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Selecting design fires

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Selecting design fires

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Abstract

The fire safety of a performance-based design is often evaluated using deterministic analysis. In deterministic analysis, a number of representative fire scenarios, *the design fire scenarios*, are described and analysed. A quantitative description of the assumed fire characteristics for each fire scenario must then be made. These assumed fire characteristics are referred to as *the design fire*, i.e. there is one design fire associated with each design fire scenario. A design fire is often described in terms of heat release rate, fire load, toxic species and smoke production rate. This report provides exhaustive guidance for selecting design fires and it should be a useful resource for the fire protection engineer working with analyses involving design fires. The report describes a step-by-step working method for selecting design fires and explains factors that affect the design fire. The report also includes relevant calculation methods and references to where more data can be found.

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Table of contents

List of symbols and abbreviations

A_f	horizontal burning area of the fuel [m²]
A_{floor}	floor area [m²]
A_t	total surface area of the enclosure, including ventilation openings [m²]
A_T	effective surface area for heat transfer (i.e. area of walls, floor and ceiling), excluding the ventilation openings [m²]
A_o	area of ventilation openings [m²]
b_i	width of opening i [m]
B_i	yield coefficient for species i [-]
c	specific heat capacity [kJ/kgK]
C_{decay}	linear decay rate coefficient [kW/s]
d	distance [m]
d_c	distance front-to-back of enclosure [m]
D	diameter [m]
E	energy released in fire [kJ]
E_{load}	fire load, i.e. the total energy available for burning of the fuel [kJ]
E_i	energy released for stage i [kJ]
$E''_{load,f}$	fire load density, i.e. the fire load per unit floor area [kJ/m²]
$E''_{load,t}$	fire load density, i.e. the fire load per total surface area of enclosure [kJ/m²]
f_i	normalized yield of species i [-]
F_{ij}	radiation view factor from surface i to surface j [-]
h_k	effective heat transfer coefficient [kW/m²K]
H_i	height of ventilation opening i [m]
H_o	height of ventilation openings [m]
k	thermal conductivity [kW/mK]
$k_1\beta$	material constant for liquid fuels [m⁻¹]
L	flame height [m]
m	mass [kg]
m_a	mass of air available [kg]
m_f	mass of gaseous fuel burned [kg]
m_i	mass of fuel/species i [kg]
m_{O_2}	mass of oxygen available [kg]
$\dot{m}_a$	mass flow rate of air [kg/s]
$\dot{m}_f$	mass loss rate of fuel [kg/s]
$\dot{m}_{f,wood}$	mass loss rate of burning wood [kg/s]
$\dot{m}_p$	plume mass flow rate [kg/s]
$\dot{m}_s$	mass loss rate for smouldering combustion [g/min]
$\dot{m}''$	mass loss rate per unit area [kg/m²s]
$\dot{m}''_\infty$	fuel burning rate for a large diameter [kg/m²s]

M	moisture content of fuel [% per dry mass]
t	time [s]
t_{decay}	time when decay ends [s]
t_{max}	time when decay starts [s]
t_p	thermal penetration time [s]
t_0	fire growth time [s]
$\dot{q}_r''$	incident radiative heat flux on exposed surface [kW/m²]
$\dot{Q}$	heat release rate [kW]
$\dot{Q}(t)$	heat release rate at time t [kW]
$\dot{Q}_{act}$	heat release rate at time of sprinkler activation [kW]
$\dot{Q}_{fo}$	heat release rate at flashover [kW]
$\dot{Q}_v$	maximum heat release rate for the ventilation-controlled fire [kW]
$\dot{Q}_{v,wood}$	maximum heat release rate for the ventilation-controlled wooden fire [kW]
$\dot{Q}_{peak}$	peak heat release rate [kW]
$\dot{Q}_0$	reference heat release rate [kW]
$\dot{Q}''$	heat release rate per unit area [kW/m²]
r	stoichiometric fuel-to-air ratio [-]
r_{O_2}	stoichiometric fuel-to-oxygen ratio [-]
R	radial distance from centre of exposing fire to exposed surface [m]
V	volume [m³]
w_c	width of wall containing ventilation openings [m]
$\dot{w}''$	water spray density [mm/s]
y_i	yield of species i [kg/kg]
$y_{i,max}$	maximum theoretical yield of species i [kg/kg]
$Y_{ox,p}$	mass fraction of oxygen in plume [-]

Greek symbols

α	fire growth coefficient [kW/s²]
α_{decay}	exponential decay rate coefficient [kW/s²]
α_d	thermal diffusivity [m²/s]
δ	thickness [m]
ΔH_c	complete heat of combustion [kJ/kg]
ΔH_{eff}	effective heat of combustion [kJ/kg]
$\Delta H_{eff,wood}$	effective heat of combustion for wood
Δt	time after sprinkler activation, $t - t_{act}$ [s]
ρ	density [kg/m³]
ρ_{air}	density of air, 1.2 kg/m³ [kg/m³]
ϕ	equivalence ratio [-]
ϕ_p	plume equivalence ratio [-]
χ	combustion efficiency [-]
χ_r	radiative fraction [-]

Abbreviations

ABS	Acrylonitrile butadiene styrene
ESFR	Early Suppression Fast Response
FB	Fibreboard
GB	Gypsum board
HRR	heat release rate
HRRPUA	heat release rate per unit area
MDF	Medium-density fibreboard
PB	Particleboard
PE	Polyethylene
PMMA	Polymethylmethacrylate
POM	Polyoxymethylene
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinylchloride
THC	total hydrocarbon

PART 1
Introduction

1   Introduction

In fire safety design, the fire protection engineer can use different methods for evaluating the performance of the fire safety design. Typically, there are two different approaches for the evaluation: the fire safety design could either be based on prescriptive solutions or performance-based solutions. For the former the functional requirements are obtained by solutions that are deemed to satisfy the functional requirements, thus often referred to as Deemed-to-Satisfy (DTS) solutions. For the latter the performance of the fire safety design is evaluated by engineering analyses [1]. In performance-based design, there are basically two different methods for analysing the design solution: qualitative and quantitative analyses [2]. In qualitative analyses the suggested design solution are evaluated by comparing the design with prescriptive design solutions [2]. The suggested design solution must provide at least equal fire safety as the prescriptive solution, which in qualitative analyses can be showed by use of logical reasoning, statistics, experience or results from testing [2]. This approach correspond to Level 0 of Pate-Cornell's [3] six levels of treatment of uncertainties in risk analysis. For more complex design solutions, or when prescriptive solutions are not applicable, quantitative analyses are required [2]. Common quantitative methods are deterministic analyses and probabilistic analyses.

Both deterministic and probabilistic analyses uses fire scenarios for analysing the performance of the design. Since the number of possible fire scenarios in a building is almost infinite, the fire scenarios are limited to representative fire scenarios, *the design fire scenarios* [4]. A representative fire scenario is assumed to provide a reasonable estimate of the average consequence of the scenarios within a fire scenario cluster [4]. Each fire scenario cluster is a group of fire scenarios having similar scenario characteristics [4]. The main difference between deterministic and probabilistic analyses are that for the former the probability of each design fire scenario is described qualitatively while for the latter it is described quantitatively [1], Another difference is how the uncertainties in the input values are treated. In deterministic analyses, the input values are chosen to represent the worst credible case. Thus, the analysis is considered to estimate a plausible upper bound of the consequence. This approach corresponds to Level 2 in Pate-Cornell [3]. In probabilistic analyses, the input values are not described just by single values. Instead, the input values are described by probability distributions, hence this approach corresponds to Level 4 in Pate-Cornell [3].

Depending on the objective for the fire safety design, different design fire scenarios could be required. When the design fire scenarios have been selected, a quantitative description of the assumed fire characteristics within each fire scenario is made [5]. These assumed fire characteristics are referred to as *the design fire,* i.e. there is one design fire associated with each design fire scenario [5]. The design fire is often described in terms of heat release rate (HRR), fire load density, toxic species production rate and smoke production rate [6]. The heat release rate is so important that it has been described as the single most important variable in fire hazard [7], thus is the design fire one very important thing to estimate.

The traditional and certainly the most common method for selecting the design fire is to chose design fires according to the estimated use and occupancy [8]. This is often done by assuming a t^2-fire where the fire growth rate is chosen according to literature suggested values depending on the use and occupancy. Sometimes the peak heat release rate for the design fire is calculated regarding ventilation limits, fuel loads or sprinkler activation. However, most often is there very little engineering work when selecting the design fire. Therefore, a more thoroughly selected design

fire would add more accuracy to the resulting design fire assumption [8] and the following fire safety design [9].

1.1 Scope

The scope of this report is to describe a method for selecting design fires, in primarily deterministic analyses, and explain factors that affect the design fire. The report also puts together relevant calculation methods and references to where more data can be found. The focus is mainly on design fires for life safety assessments, although design fires for other purposes are briefly discussed.

1.2 Objective

The objective of this report is to provide exhaustive guidance for selecting design fires and to be a useful resource for the fire protection engineer working with analyses involving design fires.

1.3 Limitations

The report is limited to the selection of the design fire and does not include complete guidance for the overall fire safety design process or the process of a fire risk assessment. Since the design fire is a part of both these processes, some information on these two subjects relevant for the selection of the design fire is however given. Still it is assumed that the reader has a basic understanding of fire safety engineering as well as fundamental knowledge of fire dynamics and fire combustion. Furthermore, the focus is mainly on design fires for life safety assessment, although design fires for other purposes are briefly treated.

1.4 Outline of the report

The report is divided into five different parts.

Part 1 – introduction
The first part of the report includes background and introduction to the report as well as scope, objective and limitations of the report. A brief overview of the fire safety design process is also given in this part.

Part 2 – theoretical section
This part presents a step-by-step working method for selecting design fires and applicable theory about fires, testing methods, and the selecting of design fires.

Part 3 – practical section
This part includes practical advices, equations to be used, references for experimental data and other relevant information for selecting design fires. The chapters within this part are analogous to the different steps in the method for selecting design fires, presented in part 2.

Part 4 – worked example
This part includes a worked example of selecting design fires in a fictive hotel. The different steps in the method for selecting design fires is used in the example, which gives a practical demonstration of the method and how the fire protection engineer should analyse the fire scenarios for selecting appropriate design fires.

Part 5 – references and appendix
The last part of the report includes references and one appendix. The appendix contains useful tables for selecting design fires. The tables are given in order of where in the step-by-step working method they probably will be useful.

2   The fire safety design process

Fire safety design is often based on prescriptive solutions in national, regional or local regulations [1]. However, many regulations give possibility for performance-based design of the fire safety. Using a performance-based approach allows more flexibility for the design than the prescriptive solution [6] since the fire protection engineer can use engineering methods to get a design that obtains "equivalent" performance to the prescriptive solution [1], possibly for a lower construction cost. The objective for the fire safety design can also be different than the one in mandatory regulations, requiring a different design solution, although the mandatory regulations always have to be fulfilled. A different objective can for example be to prevent large financial losses for a company, which is often not considered in mandatory regulations [6]. A performance-based approach is often required in such cases. Because of the gravity of the subject, it is important that the fire protection engineer uses working methods that do not overlook any crucial detail when designing and evaluating the fire safety.

For performance-based solutions, the fire safety design process should be done according to a methodical approach. One such methodical approach is proposed in *The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings* [10], see Figure 2.1.
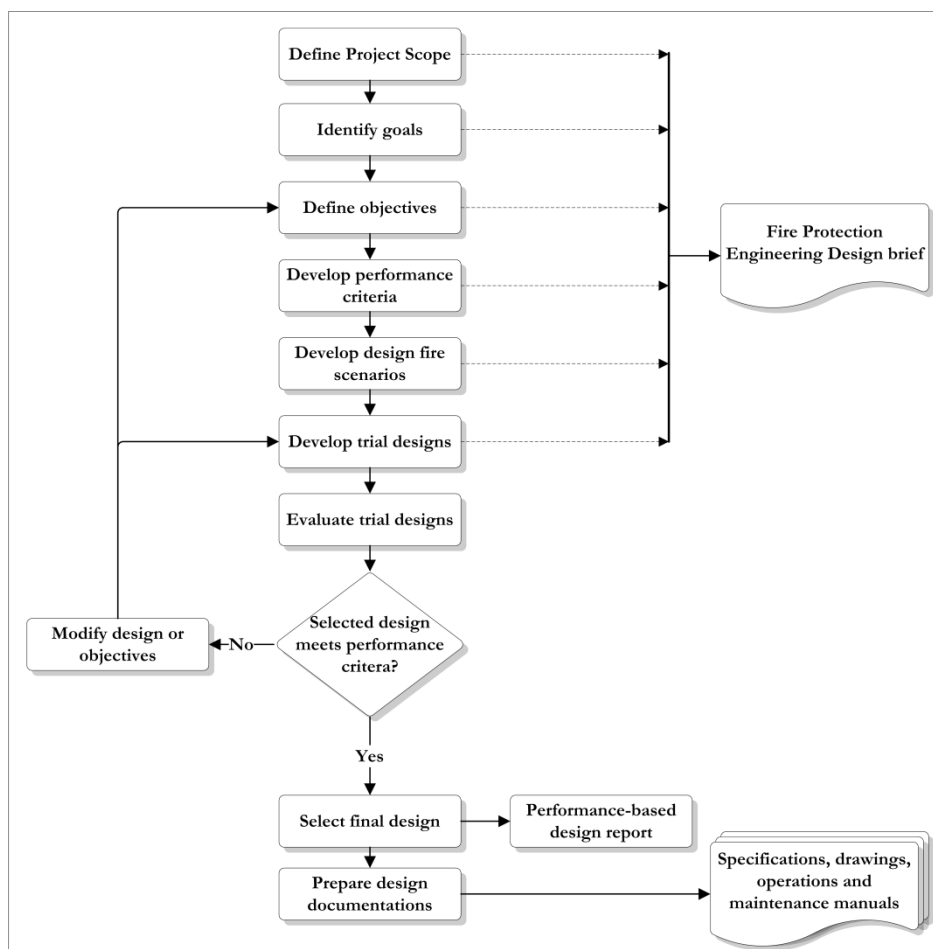
Figure 2.1. The performance-based fire safety design process as described in The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings [10].

The process starts with defining the *scope of the project* so that the fire protection engineer knows the boundaries of the design. This step often includes identification of stakeholders of the project, intended use of the object to be designed, applicable codes and regulations as well as limits in project budget and schedule [10]. The next step is to identify the *fire safety goals* of the project and describe them qualitatively [11]. Fire safety goals can be divided into four fundamental categories: life safety, property protection, protection of continuity of operations and environmental protection [11]. Goals can come from mandatory regulations or from the commissioner of the building project. When the goals of the project has been identified they should be further refined into *fire safety objectives*. Basically the fire safety objectives are divided into two different categories, the building commissioner's objectives and the design objectives. The former are often described in terms of acceptable loss or acceptable level of risk. For example, a building commissioner's objective can be a maximum fire-related downtime or a maximum damage in monetary terms [11]. The task for the fire protection engineer is to translate these objectives into values that can be quantified in fire safety engineering terms, called the design objectives [10]. Example of design objectives can be to prevent flashover or to prevent the fire to spread from the room of origin. Since the design objectives are described in engineering terms rather than measureable values, they must be expressed as *performance criteria*. Performance criteria might include threshold values for temperatures, smoke or toxic gases concentrations, distance to smoke layer or other measurable or calculable parameters [11].

When the performance criteria have been set, the engineer needs to develop and analyse design alternatives that meet these criteria. This is done by first performing a risk identification which identifies the possible fire scenarios that can occur and then choose the most relevant fire scenarios to analyse, called the *design fire scenarios*. One or more potential design solutions (*trial designs*) are then created based on the scope of the project, the performance criteria and the design fire scenarios [10]. At this stage it is useful to develop a *Fire Protection Engineering Design brief* that is handed out to the stakeholders for review and concurrence [10]. This design brief should document the project scope, goals, objectives, trial designs, performance criteria, design fire scenarios and analysing methods [10]. Documenting and agreeing on these subjects avoids possible misunderstanding later in the process [10].

Each of the trial designs are then *evaluated* whether they meet the performance criteria or not. Evaluation can be done in qualitative or quantitative analyses [2]. If no trial designs meet the performance criteria, the fire protection engineer needs to alter the design and then re-evaluate the new design. If there seems to be no design that possible could meet the performance criteria, then the fire safety objectives and the performance criteria could be re-evaluated. Objectives or performance criteria could, based on the new information that has occurred during the evaluation, be considered being too high and therefore perhaps be modified. If there is one or more trial design that meets the performance criteria, one final design among these is then selected. It is required to perform a complete documentation of decisions and conclusions made during the entire analyse and design process, called the performance-based design report. The final step in the process is then to make detailed design documents including specifications, drawings, building operations and maintenance manuals [10].

This is only a short review of the fire safety design process and complete guidance for how to work with fire safety design is beyond the scope of this report. For more information on the subject see for example [1,6,10,12].

2.1 Evaluation of the trial designs

The process of evaluating whether the trial designs meet the performance criteria could be done in different ways, depending on the requirements of the scope of the design [1]. There are basically two different methods for analysing the design: qualitative and quantitative analyses [6]. In qualitative analyses the suggested design solution are evaluated by comparing the performance of the design with prescriptive design solutions, using logical reasoning, statistics, experience or results from testing [2]. Quantitative analyses could be either deterministic or probabilistic. The main difference between deterministic analyses and probabilistic analysis are that for the former the probability for each design fire scenario is described qualitatively while for the latter it is described quantitatively [1]. In both deterministic and probabilistic analysis the consequence for each design scenario is calculated and described quantitatively.

2.1.1 Deterministic analysis

Deterministic analysis, or scenario-based analysis, is a very common approach for evaluating the fire safety design. Since the number of possible fire scenarios in a building is almost infinite, the fire scenarios are limited to representative fire scenarios, *the design fire scenarios* [4]. A representative fire scenario is assumed to provide a reasonable estimate of the average consequence of the scenarios within a fire scenario cluster [4]. Each fire scenario cluster is a group of fire scenarios having similar scenario characteristics [4]. The selection of relevant fire scenarios is done so the number of fire scenarios is manageable to analyse [5]. The selection can most often be done based on engineering judgement of which fire scenario clusters result in a potential large hazard to the fire safety [10]. Here, hazard is often expressed in terms of risk to the fire safety objectives, defined as the probability of the fire scenario to happen and the consequence if it does. Furthermore, selection of design fire scenarios can also be determined by mandatory regulations and recommendation (e.g. [13,14]). The selected design fire scenarios should be the *worst credible* fire scenarios, not the worst possible and not the average [6]. Designing for an average fire scenario, or the most likely fire scenario, would result in insufficient fire safety since there is considerable possibility of worse fire scenarios to happen, while the worst possible fire scenario would lead to an over-conservative and expensive design [6].

One approach for ranking the fire scenarios is to categorise the possible fire scenarios into three different groups based on their likelihood of occurrence: basic design fire scenarios, high-challenge fire scenarios and worst-case fire scenarios [15]. The basic design fire scenarios are scenarios with a reasonable likelihood of occurrence and representative scenarios in this category are used for evaluating the fire safety design [15]. However, high-challenge fire scenarios represent failure events and other more unusual events that still are considered possible [15]. Thus, the design must have sufficient fire safety for the scenarios in this category as well [15]. Worst-case fire scenarios are scenarios with potential of high severity and consequences but with low likelihood of occurrence [15]. They are not used for design, but this category must still be considered to make sure they have very low probability [15].

Depending on the design objective, different design fire scenarios could be needed [5]. It is crucial that the design fire scenarios are chosen so they are well representing the fire scenarios that were not chosen. This means that the fire scenarios not chosen for analysis would not change the conclusions if they were included [5].

When the design fire scenarios have been selected, a quantitative description of the assumed fire characteristics within each fire scenario is made [5]. These assumed fire characteristics are referred to as *the design fire*, i.e. there is one design fire associated with each design fire scenario [5]. The design fire is often described in terms of heat release rate, fire load density, toxic species production rate and smoke production rate [6]. The heat release rate is so important that it has been described as the single most important variable in fire hazard [7], thus the design fire is very important to estimate accurately.

When selecting the design fire, it is desirable that every assumed fire characteristics describe the worst credible fire. This is done by looking at data for many different materials and objects, and choosing a value in the upper-region of the data (or the lower-region depending on the parameter). For example, by looking at peak heat release rates for different sofas a 95-percintile value can be chosen if the statistical data is large. If only a few peak heat release rates are given, engineering judgement must be made if the maximum value should be used or if another value is more appropriate. For very scarce data, more conservative values are needed.

However, it is necessary to consider the selection of the design fire as a part of the selection of the design fire scenario. This means that the selection of the design fire cannot be totally isolated from the selection of the design fire scenario, since it is the worst credible design fire scenario that should be designed for. Combining rapid fire development with peak populations, conservative pre-movement and travel time and a major egress exit blocked might lead to an over-conservative design. For example, if the evacuation analysis is very conservative, the selected design fire could then be less conservative.

2.1.2 Probabilistic analysis

In probabilistic analysis, both the probability and the consequence of each fire scenario cluster are quantified. The consequence of a fire scenario cluster is estimated by analysing representative fire scenarios, the *design fire scenarios*, similar to the approach in deterministic analysis. However, probabilistic analysis often describes the uncertainties in the input values by probabilistic distributions rather than using worst-credible values. The main advantage of probabilistic analysis is that the total risk from the fire scenarios can be quantified, using different risk measures. The safety of the proposed design can then be ensured by comparing the actual risk with a tolerable level of risk [16].

PART 2
Theoretical section

3   Working method

This chapter includes a description of a suggested step-by-step working method for selecting design fires. It is assumed that relevant design fire scenarios already has been determined, as well as the other preceding steps in the fire safety design process as described in Chapter 2.

The design fire is affected by a number of factors determined in the preceding analysis. To be able to select the design fire, the following input from the preceding process is most often needed [17]:

- Building characteristics
- Enclosure characteristics
- Environmental conditions
- Fuel characteristics
- Design fire scenarios

A checklist of factors affecting the selection of the design fire, that might be determined in preceding analysis of the fire safety design process, is given in Table 3.1.

Table 3.1.   Checklist of factors affecting the selection of the design fire. From [17].

