s]
0	Aisle between rows of seats	120	0.42	-[1]	0.63[1]	75.60	-	-	-
1-1	Lateral stairway upwards[2]	2	1.20	0.8	0.96	1.92	10.0	0.6	16.7
1-2	Middle stairway up[2]	2	1.80	0.8	1.44	2.88	10.0	0.6	16.7

1-3	Staircase between lateral aisle stairway and wall plate	2	1.60	0.8	1.28	2.56	1.5	0.6	2.5
1-4	Stairs between the middle aisle stairway and the wall plate	2	2.00	0.8	1.60	3.20	1.5	0.6	2.5
1-5	Lateral bottleneck in the wall plate	2	1.40	0.9	1.26	2.52	0.3	1.0	0.25
1-6	Door in the wall plate for middle aisle stairway	2	2.00	0.9	1.80	3.60	0.3	1.0	0.25
1-7	Route between wall plate and entrance doors3	4	2.50	1.1	2.75	11.00	15.0	1.0	15.0
1-8	Entrance door	2	2.00	0.9	1.80	3.60	0.5	1.0	0.5
1-9	Stairs in Foyer[4]	2	2.40	0.8	1.92	3.84	15.0	0.6	25.0
2-1	Lateral aisle stairway downwards[2]	2	1.20	0.8	0.96	1.92	10.0	0.6	16.7
2-2	Middle aisle stairway downwards[2]	2	1.80	0.8	1.44	2.88	10.0	0.6	16.7
2-3	Stairs from middle middle aisle stairway to the front	2	2.00	0.8	1.60	3.20	0.7	0.6	1.17
2-4	Stairs from the middle aisle stairway to the front	2	1.20	0.8	0.96	1.92	0.7	0.6	1.17
2-5	Route between stairs and emergency exit	4	1.20	1.1	1.32	5.28	10.0	1.0	10.0
2-6	Front emergency exit door	2	2.00	0.9	1.80	3.60	0.5	1.0	0.5

[1] The capacity between the rows is independent of the width. According to [A2.22] for "normal" movement for persons in "mid-season street clothes".

[2] Steps are conservatively regarded as stairs with the same up and down movement parameters.

[3] If the area between the wall panel and the exit is used for exhibitions etc., the minimum width should be ensured.

[4] The staircase is divided in the middle by a double handrail according to [A2.1].

Table A2.17 P&M, 1st escape route - Parameters of the path elements for "normal conditions" with a projection area of 0.113 m²/P

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Weg entlang der seitlichen Stufengänge																		
Nr.	**Bezeichnung und Lage des Wegelements**	**Anz.**	**Personen im Rettungs-weg**	**max. Lauflänge [m]**	**freie Durch-gangs-breite [m]**	**Dichte [P/m²]**	**Dichte [m²/m²]**	**erf. spez. Fluss [P/(m*s)]**	**erf. spez. Fluss [m²/(m*min)]**		**spez. Fluss [P/(m*s)]**	**spez. Fluss [m²/(m*min)]**	**Gesamt-fluss [P/s]**	**Gesamt-fluss [m²/min]**	**Geschw [m/s]**	**Geschw [m/min]**	**Stau-zeit [s]**	**Lauf-zeit [s]**
0	Gang zwischen den Sitzreihen	20	200		0.42						f		*12.60*	*85.43*				
1-1	seitl. Stufengang aufwärts	1	200	2.5	1.20	8.14	**0.920**	10.50	71.19	Stau	0.89	**6.06**	1.07	7.27	0.11	**6.58**	186.5	22.8
1-3	Treppe zwischen seitl. Stufengang und Wandscheibe	1	200	1.5	1.60	2.04	**0.230**	0.67	4.55		0.67	**4.55**	1.07	7.27	0.33	**19.73**		4.6
1-5	Engstelle an der Wandscheibe	1	200	0.3	1.40	0.97	**0.110**	0.77	5.19		0.77	**5.19**	1.07	7.27	0.78	**46.88**		0.3
1-7	Weg zwischen Wandscheibe und Eingangstüren	1	200	15.0	2.50	0.58	**0.065**	0.43	2.91		0.43	**2.91**	1.07	7.27	1.46	**87.80**		10.3
1-8	Eingangstür	1	200	0.5	0.90	2.35	**0.265**	1.19	8.08		1.19	**8.08**	1.07	7.27	0.51	**30.48**		1.0
Weg entlang der mittleren Stufengänge																		
Nr.	**Bezeichnung und Lage des Wegelements**	**Anz.**	**Personen im Rettungs-weg**	**max. Lauflänge [m]**	**freie Durch-gangs-breite [m]**	**Dichte [P/m²]**	**Dichte [m²/m²]**	**erf. spez. Fluss [P/(m*s)]**	**erf. spez. Fluss [m²/(m*min)]**		**spez. Fluss [P/(m*s)]**	**spez. Fluss [m²/(m*min)]**	**Gesamt-fluss [P/s]**	**Gesamt-fluss [m²/min]**	**Geschw [m/s]**	**Geschw [m/min]**	**Stau-zeit [s]**	**Lauf-zeit [s]**
0	Gang zwischen den Sitzreihen	20	300		0.42						f		*12.60*	*85.43*				
1-2	Mittelstufengang	1	300	2.5	1.80	8.14	**0.920**	7.00	47.46	Stau	0.89	**6.06**	1.61	10.91	0.11	**6.58**	186.5	22.8
1-4	Treppe zwischen seitl. Stufengang und Wandscheibe	1	300	1.5	2.00	3.27	**0.370**	0.80	5.45		0.80	**5.45**	1.61	10.91	0.24	**14.68**		6.1
1-6	Engstelle an der Wandscheibe	1	300	0.3	2.00	1.06	**0.120**	0.80	5.45		0.80	**5.45**	1.61	10.91	0.76	**45.49**		0.3
1-7	Weg zwischen Wandscheibe und Eingangstüren	1	300	4.0	2.50	1.06	**0.120**	0.64	4.36		0.64	**4.36**	1.61	10.91	0.61	**36.58**		6.6
1-8	Eingangstür	1	300	0.5	1.10	4.42	**0.500**	1.46	9.92		1.46	**9.92**	1.61	10.91	0.33	**19.83**		1.5
Zusammenfluss im Foyer																		
1-9	Treppe im Foyer	1	500		**2.40**	8.14	0.920	1.12	7.58	Stau, da Max: 7.47 [m²/(m* min)]	0.65	**4.44**	1.57	10.66	0.08	**4.83**	318.1	

Table A2.18 P&M, 2nd escape route - Parameters of the path elements for "normal conditions" with a projection area of 0.113 m²/P