	Factors affecting the design fire
Building characteristics	Dimensions of building Geometry of building Nature of construction of building (materials and method)
Enclosure characteristics	Wall and ceiling linings Ventilation conditions (natural or mechanical) Thermal properties of enclosure boundaries
Environmental conditions	Ambient temperature conditions Ambient air movement
Fuel characteristics	Fuel type Fuel quantity Fuel location Fuel arrangement Wall and linings
Design fire scenario	Ignition sources Ignition location Fuel involved in ignition Type of fire growth Unusual fire hazard Events influencing fire growth e.g. window breakage.

The process of selecting design fires is somewhat integrated in the development of design fire scenarios and it is therefore an iterative process where things established in the design fire can affect the design fire scenario and vice versa. The description of the working method is attempting to point out steps in the process that often results in modifications of the design fire scenario. The method of selecting the design fire is shown in Figure 3.1.
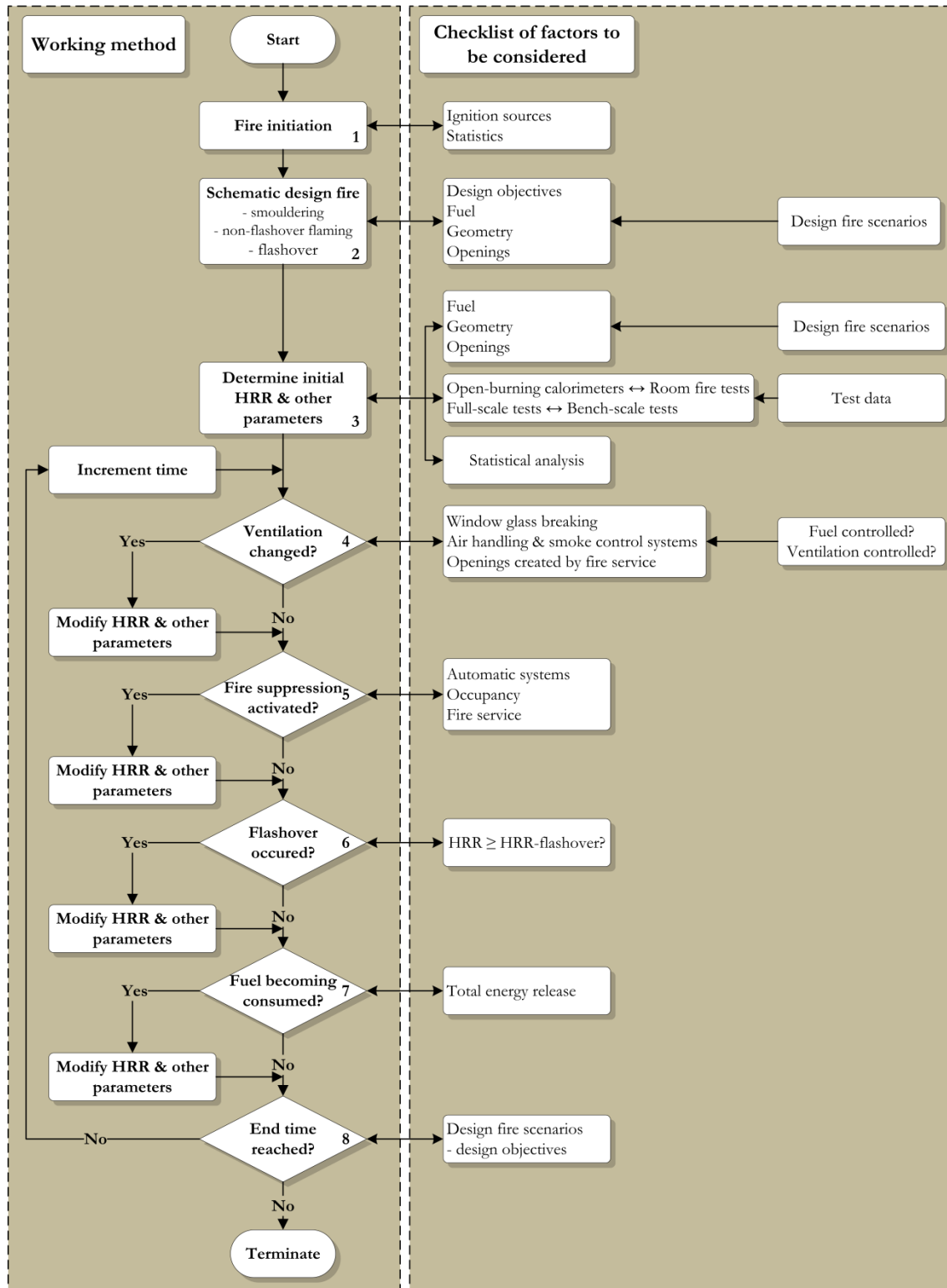
Figure 3.1. The step-by-step working method for selecting design fires, modified from method proposed in [18].

Notice that some computer models such as Zone models and Field models are able to model influences from the design fire scenario and change the design fire according to these. The effect of sprinkler activation, window glass breaking and activation of smoke management systems is factors that could be modelled in computer models. In addition, the continuous development of computer models will lead to that more influences from the design fire scenario can be modelled in the future. For example, the development of flame spread modelling in CFD-program could lead to the possibility of using such models for selecting the design fire [19]. However, the fire protection engineer must assess whether the effect on the design fire from such factors should be modelled in a computer model or if such effects instead should be taken account for when selecting the design fire. Methods for estimating the influence on the design fire from such factors manually are given in this report. It is recommended that the effect on the design fire of such factors is estimated manually, to at least compare it with the result of the model.

PART 2

Step 1 – Fire initiation

The first step in the process is to describe the fire initiation, if it has not been determined in the design fire scenario. The fire initiation involves the ignition process and the development of a self-sustainable combustion reaction [20]. A normal assumption in fire safety evaluation is that the fire initiation already has occurred [18] and the fire initiation phase is therefore often excluded in the design fire curve [10]. If the fire initiation phase, also called the pre-burning time, is excluded in the design fire, it is important to take the smoke produced during this stage under consideration in the subsequent calculations. For the activation of detection system, it is conservative to ignore the smoke already produced, while for the calculation of smoke affecting people in a building it is not. However, analysis of the fire initiation could be needed for describing the initial characteristics of the design fire. This is done by analysing potential sources of ignition and fuel, or fuel package, likely to be first ignited [17]. It can be based on engineering judgement or by analysis of relevant fire statistics. See Table 3.2 for example of potential sources of ignition.
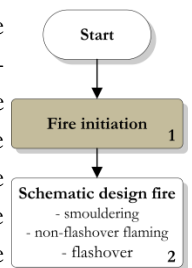
> Identification of potential sources of ignition and item likely to be first ignited is often based on analysis of relevant fire statistics or on engineering judgement.

Table 3.2. Potential sources of ignition. From [17].

Potential sources of ignition
Smokers' materials
Open flames
Electric, gas or oil heaters
Hot working
Cooking
Engines or boilers
Machinery or office equipment
Lighting equipment
Friction from drive belts
Reactive dusts
Static electricity
Metal impact
Arson

Step 2 – Schematic design fire
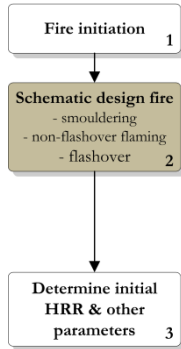
With knowledge of type and amount of fuel that is likely to be first ignited together with the potential ignition source and ventilation conditions, the engineer can assess whether the combustion will be smouldering of flaming. Assessment if the fire has the potential to lead to flashover can also be made at this stage.

Notice that the schematic design fire could have been decided already in the design fire scenario, depending on design objectives or affected regulations. For example, many mandatory regulations and recommendations (e.g. [13,14]) states that design fire scenarios with both smouldering and flaming fires should be analysed during performance-based design of life safety. Even in situations where the statutory regulations do not apply, a well chosen group of design fire scenarios for evaluating life safety should in most cases include both smouldering and flaming fire scenarios, since the two types result in essentially different hazards.

> A group of design fire scenarios for evaluating life safety should in most cases include scenarios of both smouldering and flaming fires.

Step 3 – Initial fire characteristics
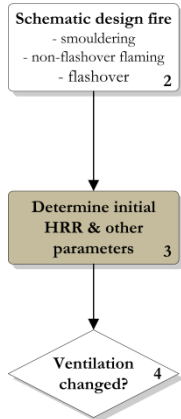
When the schematic design fire has been determined, next step is to establish initial fire characteristics such as heat release rate, fire growth rate, yields of combustion products, and fire load [18]. This can be done by analysing the fire characteristics of the products involved, building geometry, and available openings as described in the design fire scenario. With this information, it is possible to estimate how the fire will develop and spread. The fire characteristics of single products can be determined from test data such as open-burning calorimeters, room-fire tests, full-scale tests, and bench-scale tests [21]. Based on products and occupancy in the design fire scenario, relevant test data can be found for the actual product, similar type of products or occupancy-based fuel packages. Statistical analysis of several appropriate test data can also be made to derive the initial fire characteristics. A mixture of all the mentioned methods is also common. If test data is used, it is important to know the limitations of the test method used and if there is enclosure or scaling effects that need consideration [21].

The initial fire characteristics can also have been determined already in the design fire scenario. Mandatory regulations and recommendations (e.g. [13,14]) can require analysis of design fire scenario with a certain fire growth rate and peak heat release rate.

The initial fire characteristics can be a description of just the growth period or it can be a full description of the growth stage, the fully developed stage and the decay stage. There are many factors that depend on the initial fire characteristics and also affect the same; therefore, the initial fire characteristics can be changed according to their influences [18]. This is taking under consideration in the following steps of the method. As mentioned earlier in this chapter, the influence on the design fire for many of these factors can also be modelled in relevant computer models. Furthermore, the development of computer models will lead to that more of these factors can be taken account for directly in the computer model. However, it is recommended that the influences on the design fire of such factors are estimated manually, to at least compare it with the result of the model.

> It is recommended that the effect on the initial fire characteristics from factors such as changes in ventilations, fire suppression systems, flashover etcetera is estimated manually, to at least compare it with the result of the used computer model.

14

Determine initial
HRR & other
parameters   3

Ventilation
changed?   4

Fire suppression 5
activated?

PART 2

Step 4 – Ventilation

One very important thing affecting the heat release rate and yields of combustion products is the ventilation conditions [18]. Two main types of fires are the fuel-controlled fire and the ventilation-controlled fire. During the course of the fire, the fire can change between being fuel-controlled and being ventilation-controlled. This can be due to the natural stages of the fire or by factors affecting the ventilation. For example, a window glass breaking, the activation of a smoke control system or openings created by the fire service will result in changes in the ventilation [18]. Thus, it is necessary to calculate the time at which these factors change the available ventilation and determine how this will affect the fire [18].

> The available ventilation can change during the fire, as a result of events like window glass breaking, operation of air handling or smoke control systems, doors or other partitions burning through or openings created by the fire service [18].

Step 5 – Fire suppression

Another factor considerable affecting the initial fire characteristics is the activation of any suppression system. The initial fire characteristics must therefore be modified if there is an activation of a suppression system. The possible effect on the fire could be many; it could prevent the fire to lead to flashover, it could reduce the fire growth rate or peak heat release rate or it could completely extinguish the fire. The suppression system could be an automatic water sprinkler system, fire fighting activities by the occupants or intervention from the fire service. In fire safety analysis, it is common to analyse fire scenarios were the occupants are assumed to not be able to extinguish the fire. Thus, the fire scenarios where the occupants will be able to extinguishing the fire are not considered to represent any fire scenario cluster (i.e. the fire scenario is not estimating the average consequence of the fire scenario cluster). Therefore, unless there is very good reason to believe the occupants will always engage in effective fire fighting activities (e.g. trained industry fire services); the occupants are assumed to not affect the design fire [18]. The same counts for interventions of the municipal fire service; unless an appropriate model for calculating fire service intervention and effectiveness is used, the fire service is often assumed not affecting the design fire [5].

Ventilation   4
changed?

Fire suppression 5
activated?

Flashover   6
occured?

> In fire safety analyses, it is common to assume that fire fighting activities by occupants and interventions by the fire service will *not* affect the initial fire characteristics.

Step 6 – Flashover

The next step is to analyse if there is a possibility for a flashover to occur. Flashover is often assumed to take place when the upper layer temperature reaches 500-600°C or the radiation to the floor of the compartment reaches between 15 to 20 kW/m² [22]. However, this assumption is only applicable for small enclosures.

Since flashover, by definition [5], is described as a rapid transition from a local fire to the involvement of all combustible materials within an enclosure, it is common to assume that the heat release rate instantaneously increases to the peak heat release rate after flashover [18]. Following flashover, the fire is described as fully developed, having a constant heat release rate limited either by the available combustible surfaces or the available ventilation [5].

Fire suppression 5
activated?

Flashover   6
occured?

Fuel becoming   7
consumed?

> After flashover, the heat release rate is often assumed to instantaneously increase to the peak heat release rate determined either by the fuel or the available ventilation.
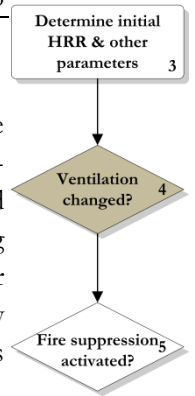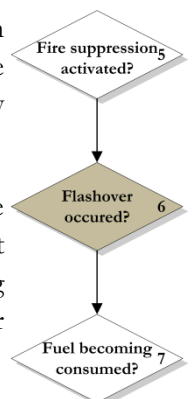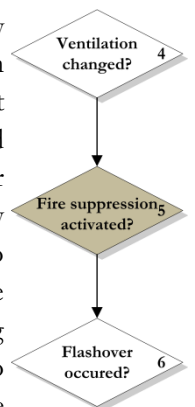
Step 7 – Fuel becoming consumed

When most of the fuel has been consumed, and the fire is no longer spreading to the adjoining items, the heat release rate decreases [5]. The fire is said to be in the decay stage. This is normally assumed to begin when 70-80 percent of the fuel has been consumed [5,17,23]. When decay has started, the heat release rate needs to be decreased accordingly to the assumed decay rate. If experimental data are not available, engineering approximations of the decay rate has to be done [12]. The decay rate may be assumed to be a linear decrease [5], an exponential decrease or as the inverse of the fire growth [23]. For a linear decrease, the decrease is assumed to be linear over a time period so the integral of the heat release rate corresponds to the energy of the remaining fuel [5]. The inverse of the fire growth means that the decay for fast-growing fires is assumed to be fast and slow-growing fires is assumed to decay slowly [23]. However, for many design purposes (e.g. life safety design), analysis after the beginning of the decay stage is often unnecessary [17].

> The decay stage is often assumed to begin when 70-80 percent of the fuel has been consumed.

Step 8 – End time

The final step in the process is to determine whether the end time has been reached or not. The end time has been reached when [18]:

- all the fuel has been consumed;
- the end time determined in the design fire scenario has been reached or
- the fire protection engineer judge that sufficiently long time period of the design fire has been determined to evaluate the trial design, on account of the design objective.

If the end time has not been reached, the next iteration of the analysis of factors affecting the initial design fire is done until the end time has been reached [18].
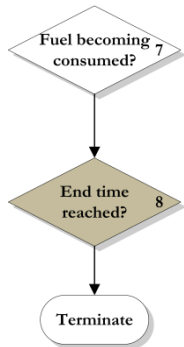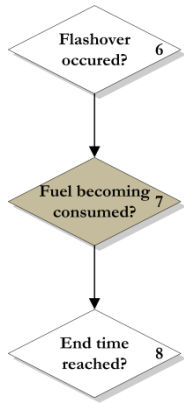
4   Enclosure fire development

This section gives a brief overview of the main stages of fire development within an enclosure. The main stages are most often defined as [22]:

- ignition ⎫
- growth ⎬ pre-flashover
- flashover
- fully developed fire ⎫
- decay ⎬ post-flashover

Notice that flashover does not necessarily occur [17]. In some sources (e.g. [20,24]) the ignition and growth stage is simply described as the growth stage, or the pre-flashover stage. The next step is there called the fully developed stage, the burning stage or the post-flashover stage and the last stage is called the decay stage. Before effective ignition has occurred, there is a pre-burning time that can last for a few seconds up to several hours. The process of pre-burning and effective ignition is also referred to as the fire initiation phase. For a schematic figure of the main stages of fire development within an enclosure, see Figure 4.1.
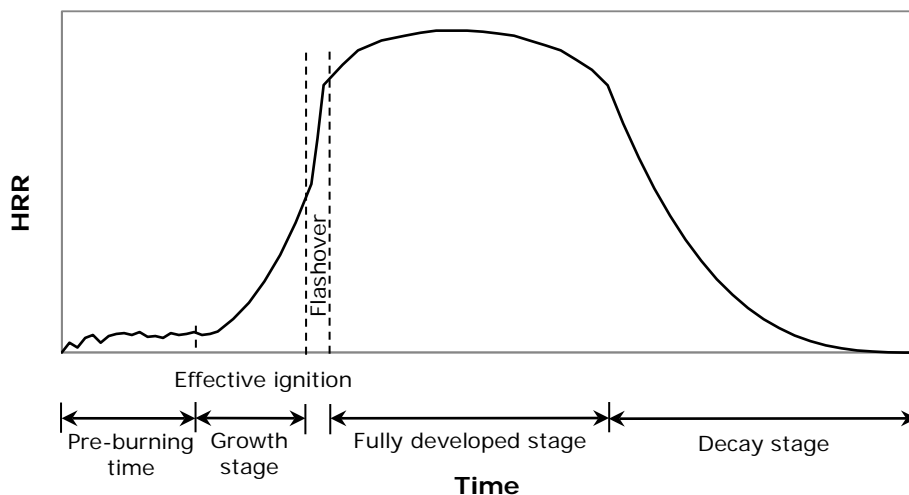
Figure 4.1. Schematic figure of the main stages of fire development within an enclosure.

Ignition

Ignition can be described as a process that leads to an exothermic reaction, which produces temperatures greatly above the ambient [22]. The exothermic reaction could be either a smouldering combustion process or a flaming combustion process [22]. There are basically two different types of ignition processes: piloted ignition and spontaneous ignition [22]. The piloted ignition is characterized by the presence of a pilot source, such as flames or sparks, which ignite the flammable vapour/air mixture [24]. For spontaneous ignition, or auto-ignition, the combustion process develops due to sufficiently high temperature, without the presence of a pilot.

Growth

Following effective ignition, the fire starts to grow. The fire growth rate depends on [22]:

- the type of combustion process;
- the type of fuel burning;
- ventilation conditions and
- interactions with the surroundings.

The amount of heat and smoke produced during the fire growth stage prior to flashover is very important in fire safety engineering when evaluating the life safety in a building [20].

Flashover

Flashover is the rapid transition from a localized fire to a fire including all the combustible materials within the enclosure [5]. Flashover is often assumed to take place when the upper layer temperature reaches 500-600°C or the radiation to the floor of the compartment reaches between 15 to 20 kW/m² [22], which is valid for small enclosures.

Fully developed fire

The fully developed fire is the stage where the fire reaches its peak heat release rate. The peak heat release rate can be limited either by the available ventilation or by the available combustible surfaces. The fire is called being ventilation-controlled or fuel-controlled, respectively [17].

Decay

The last stage for the enclosure fire is the decay stage. In this stage, the amount of combustible volatiles decreases because the fuel becomes consumed, which will lead to a decrease of the fire intensity [24].

5 Combustion

As mentioned in Chapter 4, there are basically two different types of combustion; flaming and smouldering. This chapter gives a brief overview of the characteristics of the two types. For more exhaustively information about combustion processes, see for example [24,25].

5.1 Smouldering combustion

Smouldering combustion is a flameless combustion process that may produce a certain amount of unburned combustible gases, soot and other combustion products but very little heat [17]. Smouldering combustion normally results in very slow fire development [20]. The likelihood for a smouldering combustion is determined by [17]:

- the nature of the fuel;
- ventilation conditions and
- the strength of the ignition source.

Only some types of fuel can undergo self-sustained smouldering combustion; that is fuel which forms a carbonaceous char when heated [24]. Limited ventilation can increase the possibility for a smouldering combustion to continue. A small ignition source could lead to smouldering combustion for fuel where a larger ignition source instead would result in flaming combustion. Smouldering combustion could lead to flaming combustion if the flow rate of volatiles from the fuel is increased above a certain value or if the ventilation is increased, depending on the situation of the smouldering fire [24].

The incomplete combustion that occurs produces unburned combustible gases such as carbon monoxide (CO) that might fill up an enclosure. If the enclosure is suddenly ventilated, it could result in ignition of the gases produced, which under some circumstances would lead to backdraft or smoke explosion [17]. Smouldering combustion could also lead to untenable conditions due to toxic gases and smoke [17].

5.2 Flaming combustion

Flaming combustion occurs when flammable vapour is ignited. The fuel producing the flammable vapour could be a gas, a liquid or a solid. For a liquid or a solid, external heating is required to evaporate or pyrolyse enough volatiles so it can be ignited, except for a liquid with a flashpoint below the ambient temperature [20]. A combustible gas just needs to mix with air so the concentration is within the limits of flammability. Where there is a flaming combustion, the flame generally heats the liquid or solid fuel so it produces sufficient volatiles to sustain the flame.

6 Quantifying design fires

In Chapter 4 and 5, the fire characteristics are described qualitatively. To do assessments of the consequences of a fire, the fire characteristics must be described in a quantitative way. Most often the fire characteristics of the design fire are described by a relationship between heat release rate and time [10]. This also includes estimated time of key stages in fire development, i.e. time for ignition, growth, flashover, the fully developed stage and the decay stage [10]. Example of a design fire is shown in Figure 6.1.
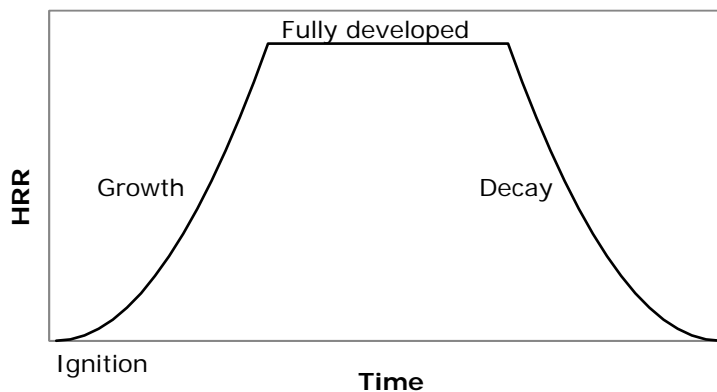
Figure 6.1. Example of the characteristics of a design fire. Based on [10].

Estimation of time for key stages to occur is based on the fire characteristics of the products involved. The characteristics of a burning product could be determined by analysis of fire statistics, fire tests, fire models, and other sources of data. Typically approaches for determine fire characteristics of a product are [8,26]:

1) using actual tests for the product in question;
2) using actual tests for similar products;
3) using algorithms derived from tests with similar products and dimensional characteristics;
4) using calculations based on tested properties and materials or
5) using mathematical models of fire spread and development.

In addition, the quantitative description of the design fire can also be done without specifying the products involved, i.e. the design fire is determined based only on the estimated use and occupancy.

6.1.1 Using actual tests

Where actual tests are available for the product in question, they could be used to quantify the fire characteristics of the burning product. However, because buildings are redecorated, furniture are changed etcetera, this approach is only suitable when the conditions in the enclosure is fixed [8]. Thus, another approach could be to use actual test for similar products within a certain product category, e.g. a group of upholstered chairs or wooden tables. The fire protection engineer can then assess whether it is reasonable to use the most extreme test value or an average value, see Section 7.4.1 for more information on how to choose values from a series of tests. This method does not require the furnishings to be fixed and should therefore be widely useful [8].

Furthermore, when using actual tests, the testing method used must be considered to be applicable in the scenario being analysed. For further guidance on that subject, see Chapter 7.

6.1.2   Using algorithms derived from tests

In many cases, fire characteristics of a burning product have been expressed by empirical correlations by looking at collection of test data for similar products. The correlation usually expresses the fire characteristics in terms of a common dimension, such as occupied floor area [26]. One frequently used correlation is that for calculating the mass release rate from a pool fire [26]:

$$\dot{m}'' = \dot{m}''_\infty \cdot \left(1 - e^{-k_1\beta D}\right) \tag{6.1}$$

where:

$\dot{m}''$ = free burn mass loss rate per unit area [kg/m²s]
$\dot{m}''_\infty$ = fuel burning rate for a large diameter [kg/m²s]
$k_1\beta$ = material constant for liquid fuels [m^{-1}]
D = pool diameter [m]

Normalized data for burning rates per unit area in tests for different products have also been developed and can be found in various literatures, see Appendix A, Section A.3.2 for examples.

6.1.3   Calculations based on tested properties and materials

General estimations of fire characteristics can also be made by analysing the characteristic burning behaviour of the constituent materials, e.g. for upholstered furniture do estimations based on the burning behaviour of fabric and foam [8]. The fire properties of the products or constituent materials can be determined by small-scale tests. Here, it is important to consider scaling effects when using these data for predicting large-scale behaviour. For more discussion on that subject, see Chapter 7.

6.1.4   Mathematical models of fire spread and development

In lack of relevant test data of the product, it could be possible to use mathematical models and fire simulations to predict the fire development [27]. Fundamental physical and chemical properties of the constituent materials are however needed. In this approach, flame spread is estimated by use relevant flame spread models. Many attempts have been made for using CFD-simulations to calculate flame spread [19,27,28,29]. As this is a relatively new technology, still in an embryonic stage, careful considerations are needed when using this type of predictions [19].

6.1.5   Estimations based on use and occupancy

One common approach for quantifying the design fire is to estimate the fire characteristics based only on use and occupancy. This is a rather simple method since suggested values can be found in various literatures. On the other hand, the method is so crude that it is questionable [8]. This can be pointed out by the various values of growth rates for the same type of occupancy in different references [13,17,22]. Using literature suggested values should, hopefully, result in conservative assessments, but the user has no way of knowing if and how conservative the assessment is. Therefore, by quantifying the design fire based on engineering judgement of the conditions in the actual building rather than using literature suggested values would significant add more accuracy to the design fire and the subsequent evaluation.

7 Uncertainties with experimental data

For the selection of design fires, parameters such as heat release rate, fire growth rate, yields of combustion products and fire load might be determined by looking at burning test data of materials and products, as described in Chapter 6. However, when using such test data, it is important to know how the conditions during the test affect the parameters that are to be determined. With knowledge of this, the fire protection engineer can assess if the test method is applicable in the scenario being analysed or if adjustments of the parameters are needed. This section aims at giving some guidance for which factors are needed consideration when using different test methods to determine parameters in the design fire. Hence, this section includes neither theoretical background of different test methods nor a full description of the setup of each mentioned test method. For this, the reader should refer to [21,30] or the appropriate standardization document for each test method.

7.1 Measuring technique

Since the heat release rate has been described as the single most important variable in fire hazard assessment [7], most of today's test methods are capable of measuring the heat release rate. Measuring the heat release rate is called *calorimetry* and the apparatus for measuring heat release rate is referred to as a *calorimeter* [30]. The most common method for measuring the heat release rate is oxygen consumption calorimetry, where it is assumed that the amount of energy released per unit mass of oxygen consumed is constant, equal to 13.1 MJ/kg of oxygen consumed. This value is an average value for a large set of materials and is found to be accurate within ±5 percent with only a few exceptions [30]. The oxygen consumed is measured by measuring the oxygen level in the smoke collected by a hood close to the burning product. Many test methods are also capable of measuring other parameters such as mass loss rate, smoke production rate and toxic gases concentrations [30]. Measurement of the heat release rate and other parameters can be made in either full-scale or bench-scale tests.

7.2 Full-scale methods

The full-scale methods of testing burning behaviour of materials and products can be grouped into two different categories: open-burning calorimeters and room-fire tests [21]. Examples of the first category are the furniture calorimeter and the industry calorimeter, while an example of the second category is the ISO 9705 Room-Corner test [31]. In open-burning calorimeters, room effects are minimized by exhausting the hot gases through a hood above the tested product and with no limitations on air supply to the fuel [22]. For room-fire tests, the tested product is burning within an enclosure, resulting in the build-up of a hot gas layer and limited air supply through the openings of the room. The hood collecting the hot gases is instead placed just outside the opening of the room.

The first obvious concern when using full-scale test methods is whether the tested product can describe the specific fuel source in question [21]. The next main concern is if the used test method can represent the conditions of the design fire scenario. For example, using open-burning calorimetry data for fire scenarios in small enclosures with limited ventilation is not appropriate without analysing carefully if any adjustments to the data have to be made. If room-fire tests are used, one concern is whether the test enclosure represents the enclosure in the fire scenario [21].

7.3   Bench-scale methods

Bench-scale methods have the advantage of using small specimens, thus it does not require the availability of large-size specimen and it results in lower costs [21]. In addition, measuring the heat release rate in a bench-scale test is an easy task [21]. However, it has the disadvantage that the bench-scale data cannot be used directly; it might only be used for the prediction of full-scale behaviour. The most common bench-scale test is the cone calorimeter [21].

7.4   Using test methods to determine parameters

Preferably, full-scale test data should be used for determine initial fire characteristics of each product identified in the design fire scenario [21]. If the full-scale tested product is believed to describe the fire characteristics of the product identified in the design fire scenario, next thing is to assess whether the conditions of the design fire scenario has room effects that are needed consideration. The presence of a hot gas layer and limitations of air supply result likely in considerable room effects. Results from open-burning calorimeters and room-fire tests are clearly identical at very low heat release rates, meaning there is no considerable room effects at that point [21]. If the fire is so large it could cause flashover, the difference between open-burning and room-fires will be significant. For upholstered furniture's, studies [32] has shown that for heat release rates up to about 600 kW, room effects were not measureable. The same study also showed that between 600 kW and 1 MW about 20 percent higher heat release rates were measured for the room-fire test. For mattresses, room effect was identified at much lower heat release rates [21]. Babrauskas [21] point out that the degree by which the room affects the heat release rate is determined by the fuel package view factor to itself. Fuel packages like a mattress or a liquid pool have a view factor of 0 to itself and 1.0 to the room, meaning the fuel package is fully exposed to the room and therefore show greater influence from the presence of a room. Similar, an upholstered chair has a bigger view factor to itself as it "sees" it own surfaces and thus tends to be less affected by the presence of a room [21].

If the design fire scenario is identified to have significant room effects, room-fire tests should preferably be used. If room-fire tests are available, then it must be assessed if the test enclosure corresponds to the enclosure in the fire scenario on account of room geometry, size, and ventilation conditions [21]. In addition, other factors that affect the burning behaviour of the product must be similar between the fire scenario and the room-fire test (e.g. ambient temperature, fuel temperature, ignition source, radiative surfaces, and oxygen concentrations).

When full-scale tests are not available, bench-scale test data must be used. The bench-scale data can be used either to obtain fundamental chemical and physical properties of the material or to estimate the heat release rate for full-scale fuel packages. For the former, the material properties are used in some pyrolysis model to calculate the heat release rate of fuel packages in larger scales. For the latter, predictive models are used for estimating the fire behaviour of the material in full-scale tests [30]. Since the predictive models can be rather complex and narrow in their use (i.e. each model are only valid for a certain type of material), it is not meaningful to give examples of them here.

7.4.1 Choosing values from several test data

One widely useful approach for determine fire characteristics of a product is to use test data for similar products within a certain product category, e.g. a group of upholstered chairs or wooden tables [8]. The main concern when using this approach is what value should be used from the data set. One approach is to use the most extreme value in the entire data set for fire growth, peak heat release rate, and yields of combustion products etcetera. However, this might result in very conservative values, especially if there is a tested product with very extreme values in comparison with the others. Then, the information from all the tests having more moderate values are not being considered at all. Therefore, another approach is to use statistical analysis of the test data to derive the value to be used. For example, one such statistical analysis is to use the 95-percentile, if the set of test data is large. Natori et. al. [33] suggests instead adding one standard deviation to the average value: $x = \bar{x} + std.dev$ where $\bar{x}$ is the average value.

PART 2

25

PART 3
Practical section

8   Fire initiation

As mentioned in Chapter 3, fire initiation could already have been described in the design fire scenario and assumed to already happen, thus the fire initiation phase is often excluded in the design fire curve. However, the fire initiation could significant affect the initial characteristics of the design fire. Therefore, it might be necessary to analyse the fire initiation process regarding the possibility for different ignition sources and starting objects.

Identification of ignition sources and starting objects could be based on analysis of relevant fire statistics. Fire departments usually have some reporting system for collecting national statistics of fires which they respond to. Fires with fatal casualties are usually also subject for accident investigation, which often results in available fire statistics. There are some useful fire statistics databases available online:

- http://www.usfa.dhs.gov/statistics/ (U.S. statistics)
- http://www.nfpa.org/ > Research > Fire statistics (U.S. statistics)
- http://www.communities.gov.uk/fire/researchandstatistics/firestatistics/ (U.K. statistics)
- http://ida.msb.se/ (only in Swedish)

A more exhaustive guide of how to use fire statistics in risk analysis of fire initiation is given in [34].

When using fire statistics, especially from other countries, it is necessary to consider whether they are applicable for the object under consideration. Differences in culture, financial standards, building structure etcetera would perhaps affect the probability for different ignition sources and fires.

> Some fire statistics of ignitions sources and starting objects are shown in Appendix A, Section A.1. Some tables of ignition characteristics are also given. A more exhaustive guide of how to use fire statistics in risk analysis of fire initiation is given in [34].

If fire statistics are not available or not applicable, the fire protection engineer can do assessment of possible ignition sources and starting objects based on the presence of heat sources, fuel packages and occupants [5]. When looking at ignition sources, the energy from a possible ignition source might be compared against the energy required for ignite the possible fuel in its given form [35]. That is, a fuel is more easily ignited if it is more finely divided rather than a solid mass [35]. Furthermore, factors like time of exposure to the source of energy and distance to the energy source should be considered when analysing if the fuel is likely to be ignited [35].

In buildings other than dwellings, the probability for arson must also be considered when selecting the design fire [17]. Malicious fires are characterized by multiple sources of ignition and use of liquid fuel such as petrol, white spirit or methylated spirit, which can significantly accelerate the fire growth [17].

Fire initiation 1

Schematic design fire
- smouldering
- non-flashover flaming
- flashover 2

Determine initial
HRR & other
parameters 3
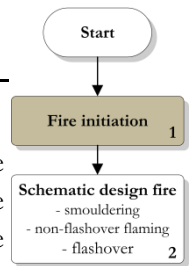
9 Schematic design fire

If the schematic design fire has not been decided in the design fire scenario, the fire protection engineer needs to assess whether the combustion will be smouldering or flaming. Assessment of what heat release rate is needed to cause flashover should also be made at this stage.

9.1 Smouldering or flaming

Unfortunately, there are virtually no quantitative methods to estimate the probability for a smouldering combustion [5]. Thus, it must be estimated qualitatively whether the fire initiation would lead to flaming or smouldering combustion. This is done by analysing the factors that affect the likelihood for the combustion process to be either smouldering or flaming:

PART 3

- the nature of the fuel;
- ventilation conditions and
- the strength of the ignition source.

Only some type of fuel can undergo self-sustained smouldering combustion, i.e. fuel which forms a carbonaceous char when heated [24]. Products made of materials such as paper, cellulosic fabrics, sawdust, fibreboard and latex rubber as well as some expanded thermoplastics can have smouldering combustion [24]. Upholstered furniture and bedding is also some common products that can have smouldering combustion [5]. Materials that melt and shrink away from the ignition source will not lead to smouldering combustion [24].

> Some typical materials for smouldering combustion is paper, cellulosic fabrics, sawdust, fibreboard, latex rubber and some expanded thermoplastics [24]. Upholstered furniture and bedding can also have smouldering combustion [5]. Materials that melt and shrink away from the ignition source will *not* have smouldering combustion [24].

Smouldering combustion occurs often under limited ventilation conditions [17]. A smouldering combustion could transform into flaming combustion if the ventilation is increased [17].

A small ignition source could lead to smouldering combustion for fuel where a larger ignition source would instead result in flaming combustion. Typical ignitions sources for smouldering combustion are cigarettes, hot objects and electric sparks [5].

9.2 Predicting flashover

For flaming combustion, the fire could lead to flashover. Estimating the heat release rate required for flashover, $\dot{Q}_{fo}$, at this stage might simplify the following analysis. For example, calculations of further flame spread to adjacent items are unnecessary once the heat release rate to cause flashover has been reached by the items already burning. Equations for calculating $\dot{Q}_{fo}$ are given in Chapter 13, where flashover is more exhaustively analysed.
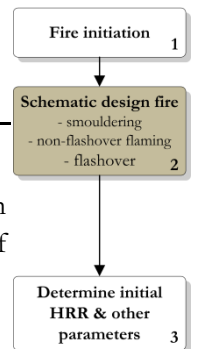
9.3   Suggested approach

If the schematic design fire has not been decided in the design fire scenario, the following approach is suggested to determine the schematic design fire.

If all these three criteria are fulfilled, a smouldering schematic design fire should be chosen:

1) the material is a material that can undergo smouldering combustion (e.g. paper, cellulosic fabrics, sawdust, fibreboard, latex rubber, upholstered furniture, bedding). The material is not a material that melts and shrinks when heated by an ignition source;
2) ventilation conditions are limited (e.g. small enclosures with limited or no openings);
3) the ignition source is small, typically up to a few kW (e.g. cigarettes, hot objects, electric sparks).

If any of these criteria is not fulfilled, a flaming fire can be chosen. The heat release rate to cause flashover for flaming fires should then be calculated, using the methods described in Chapter 13.

10 Initial fire characteristics

Schematic design fire
- smouldering
- non-flashover flaming
- flashover 2
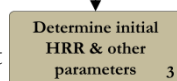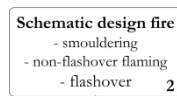
Initial heat release rate and other initial parameters such as yields of combustion and fire load might be determined by analysing the fire characteristics of the products involved, building geometry and available openings as described in the design fire scenario.

Since the ignition source, the starting object and the schematic design fire have been identified in the previous steps, the next thing to consider is how the fire will grow and which fuel packages that is likely to be involved. For design of buildings not yet built, identifications of fuel packages must be based on the intended use and occupancy. For existing buildings, products and fuel packages can be identified directly.

Depending on the schematic design fire, different approaches for estimating some of the initial fire characteristics are needed.

10.1 Smouldering fires

For smouldering fires, Quintiere et. al. [36] developed an expression to calculate the mass loss rate:

$$\dot{m}_s = \begin{cases} 0.1t + 0.0185t^2, & 0 < t < 60 \\ 73, & 60 \leq t \leq 120 \end{cases} \tag{10.1}$$

where:

$\dot{m}_s$ = mass loss rate for smouldering combustion [g/min]
t = time [min]

Notice that $\dot{m}_s$ is given in g/min and t is given in minutes.

10.2 Flaming fires

The initial heat release rate of the flaming fire is determined by analysing two main stages; the growth stage and the fully developed stage.

10.2.1 Growth stage – heat release rate

The most common way to describe the heat release rate during the growth stage is with the t²-fire, i.e. the heat release rate is given by:

$$\dot{Q} = \alpha t^2 \tag{10.2}$$

where:

$\dot{Q}$ = heat release rate [kW]
α = fire growth coefficient [kW/s²]
t = time [s]

The fire growth factor in Equation (10.2) could also be expressed as:

$$\alpha = \frac{\dot{Q}_0}{t_0{}^2} \tag{10.3}$$

where:

α = fire growth coefficient [kW/s²]
$\dot{Q}_0$ = reference heat release rate [kW]
t_0 = fire growth time [s]

The reference heat release rate, $\dot{Q}_0$, is usually taken to be 1055 kW (= 1000 Btu/s) and t_0 is the time to reach $\dot{Q}_0$. Values for α and time to reach 1055 kW for different growth rates is given in Table 10.1.

Table 10.1. Values for α and time to reach 1055 kW for different growth rates [22].

Growth rate	Fire growth factor, α [kW/s²]	Time [s] to reach 1055 kW
Slow	0.003	600
Medium	0.012	300
Fast	0.047	150
Ultra-fast	0.188	75

Recommendations for fire growth based on the estimated use and occupancy can be found in various literatures. Some examples are given in Table 10.2

Table 10.2. Examples of fire growth rates based only on estimated use and occupancy, found in various literatures.

Occupancy	Growth rate
Dwellings	Fast [13]
	Medium [17]
	Medium [22]
Schools, offices	Medium [13]
	Medium [17]
	Fast [22]
Hotels, nursing homes etcetera	Fast [13]
	Fast [22]
Shopping centres, entertainment centres	Fast [13]
	Fast [17]
	Ultra-fast [22]

However, as already mention in Section 6.1.5, it is better to determine initial fire growth characteristics of the design fire by looking at fire tests for real products. At first, assessment of which product, or which type of products, that will be involved in the fire growth should be made. Next task is to find fire tests that can describe the burning behaviour of each product. The test data can be in small- or full-scale and for the actual product in question, similar products or for the constituent materials of the product. The fire growth characteristic of each product can then be established, with some engineering judgement.

By looking at test data, fire growth characteristics can be estimated for single products. Several sources for finding test data in small- and full-scale tests are available online:

- http://www.brand.lth.se/forskning/initial_fires – contains the report *Initial fires* by Särdqvist [37], together with a zip-file of all the test data in the report.
- http://www.sp.se/fire/fdb – *SP Fire Database* from SP Swedish National Testing and Research Institute, Borås. (free registration needed)
- http://www.fire.nist.gov/fastdata/ - Test database from the National Institute of Standards and Technology, NIST.

> Furthermore, there are collections of test data available in literatures:

- Heat release rates by Babrauskas [21] in the SFPE Handbook of Fire Protection Engineering;
- Design fires for enclosures by Hertzberg, Sundström and van Hees [8];
- Design fires for preflashover fires by Höglander and Sundström [32];
- Design fires for Commercial Premises: Results of Phase I [38] and Results of Phase II [39];
- Heat release in fires by Babrauskas and Greyson [40].

To establish the fire growth characteristics, the heat release rates for the different products can be super positioned depending on when the different fuel packages are calculated to ignite. Ignition of a second fuel package is caused either by direct flame contact or by radiant energy [25]. For the case of direct flame contact, the objects need to be close together (maybe < 0.3 m) [25]. The ignition time of a second object due to flame contact can be assumed to be the time when flame contact occurs [25]. For radiant ignition, radiation to the second fuel package comes from the flame above the burning object, hot gases in the room and other bounding surfaces in the room [25]. However, radiation from hot gases and other surfaces can be assumed to be negligible prior to flashover, i.e. radiation to second fuel packages comes only from the flame above the first burning item [25]. Calculation of radiative ignition requires detailed information on the fuel packages and their arrangements in the enclosure [22] and an alternative approach is to assume that adjacent fuel packages to the starting item will ignite at the same time.

> The ignition time of a second item due to direct flame contact can be assumed to be the time when flame contact occurs [25]. For radiant ignition, radiation to the second item prior flashover can be assumed to come only from the flame above the first burning item [25].

The radiative heat flux from an exposing fire can be estimated by two different methods [24]:

Alternative 1
The radiative heat flux from an exposing fire can be estimated by [24]:

$$\dot{q}_r'' = \frac{\chi_r \dot{Q}}{4\pi R^2}$$

(10.4)

where:

$\dot{q}_r''$ = incident radiative heat flux on exposed surface [kW/m²]
χ_r = radiative fraction of exposing fire [-]
$\dot{Q}$ = heat release rate of the exposing fire [kW]
R = radial distance from centre of exposing fire to exposed surface [m]

Here, it is assumed that the radiative heat flux originates from a point source on the flame centre axis at a height $0.5L$ above the fuel surface, where L is the flame height [24], see Figure 10.1.

PART 3
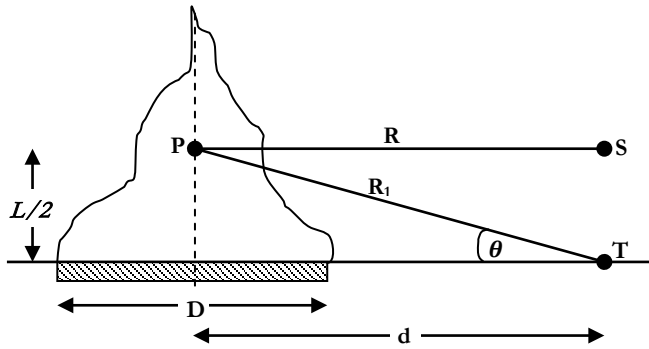
Figure 10.1. The radiative heat flux received at surface S with a radial distance R from a fire of diameter D and an equivalent point source P. The figure also show the radiative heat flux received at point T at a distance R_1 [24]. Based on figure in [24].