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Weg entlang der seitlichen Stufengänge																		
Nr.	**Bezeichnung und Lage des Wegelements**	**Anz.**	**Personen im Rettungs-weg**	**max. Lauflänge [m]**	**freie Durch-gangs-breite [m]**	**Dichte [P/m²]**	**Dichte [m²/m²]**	**erf. spez. Fluss [P/(m*s)]**	**erf. spez. Fluss [m²/(m*min)]**		**spez. Fluss [P/(m*s)]**	**spez. Fluss [m²/(m*min)]**	**Gesamt-fluss [P/s]**	**Gesamt-fluss [m²/min]**	**Geschw [m/s]**	**Geschw [m/min]**	**Stau-zeit [s]**	**Lauf-zeit [s]**
0	Gang zwischen den Sitzreihen	20	200		0.42						f		12.60	85.43				
2-1	seitl. Stufengang abwärts	1	200	2.5	1.20	8.14	**0.920**	10.50	71.19	Stau	0.65	**4.44**	0.79	5.33	0.08	**4.83**	254.5	31.1
2-4	Treppe vom seitl. Stufengang nach vorne	1	200	0.7	1.20	8.14	**0.920**	0.65	4.44		0.65	**4.44**	0.79	5.33	0.08	**4.83**		8.7
2-5	Weg zwischen Treppe und Notausgang	1	200	10.0	1.20	1.11	**0.125**	0.65	4.44		0.65	**4.44**	0.79	5.33	0.60	**36.00**		16.7
2-6	Notausgang	1	200	0.5	1.00	1.02	**0.115**	0.79	5.33		0.79	**5.33**	0.79	5.33	0.77	**46.18**		0.6
Weg entlang der mittleren Stufengänge																		
Nr.	**Bezeichnung und Lage des Wegelements**	**Anz.**	**Personen im Rettungs-weg**	**max. Lauflänge [m]**	**freie Durch-gangs-breite [m]**	**Dichte [P/m²]**	**Dichte [m²/m²]**	**erf. spez. Fluss [P/(m*s)]**	**erf. spez. Fluss [m²/(m*min)]**		**spez. Fluss [P/(m*s)]**	**spez. Fluss [m²/(m*min)]**	**Gesamt-fluss [P/s]**	**Gesamt-fluss [m²/min]**	**Geschw [m/s]**	**Geschw [m/min]**	**Stau-zeit [s]**	**Lauf-zeit [s]**
0	Gang zwischen den Sitzreihen	20	300		0.42						f		12.60	85.43				
2-2	Mittelstufengang	1	300	2.5	1.80	8.14	**0.920**	7.00	47.46	Stau	0.65	**4.44**	1.18	7.99	0.08	**4.83**	254.5	31.1
2-3	Treppe vom Mittel-stufengang nach vorne	1	300	1.5	2.00	0.84	**0.095**	0.59	4.00		0.59	**4.00**	1.18	7.99	0.71	**42.63**		2.1
2-5	Weg zwischen Treppe und Notausgang	1	300	10.0	1.20	2.79	**0.315**	0.98	6.66		0.98	**6.66**	1.18	7.99	0.35	**20.93**		28.7
2-6	Notausgang	1	300	0.5	1.00	2.26	**0.255**	1.18	7.99		1.18	**7.99**	1.18	7.99	0.52	**31.24**		1.0

Dynamic flow model according to Predtetschenski and Milinski

Within the framework of the hydraulic approach, the dynamic flow models take into account during crowd flow across a distance, the crowd density may change and this may result in changing walking speeds and flow capacities. This relationship is also referred to as the fundamental diagram. In the approach according to Predtetschenski and Milinski (P&M) a projection surface [A2.22] introduced to take different groups of persons into account, so that the density of persons is not given in [P/m²] but in [m²/m²].

Assuming that the group consists of people in "mid-season street clothes", the average projection area is 0.113 m²/P, so that the correlation between person density and walking speed (a) or person flow (b) is overseen by the fundamental diagrams shown in Figures A2.35a+b.

In order to obtain the density of persons in [m²/m²] in the model [A2.22], a specific flow ("movement intensity ") q_i at the route element i is assumed, which is composed of the density D times the velocity v.

$$q_i = D \cdot v \tag{A2.40}$$

It is assumed that the flow q_{i+1} in the next path element i+1 is calculated from the ratio of the path widths b to

$$q_{i+1} = q_i \cdot {}^{b_i}\!/_{b_{i+1}} \tag{A2.41}$$

takes. According to the relationships shown in Figure A2.35, the flow q_{i+1} results in a new density and walking speed for the path element i+1. If the route element i+1 cannot cover the specific flow q_{i+1} required by the change of the path width, a congestion occurs and the calculation continues with the values for maximum density. The procedure is somewhat more complex than the simple capacity analysis, but the calculation steps can also be partially automated.

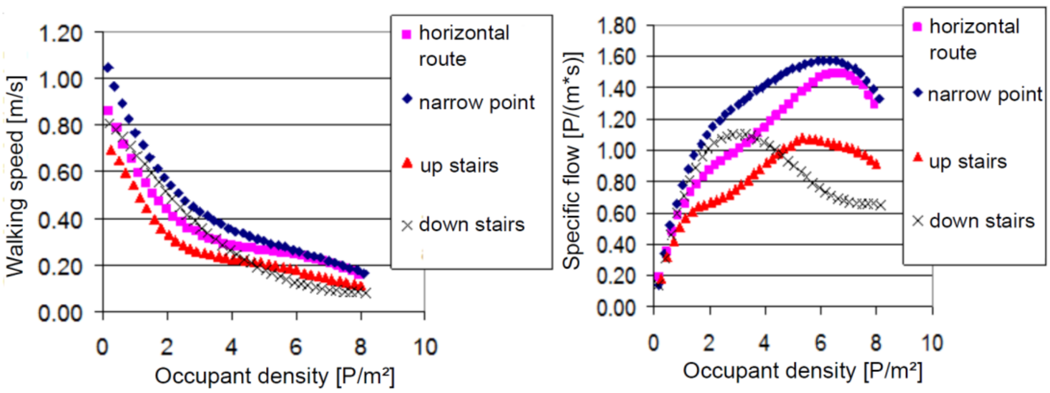


Figure A2.35 The relationship between density of persons and (a) walking speed or (b) specific flow on different route elements for "normal conditions" from values according to [A2.22]

Since the lecture hall is axially symmetrical, the evacuation of 500 persons is considered over a lateral (200 P) and central (300 P) staircase [A2.28]. Table A2.17 and Table A2.18 show the parameters for pedestrian densities (column 8), pedestrian flows (columns 10, 13, 15) and velocities (column 17) in the notation according to P&M [A2.22] relation to the projection area of 0.113 P/m^2 for the 1st and 2nd escape route.