As shown in Figure 10.1, R is the radial distance between the assumed point source on the axis to the exposed surface S. However, if the exposed surface is at an angle θ to the line-of-sight (PT), the distance from the exposed surface T and the point source will be R_1, where $(R_1)^2 = (L/2)^2 + d^2$ and the radiative flux will then be reduced by a factor $\cos \theta$ [24]:

$$\dot{q}''_{r,T} = \frac{\chi_r \dot{Q} \cos \theta}{4\pi (R_1)^2} \tag{10.5}$$

By setting $\dot{q}''_r$ to the required incident radiative heat flux for piloted ignition of the exposed fuel, NFPA 92B [26] uses Equation (10.4) to estimate if adjacent combustible items should be included in the design fire during the fire growth stage:

$$R = \sqrt{\frac{\chi_r \dot{Q}}{4\pi \dot{q}''_r}} \tag{10.6}$$

Alternative 2
An alternative method for estimating the incident radiative heat flux is to approximate the flame by a vertical rectangle, with the dimensions L x D. The radiative heat flux at a distant point T can then be estimated by:

$$\dot{q}''_{r,T} = \frac{F_{FT} \cdot 0.5 \cdot \chi_r \dot{Q}}{L \cdot D} \tag{10.7}$$

where:

$\dot{q}''_{r,T}$ = incident radiative heat flux on exposed surface T [kW/m²]
F_{FT} = radiation view factor between flame and exposed surface T [-]
χ_r = radiative fraction of exposing fire [-]
$\dot{Q}$ = heat release rate of the exposing fire [kW]

Limits: Equation (10.4)-(10.7) is based on free-burning conditions, without influences of a hot gas layer or hot surfaces radiating to the exposed fuel [26]. The equations are based only on irradiance from the exposing fire. Therefore, preheating of the exposed fuel due to heat transfer by convection or conduction is not taking account for. Furthermore, neither the time of exposure nor the likelihood for an ignition pilot to be present is taking account for in the equation. On the other hand, several assumptions is made in the equations which instead lead to overestimation of the radiative heat flux, i.e. the combustion efficiency is assumed to be 100 percent and the flame having an uniform temperature [24].

If the radiative fraction of the exposing fuel is unknown, a value of 0.3 can be used in Equation (10.4)-(10.7) [26]. If the incident radiant flux required for piloted ignition of exposed fuel is unknown, a value of 10 kW/m² can be used in Equation (10.4)-(10.7) [26].

However, Equation (10.4)-(10.7) requires detailed information about the arrangements of the fuel packages in the enclosure as well. Though, the equations can give some guidance for what distance the exposing fire will cause radiation fluxes sufficient to ignite adjacent items.

From a series of ignition experiments of adjacent items, Babrauskas [41] did several conclusions for the potential of ignition for a second item. Three different ignitability levels are used to describe the ease for ignition [41];

- 10 kW/m² (especially easily ignitable);
- 20 kW/m² (normal ignition range) and
- 40 kW/m² (difficult to ignite).

PART 3

Most common furnishing items require a minimum of 20 kW/m² irradiance for ignition and would usually not be involved in fire growth if placed at least 1 m away from the initial fire source [41]. This conclusion is only valid prior to flashover [41].

If the starting item has a fire growth sufficient to cause flashover within a very short period of time, calculations of the contribution of the other fuel packages during the growth stage might be unnecessary. This might also be the case for when a fuel package sufficient to cause flashover within a very short period of time has been ignited from the starting item.

10.2.2 Fully developed fire – peak heat release rate

When the fire growth has been determined, next thing is to determine the fire characteristics of the fully developed fire. To do this, assessment of the peak heat release rate, $\dot{Q}_{peak}$, must be made. The peak heat release rate can be limited either by the available ventilation or the available combustible surfaces (i.e. ventilation-controlled or fuel-controlled, respectively). Therefore, peak heat release rates for both ventilation-controlled and fuel-controlled fires should be calculated. However, it is important to know that excessive gaseous fuel might be produced and combusted in adjacent room for ventilation-controlled fires [22]. For fire compartments where significant burning in adjacent rooms can be expected (e.g. a fire in a small room with openings to a large adjacent room), the peak heat release should be based on the amount and type of fuel available, i.e. the fuel-controlled heat release rate [22]. For fire scenarios in a single room or in a room with no opening to adjacent rooms, the peak heat release rate is chosen to the *lower* value of the ventilation-controlled and the fuel-controlled heat release rate.

> For fire scenarios in a single room or in a room with no opening to adjacent rooms, the peak heat release rate, $\dot{Q}_{peak}$, is determined by calculating heat release rates for ventilation-controlled and fuel-controlled fires and choosing the *lower* value of those two. For fire scenarios where significant burning in adjacent room can be expected, the peak heat release rate should be based on the fuel-controlled heat release rate.

10.2.3 Calculating the peak heat release for the fuel-controlled fire

If peak heat release rates have been measured in full-scale tests for the products in question, calculating the peak heat release rate for the fuel-controlled fire is an easy task. It is simple derived by looking at the peak heat release rates for each product and adding them to a total peak heat release rate, provided that all fuels are assumed to reach its peak release rate at the same time. If some of the fuel has reached its decay stage, this must be taken in consideration. The conditions during the fire test must also be similar to the conditions in the design fire scenario, see Chapter 7 for more information in that subject.

The peak heat release rate for the fuel-controlled fire can also be estimated by looking at values for heat release rates per unit area, HRRPUA, for the product in question and by estimating the maximum area of the fire. The peak heat release rate is then given by:

$$\dot{Q} = \dot{Q}'' A_f \tag{10.8}$$

where:

$\dot{Q}$ = total heat release rate [kW]

$\dot{Q}''$ = heat release rate per unit area [kW/m²]

A_f = horizontal burning area of the fuel [m²]

Sometimes the mass loss rate per unit area is given for the fully involved combustible, the peak release rate can then be estimated by:

$$\dot{Q} = \dot{m}'' A_f \Delta H_{eff} \tag{10.9}$$

where:

$\dot{Q}$ = total heat release rate [kW]

$\dot{m}''$ = mass loss rate per unit area [kW/m²]

A_f = horizontal burning area of the fuel [m²]

ΔH_{eff} = effective heat of combustion [kJ/kg]

Limits: Values for heat release rate per unit area and mass loss rate per unit area is usually given for fully involved combustible assuming negligible radiative feedback from the surroundings. Thus, when using Equation (10.8) and Equation (10.9), influences from a possible hot gas layer must be taken under consideration.

ΔH_{eff} is given by [22]:

$$\Delta H_{eff} = \chi \Delta H_c \tag{10.10}$$

where:

χ = combustion efficiency [-]

ΔH_c = complete heat of combustion [kJ/kg]

The combustion efficiency for fuels burning with a hardly visible flame, e.g. alcohols such as methanol and ethanol, has combustion efficiency close to 100 percent [22]. For fuels with sooty flames, the combustion efficiency is significant lower, typically around 60 to 70 percent [22].

When there is no information about the fire characteristics of the product involved, some coarse estimates of peak heat release rate for the fuel-controlled fire based on occupancy can be made by using the values in Table 10.3 and Table 10.4.

Table 10.3. Examples of peak heat release rates based only on estimated use and occupancy, found in [2]. The 5 MW peak heat release rate is considered to be for smaller rooms such as those in offices, apartments and health care units [2]. The 10 MW peak heat release rate is based on value for shopping centres [2].

Occupancy	Peak HRR [kW]
Office and schools	5 000
Dwelling, hotel, health care unit	5 000
Public assembly hall, shop	10 000

Table 10.4. Examples of suggested heat release rate per unit area for fuel-controlled fires, based on occupancy [42]. The HRRPUA is given for the estimated maximum area of the fire [42].

Occupancy	HRRPUA, $\dot{Q}''$ [kW/m²]
Dwelling	250
Hospital (room)	250
Hotel (room)	250
Library	500
Office	250
Classroom of a school	250
Shopping centre	250
Theatre (cinema)	500
Transport (public spaces)	250

PART 3

10.2.4 Calculating the peak heat release for the ventilation-controlled fire

The peak heat release rate for the ventilation-controlled fire can be estimated by first calculating the flow of air into the enclosure [22]:

$$\dot{m}_a = 0.5 A_o \sqrt{H_o} \qquad (10.11)$$

where:

$\dot{m}_a$ = mass flow rate of air [kg/s]
A_o = area of ventilation openings [m²]
H_o = height of ventilation openings [m]

Limits: Equation (10.11) estimates the air mass flow rate of fires where the gas temperature is at least twice the ambient temperature (measured in Kelvin) and where the gas temperature is uniformly distributed over the entire volume [22]. This is often the case for post-flashover fires; hence can Equation (10.11) be used for calculating air mass flow rates for post-flashover fires [22].

By assuming that each kilogram of oxygen used for combustion produces approximately 13.1 MJ and that 23 percent mass of air is oxygen, the maximum heat release rate for complete combustion is given by:

$$\dot{Q}_v \approx 1500 A_o \sqrt{H_o} \qquad (10.12)$$

where:

$\dot{Q}_v$ = maximum heat release rate for the ventilation-controlled fire [kW]

Limits: Equation (10.12) assumes complete combustion of all the oxygen entering the enclosure. In real fires, complete combustion of all the available oxygen is unlikely.

For enclosures with more than one opening, weighted values of A_o and H_o can be determined by Figure 10.2 and Equation (10.13)-(10.14) [22]:

$$A_o = A_1 + A_2 + \ldots + A_6 = b_1 H_1 + b_2 H_2 + \ldots + b_6 H_6 \tag{10.13}$$

$$H_o = \frac{(A_1 H_1 + A_2 H_2 + \ldots + A_6 H_6)}{A_o} \tag{10.14}$$
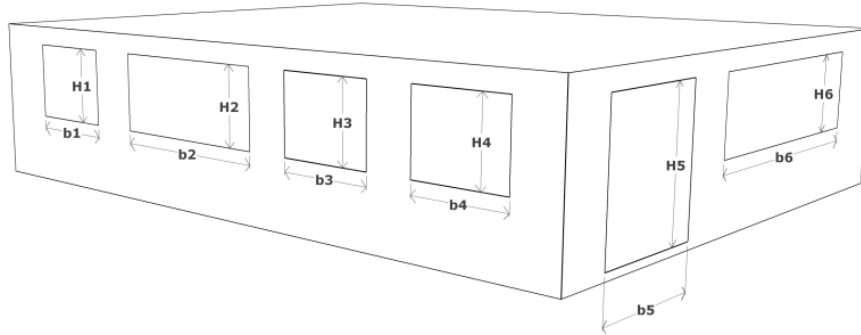
Figure 10.2. Symbols for determination of weighted values of A_o and H_o, for enclosures with more than one opening. Based on [22].

Furthermore, considerations must be made for large enclosures, or for enclosures with very small openings, since the available oxygen within the enclosure at the beginning can allow higher heat release rates than indicated by Equation (10.12). By assuming that combustion is possible until the oxygen level decreases to 10 mass percentages of air and each kilogram oxygen produces 13.1 MJ, the energy released in a fire from combustion of the oxygen within an enclosure can be estimated by:

$$E = 13100 \cdot V \cdot (0.23 - 0.10) \cdot \rho_{air} \tag{10.15}$$

where:

E = energy released in fire [kJ]
V = volume of enclosure [m³]
ρ_{air} = density of air, 1.2 kg/m³ [kg/m³]

The energy released can then be used for estimating the heat release rate possible within the enclosure:

$$E = \int_0^t \dot{Q}(t)\, dt \tag{10.16}$$

where:

$\dot{Q}$ = heat release rate [kW]
t = time of burning [s]

An equation for calculating ventilation-controlled mass loss rate of burning wooden fuel is given in [17]:

$$\dot{m}_{f,wood} = 0.02\sqrt{A_T(w_c/d_c)A_oH_o^{1/2}}$$ (10.17)

where:

$\dot{m}_{f,wood}$ = mass loss rate of burning wood [kg/s]

A_T = effective surface area for heat transfer (i.e. area of walls, floor and ceiling), excluding the ventilation openings [m²]

w_c = width of wall containing ventilation openings [m]

d_c = distance front-to-back of enclosure [m]

PART 3

Hence, the heat release rate for a wooden fuel can be calculated by:

$$\dot{Q}_{v,wood} = \dot{m}_{f,wood}\Delta H_{eff,wood}$$ (10.18)

where:

$\dot{Q}_{v,wood}$ = maximum heat release rate for the ventilation-controlled wooden fire [kW]

$\dot{m}_{f,wood}$ = mass loss rate of burning wood [kg/s]

$\Delta H_{eff,wood}$ = effective heat of combustion for wood [kJ/kg]

Limits: Equation (10.17) is an empirical correlation based on experiments of wooden cribs, with small fire loads and conventional shapes of enclosures [17]. Considerations are needed when using the model for enclosures with large widths and depths in relation to height [17]. The model is not valid for fires consisting of mainly plastics and/or liquid fuels [17].

Values of $\Delta H_{eff,wood}$ for different types of wood are given in Appendix A, Section A.3.2.

10.3 Prediction of combustion products species

The quantified design fire must, in addition to the parameters determined in Section 10.1 and 10.2, include estimations of the production of combustion products from the fire. Especially species such as CO, CO_2, O_2, hydrocarbons and soot is of interest [22]. These species are important for the evaluation of the effect of smoke and combustion products on people, property, equipment and operations [22].

Prediction of the generation of soot and combustion products must often be based on measurements rather than fundamental theory of the combustion reaction, since the reaction can be very complex for the fuels involved [22]. There are some factors affecting the generation of soot and combustion products for a given fuel [22]:

- type of combustion process (i.e. smouldering or flaming);
- the amount of air (or oxygen) available and
- retardation of the combustion reaction due to involvement of chemical agents.

Typically, soot and combustion products are expressed as yields of species i, defined as the mass of species i produced per mass of fuel burned [22]:

$$y_i = \frac{m_i}{m_f}$$ (10.19)

where:

y_i = yield of species i [kg/kg]

m_i = mass of species i produced [kg]

m_f = mass of gaseous fuel burned [kg]

For oxygen, yield is instead expressed as the mass of oxygen *consumed* per mass of fuel burned [22]. As already mentioned, the yield of species is affected by the amount of air (or oxygen) available. Thus, an equivalence ratio has been derived for expressing the overall ventilation situation within a fire compartment [43]:

$$\phi = \frac{m_f/m_{O_2}}{r_{O_2}} \tag{10.20}$$

where:

ϕ = equivalence ratio [-]
m_f = mass of gaseous fuel burned [kg]
m_{O_2} = mass of oxygen available [kg]
r_{O_2} = stoichiometric fuel-to-oxygen ratio [-]

The equivalence ratio can also be expressed in terms of air available:

$$\phi = \frac{m_f/m_a}{r} \tag{10.21}$$

where:

m_f = mass of gaseous fuel burned [kg]
m_a = mass of air available [kg]
r = stoichiometric fuel-to-air ratio [-]

Notice that in some tabulated data, the ratio r is given as the air-to-fuel ratio instead of the fuel-to-air ratio [43]. Therefore, caution must be made when using tabulated values.

Following the definitions in Equation (10.20) and (10.21), well-ventilated fire conditions correspond to $\phi < 1$ and under-ventilated conditions to $\phi > 1$. Another expression of the equivalence ratio in terms of air flow rate is also given [22]:

$$\phi = \frac{\dot{m}_f/\dot{m}_a}{r} \tag{10.22}$$

where:

$\dot{m}_f$ = mass loss rate of fuel [kg/s]
$\dot{m}_a$ = mass flow rate of air [kg/s]
r = stoichiometric fuel-to-air ratio [-]

By assuming that the mass flow rate of air into the upper layer is equal to the plume mass flow rate, Equation (10.22) can be expressed as:

$$\phi_p = \frac{\dot{m}_f}{r Y_{ox,p} \dot{m}_p} \tag{10.23}$$

where:

ϕ_p = plume equivalence ratio [-]
$\dot{m}_f$ = mass loss rate of fuel [kg/s]
$\dot{m}_p$ = plume mass flow rate [kg/s]
$Y_{ox,p}$ = mass fraction of oxygen in plume [-]
r = stoichiometric fuel-to-air ratio [-]

Two different expressions can be used for estimating the equivalence ratio. The first is based on Equation (10.23):

$$\phi_p = \frac{\dot{Q}/\Delta H_{eff}}{rY_{ox,p}\dot{m}_p} \tag{10.24}$$

where:

$\dot{Q}$ = heat release rate [kW]

ΔH_{eff} = effective heat of combustion [kJ/kg]

In Equation (10.24), the plume mass flow rate, $\dot{m}_p$, is calculated by an appropriate plume equation. Plume equations and their limitations can be found in [22]. The second expression for estimating the equivalence ratio is [43]:

PART 3

$$\phi = \frac{\dot{Q}}{3030 \cdot \dot{m}_a} \tag{10.25}$$

where:

$\dot{Q}$ = heat release rate of fire [kW]

$\dot{m}_a$ = mass flow rate of air [kg/s]

Here, it is assumed that each kilogram of oxygen used for combustion produces approximately 13.1 MJ and that 23 percent mass of air is oxygen [43]. The mass flow rate of air, $\dot{m}_a$, can be calculated using Equation (10.11).

Limits: For Equation (10.24)-(10.25), the heat release rate should be the theoretical heat release rate for the fuel-controlled fire. Using a heat release rate derived from assuming complete combustion of the available oxygen would simply result in an equivalence ratio of 1.0.

The normalized yield, f_i, is the yield of species i divided by the maximum theoretical yield of species i for a given fuel [43]:

$$f_i = \frac{y_i}{y_{i,max}} \tag{10.26}$$

where:

f_i = normalized yield of species i [-]

y_i = yield of species i [kg/kg]

$y_{i,max}$ = maximum theoretical yield of species i [kg/kg]

The maximum theoretical yield is the maximum yield for species i for the stoichiometric reaction and can be easily calculated when knowing the chemical formula of the fuel.

EXAMPLE 10.1.

For propane, C_3H_8, the maximum theoretical yield for CO_2 is calculated by assuming that all carbon atoms in propane produces CO_2, i.e. one mole of propane produces three mole of CO_2. The maximum theoretical yield for CO_2 is then given by:

$$y_{CO_2,max} = \frac{m_{CO_2}}{m_{C_3H_8}} = \frac{3 \cdot (12 + 2 \cdot 16)}{(3 \cdot 12 + 8 \cdot 1)} = 3$$

Similar, the maximum theoretical yield of CO for propane is:

$$y_{CO,max} = \frac{m_{CO}}{m_{C_3H_8}} = \frac{3 \cdot (12 + 16)}{(3 \cdot 12 + 8 \cdot 1)} = 1.91$$

Here, each mole of propane is assumed instead to produce three mole of CO.

For oxygen, the maximum theoretical yield is calculated instead by the mass of oxygen needed for stoichiometric reaction divided by mass of fuel.

Now, a simple model for ideal complete combustion of a fuel can be expressed in terms of equivalence ratio and normalized yields. First, we assume that for well-ventilated conditions ($\phi < 1$) there is sufficient supply of oxygen available for complete combustion of the fuel to CO_2 and H_2O [43]. For under-ventilated conditions ($\phi > 1$), there is insufficient oxygen available to completely burn the fuel [43]. Thus, combustion products will also include excess fuel, assumed to be total hydrocarbon (THC) [22]. These assumptions can be summarized [43]:

$$\text{For } \phi < 1 \qquad\qquad f_{CO_2} = f_{H_2O} = f_{O_2} = 1 \qquad\qquad (10.27)$$

$$f_{CO} = f_{H_2} = f_{THC} = 0 \qquad\qquad (10.28)$$

$$\text{For } \phi > 1 \qquad\qquad f_{CO_2} = f_{H_2O} = f_{O_2} = \frac{1}{\phi} \qquad\qquad (10.29)$$

$$f_{CO} = f_{H_2} = 0 \qquad\qquad (10.30)$$

$$f_{THC} = \frac{m_f - m_{f,reacted}}{m_f} = 1 - \frac{rm_{ox}}{m_f} = 1 - \frac{1}{\phi} \qquad\qquad (10.31)$$

This ideal model assumes no production of CO and H_2 [22]. However, fire experiments [44] shows that significant levels of both CO and H_2 are produced at higher equivalence ratios (i.e. under-ventilated conditions) [43]. On the other hand, these experiments show good agreement with the theory for the production of CO_2, O_2, H_2O and THC, especially for well-ventilated conditions [22]. Therefore, further studies [22,43] have derived other correlations for CO yield and yields during under-ventilated condition, to get better agreement with the experimental results. Gottuk and Lattimer [43] propose correlations for CO yield with different levels of complexity, where the least complicated are:

$$\text{For } \phi < 0.5 \qquad\qquad f_{CO} = 0 \qquad\qquad (10.32)$$

$$\text{For } 0.5 < \phi < 1.5 \qquad\qquad f_{CO} = 0.2\phi - 0.1 \qquad\qquad (10.33)$$

$$\text{For } \phi > 1.5 \qquad\qquad f_{CO} = 0.2 \qquad\qquad (10.34)$$

The more complicated correlations represent the CO yield dependence on temperature better [43]:

$$\text{For } T < 800\,K \quad y_{CO} = \left(\frac{0.19}{180}\right) tan^{-1}\big(10(\phi - 0.8)\big) + 0.095 \qquad\qquad (10.35)$$

$$\text{For } T > 900\,K \quad y_{CO} = \left(\frac{0.22}{180}\right) tan^{-1}\big(10(\phi - 1.25)\big) + 0.11 \qquad\qquad (10.36)$$

where T is the average upper-layer temperature and $tan^{-1}(X)$ is in degrees. Notice that Equation (10.35) and (10.36) expresses the yield of CO instead of the normalized yield of CO.

Correlations for predicting CO_2, H_2O and O_2 yields during under-ventilated conditions are also suggested [43]:

$$\text{For } \phi > 1 \qquad\qquad f_{CO_2} = \frac{B_{CO_2}}{\phi} \qquad\qquad (10.37)$$

$$f_{H_2O} = \frac{B_{H_2O}}{\phi} \qquad\qquad (10.38)$$

$$f_{O_2} = \frac{B_{O_2}}{\phi} \qquad\qquad (10.39)$$

where B_{CO_2}, B_{H_2O} and B_{O_2} are yield coefficients for CO_2, H_2O and O_2, respectively. Suggested values of yield coefficients are given in Table 10.5.

PART 3

Table 10.5. Suggested values for yield coefficients, depending on the average upper-layer temperatures [**43**].