For the 1st escape route, the initial conditions to be applied are that the persons streaming out of the rows of seats on the stairways (elements 1-1 or 1-2) lead to a maximum person density of 8.14 P/m^2 (column 7). Figure A2.43 a+b then shows a speed of 0.11 m/s (column 16) and a specific flow of 0.89 P/(m*s) (column 12) for the staircases as the "stairs upwards" route element. For the other route elements, the required flow is first determined, which results from the existing flow times the ratio of the route widths. If the required flow can be covered by the route element (see Figure A2.43 b), the new person density and speed results. For the route elements up to the stairs in the foyer, no further congestion will result. Both partial flows pass through the entrance door (no. 1-8) at 2 x 1.61 P/s (column 14).This requires a specific flow (col. 9) of 3.22 P/s / 2.4 m = 1.12 P/(m*s) on the stairs (nos. 1-9), which is no longer possible due to the "stairs downwards" (see Figure A2.41b). In the model, a dam with maximum passenger density and low specific flow of only 0.65 P/(m*s) over the stairs is assumed (see Figure A2.43 b). 500 persons need 500 P / (0.65 P/(m*s) * 2.4 m) ≈ 318 s (col. 18) to pass the stairs. Together with the time taken for the head of the crowd (column 19), this results in a movement time until entering the foyer stairs of 318 s + 39 s = 347 s. It can also be taken into account that the last approx. 81 people are present on the cross passage between the exit door (1-8) and stairs (1-9) over an area of approx. 10 m^2 without congestion back into the lecture hall. This results in $t_{movement-1}$ = 347 s - 81 P / (0.65 P/(m*s) * 2.4 m) ≈ 295 s for the time until leaving the lecture hall.

Table A2.18 applies to the 2nd escape route. On the rows of steps (no. 2-1 and 2-2) the maximum density of persons is reached again, thus limiting the flow of persons. No further congestion occurs along the escape route. The movement time is $t_{movement-2}$ = 63 s + 255 s = 318 s.

Microscopic modeling with ASERI

The basis of the ASERI evacuation model [A2.26] is a description of the individual movement of the simulated persons (agents), whereby essential aspects for the escape behavior such as reaction and delay times, choice of escape route, behavior in case of congestion, individual mobility and space requirements are explicitly considered in the simulation. The building geometry is depicted three-dimensionally in the details relevant to the evacuation process (Figure A2.36). When selecting the individual escape route, individual preferences or an individual reaction to congestion formation are possible in addition to the usual standards (locally or globally shortest route, even utilization of the exits). The movement of persons is based on the simulation of elementary movement sequences within a crowd of people (unlocking, evading, overtaking minimum distance). In terms of space requirements, a "pedestrian" type agent in ASERI is characterized by shoulder and chest width as well as unobstructed ground level walking speed. On stairs the walking speed is reduced according to an empirical reduction factor, depending on the geometry of the steps. For the calculations, the basic setting recommended for mathematical verifications (movement mode ”evacuation”, inhomogeneous population) was used.