Yield coefficient	$T < 800\ K$	$T > 900\ K$
B_{CO_2}	0.77	0.88
B_{H_2O}	0.95	NA
B_{O_2}	0.92	0.97

Limits: Equations (10.27)-(10.39) are assuming a two-layer steady state situation [43]. These equations may not provide the *maximum* levels of incomplete combustion products produced in a fire [43]. Therefore, sensitivity analysis of the results is required.

10.3.1 Suggested approach

To summarize, yields of CO_2, H_2O, O_2 and soot have been found to be relatively constant for a given fuel under well-ventilated conditions [22]. However, yields of CO are also affected by the equivalence ratio during well-ventilated conditions. During under-ventilated conditions, all yields of species are strongly dependent on the equivalence ratio.

For predicting species produces in a real fire, Equations (10.27)-(10.39) have some shortcomings which require some treatment. Firstly, real fires are usually transient [22]. Secondly, the equations assume relatively pure fuels, which may not be the case for real fires [22]. Thirdly, smoke is often transported from the fire compartment to other rooms and corridors, resulting in air entrainment into the plume which might significant change the concentrations of the plume [22]. Thus, when predicting the species produces in a fire, the following approach is suggested:

- The smoke filling stage of a compartment fire results in a quasi-steady situation in the upper layer [43]. Hence, when predicting the yields of species, this stage could be treated as a steady state situation for slow growing fires or fires within a large enclosure.
- Equivalence ratios can be estimated by using Equation (10.24) or (10.25). For the fire growth, the heat release rate for when the equivalence ratio becomes bigger than one ($\phi > 1$) can be calculated and the fire is then assumed well-ventilated up to this heat release rate.
- During the initial stage of the fire (i.e. the growth stage), well-ventilated conditions ($\phi < 1$) can most often be assumed.
- Yields for well-ventilated conditions can be taken directly from experimentally derived yield data of the fuel in question, given that the fuel has been tested under such ventilation condition. Alternatively, the yield of species for well-ventilated conditions can be estimated by use of maximum theoretical yields and Equations (10.27),(10.32) and (10.33).

- Yield for under-ventilated conditions ($\phi > 1$) cannot be taken directly from tabulated values, since it is so dependent on the equivalence ratio. It is better to use Equations (10.32)-(10.39) to calculate yields for the equivalence ratio in question.

Tables for determine yields of species for a selection of fuels are given in Appendix A, Section A.3.3. More comprehensive tables are found in [58]

If information about yields of species cannot be found for the fuel in question, some suggested values are given in different references, see Table 10.6, Table 10.7 and Table 10.8 for examples.

Table 10.6. Suggested yield values for different types of occupancies [13].

Occupancy	Yield of species [kg/kg]	
	y_{CO}	y_{soot}
Offices, schools, hotels and nursing homes etcetera	0.01	0.03
Dwellings, shopping centres, entertainment centres	0.02	0.06

Table 10.7. Suggested yield values for different types of fires.

Fire type	Yield of species [kg/kg]			
	y_{CO}	y_{CO_2}	y_{O_2}	y_{soot}
Post-flashover, primary wooden fuels	0.3 [22]	1.1 [22]	0.9 [22]	-
Enclosure fires, involving materials such as computer consoles, TV monitors, electric cables, padded chairs.	0.2 [22]	1.5 [22]	1.8 [22]	-
Smouldering fire	0.50 [13]	-	-	0.15 [13]

Table 10.8. Suggested yield of soot for different types of material [17]. Yields are for well-ventilated conditions [17].

Material	Yield of soot, y_{soot} [kg/kg]	
	Flaming	Smouldering
Cellulosic	<0.01-0.025	0.01-0.17
Plastics	<0.01-0.17	<0.01-0.19

11   Ventilation

As been seen in Section 10.2 and 10.3, the available ventilation has significant impact on parameters such as heat release rate and yields of combustion products. If the burning fire is likely to change the initial conditions in the fire compartment, this must be taken under consideration.

During the fire growth, the most significant change in ventilation condition is probably caused by activation of smoke control system. The main objective of smoke management systems is to remove heat and smoke from the fire compartment [18]. This can be done by different smoke management techniques [18]:

- natural ventilation;
- zone pressurisation;
- extraction;
- dilution and
- containment.

> Time of activation for smoke management systems is easiest calculated by using computer program Detact-QS or Detact-T2, available at http://www.nist.gov/bfrl/software.cfm.

For the fuel-controlled fire, activation of a smoke management system will have small impact on the burning behaviour of the fuel. If there is a hot gas layer radiating at the burning items, activation of a smoke management system that extracts the hot gases could somewhat decrease the burning rate of the fuel. Free-burning conditions of the burning item should then be assumed.

For the ventilation-controlled fire, activation of smoke management system will have a bigger impact on the burning behaviour since the air mass flow rate into the compartment changes. Equations (10.11)-(10.18) cannot be used directly under such conditions.

The ventilation can also be changed due to doors opening or closing. For example, doors can be opened during the fire due to people evacuating. On the other hand, doors can be closed during the fire due to the activation of smoke management systems, as mentioned above.
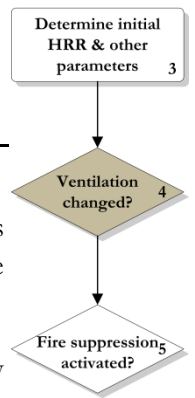
12   Fire suppression

Perhaps the most obvious factor affecting initial fire characteristics is the activation of a fire suppression system. The suppression system could be an automatic water sprinkler system, fire fighting activities by the occupants or intervention from the fire service. Typically, most fire suppression systems are designed to work at the fire growth stage [17]. Hence, only interventions from the fire service are reasonable to expect after flashover. Activation of a fire suppression system may be assumed to cause different effects on fire growth [17]:

- the fire is extinguished and the heat release rate decreases to zero after some decreasing time, see Figure 12.1(a) and (b);
- the fire is controlled by the extinguishing agent; the increase of heat release rate is stopped and the fire continues to burn at a constant rate, see Figure 12.1 (c);
- the extinguishing agent fails to stop the growing fire, see Figure 12.1 (d). The fire may grow more slowly after the activation and there can be a sudden drop in heat release rate; but fire growth is not completely stopped.
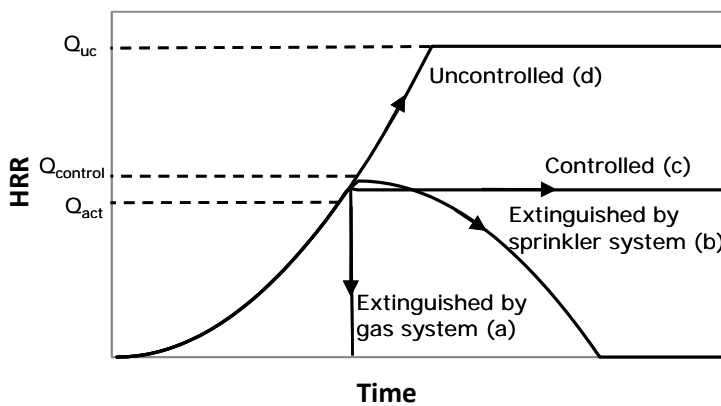
Figure 12.1. Schematic figure of the assumed effect on heat release rate for different types of suppression. Based on [17].
Q_{uc} = heat release rate for the fully developed, uncontrolled fire.
$Q_{control}$ = heat release rate at which the fire can be controlled.
Q_{act} = heat release rate when the suppression system activates.

The effect of the fire suppression system on fire growth depends on several factors [17]:

- the fire size at the time when the suppression system activates;
- type of suppression system;
- the geometry of the protected space and
- to what extent the extinguishing agent is shielded from the burning fuel.

For the selection of the design fire, the effect of fire suppression systems must be determined. Effect on the fire and possible failure of fire suppression systems could have been decided already in the design fire scenario. For example, it is common to analyse fire scenarios were the occupants are assumed to not be able to extinguish the fire. Thus, the fire scenarios where the occupants will be able to extinguishing the fire are not considered to represent any fire scenario cluster (i.e. the fire scenario is not estimating the average consequence of the fire scenario cluster). Therefore, unless there is very good reason to believe the occupants will always engage in effective fire fighting

activities (e.g. trained industry fire services); the occupants are assumed to not affect the initial fire characteristics [18]. Furthermore, interventions by fire service are often assumed not to affect the fire growth in life safety analysis, unless an appropriate model for fire service interventions and effectiveness is used [5]. Were such a model is used, a probabilistic analyse is considered to be required. Since this report focus on deterministic analyses of the life safety design, interventions by fire service is simply assumed to not affect the initial fire characteristics.

> In fire safety analyses, fire fighting activities by occupants and interventions by the fire service can be assumed to *not* affect the initial fire characteristics of the design fire scenario.

Automatic suppression systems affect the early stages of fire growth more likely than fire service interventions and fire fighting by occupants. Therefore, it is more reasonable to consider an automatic suppression system to affect the initial fire growth. However, the probability of system failure must also be considered [17]. A very conservative approach is simple assuming the automatic suppression system to have no effect on the fire growth [18]. A better way of assessing the effect of automatic suppression system is to analyse one design fire scenario with automatic suppression system failure and estimate the actual effect of the suppression system in all the other fire scenarios. The following sections describe methods and approaches for quantifying the effect of automatic suppression systems.

> For automatic suppression system, the effect on the initial fire growth should be quantified using methods and approaches described in the following sections. However, at least one design fire scenario should assume the automatic suppression system to have no effect on the fire growth.

The first thing to consider when estimating the effect of an automatic suppression system is the time of activation. It is easiest calculated by the computer program Detact-QS or Detact-T2, both which are available for free download at http://www.nist.gov/bfrl/software.cfm. It should be assumed that sprinklers and heat detectors will not be activated by a smouldering fire, since it produces very little heat [17]. When time of activation has been determined, the heat release rate at that time can be used to assess the effect of the automatic suppression system. Although the activation of an automatic suppression system affects the yield of species due to disturbance of the combustion process, the magnitude of this is far too complex to estimate. Hence, the automatic suppression system is only assumed to affect the heat release rate of the fire.

> Time of activation for automatic suppression systems is easiest calculated by using computer program Detact-QS or Detact-T2, available at http://www.nist.gov/bfrl/software.cfm. Sprinklers and heat detectors should be assumed not to be activated by smouldering fires [17]. The heat release rate at that time of activation can be used to assess the effect of the automatic suppression system.

12.1 Automatic water sprinkler systems

The most common automatic suppression system is the water sprinkler [45]. Water sprinkler systems can be designed for either controlling the fire or extinguish the fire. A controlling water sprinkler system is designed for suppressing the fire and limiting the heat release rate to reduce fire damages [45]. An extinguishing water sprinkler system is designed to operate at an early stage where the fire can be assured to be extinguished [45]. Early Suppression Fast Response (ESFR) sprinklers have been developed to make possible early activation and large water spray densities [45].

Several correlations for expressing the suppression by water sprinklers have been developed from fire experiments. There are also many rules of thumb for quantifying the effect of water sprinklers, based on experiences of water sprinkler in real fires. One such rule of thumb is the assumption that the water sprinkler will control the fire to a constant burning rate after sprinkler activation. This is somewhat a conservative assumption [20].

PART 3

> A conservative assumption is that a water sprinkler system, designed after applicable codes and standards, only prevents further fire growth after activation. Thus, the heat release rate is assumed to remain constant after activation, see Figure 12.1 (c).

Madrzykowski and Vettori [46] developed a correlation for estimating the effect of water sprinklers in office furnishings:

$$\dot{Q}(t) = \dot{Q}_{act} \cdot e^{-0.023\Delta t} \tag{12.1}$$

where:

$\dot{Q}(t)$ = heat release rate at time t [kW]

$\dot{Q}_{act}$ = heat release rate at time of sprinkler activation [kW]

Δt = time after sprinkler activation, $t - t_{act}$ [s]

Limits: Equation (12.1) is based on open-burning experiments of office furnishings [46]. The equation provides an expected upper-bound for the heat release rate at a given time after sprinkler activation for fires that are not heavily shielded [46]. The sprinkler spray density is assumed to be 0.07 mm/s or greater [46]. Thus, Equation (12.1) should only be used for fires not shielded from the sprinkler and when the sprinkler spray density is 0.07 mm/s or greater [46]

Equation (12.1) do not account for variations in water spray density. Further refinement of the correlation was done by Evans [47], to take account for variations in water spray density:

$$\dot{Q}(t) = \dot{Q}_{act} \cdot e^{\left(\frac{-\Delta t}{3.0(\dot{w}'')^{-1.85}}\right)} \tag{12.2}$$

where:

$\dot{w}''$ = water spray density [mm/s]

Limits: Equation (12.2) can be used for estimating the reduction in heat release rate of unshielded furnishing fires during water sprinkler suppression [47]. The model is based on experiments with fully involved cribs, though it does not consider the possibility of the fire to grow for some time after sprinkler activation [48].

Required water spray density for different classification of occupancies is given in Appendix A, Section A.4.1. Equation (12.1) and Equation (12.2) has been developed from fire experiments with limited heat release rate. Typical heat release rates at time of sprinkler activation were about 500 kW, with some heat release rates up to approximately 1400 kW. If the fire has grown too big, there is a possibility that the sprinkler cannot suppress the fire according to the estimates done by the correlations. Since the correlations are considered to be conservative predictions, they can be assumed to be applicable at $\dot{Q}_{act}$ slightly greater than 1400 kW.

Nystedt [2] suggest the following approach when considering activation of water sprinkler systems:

If $\dot{Q}_{act} \leq 5.0 \; MW$:

- after sprinkler activation, the heat release rate can be assumed constant for one minute, equal to $\dot{Q}_{act}$;
- then the heat release rate can be assumed to decrease to 1/3 of $\dot{Q}_{act}$;
- the heat release rate can then be assumed to be 1/3 of $\dot{Q}_{act}$ for the rest of the fire progress, considering that the sprinkler system might not completely extinguish the fire.

If $\dot{Q}_{act} > 5.0 \; MW$:

- after sprinkler activation, the heat release rate can be assumed constant, equal to $\dot{Q}_{act}$ for the rest of the fire progress.

12.1.1 Suggested approach

If the water sprinkler system is designed according to applicable codes and standards, the following approach is suggested to estimate the effect of the sprinkler:

Taken the suggested value in [2], for fires with $\dot{Q}_{act} \leq 5.0$ MW the heat release rate can be assumed to decrease after activation of the sprinkler system. For fires with $\dot{Q}_{act} > 5.0 \; MW$ the heat release rate can be assumed to be constant after activation of the sprinkler system.

For fires in light-hazard occupancies or fires with office furnishings (e.g. desks, office chairs, computers, books, papers) Equation (12.1) or Equation (12.2) can be used to estimate the reduction of heat release rate after activation. If the water spray density is known, Equation (12.2) can be used; otherwise Equation (12.1) can be used. Assessments must also be done whether the fire is likely to be shielded from the activated water sprinkler. For shielded fires (e.g. burning items under a desk), fire spread to other items is unlikely once the sprinkler is activated. This has been observed in fire experiments as well [46]. Thus, the heat release rate for shielded fires can be assumed constant after activation of water sprinklers.

If the fire scenario not mainly includes office furnishings or if the occupancy not classifies as light-hazard, the heat release rate should then be hold constant for one minute after activation. After one minute the heat release rate can be decreased to 1/3 of $\dot{Q}_{act}$.

12.2 Gaseous fire suppression systems

Gaseous fire suppression systems are often designed to completely extinguishing the fire, although the fire can re-emerge when the enclosure is re-opened [45]. Therefore, the design concentration of the gaseous extinguishing agent must be hold for a certain time allowing pre-actions against re-emerging fires.

Since the gaseous fire suppression system is designed for the specific enclosure, it can be assumed that the fire will be completely extinguished once design concentration has been reached [5,13]. Notice that there is some discharge time between activation and when design concentration has been reached. Thus, the heat release rate can continue to grow after activation until design concentration has been reached. Furthermore, gaseous fire suppression systems is often not suitable for life safety protection, since the design concentration of the gaseous extinguishing agent is either directly lethal or it reduces the oxygen level to lethal concentrations.

12.3 Other suppression systems

The effect of other suppression systems should be based on their design specifications [18]. Suppression systems designed according to applicable codes and standards can be assumed to have one of the possible effects in Figure 12.1. The factors mentioned in the beginning of this chapter should be considered when estimating the effect of other suppression systems.

PART 3

Fire suppression₅
activated?

Flashover
occured? 6

Fuel becoming 7
consumed?

PART 3

13 Flashover

Since flashover, by definition [5], is described as a rapid transition from a local fire to the involvement of all combustible materials within an enclosure, it is common to assume that the heat release rate after flashover instantaneously increases to the peak heat release rate [18]. Following flashover, the fire is described as fully developed, having a constant heat release rate determined either by the fuel or the ventilation available [5]. Two different correlations can be used for predicting the heat release rate needed for flashover to occur, named Alternative 1 and 2 below.

> After flashover, the heat release rate is often assumed to instantaneously increase to the peak heat release rate determined either by the fuel or the ventilation available.

Alternative 1

If the thermal properties of the linings are to be considered, the following equation by McCaffrey et. al [49] may be used:

$$\dot{Q}_{fo} = 610(h_k A_T A_o \sqrt{H_o})^{1/2} \tag{13.1}$$

where:

$\dot{Q}_{fo}$ = heat release rate at flashover [kW]
h_k = effective heat transfer coefficient [kW/m²K]
A_T = effective surface area for heat transfer (i.e. area of walls, floor and ceiling), excluding the ventilation openings [m²]
A_o = area of ventilation openings [m²]
H_o = height of ventilation openings [m]

In Equation (13.1), flashover is assumed to occur at a uniform upper-layer temperature rise of 500°C. The effective heat transfer coefficient in Equation (13.1) can be approximated by [49]:

$$\text{For } t < t_p \qquad\qquad h_k = \sqrt{\frac{k\rho c}{t}} \tag{13.2}$$

$$\text{For } t \geq t_p \qquad\qquad h_k = \frac{k}{\delta} \tag{13.3}$$

where:

t = time [s]
t_p = thermal penetration time [s]
k = thermal conductivity of the enclosure boundaries [kW/mK]
ρ = density of the enclosure boundaries [kg/m³]
c = specific heat capacity of the enclosure boundaries [kJ/kgK]
δ = thickness of the enclosure boundaries [m]

The thermal penetration time, t_p, is the time at which the conduction can be considered to approach stationary heat conduction [22]. This time is given by [22]:

$$t_p = \frac{\delta^2}{4\alpha_d} \tag{13.4}$$

where:

α_d = thermal diffusivity [m²/s]

55
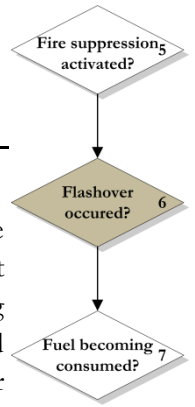
α_d is given by [22]:

$$\alpha_d = \frac{k}{\rho c} \tag{13.5}$$

For most normal compartments, the thermal penetration time will be significant longer than the time for which it is likely for flashover to occur [22]. Interventions from the fire service will probably also happen earlier than the thermal penetration time [22].

Alternative 2
Thomas [50] developed an equation for calculating the heat release rate required to cause flashover, based on the assumption that flashover occurs at a uniform upper-layer temperature rise of 600°C:

$$\dot{Q}_{fo} = 7.8A_t + 378A_o\sqrt{H_o} \tag{13.6}$$

where:
$\dot{Q}_{fo}$ = heat release rate at flashover [kW]
A_t = total surface area of the enclosure, including ventilation openings [m²]
A_o = area of ventilation openings [m²]
H_o = height of ventilation openings [m]

Limits: Equation (13.1) and (13.6) are only valid when there is a two-dimensional flow in the vertical ventilation opening, i.e. the equations are not valid for the smoke-filling phase [17]. The equations are not applicable for ventilation-controlled fires [17]. Special care has to be taken [17]:

1) when the enclosure has more than one opening;
2) when the enclosure are very well-insulated or in other situations when $h_k \rightarrow 0$;
3) when fire growth is extremely fast;
4) for fires in corners or close to walls and
5) for complicated room geometries.

The enclosures in the experiments for obtaining the correlation in Equation (13.1) were in the range of 0.3 m to 2.7 m high by 0.14 m² to 12 m² floor area [49]. The openings were in the range of 0.03 m² to 1.9 m² [49]. Equation (13.1) should only be used for enclosures with similar geometry and openings.

13.1.1 Suggested approach

When estimating the possibility for a flashover to occur, the heat release rate required for flashover should be compared against the peak heat release rate calculated in Section 10.2.2. If $\dot{Q}_{fo} < \dot{Q}_{peak}$, flashover will most certainly occur. When the fire has grown to $\dot{Q}_{fo}$, the heat release rate should instantaneously be increased to the peak heat release rate.
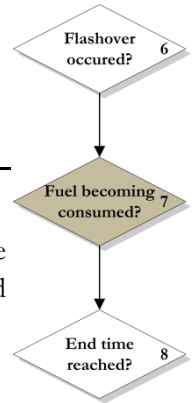
14   Fuel becoming consumed

When most of the fuel has been consumed, the heat release rate decreases [5]. The fire is said to be in the decay stage. Decay can be assumed to begin when 80 percent of the fuel has been consumed [18,20,23]. The heat release rate may then be assumed to decay at [18,23]:

- a rate determined experimentally;
- a linear rate;
- a rate inverse of the fire growth rate or
- any rate that can be justified.

The total energy released for combustion of all combustible materials in an enclosure is denoted the fire load, given by

$$E_{load} = \sum m_i \Delta H_{eff,i} \tag{14.1}$$

where:

E_{load} = fire load, i.e. the total energy available for burning of the fuel [kJ]
m_i = mass of fuel i [kg]
$\Delta H_{eff,i}$ = effective heat of combustion of fuel i [kJ/kg]

Thus, the decay stage is assumed to begin when 80 percent of E_{load} has been consumed. ΔH_{eff} is sometimes named the effective calorific value or the chemical heat of combustion. The effective heat of combustion is related to the complete heat of combustion according to [22]:

$$\Delta H_{eff} = \chi \Delta H_c \tag{14.2}$$

where:

χ = combustion efficiency [-]
ΔH_c = complete heat of combustion [kJ/kg]

Furthermore, the effective heat of combustion can be calculated by [17]:

$$\Delta H_{eff} = \Delta H_c(1 - 0.001M) - 0.025M \tag{14.3}$$

where:

M = moisture content of fuel [% per dry mass]

ΔH_c for common fuels are given in Appendix A, Section A.5.1.