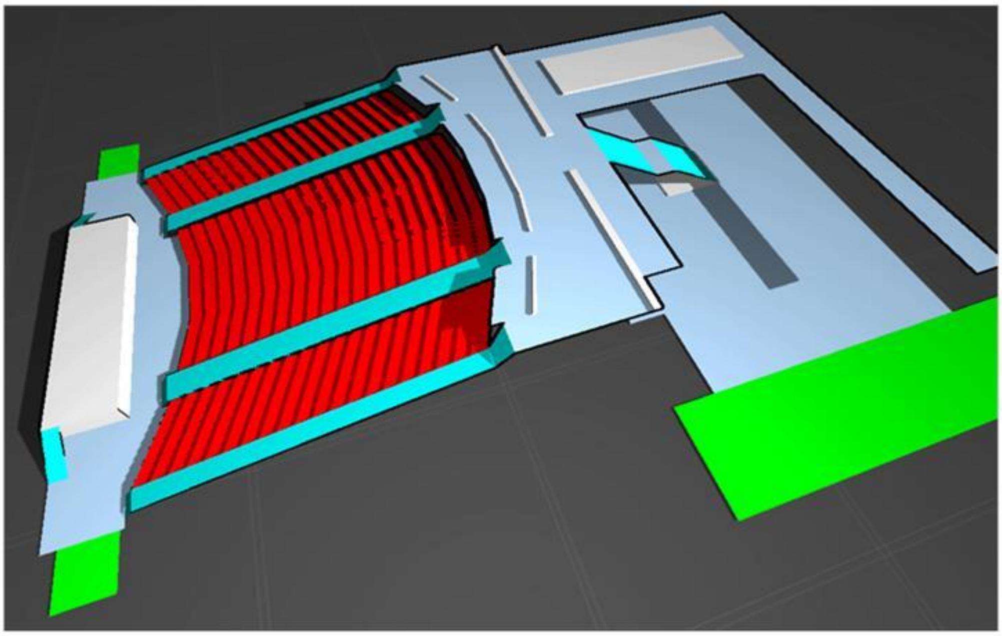


Figure A2.36 ASERI - 3D view of the simulation model with stairs in the foyer

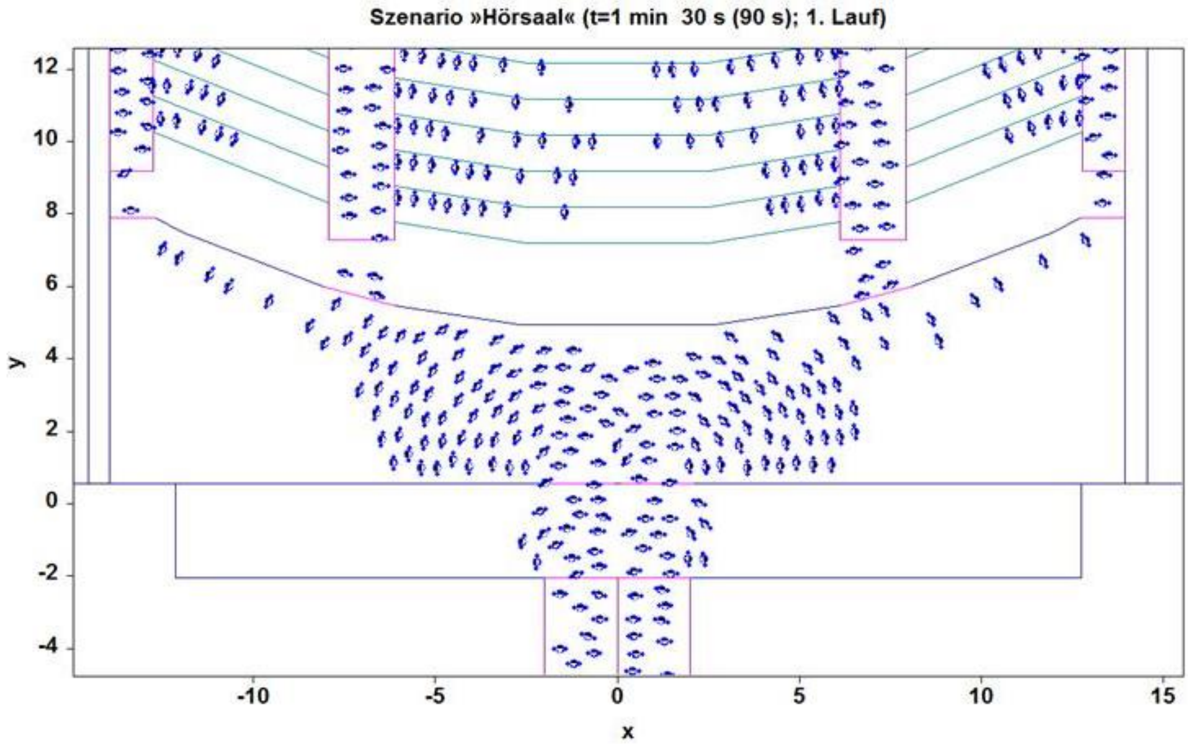


Figure A2.37 Congestion in the area in front of the main exits (1st escape route) for an ASERI simulation

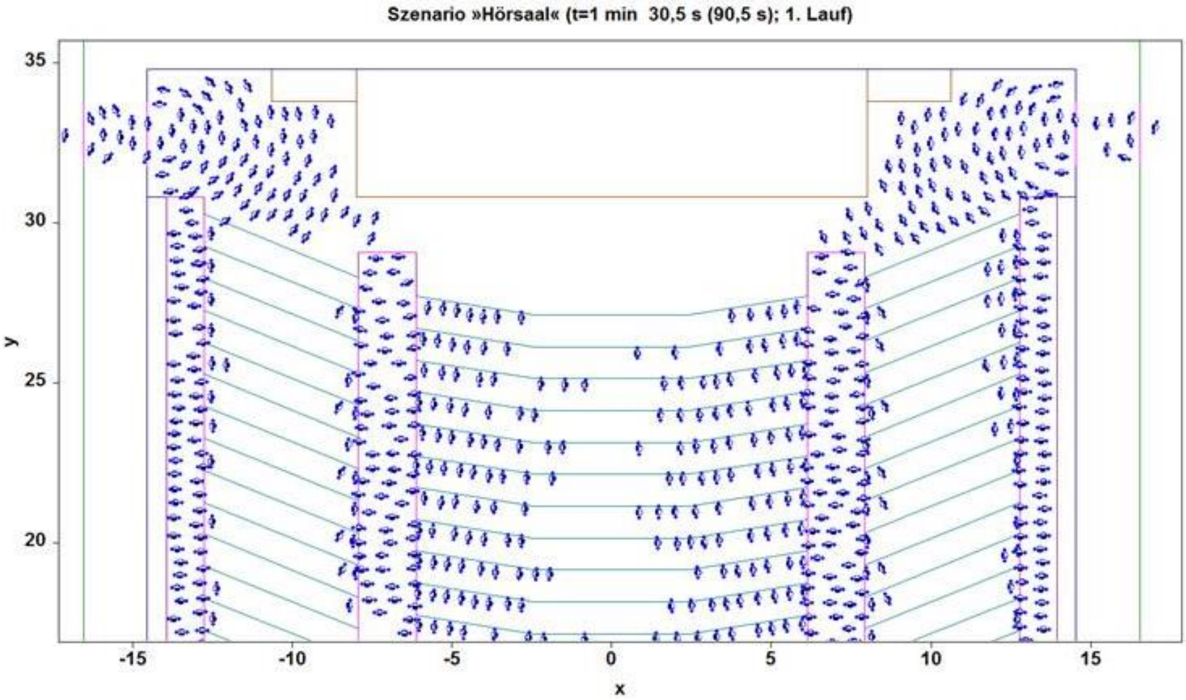


Figure A2.38 Congestion in front of the emergency exits next to the podium (2nd escape route) for an ASERI simulation

The floor plan in Figure A2.39 shows a section of the scenario with the upper part of the auditorium, the foyer and the upper section of the stairs leading to the main entrance. It can be seen that during the simulation for an evacuation via the 1st escape route, congestion occurs not only in front of the stairs in the foyer building, but especially in the area in front of the main exits, which also temporarily obstructs the flow of people from the two central exits of the auditorium.

For the 2nd escape route, there are congestions directly in front of the two emergency exits (Figure A2.38). These obstruct the inflow from the lateral aisle stairways, so that the persons in the side rows of seats partially swerve to the middle aisle stairways.

Table A2.19 ASERI - Escape times for the 1st and 2nd escape routes

Escape time	1ST escape route	2ND escape route
Minimum	321 s	306 s
Maximum	328 s	319 s
95 %	327 s	318 s
Average value	324 s	311 s

Table A2.19 shows the statistical evaluation of 10 calculation runs for each of the two investigated scenarios 1. and 2. escape route. The average escape time from 10 calculation runs is 324 s for the 1st escape route and 311 s for the 2nd escape route.

Microscopic modelling with buildingEXODUS

The discrete individual model buildingEXODUS [A2.22] was developed by the University of Greenwich. The geometry is represented by cells that are connected orthogonally or diagonally by arcs of a standard length of 0.5 m or 0.707 m. The lecture building with the adjacent staircase is discretized by horizontal cells, step cells, seating cells, and internal or external output cells (Figure A2.39). The persons of the preset "standard population" are located on the seats and the rows of steps. The width of the route elements was rounded in each case following the recommendation in the software documentation, so that, for example, the 1.40 m wide lateral bottle necks at the wall plate (No. 5) is only shown as 1.00 m wide passages. With regard to movement on the steps, there is the alternative option of selecting a walk width of 0.76 m for persons, which should take into account the fluctuating movement of persons on stairs. Since the gradient on the rows of steps is small and two persons can sit next to each other on one step, this option was not activated and a step width of two cells (1 m) was used. The default value of the maximum specific flow rate at the exits of 1.33 P/(m*s) was adopted. In contrast to the other models, a response time of 0 to 30 s was used here.