> The decay stage can be assumed to begin when 80 percent of the fuel has been consumed [18,20,23], i.e. 80 percent of E_{load} has been consumed.

The fire load density is one common way of expressing the fire load per unit area [22]. In some countries, the fire load density is given per unit floor area [22]. In other countries, the fire load density is instead given per total surface area of the enclosure, A_t. Hence, these two fire load densities are given by:

$$E''_{load,f} = \frac{E_{load}}{A_{floor}}$$ (14.4)

$$E''_{load,t} = \frac{E_{load}}{A_t}$$ (14.5)

where:

$E''_{load,f}$ = fire load density, i.e. the fire load per unit floor area [kJ/m²]
$E''_{load,t}$ = fire load density, i.e. the fire load per total surface area of enclosure [kJ/m²]
A_{floor} = floor area [m²]
A_t = total surface area of the enclosure, including ventilation openings [m²]

The fire load density for different occupancies is given in Appendix A, Section A.5.2. The energy released from a fire between time t_i and t_j can be calculated by:

$$E = \int_{t_i}^{t_j} \dot{Q}(t)\, dt$$ (14.6)

where:

E = energy released in fire [kJ]
$\dot{Q}(t)$ = heat release rate at time t [kW]
t_i, t_j = time when the fire releases energy [s]

The decay characteristics (i.e. duration time and rate of decay) should preferably be determined by analysing real fire test of the burning products. Decay characteristics from fire tests of products with similar materials can also be used to assess the decay characteristics of the fuel in question. Assessment of the best decay rate to describe the decay in the fire tests should then be made (e.g. linear, exponential).

Natori et. al [33] calculates the exponential fire decay rate according to:

$$\dot{Q}(t) = \alpha_{decay}\left(t_{decay} - t\right)^2$$ (14.7)

where:

$\dot{Q}(t)$ = heat release rate at time t [kW]
α_{decay} = exponential decay rate coefficient [kW/s²]
t_{decay} = time when decay ends [s]
t = time [s]

Here, α_{decay} is given by:

$$\alpha_{decay} = \frac{\dot{Q}_{peak}}{\left(t_{decay} - t_{max}\right)^2}$$ (14.8)

where:

$\dot{Q}_{peak}$ = peak heat release rate [kW]
t_{max} = time when decay starts [s]

For an example of heat release rate from experiment together with the approximated curve, following the symbols given above, see Figure 14.1.
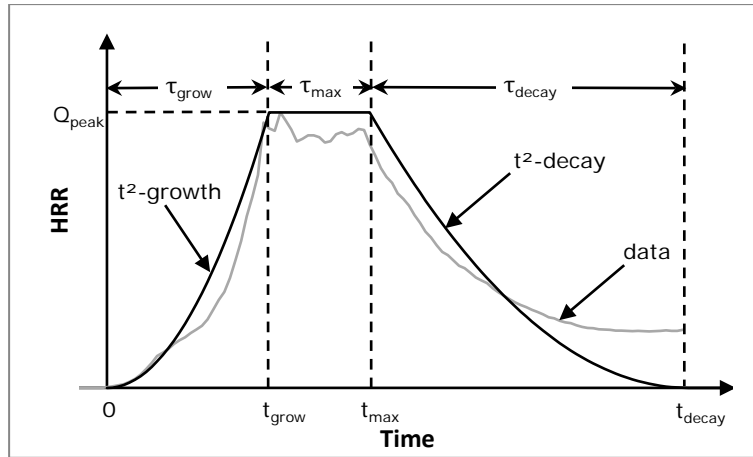
Figure 14.1. HRR data from experiment and approximated curve with t²-growth, steady burning and t²-decay. Based on [33].

For linear decay, the following expression can be used:

$$\dot{Q}(t) = C_{decay}(t_{decay} - t) \tag{14.9}$$

where:

$\dot{Q}(t)$ = heat release rate at time t [kW]
C_{decay} = linear decay rate coefficient [kW/s]
t = time [s]

Here, C_{decay} is given by:

$$C_{decay} = \frac{\dot{Q}_{peak}}{(t_{decay} - t_{max})} \tag{14.10}$$

where:

$\dot{Q}_{peak}$ = peak heat release rate [kW]
t_{decay} = time when decay ends [s]
t_{max} = time when decay starts [s]

Equation (14.7)-(14.10) can be useful for describing the decay stage of the fire, for either a t²-decay or a linear decay. If experimental data of the decay stage is not available, a linear decrease rate can be assumed [5].

The design fire scenario most often includes several different burning products, thus it is rare to find all the burning products in one fire test. Assessing the overall decay rate for all the combustibles can sometimes be difficult. A simple, conservative approach is to assume a linear decay rate so the remaining 20 percent of the fuel has been completely burned when decay stage is ended.

Total energy release in a fire is often calculated by summing the energy released in the fire growth stage, the fully developed stage and the decay stage:

$$E_b = \sum_{i=1}^{n} E_i \tag{14.11}$$

where:

E_i = energy released for stage i [kJ]

For the heat release rate curve showed in Figure 14.2, the total energy is given by adding the separate energies E_1, E_2 and E_3.
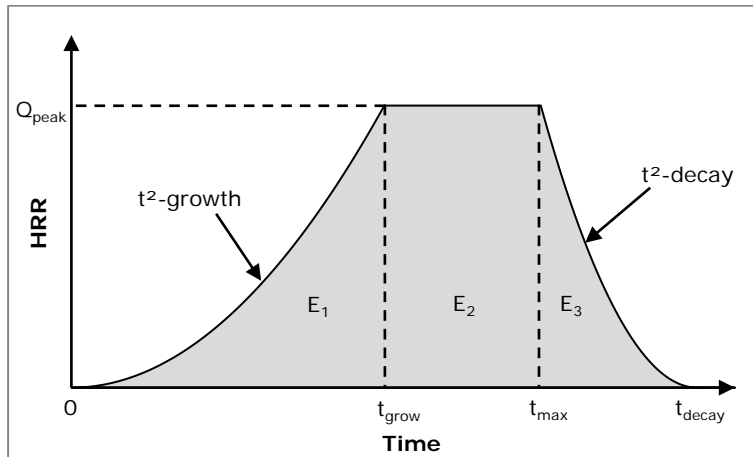
Figure 14.2. Heat release rate curve were the energy released is the area under the curve, i.e. $E_b = E_1 + E_2 + E_3$.

Following the symbols used in Figure 14.2, the energy released in the different stage is given by Equations (14.12)-(14.14).

The energy released during the fire growth of a t^2-fire is given by:

$$E_1 = \int_0^{t_{grow}} \dot{Q}(t)\, dt = \left[\frac{\alpha t^3}{3}\right]_0^{t_{grow}} = \frac{\alpha (t_{grow})^3}{3} \tag{14.12}$$

The energy released during the fully developed stage is given by:

$$E_2 = \int_{t_{grow}}^{t_{max}} \dot{Q}(t)\, dt = \left[\dot{Q}_{peak}\right]_{t_{grow}}^{t_{max}} = \dot{Q}_{peak}(t_{max} - t_{grow}) \tag{14.13}$$

The energy released during the decay stage for a t^2-decay rate is given by:

$$E_3 = \int_{t_{max}}^{t_{decay}} \dot{Q}(t)\, dt = \left[\frac{\alpha_{decay} t^3}{3}\right]_{t_{max}}^{t_{decay}} = \alpha_{decay}\left(\frac{(t_{decay})^3}{3} - \frac{(t_{max})^3}{3}\right) \tag{14.14}$$

Where a linear decay rate has been chosen, the energy released during the decay stage is instead given by:

$$E = \int_{t_{max}}^{t_{decay}} \dot{Q}(t)\, dt = \frac{\dot{Q}_{peak}(t_{decay} - t_{max})}{2} \tag{14.15}$$

15   End time

The final step in the process is to determine whether the end time has been reached or not. The end time has been reached when [18]:

- all the fuel has been consumed;
- the end time determined in the design fire scenario has been reached or
- the fire protection engineer judge that sufficiently long time period of the design fire has been determined to evaluate the trial design, on account of the design objective.

If the end time has not been reached, the next iteration of the analysis of factors affecting the initial design fire is done until the end time has been reached [18].

When the design fire has been selected, it is important to perform a sensitivity analysis of the parameters selected in the design fire. Typically, values such as fire growth coefficients, peak heat release rates, yields of combustion species and fire loads should be changed in the sensitivity analysis to find parameters that significant affect the subsequent fire safety evaluation.

PART 3
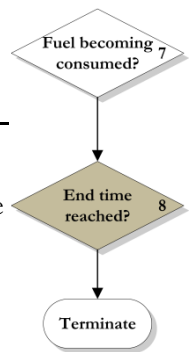
PART 4
Worked example

16   Worked example

This chapter includes a worked example of selecting a design fire by the step-by-step working method presented in Chapter 3. The example is for selecting design fires that can be used for evaluating the fire safety design of a fictive hotel. The fire safety goals are life safety and property protection. The fire safety goals are further refined into two fire safety objectives, the first is that people should be able to evacuate before untenable conditions occur in hotel rooms or hotel corridor and the second is that the fire should not spread from the room of origin. One of the design fire scenarios that were decided in the preceding analysis was a fire scenario in one of the hotel rooms, and the worked example will be limited to the selection of design fires in the hotel room. The trial design that also has been developed suggests a water sprinkler system in both the public areas and the guest rooms. However, for the design fire scenario in the hotel room, design fires for both normal sprinkler operation and sprinkler failure should be selected.

16.1 Fire initiation

Identification of likely ignition sources and starting objects can here be done by analysing fire statistics of structure fires in hotel and motels in the U.S.; see Table A.3, Table A.4 and Table A.7 in Appendix A. Here, the U.S. statistics have been assumed to be applicable for the country in question. The most common igniting heat source which causes civilian deaths and injuries is smoking materials. Confined cooking fire is the by far most common fire, but this is unlikely in the design fire scenario being analysed in the worked example (i.e. the fire scenario in the hotel room). Unclassified heat from powered equipment is the second most common for both the cause of fires and the cause of civilian injuries. Arson is one ignition source that cannot be ignored for public buildings [17]; see for example Table A.2 in Appendix A.

Mattresses and beddings are the most common first ignited items to cause civilian deaths and injuries. Appliance housing or casing together with rubbish, trash or waste is also starting objects that cause both many fires and civilian injuries. Rubbish, trash or waste is somewhat more likely than appliance housing or casing in the fire scenario being analysed.

Based on the above, the ignition source for the design fire scenario in the hotel room can be assumed to be some smoking materials (e.g. a burning cigarette) or powered equipment which ignites the mattress and bedding in the room. A fire in the mattress and bedding is assumed to also represent the potential fire hazard from a fire in rubbish, trash or waste. Arson could also be assumed in the hotel room, where liquid fuel (e.g. petrol) works as an accelerator for the ignition of the fire.

16.2 Schematic design fire

The identified starting object has potential of both flaming and smouldering combustion. Ignition of the mattress and bedding by a cigarette could lead to a smouldering fire, although ignition from the burning cigarette could, as well as the powered equipment, also lead to a flaming fire. For an arson fire, the use of an accelerator would enhance the possibility for a flaming combustion. However, the two types of fires result in essentially different hazards, therefore should design fires of both flaming and smouldering combustion be selected in the hotel room.
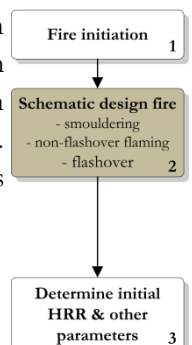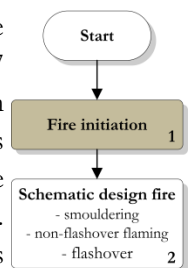
The heat release rate required for flashover, $\dot{Q}_{fo}$, can be calculated by Equation (13.1) or (13.6). The dimensions of the hotel room being analysed in the fire scenario was identified as 4 x 5 x 2.4 m³ (Width x Length x Height) and the walls and ceiling to be made mainly of concrete, thus is $k\rho c$ approximately 2 kWs/m⁴k² [22].

By assuming characteristic time for flashover to be five minutes, Equation (13.2) yields:

$$h_k = \sqrt{\frac{2}{300}} \approx 0.082 \; kW/m^2K$$

Since the thermal properties of the enclosure are known, Equation (13.1) can be used for calculating the heat release rate required for flashover. The door to the hotel room is assumed to be left open after evacuation and thus become the main ventilation opening (i.e. comfort ventilation and other ventilation openings are negligible). The dimension of the door was identified as 0.9 x 2.1 m² (Width x Height). However, if flashover occurs, windows can be assumed to break and to be fully open. One window was suggested in the trial design for each hotel room and each window was identified as 1.2 m wide by 1.5 m high. Hence, following flashover the available opening will consist of one door with dimension 0.9 m wide by 2.1 m high and one window with dimension 1.2 m wide by 1.5 m high. Weighted values of A_o and H_o can be determined by Figure 10.2 and Equation (10.13)-(10.14) [22]:

$$A_o = A_{door} + A_{window} = 0.9 \cdot 2.1 + 1.2 \cdot 1.5 \approx 3.7 \; m^2$$

$$H_o = \frac{A_{door} \cdot H_{door} + A_{window} \cdot H_{window}}{A_o} = \frac{1.89 \cdot 2.1 + 1.8 \cdot 1.5}{3.7} \approx 1.8 \; m$$

Therefore, the heat release rate required for flashover is:

$$\dot{Q}_{fo} = 610 \cdot \left(0.082 \cdot [(2 \cdot (4 \cdot 5 + 4 \cdot 2.4 + 5 \cdot 2.4)) - 3.7] \cdot 3.7 \cdot \sqrt{1.8}\right)^{1/2} = 3.5 \; MW$$

16.3   Initial fire characteristics

The initial heat release rate and other parameters are determined for the hotel room in Section 16.3.1-16.3.3.

16.3.1 Flaming combustion

Three heat release rate curves for mattresses were found at SP Fire Database [51] and three in Särdqvist [37], see Figure 16.1. The three named CBUF 1:21-1:23 were measured in furniture full-scale calorimeter and the other three were measured in room calorimeter.

Schematic design fire
- smouldering
- non-flashover flaming
- flashover   2

Determine initial
HRR & other
parameters   3

Ventilation   4
changed?
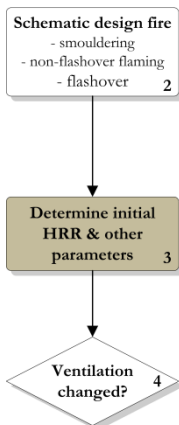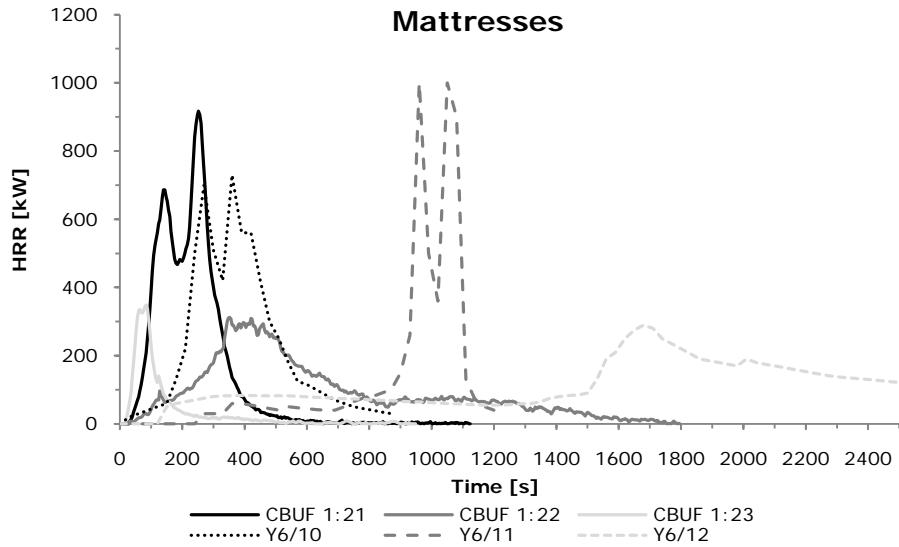
Figure 16.1. Heat release rates for different mattresses. CBUF 1:21-1:23 were measured in Furniture full-scale calorimeter and Y6/10-12 were measured in room calorimeter. Data taken from [37,51]

The difference between the room calorimeter and the furniture calorimeter is assumed to be negligible for the fire growth stage. However, the peak heat release rate can be assumed to be somewhat affected by room effects since the hotel room is relatively small and a hot gas layer probably would be present.

To determine the fire growth rate for an unspecified mattress and bedding, the fire growth in the fire tests must first be approximated by t²-growth curves; see Figure 16.2.
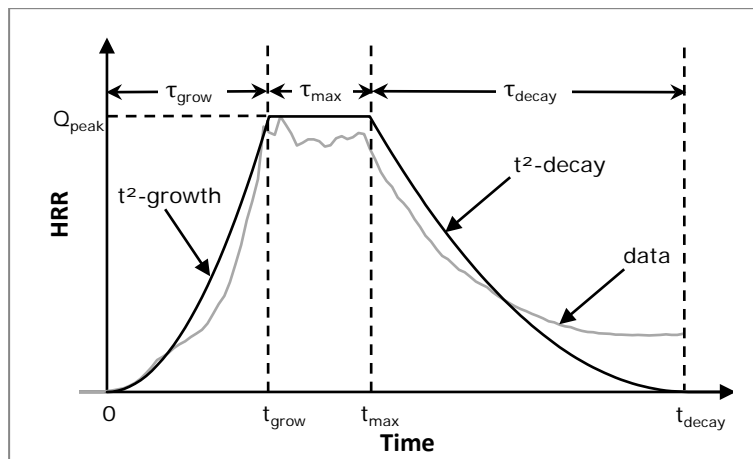
Figure 16.2. HRR data from experiment and approximated curve with t²-growth, steady burning and t²-decay. Based on [33].

The fire growth coefficient, α, was determined by first collecting the fire growth time, τ_{grow}, and the heat release rate at that time for each fire test, see Table 16.1.

Table 16.1. Time for fire growth and the heat release rate at time t_{grow} for the fire tests showed in Figure 16.1. The calculated fire growth coefficients are also given.

Fire test	τ_{grow} [s]	$\dot{Q}_{peak,1}$ [kW]	α [kW/s²]
CBUF 1:21	144	687	0.033
CBUF 1:22	352	313	0.003
CBUF 1:23	64	336	0.082
Y6/10	270	700	0.010
Y6/11	960	1000	0.001
Y6/12	1680	290	1E-4
		Average (std. deviation)	0.021 (0.032)

The fire growth coefficient for each curve was calculated using Equation (10.2). As mentioned in Section 7.4.1, choosing one value from a set of test data can be done in different ways. One way of choosing a representative value is to add one standard deviation to the average value [33], thus the representative fire growth coefficient for the mattresses is then $0.021 + 0.032 = 0.054 \, kW/s^2$. Another approach is to choose the 95-percentile, which can be calculated in different ways. The easiest way is to use a linear interpolation between the closest rank numbers. This is done by sorting the values from the lowest to the highest and then calculating the rank number N: $N = 0.95 \cdot n = 0.95 \cdot 6 = 5.7$ where n is the number of data values. Hence, the 95-percentile for the fire growth coefficient is between the 5th and 6th value and can be calculated by interpolation: $0.033 + (5.7 - 5)(0.082 - 0.033) = 0.067 \, kW/s^2$. However, this method only accounts for the two values being interpolated between. Another way of calculating the 95-percentile is to assume a normal distribution and calculating the 95-percentile by: $\bar{x} \pm z \cdot \frac{s}{\sqrt{n}}$ where $\bar{x}$ is the average value, $z = 1.96$ (for the 95-percentile) and s is the standard deviation. The 95-percentile is then $0.021 + 1.96 \cdot \frac{0.032}{\sqrt{6}} = 0.047 \, kW/s^2$. A more conservative approach is to use the highest value and the fire growth coefficient would then be 0.082 kW/s².

The examples above show that different approaches for choosing the representative value give different values. The different approaches yield values for the fire growth coefficient between 0.047-0.082 kW/s². Therefore, it is important for the fire protection engineer to consider what value is best describing the test data set and the value used should represent the worst credible case.

Based on the test data, the fire growth coefficient 0.054 kW/s² was here considered to best represent an unspecified mattress. The fire growth curve for the fire growth coefficient 0.054 kW/s² is shown in Figure 16.3 together with the experimental data.
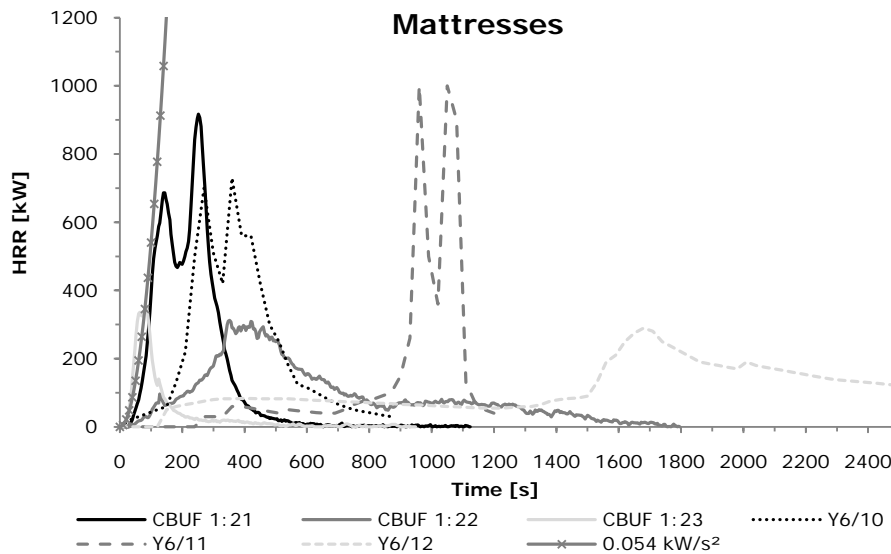
Figure 16.3. Comparison between the fire growth curve for the fire growth coefficient 0.054 kW/s²
and the experimental data.