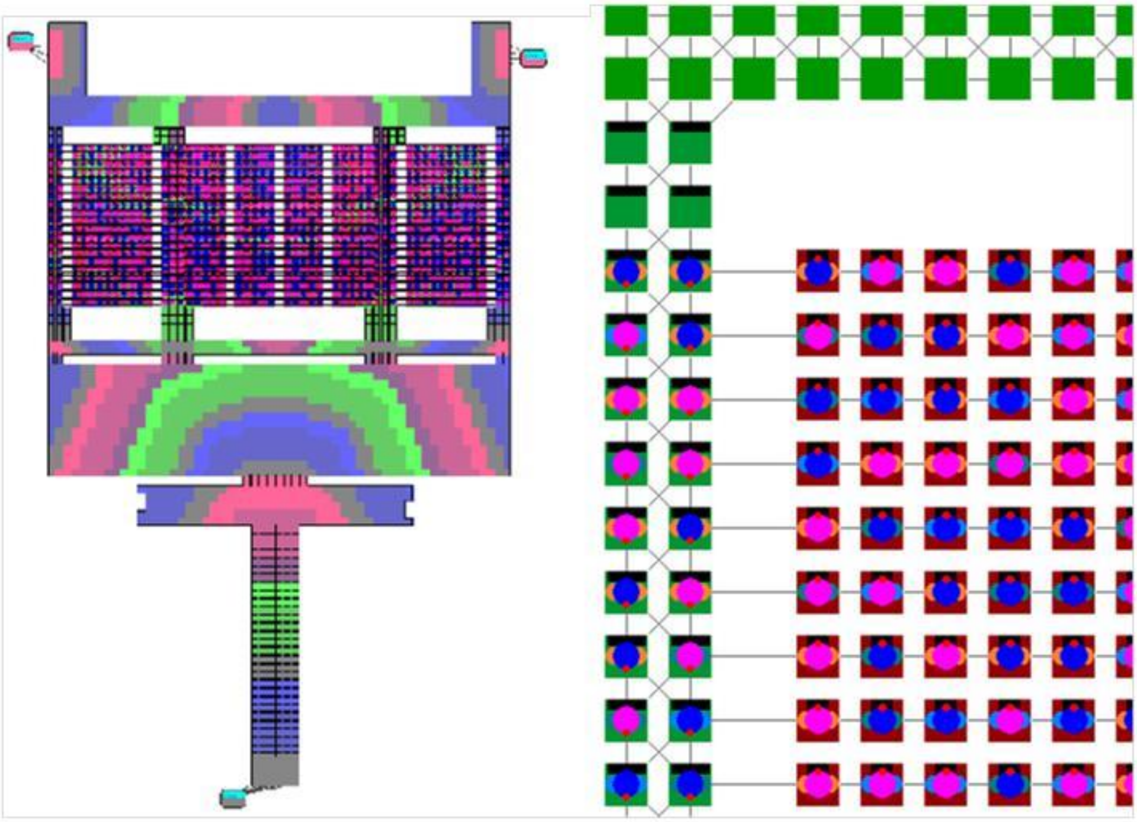


Figure A2.39 Lecture hall discretised with buildingEXODUS with stairs to the foyer (left). On the right a detailed section of the seating and the left staircase.

When escaping via the 1st escape route, the flow of people on the stairways is limited. In front of the staircase (Nos. 1-9) in the foyer building, small temporary congestions form that do not affect the auditorium. The average duration of escape from four stairways is 382 s.

With the 2nd escape route, the flow of people is again limited on the stairways. For this purpose, small stationary congestions are displayed in front of the emergency exits (no. 2-6). The average escape time from four rake aisles is 265 s.

Microscopic modeling with FDS+Evac

Evac [A2.24] is an additional module for the CFD model FDS. A grid with a grid width of 0.2 m forms the basis of the analysis. As in the buildingEXODUS model, the rows of seats are simplified and straight-lined. The persons correspond to the FDS+Evac standdard population "adult" with a free walking speed of 1.25 ± 0.30 m/s. The speed on stairs for up and down movement is assumed to be 50% of the free walking speed. The actors reach the available exits via potential differences. At the beginning of the simulation the persons are in the rows of seats and the aisle stairways. For both scenarios 10 calculation runs each were performed and the arithmetic mean of the escape time was calculated.

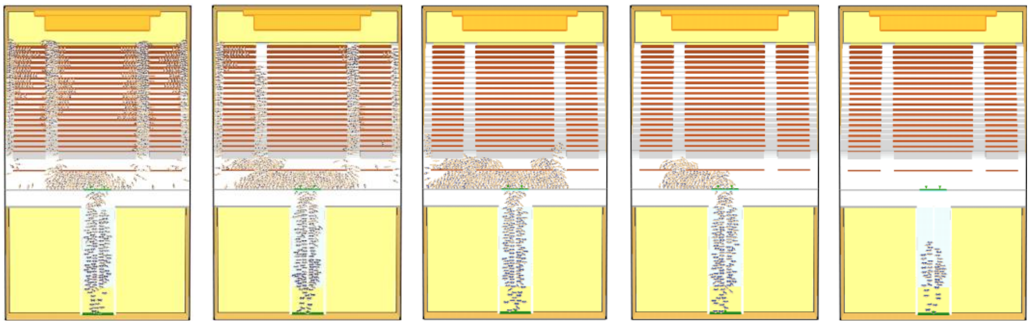


Figure A2.40 FDS+Evac - Positions of persons after 80, 160, 240, 320 and 400 seconds for the 1st escape route (S. Schelter)

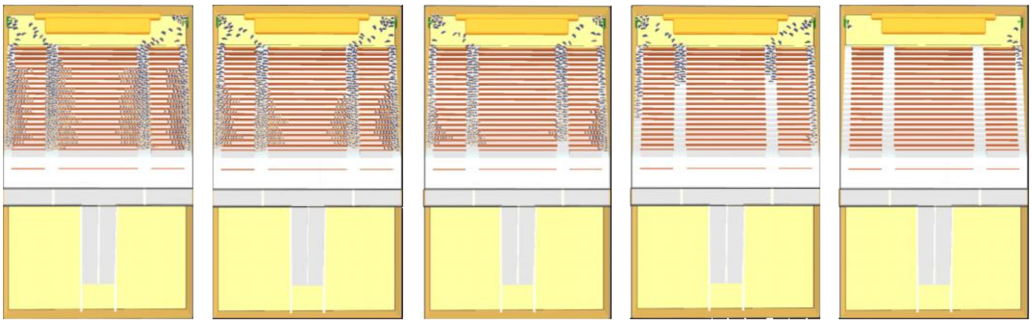


Figure A2.41 FDS+Evac - Positions of persons after 45, 90, 135, 180 and 225 seconds for the 2nd escape route (S. Schelter)