Peak heat release rates for different mattresses and testing methods were found in [21]; see
Table A.10 and Table A.11 in Appendix A. The full-scale peak heat release rates ranges from 17 kW
up to 2720 kW. The peak heat release rates from Table A.10 and Table A.11 were used as data for
determine the fuel-controlled peak heat release rate. The values below 100 kW were excluded since
they are assumed to represent non-propagating fires, which is not the case in the fire scenario. The
peak heat release rates measured for the mattresses in Figure 16.1 was also added to the data,
resulting in a total of 15 data values for peak heat release rates, see Table 16.2.

Table 16.2 Peak heat release rate for different fire tests of mattresses. Average value and standard
deviation for the peak heat release rate data is also given.

Fire test	Padding material	Peak HRR [kW]
CBUF 1:21	-	917
CBUF 1:22	-	313
CBUF 1:23	-	348
Y6/10	-	730
Y6/11	-	1 000
Y6/12	-	290
-	**Latex foam**	2 720
-	**Polyurethane foam**	2 630
-	**Polyurethane foam**	1 620
-	**Polyurethane foam**	1 580
-	**Polyurethane foam**	760
-	**Polyurethane foam**	1 716
-	**Melamine-type PUR/ cotton batting/ polyester fibre pad**	547
-	**Polyurethane foam/ cotton batting/ polyester fibre pad**	380
-	**Polyurethane foam/ polyester fibre pad**	335
	Average (std. deviation)	1 059 (818)

Adding one standard deviation to the average value yields in a peak heat release rate of 1877 kW. Calculating the 95-percentile with linear interpolation between the closest rank yields instead of a peak heat release rate of 2653 kW. Calculating the 95-percentile by assuming a normal distribution yields a peak heat release rate of 1473 kW. The highest peak heat release rate in the data set was 2720 kW. Hence, the different approaches for choosing representative values from a test data set yield values between 1473 kW and 2720 kW. Here, the 2653 kW value was considered to best represent the peak heat release rate for an unspecified mattress.

Since it is likely for other items to ignite and considerable contribute to the fire growth, flame spread to other items must be analysed. First, analysis should be made of what combustible items are reasonable to found in the design fire scenario. In a hotel room, there is often a night stand on each side of the bed. Furthermore, there are also often wooden chest of drawers, wardrobes, tables, chairs and TVs in a hotel room. By using Equation (10.4), (10.5) or (10.7), assessment can be made for the heat release rate required for igniting objects at different distances. Based on Table A.5, the minimum radiant flux for piloted ignition for wood and plastics can be assumed to be 10 kW/m². The radiative fraction for mattresses is unknown, thus is a conservative value of 0.3 chosen [26].

Since the night stands are placed closest to the mattress, they can be assumed to be the first adjacent items to be ignited. By assuming a radial distance of 1.0 m from centre of the flame to the night stand gives, from Equation (10.4), the heat release rate required for igniting the night stands:

$$\dot{Q} = \frac{\dot{q}_r'' 4\pi R^2}{\chi_r} = \frac{10 \cdot 4 \cdot \pi \cdot 1^2}{0.3} \approx 420 \; kW$$

This means that the radiative heat flux from the mattress to the night stands reaches 10 kW/m² when the heat release rate from the mattress is 420 kW. The night stands are assumed to instantaneously ignite when the radiative heat flux reaches 10 kW/m², which can be considered to be a conservative assumption. The time of ignition is then:

$$t = \sqrt{\frac{420}{0.054}} \approx 90 \; s$$

Hence, the fire growth rate increases after 1.5 minutes due to the ignition of the night stands. The total heat release rate is after 1.5 minutes calculated by adding the heat release rate from the night stands to the heat release rate from the mattress. Values for the fire growth rate and the heat release rate per unit area (HRRPUA) for a particleboard wardrobe/chest of drawer were found in [22]. It suggest a fire growth coefficient *fast* (0.047 kW/s²) and HRRPUA of 2550 kW/m² for the wooden chest of drawer. Since the geometry and the constituent material are similar, it can be assumed that these fire characteristics can describe the fire characteristics of the night stands as well. The size of a normal night stand is assumed to be 0.5 x 0.5 m² (Width x Length), thus the floor area occupied by the night stand is 0.25 m². The peak heat release rate for one night stand is then $0.25 \cdot 2550 = 638 \; kW$, if difference in height between the night stands and the wardrobe/chest of drawer is assumed to be negligible. The peak heat release rate for the night stands is then reached $t = \sqrt{\frac{638}{0.047}} \approx 120 \; s$ after ignition. Thus, the heat release rate for the night stands should be limited to 638 kW two minutes after ignition of the night stands. The principle of superposition the heat release rate to a total heat release rate is given in Table 16.3.

Table 16.3. The principle of superposition the heat release rate for items ignited at different times. The heat release rate for the mattress is given by a t²-fire with the fire growth coefficient 0.054 kW/s², and the heat release rate for the night stands are following a *fast* (0.047 kW/s²) growing t²-fire.

Time [min]	Heat release rate [kW]			Total HRR [kW]
	Mattress	Night stand	Night stand	
0	0	0	0	0
0.5	49	0	0	49
1	194	0	0	194
1.5	437	0	0	437
2	778	42	42	862
2.5	1215	169	169	1553
3	1750	381	381	2512
3.5	2381	638	638	3657
4	2644	638	638	3920

PART 4

Recalling the estimated heat release rate for flashover, $\dot{Q}_{fo} = 3.5\ MW$, from Section 16.2, the fire from the mattress and the night stands are sufficient to cause flashover in the hotel room after approximately three and a half minutes, see Table 16.3. The heat release rate should then be instantaneously increased to the peak heat release rate for the hotel room, limited either by the ventilation or the fuel available. The contribution on the fire growth from other items being ignited during the short period of time between the ignition of the night stands and flashover are assumed to be negligible, especially since the estimation of the ignition time for the night stands is considered to be somewhat conservative.

The peak heat release rate for the ventilation-controlled fire can be calculated by Equation (10.12). The door to the hotel room can be assumed to be left open when the hotel room has been evacuated. The door was identified as 0.9 m wide by 2.1 m high. Furthermore, the window in the hotel room can be assumed to break and be fully opened following flashover. The comfort ventilation is assumed to have negligible effect on the air supply for the fire. Thus, recalling the weighted values of A_o and H_o from Section 16.2, the peak heat release rate for the ventilation-controlled fire is:

$$\dot{Q}_v = 1500 \cdot 3.7 \cdot \sqrt{1.8} \approx 7.4\ MW$$

However, the oxygen available for combustion within the volume of the enclosure must also be estimated. The volume of the hotel room is $4 \cdot 5 \cdot 2.4 = 48\ m^3$. Equation (10.15) gives the energy that can be released for combustion of the available oxygen:

$$E = 13100 \cdot V \cdot (0.23 - 0.10) \cdot \rho_{air} = 13100 \cdot 48 \cdot (0.23 - 0.10) \cdot 1.2 \approx 98\ MJ$$

Next step is to assess which heat release rate is required for releasing 98 MJ of energy. Here, by using the peak heat release rate calculated by Equation (10.12), the time required for releasing 98 MJ with that constant heat release rate can be estimated by Equation (10.16):

$$t = \frac{E}{\dot{Q}} = \frac{98000}{7400} \approx 13\ s$$

This means that the oxygen available for combustion within the hotel room is consumed after 13 seconds with a heat release rate of 7.4 MW. Since the fire probably will burn more than 13 seconds, the oxygen within the hotel room at the beginning of the fire can be ignored.

EXAMPLE 16.1.

What if Equation (10.16) would have given another value for the time t? For example, if the volume of the enclosure would have been 1800 m³, the energy released for combustion of the available oxygen would then have been 3680 MJ. Then, the time for releasing 3680 MJ with a 7.4 MW fire would instead be approximately 500 seconds (8.3 minutes). A fire significant greater than 7.4 MW would then be possible for the first 5 to 8 minutes, depending on the heat release rate.

Therefore, another approach could be to use the peak heat release rate for the fuel-controlled fire in Equation (10.16) and see if the fire is more likely to be fuel-controlled, i.e. the fuel-controlled peak heat release rate can burn for a very long time without the fire becoming ventilation controlled.

Since the total fuel-controlled peak heat release rate from the mattress and the two night stands are $2644 + 2 \cdot 638 = 3920 \, kW$, and there is more fuel available in the hotel room such as chest of drawers, wardrobes, TV, combustible linings etcetera, the fire will certainly be ventilation-controlled after flashover (i.e. $\dot{Q}_{fuel-controlled} \gg \dot{Q}_{ventilation-controlled}$). For example, the peak heat release rate for single wardrobes ranges between 300-6400 kW in Särdqvist [37], and a representative value should be somewhere in the upper region, so even a very rough estimate of the total peak heat release rate for all the combustible items and materials in a hotel room would be significant greater than the ventilation-controlled peak heat release rate of 7.4 MW.

To summarize, the initial heat release rate curve for the hotel room is then determined by the total heat release rate given in Table 16.3 up to three and a half minutes, then the heat release rate is instantaneously increased to 7.4 MW, see Figure 16.4.
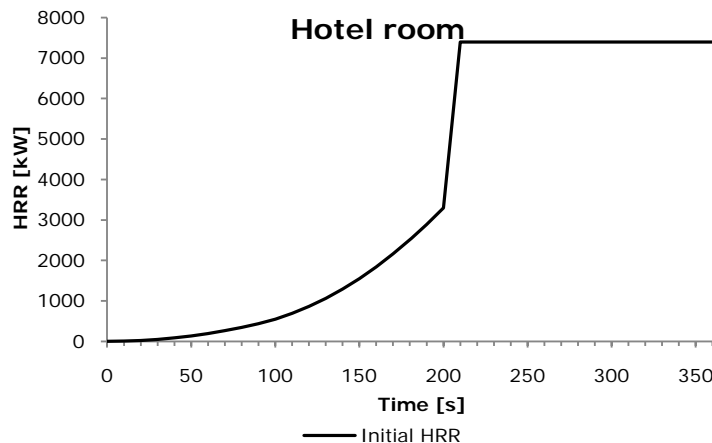
Figure 16.4. The initial heat release rate curve for the hotel room.

16.3.2 Smouldering combustion

The parameters for the smouldering fire are expressed in terms of mass loss rate rather than the heat release rate. The mass loss rate for smouldering combustion is given by Equation (10.1). The mass loss rate curve for smouldering fire in the hotel room, calculated by Equation (10.1), is given in Figure 16.5.
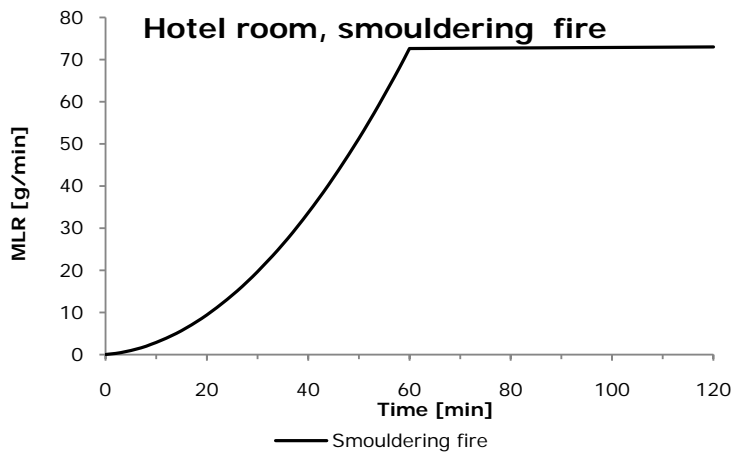
Figure 16.5. Mass loss rate in g/min for a smouldering fire in the hotel room.

16.3.3 Yield of combustion products species

For the initial stage of the fire in the hotel room, i.e. the fire growth stage, well-ventilated conditions can be assumed. The mattress can be assumed to consist mainly of some flexible polyurethane foam, thus can yield of species for such materials be used. Yields of species measured in experiments for polyurethane foams are given in Table A.15. Since the yield of species is rather difficult to predict and greatly depending on the ventilation-condition, the highest value for flexible polyurethane foam is chosen for a more conservative approach. Thus, the well-ventilated yield of species is:

$y_{CO_2} = 1.57$
$y_{CO} = 0.042$
$y_{HC} = 0.005$
$y_{soot} = 0.227$

After flashover, under-ventilated conditions can be assumed. For estimating the under-ventilated yield of species, the equivalence ratio must be calculated using Equation (10.24) or Equation (10.25). However, the ventilation-controlled peak heat release rate cannot be used since it would simply result in an equivalence ratio of 1. Estimating the total peak heat release rate for open-burning of all the combustible items that possible could be found in a hotel room is unsuitable, since it would simply have too many uncertainties. Such an approach is more appropriate for fire scenarios with only a few combustible items. Therefore, suggested values for post-flashover fires must be used, see Table 10.7. Unfortunately, values for y_{HC} and y_{soot} are not given. The yield of CO for well-ventilated and under-ventilated conditions differs with a factor of ten, hence is the yield values for hydrocarbon and soot also assumed to follow this correlation as well. The yield of species for under-ventilated conditions would then be:

$y_{CO_2} = 1.1$
$y_{CO} = 0.3$
$y_{O_2} = 0.9$
$y_{HC} = 0.05$
$y_{soot} = 2.27$

16.4 Ventilation changed

Determine initial
HRR & other
parameters   3

Ventilation
changed?   4

Fire suppression 5
activated?

The hotel room have no smoke management systems present and any changes in the comfort ventilation are assumed to have negligible effect on the air supply for the fire. Furthermore, the windows in the hotel were identified in the trial design to be at least double-pane, resulting in total window glass breaking to be unlikely before flashover. However, which already has been considered in Section 16.2-16.3, windows can be assumed to break and be fully opened following flashover.
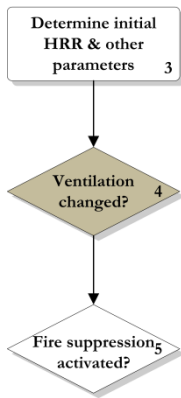
16.5 Fire suppression activated

Ventilation
changed?   4

Fire suppression 5
activated?

Flashover
occured?   6

Fire fighting activities by occupants and interventions by the fire service is assumed to not affect the initial heat release rate. However, for the fire scenario where the automatic water sprinkler system is assumed to operate normally, the effect of sprinkler activation must be analysed.

Hotels are classified as Ordinary Hazard 1 (OH1) according to Swedish Standard SS-EN 12845:2004 [52]. The maximum operation area per sprinkler for OH1 is 12 m², thus is two sprinklers required in a hotel room of 20 m². The trial design suggests sprinkler activation temperature to be 68°C, the response time index (RTI) for the standard response sprinkler to be 80 $m^{1/2}s^{1/2}$ and the distance between the two sprinklers to be three meters. The activation time can then be calculated using Detact-QS for the total heat release rate for the mattress and night stands and the ceiling height above fuel 1.9 m (the fuel is assumed to be 0.5 m above the floor). The activation time is calculated to approximately 120 seconds and the heat release rate should then be decreased after sprinkler activation, since the fire is not likely to be shielded from the sprinkler. The heat release rate at sprinkler activation is $\dot{Q}_{act} = 863\ kW$, see Table 16.3.

The conditions of the fire scenario is quite similar to the experiments done by Evans [47], and although the hotel is not classified as an light-hazard occupancy, it is reasonable to believe the effect of water sprinkler on the heat release rate will follow Equation (12.2). The water spray density for OH1 is minimum 0.083 mm/s, see Table A.16. Here, it is assumed that only one sprinkler has activated. For the heat release rate curve with sprinkler activation, see Figure 16.6.
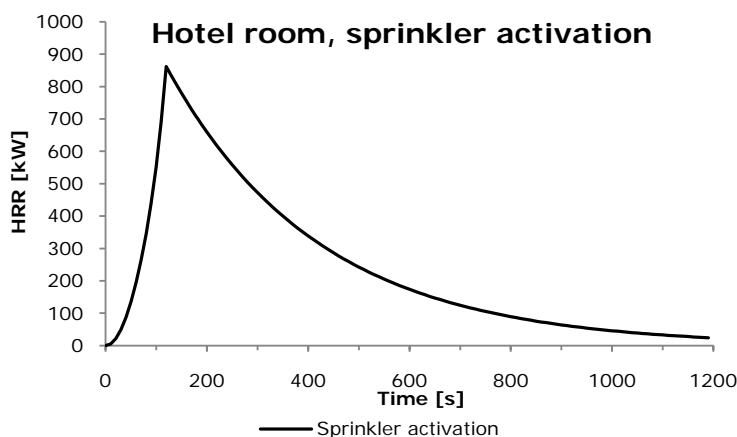
Figure 16.6. Heat release rate for the hotel room with sprinkler activation.

16.6 Flashover occurred

For the fire scenario with sprinkler activation, flashover is prevented by the water sprinkler system since $\dot{Q}_{act} < \dot{Q}_{fo}$, see Figure 16.6. Were sprinkler failure is assumed, the fire will lead to flashover and the heat release rate should be instantaneously increased to the peak heat release rate for the ventilation controlled fire, see Figure 16.4.
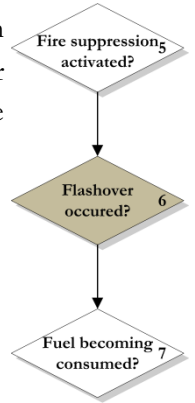
PART 4

16.7 Fuel becoming consumed

For the fire scenario where the water sprinkler system is assumed to operate normally, the decay stage is described in Section 16.5 and no change in the heat release rate curve is needed to account for the fuel becoming consumed. For the fire scenario where the sprinkler is assumed to fail, the decay stage can be assumed to begin when 80 percent of the fuel has been consumed. Thus, the fire load of the hotel room must be calculated. From Table A.18, the 80-percentile value for fire load density, $E''_{load,t}$, in hotels is 81 600 kJ/m². Thus, the fire load in the hotel room can be calculated by Equation (14.5):

$$E_{load} = 81\ 600 \cdot \left(2 \cdot (5 \cdot 4 + 5 \cdot 2.4 + 4 \cdot 2.4)\right) \approx 6800\ MJ$$

80 percent of the fire load is then 5440 MJ. The energy released before flashover can be calculated from Equation (14.12) for the different burning items (i.e. the mattress and the night stands):

$$E_{1,mattress} = \frac{0.054 \cdot 210^3}{3} \approx 167\ MJ$$

$$E_{1,night\ stands} = 2 \cdot \left(\frac{0.047 \cdot (210 - 90)^3}{3}\right) \approx 54\ MJ$$

Here, 210 is the time in seconds for flashover and 90 is the time in seconds for ignition of the night stands. The duration of the fully developed stage will be until the remaining $5440 - 167 - 54 = 5219\ MJ$ is released. The time for the beginning of the decay stage is then given by Equation (14.13):

$$E_2 = \dot{Q}_{peak}(t_{max} - t_{grow}) \Rightarrow t_{max} = \frac{E_2}{\dot{Q}_{peak}} + t_{grow} = t_{max} = \frac{5\ 219\ 000}{7400} + 210 \approx 915\ s$$

The remaining 20 percent of fuel can then be assumed to be burned under a linear decay rate, which can be calculated by Equation (14.15):

$$E_3 = \frac{\dot{Q}_{peak}(t_{decay} - t_{max})}{2} \Rightarrow t_{decay} = \frac{2 \cdot E + \dot{Q}_{peak}t_{max}}{\dot{Q}_{peak}} = \frac{2 \cdot 1360\ 000 + 7400 \cdot 915}{7400} \approx 1280\ s$$
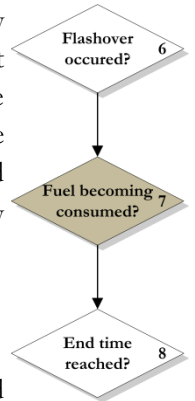
t_{decay} is then 1280 seconds (21.3 minutes) and the linear decay rate coefficient is given by Equation (14.10):

$$C_{decay} = \frac{7400}{(1280 - 915)} \approx 20.3 \, kW/s$$

For the heat release rate curve for the hotel room with sprinkler failure, see Figure 16.7.
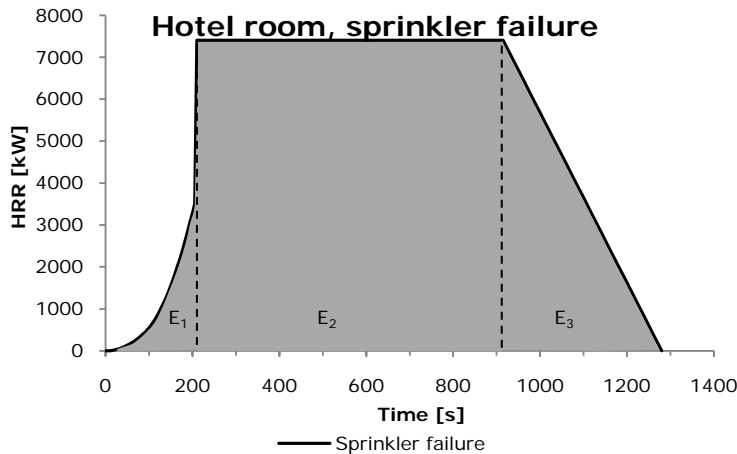
Figure 16.7. The heat release rate curve in the hotel room for sprinkler failure.

16.8 End time reached

Both the design fires for sprinkler operating normally and sprinkler failure have reached the decay stage. For the fire scenario with sprinkler failure, a complete description of the fire growth stage, the fully developed stage and the decay stage has been done. The total burning time is for almost 21 minutes, which in this case is sufficient for evaluating the life safety and the possibility for fire spread from the room of origin. The fire scenario with the sprinkler operating normally has been determined for 20 minutes and the heat release rate has then decreased to a level where further analysis of the fire is unnecessary. Thus, the final selected design fires are given in Figure 16.6 and Figure 16.7.

When the two design fires have been selected, it is important to perform a sensitivity analysis of the parameters selected in the design fire. Typically, values such as fire growth coefficients, peak heat release rates, yields of combustion species and fire loads should be changed in the sensitivity analysis to find parameters that significant affect the subsequent fire safety evaluation.
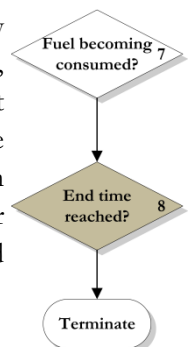
PART 5
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17   References

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Appendix A – Tables

This appendix includes tables with useful data.

A.1   Fire initiation

This section includes tables useful for determine the fire initiation.

A.1.1 Ignition sources

Table A.1.   Characteristics of ignition sources [53].