Although the geometry of the room and the distribution of people are mirror-symmetrical, an asymmetrical distribution of the congestion is evident when using the first escape route (seeFigure A2.42). In the case of several existing doors (here: two exit doors located directly next to each other), FDS+Evac uses a special approach to estimate for the individual actor which route could be the most effective and thus the fastest. This procedure is repeated at regular intervals, which may also lead to a change in the preferred exit if another exit appears to be much more suitable. However, this reorientation is not fundamentally congestion-dependent, but can take place well before such a change occurs, e.g., due to interactions with other people. For the 1st escape route, it can now be observed that in the area of the exits such a change of the preferred exit hardly ever occurs, which is why one door is partially blocked by the persons at the other door. This leads to a one-sided increase in congestion in the door area. This unrealistic effect was eliminated in a later version of FDS+Evac. The escape time until people pass the auditorium doors averages 373 s (fluctuation range < 2%) with a maximum specific flow at the doors of 0.85 P/ms.

Similarly, when using the 2nd escape route, significant congestion occurs when entering the staircase aisles (Figure A2.43). In the area of the emergency exits, on the other hand, only minor congestions are recorded, so that the escape duration averages 239 s (fluctuation margin < 3 %). The maximum specific flow at the doors is 1.5 P/ms.

Microscopic modeling with PedGo

The basis of the simulation with PedGo [A2.24] is a multi-agent model on a square cell grid with an edge length of 0.4 m, resulting in a cell area of 0.16 m² (Figure A2.42). The area of the cell corresponds to the standing area of a person in a dense crowd. In contrast to buildingEXODUS, edges are not explicitly represented. Each cell is connected to all accessible eight neighboring cells. There are too common and not accessible (wall, furniture, etc.) cells. Persons are represented as individuals (agents) with independent behavior, abilities and goals in discrete space and discrete time. Each person stands on a cell and moves from cell to cell towards the exit during the evacuation. Doors reduce the flow of people. To account for this effect, the simulated persons on door cells reduce their walking speed to a quarter. Stair cells are introduced to take stairs into account. Here the persons move at half speed. On their way to the exit cells the persons follow the routes given by the user. Each person has an individual set of parameters which is reassigned before each program run and which also contains the running speed (to be specified in cells/second) and the reaction time. The parameters shown in Table A2.20 were used to model the auditorium. The exact meaning of the parameters is explained in [A2.24].

For the 1st escape route, the escape time (average value from 500 calculation runs) is 348 seconds (standard deviation 7 s) for leaving the lecture hall, for the 2nd escape route correspondingly 276 s (standard deviation 5 s). Significant congestion (defined here as areas where a density of 4 persons/m^2 or more occurs during at least 10% of the average total escape time) occurs on the stairways (1st escape route) or in front of the emergency exits 2-6 (2nd escape route) (Figures A2.43 and A2.44). Table A2.21 shows the statistical evaluation of each of the 500 calculation runs, where seed indicates the initialization of the random number generator.

Table A2.20 PedGo - Input parameters

	Min	Max	Mean	Stddev.	Distribution
v_{max} (in cells/second)	2	5	3	1	normal
Patience	not distributed				
Sway	1	5	3	2	normal
Reaction	0	0	-	-	equal
Dawdle	0	30	15	5	normal
Inertia	1	5	3	2	normal
Group cohesion	None				

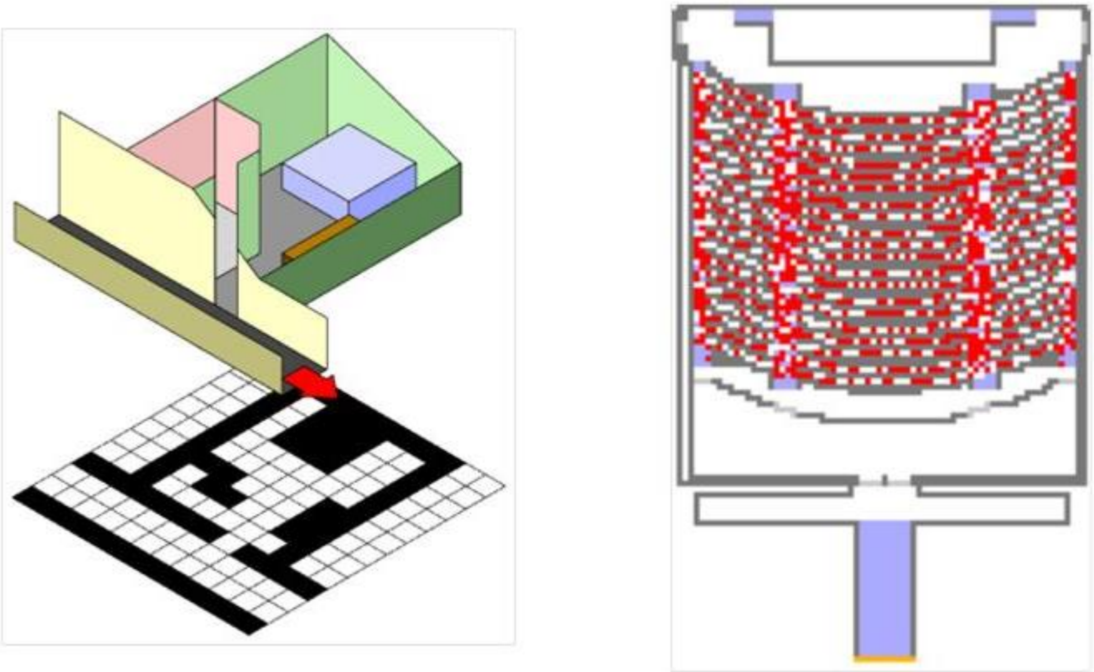


Figure A2.42 PedGo - Discretization and initial situation (H. Klüpfel)

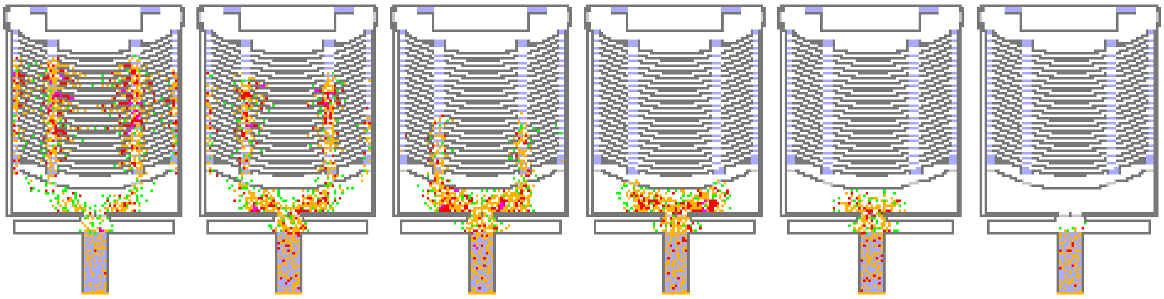


Figure A2.43 PedGo, 1st escape route - positions of persons after 1, 2, 3, 4, 5 and 6 min (H. Klüpfel)

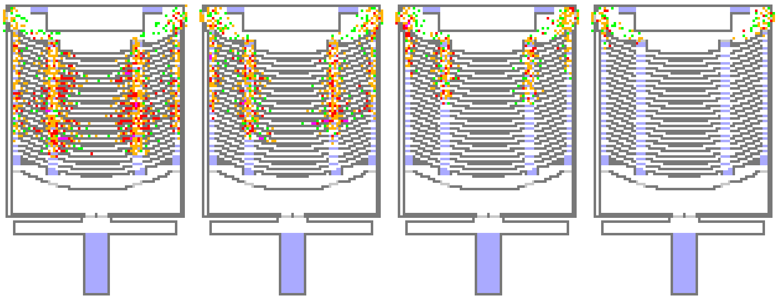


Figure A2.44 PedGo, 2nd escape route - positions of persons after 1, 2, 3 and 4 min (H. Klüpfel)

Table A2.21 PedGo - Summary of results

	1st escape route			2nd escape route		
	s	h:min:s	seed	s	h:min:s	seed
Average value	348	00:05:48	4750	276	00:04:36	4713
Standard deviation	7	00:00:07	---	5	00:00:05	---
95%-fractile <	352	00:05:52	4741	285	00:04:45	4712

A2.8 Comparison of results

Table A2.22 shows the average values of the calculated escape times for the two lecture hall scenarios first and second escape route in comparison. The mean value from all model calculations for the evacuation of the lecture hall (escape time) is 338 s (1st escape route) and 285 s (2nd escape route). This means that there are deviations between the models of -16 % to +13 %. These are thus within a range that is typical for engineering calculation methods in fire protection. It also shows that a simple model such as the capacity analysis does not always provide the most conservative results.

As explained in Chapter 9, it is not sufficient to base the assessment solely on the calculated escape or evacuation times. Rather, the quality of the evacuation - and thus especially the congestion situation - should also be assessed. The location of the main congestion situations in the individual calculations and simulations is not always uniform. One reason for this is that the location of the congestion can change due to small changes in the route widths, as can already occur, for example, due to rounding in discrete models. Further model-specific effects were discussed in the description of the individual model calculations.

In summary, it can be seen that critical points should be considered in detail in case of doubt, whereby a sensitivity analysis and, under certain circumstances, consideration with different models can be helpful.

Table A2.22 Calculated escape times and compression characteristics

Model	1st escape route t_{escape}	1st escape route congestion	2nd escape route t_{escape}	2nd escape route congestion
Capacity analysis	304 s	Entrance door (no. 1-8)	298 s	Emergency exit (no. 2-6)
Predtetschenski & Milinski	295 s	Aisle Stairways Foyer stairs	318 s	Aisle stairways
buildingEXODUS	382 s	Aisle stairways	266 s	Aisle stairways
PedGo	348 s	Aisle stairways Main exits Foyer stairs	276 s	Aisle stairwaysEmergency exit
FDS+Evac	373 s	Aisle stairwaysMain exits	239 s	Aisle stairways
ASERI	324 s	Aisle stairwaysMain exits	311 s	Aisle stairways Emergency exit

The simulation calculations were performed and documented within the framework of the study [A2.26].

A2.9 Final review

On average over all model calculations for the evacuation of the lecture hall, the escape time is 338 s (1st escape route) and 285 s (2nd escape route). Together with the pre-movement time of 120 s this results in an evacuation time of 458 s for the first escape route.

For the fire scenario in the lecture hall, a comparison of the times until the performance criteria "optical density" (380 s) and "height of the low-smoke layer" (205 s) from Table A2.13 are not met with the specified evacuation time shows that a conservative approach cannot prove that the lecture hall is safe to evacuate, although it is essentially eligible for approval under the German building law.

If it is assumed that the evacuation process is not significantly influenced by reaching the above-mentioned criteria, the additional consideration of the FED (FED > 0.3 after 717 s) also shows, however, that even under particularly conservative conditions (higher fire growth rate and failure of the SHE) no catastrophic outcome is predicted.

For a conservative fire scenario in conjunction with a design-based evacuation scenario, a safety factor of > 1.5 should be aimed for together with the criteria "height of the low-smoke layer" or "recognition distance". It must be taken into account that the fire scenario, e.g. a cloakroom fire, can render parts of the escape route unusable.

In addition, more extreme scenarios should be examined, in which overcrowding of the place of assembly and/or the failure of escape routes etc. are assumed. For these scenarios, the less conservative FED together with a safety factor can be used as an assessment criterion. Since the escape times are in a simple relation to the number of persons and the width of the bottlenecks, a maximum number of persons can alternatively be determined for the limit state of fulfilment of the safety objective. This allows the design reserves of the building to be identified.

The development of graded scenarios is based on the procedure for safety considerations in the area of plant safety, which differentiates between "accidents to be prevented" and "accidents occurring despite preventative measures".

Further considerations on the safety level and design fires in places of assembly that are eligible for approval according to the German Model Regulation Governing Places of Assembly (MVStättV) [A2.1] are given in [A2.28], [A2.30]

A2.10 Literature on Annex 2

[A2.1] Musterbauordnung – MBO, Fassung November 2002, zuletzt geändert im Februar 2019.

[A2.2] Musterverordnung über den Bau und Betrieb von Versammlungsstätten (Muster-Versammlungsstättenverordnung – MVStättV), ARGEBAU Fachkommision Bauaufsicht, Fassung Juli 2014, www.is-argebau.de.

[A2.3] Begründung und Erläuterung zur Muster-Versammlungsstättenverordnung (MVStättV), ARGEBAU Fachkommission Bauaufsicht, Fassung Juli 2014.

[A2.4] DIN EN 1991-1-2/NA:2015-09, Nationaler Anhang – National festgelegte Parameter – Eurocode 1: Einwirkungen auf Tragwerke – Teil 1.2: Allgemeine Einwirkungen – Brandeinwirkungen auf Tragwerke.

[A2.5] *BUB, H.; KERSKEN-BRADLEY, M.; HOSSER, D.; NOWAK, H.; SCHNEIDER, U.; SCHUBERT, K.-H.*: Empfehlungen zur Festlegung von Sicherheitsanforderungen im konstruktiven baulichen Brandschutz. NABau im DIN, März 1979.

[A2.6] *BUB, H.; HOSSER, D.; KERSKEN-BRADLEY, M.; SCHNEIDER, U.*: Eine Auslegungssystematik für den baulichen Brandschutz. Berlin: Verlag E. Schmidt, 1983.

[A2.7] DIN EN 1990:2002-10, Eurocode: Grundlagen der Tragwerksplanung.

[A2.8] *HOSSER, D.; WEILERT, A.; KLINZMANN, C.; SCHNETGÖKE, R.; ALBRECHT, C.*: Erarbeitung eines Sicherheitskonzeptes für die brandschutztechnische Bemessung unter Anwendung von Ingenieurmethoden gemäß Eurocode 1 Teil 1-2. Institut für Baustoffe, Massivbau und Brandschutz, TU Braunschweig, November 2008, IRB Bauforschung, Band T 3221.

[A2.9] *MCGRATTAN, K. B.; FORNEY, G.*: Fire Dynamics Simulator (Version 4), Users Guide, NIST Special Publication 1018, National Institute of Standards and Technology, Gaitherburg, Maryland, USA, 2004.

[A2.10] *MCGRATTAN, K. B.; FORNEY, G.*: Fire Dynamics Simulator (Version 6), Users Guide, SVN Respository Revision : 14173, NIST Special Publication 1019, National Institute of Standards and Technology, Gaitherburg, Maryland, USA, 2012.

[A2.11] *MCGRATTAN, K. B.; HOSTIKKA, S.*: Fire Dynamics Simulator (Version 5), Technical Reference Guide, Volume 3: Validation, SVNRespository Revision: 7033, NIST Special Publication 1018-5, National Institute of Standards and Technology, Gaitherburg, Maryland, USA, 2010.

[A2.12] *RIESE, O.*: Ermittlung der Brandwirkungen mit Brandmodellen. In: Hosser, D. (Hrsg.): Braunschweiger Brandschutz-Tage ’05, 11. Fachseminar Brandschutz – Forschung und Praxis, 28. und 29. September 2005. Institut für Baustoffe, Massivbau und Brandschutz, Heft Nr. 185, 2005.

[A2.13] DIN EN 1991-1-1:2010-12, Eurocode 1 – Grundlagen der Tragwerksplanung und Einwirkungen auf Tragwerke – Teil 1-1: Grundlagen der Tragwerksplanung.

[A2.14] DIN EN 1991-1-2:2010-12, Eurocode 1 – Einwirkungen auf Tragwerke – Teil 1-2: Allgemeine Einwirkungen – Brandeinwirkungen auf Tragwerke.

[A2.15] DIN EN 1993-1-2:2010-12, Eurocode 3 – Bemessung und Konstruktion von Stahl

[A2.16] Prüfbericht Nr.: F.3-012/88 des Forschungsinstituts für Wärmeschutz e. V. München.

[A2.17] DIN EN 1993-1-1:2010-12, Eurocode 3 – Bemessung und Konstruktion von Stahlbauten – Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau.

[A2.18] Schneider Bautabellen für Ingenieure, 20. Auflage, Werner Verlag, 2012.

[A2.19] ANSYS Rev. 8.0: Swanson Analysis Systems, Inc. Houston (USA).

[A2.20] *PURSER, D.*: Toxicity assessment of combustion products and human behaviour in fires. In: Conference proceedings 10th IBS "Engineering Methods of Fire Protection", 6 and 7 June 2005 in Hannover. vfdb / iBMB, 2005.

[A2.21] *PURSER, D. A.; McALLISTER, J.L.*: Assessment of Hazards to Occupants from Smoke, Toxic Gases and Heat. in: SFPE Handbook of Fire Protection Engineering, Springer New York, 5th Ed. 2016.

[A2.22] *PREDTETSCHENSKI, V. M.; MILINSKI, A. I.*: Personenströme in Gebäuden – Berechnungsverfahren für die Projektierung. Verlagsgesellschaft Rudolf Müller, Köln-Braunsfeld. 1971.

[A2.23] *GALEA, E.R. ET AL.*: buildingExodus 4.00, Users Guide and Technical Manual. University of Greenwich. Greenwich. 2004.

[A2.24] PedGo Handbuch: TraffGo HT GmbH, Version 2.5. Duisburg, 2011.

[A2.25] *KORHONEN, T.; HOSTIKKA, S.*: Fire Dynamics Simulator with Evacuation: FDS+Evac, Technical Reference and User`s Guide (FDS 5.5.3, Evac 2.2.3), VTT Technical Research Centre of Finland, 2010.

[A2.26] Referenzhandbuch ASERI: Ausgabe März 2011 für Version 4.8.

[A2.27] *FORELL, B.; KLÜPFEL, H.; SCHNEIDER, V.; SCHELTER, S.*: Vergleichende Anwendung verschiedener Räumungsmodelle. Tagungsband zur 59. vfdb Jahresfachtagung 2011, 30. Mai bis 1. Juni, Berlin, S. 465-493.

Zweitveröffentlichung: Vergleichende Betrachtung zu Evakuierungsberechnungen, "Fire Engineering 2011" Ingenieurakademie West e.V., Düsseldorf, 6. Juli 2011, http://www.rimea.de/de/fachbeitraege/vergleichende-betrachtung-zu-evakuierungs-berechnungen/.

[A2.28] *FORELL, B.*: Lernen aus exemplarischen Schadensfällen in Diskotheken und ähnlichen Vergnügungsstätten. In: VdS (Hrsg.): Brandschutz- und Sicherheitskonzepte für große Versammlungsstätten und Bauwerke für viele Personen, Köln, 2004.

[A2.29] *MEHL, F.* : Guidelines for the preparation and testing of fire protection concepts. In: Hosser, D. (eds.): Practical seminar on fire protection for special buildings. Institute for Building Materials, Solid Construction and Fire Protection of the TU Braunschweig, issue 178, 2004.

[A2.30] *FORELL, B.*: Niveau der Personensicherheit von Versammlungsstätten - Nachweis nach vfdb-Leitfaden. vfdb-Jahresfachtagung, Leipzig, 2007.