Ignition source	Typical heat output [kW]	Burn time[a] [s]	Maximum heat flux [kW/m^2]
Cigarette 1.1 g (not puffed, laid on solid surface),			
Bone dry	5E-3	1200	42
Conditioned to 50% relative humidity	5E-3	1200	35
Methenamine pill	45E-3	90	4
Match, wodden (laid on solid surface)	80E-3	20-30	18-20
Wood cribs, BS 5852 Part 2			
No. 4 crib, 8.5 g	1	190	15[c]
No. 5 crib, 17 g	1.9	200	17[c]
No. 6 crib, 60 g	2.6	190	20[c]
No. 7 crib, 126 g	6.4	350	25[c]
Crumpled brown lunch bag, 6 g	1.2	80	-
Crumpled wax paper, 4.5 g (tight)	1.8	25	-
Crumpled wax paper, 4.5 g (loose)	5.3	20	-
Folded double-sheet newspaper, 22 g (bottom ignition)	4.0	100	-
Crumpled double-sheet newspaper, 22 g (top ignition)	7.4	40	-
Crumpled double-sheet newspaper, 22 g (bottom ignition)	17	20	-
Polyethylene waste basket, 285 g, filled with 12 milk cartons (390 g)	50	200[b]	35[d]
Plastic trash bags, filled with cellulosic trash (1.2-14 kg)[e]	120-350	200[b]	-

[a]Time duration of significant flaming.

[b]Total burn time in excess of 1800 seconds.

[c]Measured from 25 mm away

[d]As measured on simulation burner

[e]Results vary greatly with packing density

Table A.2. Ignition sources for reported fires in Sweden between years 1996-2009. Taken from the fire statistic database http://ida.msb.se/.

Ignition source	Fires between 1996-2009	
	Frequency	Percent[a] [%]
Unknown	37 409	24.1
Arson	18 058	11.6
Technical error	16 838	10.9
Chimney-fire	16 818	10.8
Stove - forgotten	15 196	9.8
Heat transfer	12 138	7.8
Other	11 389	7.3
Sparks	5 215	3.4
Candles	4 511	2.9
Smoking	4 370	2.8
Self-ignition	3 077	2.0
Children playing	2 515	1.6
Hot working	2 277	1.5
Stroke of lightning	1 534	1.0
Re-ignition	1 523	1.0
Fireworks	994	0.6
Friction	689	0.4
Explosion	571	0.4
Total	155 122	100

[a]Rounded numbers. Therefore; the numbers do not sum up to exactly 100 percent.

Various reports of fire statistics can be found at http://www.nfpa.org/ > Research > Fire reports. For example, a report [54] for structure fires in U.S. hotels and motels is available on the webpage and some examples of the fire statistics found in the report can be seen in Table A.3 and Table A.4.

Table A.3. Equipment involved in ignition in hotels and motels in U.S. between years 2003-2007 reported by municipal fire departments [54]. Fires are annual averages rounded to the nearest ten and civilian deaths and injuries are annual averages rounded to the nearest one.

Equipment involved in ignition	Years 2003-2007					
	Fires		Civilian deaths		Civilian injuries	
Confined cooking fire	1 400	(35%)	0	(0%)	12	(8%)
No equipment involved	620	(16%)	11	(100%)	40	(26%)
Clothes dryer	370	(9%)	0	(0%)	11	(7%)
Contained trash or rubbish fire	290	(7%)	0	(0%)	2	(1%)
Unclassified heating, ventilating and air conditioning	130	(3%)	0	(0%)	21	(14%)
Fixed wiring and related equipment	120	(3%)	0	(0%)	2	(2%)
Range with or without oven, cooking surface	120	(3%)	0	(0%)	11	(7%)
Fixed or portable space heater	90	(2%)	0	(0%)	1	(1%)
Confined fuel burner or boiler fire	90	(2%)	0	(0%)	3	(2%)
Air conditioner	80	(2%)	0	(0%)	7	(5%)
Confined chimney or flue fire	80	(2%)	0	(0%)	0	(0%)
Lamp, bulb or lightning	80	(2%)	0	(0%)	0	(0%)
Fan	70	(2%)	0	(0%)	9	(6%)
Water heater	40	(1%)	0	(0%)	1	(1%)

Equipment involved in ignition	Years 2003-2007					
	Fires		Civilian deaths		Civilian injuries	
Unclassified equipment involved in ignition	30	(1%)	0	(0%)	1	(1%)
Microwave oven	30	(1%)	0	(0%)	0	(0%)
Portable cooking or warming equipment	30	(1%)	0	(0%)	5	(3%)
Elevator or lift	30	(1%)	0	(0%)	0	(0%)
Transformer or power supply	30	(1%)	0	(0%)	0	(0%)
Torch	20	(1%)	0	(0%)	6	(4%)
Other confined fire	20	(1%)	0	(0%)	0	(0%)
Other known equipment	220	(6%)	0	(0%)	20	(14%)
Total	3 970	(100%)	11	(100%)	151	(100%)

Table A.4. Heat sources for structure fires in hotels and motels in U.S. between years 2003-2007 reported by municipal fire departments [54]. Fires are annual averages rounded to the nearest ten and civilian deaths and injuries are annual averages rounded to the nearest one.

Heat source	Years 2003-2007					
	Fires		Civilian deaths		Civilian injuries	
Confined cooking fire	1 400	(35%)	0	(0%)	12	(8%)
Unclassified heat from powered equipment	400	(10%)	0	(0%)	17	(11%)
Radiated or conducted heat from operating equipment	330	(8%)	0	(0%)	15	(10%)
Contained trash or rubbish fire	290	(7%)	0	(0%)	2	(1%)
Arcing	290	(7%)	0	(0%)	15	(10%)
Smoking materials (i.e. lighted tobacco products)	230	(6%)	8	(72%)	35	(23%)
Unclassified hot or smouldering object	150	(4%)	0	(0%)	9	(6%)
Spark, ember or flame from operating equipment	140	(3%)	0	(0%)	8	(5%)
Candle	100	(3%)	1	(14%)	8	(5%)
Unclassified heat source	100	(2%)	0	(0%)	3	(2%)
Confined fuel burner or boiler fire	90	(2%)	0	(0%)	3	(2%)
Hot ember or ash	90	(2%)	0	(0%)	2	(1%)
Confined chimney or flue fire	80	(2%)	0	(0%)	0	(0%)
Cigarette lighter	50	(1%)	1	(14%)	9	(6%)
Match	40	(1%)	0	(0%)	4	(3%)
Flame or torch used for lighting	30	(1%)	0	(0%)	1	(1%)
Chemical reaction	30	(1%)	0	(0%)	3	(2%)
Other confined fire	30	(1%)	0	(0%)	0	(0%)
Other known heat source	100	(3%)	0	(0%)	5	(4%)
Total	3 970	(100%)	11	(100%)	151	(100%)

Table A.5. Criteria for ignition from various sources, summarized by [24].

Material	Critical radiant heat flux [kW/m²]		Critical surface temperature [°C]	
	Pilot	Spontaneous	Pilot	Spontaneous
'Wood'	12[a]	28[a]	350[b]	600[c]
PMMA	21[d]	-	-	-
PMMA	11[e]	-	310±3[g]	-
Polyoxymethylene (POM)	13[f]	-	281±5[g]	-
Polyethylene (PE)	15[f]	-	363±3[g]	-
Polypropylene (PP)	15[f]	-	334±4[g]	-
Polystyrene (PS)	13[f]	-	366±4[g]	-

[a]General values for wood, vertical samples.

[b]Deduced from flame spread under conditions of radiant heating.

[c]Deduced for radiative heating. Lower value observed for convective heating.

[d]Comparatively, these values are very high.

[e]Horizontal samples

[f]Horizontal samples, Factory Mutual Flammability Apparatus.

[g]Horizontal samples.

A.1.2 Starting objects

Table A.6. Starting objects for reported fires in Sweden between years 1996-2009. Taken from the fire statistic database http://ida.msb.se/.

Starting object	Fires between 1996-2009	
	Frequency	Percent[a] [%]
Other	7 785	27.5
Kitchen stove	3 373	11.9
Furnishings	2 949	10.4
Unknown	1 977	7.0
Outside of building	1 831	6.5
Other electric appliances	1 383	4.9
Paper/cardboard	1 106	3.9
Other furnishings	601	2.1
Waste	580	2.1
Heating appliances	547	1.9
Fan/other venting appliances	539	1.9
Fluorescent lamp	530	1.9
Not specified	462	1.6
Flammable liquid	423	1.5
Fluorescent luminary	402	1.4
Refrigerator/freezer	290	1.0
Heater sauna	275	1.0
Fireplace	269	1.0
Tumble and spin driers	222	0.8
Light bulb	220	0.8
Electric panel	216	0.8
Coffee maker	206	0.7
Machinery	206	0.7
Bed	203	0.7
Chimney, stove pipe, flue	196	0.7
Dishwasher	193	0.7
Clothing	174	0.6
Washing machine	168	0.6
Transformer	168	0.6
TV	146	0.5

Starting object	Fires between 1996-2009	
	Frequency	Percent[a] [%]
Car	108	0.4
Sofa/armchair	105	0.4
Curtains	96	0.3
Explosive	86	0.3
Drying cupboard	59	0.2
Flammable gas	57	0.2
Computer	46	0.2
Other vehicles	37	0.1
Iron	17	0.1
Stereo equipment/VCR	10	0.0
Stereo equipment/VCR/DVD-player	7	0.0
Train	5	0.0
Rail vehicles	1	0.0
Total	28 274	100

[a]Rounded numbers. Therefore; the numbers do not sum up to exactly 100 percent.

> Various reports of fire statistics can be found at http://www.nfpa.org/ > Research > Fire reports. For example, a report [54] for structure fires in U.S. hotels and motels is available on the webpage and an example of the fire statistics found in the report can be seen in Table A.7

<div style="float:right">PART 5</div>

Table A.7. Items first ignited in hotels and motels in U.S. between years 2003-2007 reported by municipal fire departments [54]. Fires are annual averages rounded to the nearest ten and civilian deaths and injuries are annual averages rounded to the nearest one.

Item first ignited	Years 2003-2007					
	Fires		Civilian deaths		Civilian injuries	
Confined cooking fire	1 400	(35%)	0	(0%)	12	(8%)
Contained trash or rubbish fire	290	(7%)	0	(0%)	2	(1%)
Mattress or bedding materials	240	(6%)	6	(60%)	33	(22%)
Electrical wire or cable insulation	210	(5%)	0	(0%)	11	(7%)
Linen other than bedding	190	(5%)	0	(0%)	10	(7%)
Structural member or framing	130	(3%)	0	(0%)	1	(0%)
Unclassified item	110	(3%)	2	(20%)	5	(3%)
Cooking materials	100	(2%)	0	(0%)	5	(3%)
Confined fuel burner or boiler fire	90	(2%)	0	(0%)	3	(2%)
Confined chimney or flue fire	80	(2%)	0	(0%)	0	(0%)
Unclassified furniture, utensils	70	(2%)	0	(0%)	6	(4%)
Dust, fibre, lint, including sawdust or excelsior	70	(2%)	0	(0%)	5	(3%)
Flammable or combustible liquid or gas, filter or piping	70	(2%)	0	(0%)	8	(6%)
Rubbish, trash or waste	70	(2%)	1	(11%)	5	(3%)
Appliance housing or casing	60	(2%)	0	(0%)	13	(8%)
Clothing	60	(1%)	0	(0%)	2	(1%)
Exterior wall covering or finish	50	(1%)	0	(0%)	1	(0%)
Insulation within structural area	50	(1%)	0	(0%)	2	(1%)
Unclassified structural component or finish	50	(1%)	0	(0%)	1	(0%)
Upholstered furniture	50	(1%)	0	(0%)	4	(3%)
Exterior roof covering or finish	50	(1%)	0	(0%)	0	(0%)
Unclassified soft goods or wearing apparel	50	(1%)	1	(9%)	3	(2%)
Interior wall covering	40	(1%)	0	(0%)	3	(2%)

| Item first ignited | Years 2003-2007 | | | | | |
	Fires		Civilian deaths		Civilian injuries	
Magazine, newspaper, writing paper	40	(1%)	0	(0%)	4	(3%)
Floor covering	40	(1%)	0	(0%)	2	(2%)
Box, carton, bag, basket or barrel	30	(1%)	0	(0%)	0	(0%)
Multiple items first ignited	30	(1%)	0	(0%)	0	(0%)
Unclassified organic material	30	(1%)	0	(0%)	1	(0%)
Cabinetry	20	(1%)	0	(0%)	2	(1%)
Curtains, blinds, drapery or tapestry	20	(1%)	0	(0%)	2	(1%)
Other confined fire	30	(1%)	0	(0%)	0	(0%)
Other known item	180	(5%)	0	(0%)	7	(4%)
Total	3 970		11	(100%)	151	(100%)

A.2 Schematic design fire

This section includes tables useful for determine the schematic design fire.

Table A.8. Probabilities of fire types for apartment buildings [55].

	Australia	U.S.A	Canada
Smouldering fire	24.5%	18.7%	19.1%
Non-flashover fire	60.0%	63.0%	62.6%
Flashover fire	15.5%	18.3%	18.3%

A.3 Initial fire characteristics

This section includes tables useful for determine the initial fire characteristics.

A.3.1 Fire growth

Table A.9. Fire growth coefficients for various commodities [22].

Description	α [kW/s²]	Test no.
Metal wardrobe 41.4 kg (total)	0.422	15
Chair F33 (trial loveseat) 39.2 kg	0.0066	18
Chair F21, 28.15 kg (initial stage of fire growth)	0.0344	19
Chair F21, 28.15 kg (later stage of fire growth)	0.04220	19
Metal wardrobe 40.8 kg (total, average growth)	0.0169	21
Metal wardrobe 40.8 kg (total, later growth)	0.0733	21
Metal wardrobe 40.8 kg (total, initial growth)	0.1055	21
Chair F24, 28.3 kg	0.0086	22
Chair F23, 31.2 kg	0.0066	23
Chair F22, 31.9 kg	0.0003	24
Chair F26, 19.2 kg	0.0264	25
Chair F27, 29.0 kg	0.0264	26
Chair F29, 14.0 kg	0.1055	27
Chair F28, 29.2 kg	0.0058	28
Chair F25, 27.8 kg (later stage of fire growth)	0.2931	29
Chair F25, 27.8 kg (initial stage of fire growth)	0.1055	29
Chair F30, 25.2 kg	0.2931	30
Chair F31, (loveseat) 39.6 kg	0.2931	31
Chair F31, (loveseat) 40.4 kg	0.1648	37
Chair F32, (sofa) 51.5 kg	0.1055	38
½ inch plywood wardrobe w/ fabrics 68.8 kg	0.8612	39
½ inch plywood wardrobe w/ fabrics 68.32 kg	0.8612	40
1/8 inch plywood wardrobe w/ fabrics 36.0 kg	0.6594	41
1/8 inch plywood wardrobe w/ fire-ret. (int. fin. initial)	0.2153	42

Description	α [kW/s²]	Test no.
1/8 inch plywood wardrobe w/ fire-ret. (int. fin. later)	1.1722	42
Repeat of ½ inch plywood wardrobe 67.62 kg	1.1722	43
1/8 inch plywood wardrobe w/ fire-ret. latex paint 37.26 kg	0.1302	44
Chair F21, 28.34 kg (large hood)	0.1055	45
Chair F21, 28.34 kg	0.5210	46
Chair, adjustable back metal frame, foam cushion, 20.8 kg	0.0365	47
Easy chair CO7 11.52 kg	0.0344	48
Easy chair 15.68 kg (F-34)	0.0264	49
Chair metal frame minimum cushion, 16.52 kg	0.0264	50
Chair moulded fibreglass no cushion 5.82 kg	0.0733	51
Moulded plastic patient chair, 11.26 kg	0.0140	52
Chair metal frame w/padded seat and back 15.5 kg	0.0086	53
Loveseat metal frame w/foam cushions 27.26 kg	0.0042	54
Group chair metal frame w/foam cushions, 6.08 kg	Never exceeded 50 kW	55
Chair wood frame w/latex foam cushion, 11.2 kg	0.0042	56
Loveseat wood frame w/foam cushions, 54.6 kg	0.0086	57
Wardrobe, ¾ inch particle board, 120.33 kg	0.0469	61
Bookcase plywood w/aluminium frame, 30.39 kg	0.2497	62
Easy chair moulded flexible urethane frame, 15.98 kg	0.0011	64
Easy chair, 23.02 kg	0.1876	66
Mattress and box spring, 62.36 kg (initial fire growth)	0.0086	67
Mattress and box spring, 62.36 kg (initial fire growth)	0.0009	67

A.3.2 Peak heat release rate

Table A.10. Heat release rate data for different mattresses, including bedding [21]. For the full-scale test, ignition was achieved with a wastebasket and the testing was done under conditions leading to no significant room effects [21]. The bench-scale data are peak values at 25 kW/m² irradiance [21].

Padding material	Ticking material	Combustible mass [kg]	Peak HRR, Full-scale [kW]	Bench-scale HRR [kW/m²]
Latex foam	PVC	19	2 720	479
Polyurethane foam	PVC	14	2 630	399
Polyurethane foam	PVC	6	1 620	138
Polyurethane foam	Rayon	6	1 580	179
Polyurethane foam	Rayon	4	760	NA
Neoprene	FR cotton	18	70	89
Cotton/jute	FR cotton	13	40	43

NA = Not available.

PART 5

Table A.11. Heat release rate data for different mattresses, excluding bedding [21]. Ignition was achieved with a burner flame at the end of the mattress and the testing was done under conditions leading to significant room effects [21].

Padding material	Ticking material	Combustible mass [kg]	Peak HRR, Full-scale [kW]	180 s Average HRR, Bench-scale [kW/m²]
Polyurethane foam	Unidentified fabric	8.9	1716	220
Melamine-type PUR/ cotton batting/ polyester fibre pad	Polyester/ polypropylene	NA	547	169
Polyurethane foam/ cotton batting/ polyester fibre pad	Unidentified fabric	NA	380	172
Polyurethane foam/ polyester fibre pad	PVC	NA	335	195
Melamine-type PUR	FR fabric	15.1	39	228
FR cotton batting	PVC	NA	17	36
FR cotton batting	Polyester	15.7	22	45
Neoprene	PVC	14.9	19	31

NA = Not available.

Table A.12. Heat release rate per unit floor area of fully involved combustibles for different commodities, based on negligible radiative feedback from surroundings and 100% combustion efficiency [56].

Commodity	Peak heat release rate per unit floor area $\dot{Q}''$ [kW/m²]
Wood pallets, stacked 0.46 m high (6-12% moisture)	1 400
Wood pallets, stacked 1.5 m high (6-12% moisture)	5 200
Wood pallets, stacked 3.1 m high (6-12% moisture)	10 700
Wood pallets, stacked 4.9 m high (6-12% moisture)	17 000
Mail bags, filled, stored 1.5 m high	400
Cartons, compartmented, stacked 4.6 m high	1 700
PE letter trays, filled, stacked 1.5 m high on cart	8 500
PE trash barrels in cartons, stacked 4.6 m high	2 000
PE fibreglass shower stalls in cartons, stacked 4.6 m high	1 400
PE bottles, packed in compartmented cartons	6 200
PE bottles in cartons, stacked 4.6 m high	2 000
PUR insulation board, rigid foam, stacked 4.6 m high	1 900
PS jars, packed in compartmented cartons	14 200
PS tubs, nested in cartons, stacked 4.3 m high	5 400
PS toy parts in cartons, stacked 4.6 m high	2 000
PS insulation board, rigid foam, stacked 4.3 m high	3 300
PVC bottles, packed in compartmented cartons	3 400
PP tubs, packed in compartmented cartons	4 400
PP & PE film in rolls, stacked 4.3 m high	6 200
Methyl alcohol	740
Gasoline	3 300
Kerosene	3 300
Diesel oil	2 000

PE = polyethylene, PUR = polyurethane, PS = polystyrene, PVC = Polyvinylchloride, PP = polypropylene.

Table A.13. Heat of combustion and effective heat of combustion for different wood types [57].

Wood type	Heat of combustion ΔH_c [MJ/kg]	Effective heat of combustion ΔH_{eff} [MJ/kg]
Beech	20.0	18.7
Birch	20.0	18.7
Douglas fir	21.0	19.6
Maple	19.1	17.8
Red oak	20.2	18.7
Spruce	21.8	20.4
White pine	19.2	17.8
Hardboard	19.9	-

A.3.3 Yields of combustion products

Table A.14. Physicochemical data for selected fuels [43].

Fuel	Empirical Chemical Formula of Volatiles	Empirical Molecular Weight	Maximum theoretical yields				
			y_{CO}	y_{CO_2}	y_{O_2}	y_{H_2O}	$1/r$
Acetone	C_3H_6O	58	1.45	2.28	2.21	0.93	9.45
Ethanol	C_2H_5OH	46	1.22	1.91	2.09	1.17	8.94
Hexane	C_6H_{14}	86	1.95	3.07	3.53	1.47	15.1
Isopropanol	C_3H_7OH	60	1.40	2.20	2.40	1.20	10.3
Methane	CH_4	16	1.75	2.75	4.00	2.25	17.2
Methanol	CH_3OH	32	0.88	1.38	1.50	1.13	6.43
Propane	C_3H_8	44	1.91	3.00	3.64	1.64	15.6
Propene	C_3H_6	42	2.00	3.14	3.43	1.29	14.7
Polyurethane foam	$CH_{1.74}O_{0.323}N_{0.0698}$	20	1.41	2.21	2.05	0.79	8.78
Polymethylmethacrylate (PMMA)	$C_5H_8O_2$	100	1.40	2.20	1.92	0.72	8.23
Toluene	C_7H_8	92	2.13	3.35	3.13	0.78	13.4
Wood (ponderosa pine)	$C_{0.95}H_{2.4}O$	30	0.89	1.40	1.13	0.73	4.83
Wood (spruce)	$CH_{3.584}O_{1.55}$	40	0.69	1.09	0.89	0.80	3.87

PART 5

Table A.15. Yield of species for different fire products under well-ventilated conditions [58].

Fuel	Chemical Formula	Yields of species [kg/kg]			
		y_{CO_2}	y_{CO}	y_{HC}	y_{soot}
Common gases					
Methane	CH_4	2.72	-	-	-
Ethane	C_2H_6	2.85	0.001	0.001	0.013
Propane	C_3H_8	2.85	0.005	0.001	0.024
Butane	C_4H_{10}	2.85	0.007	0.003	0.029
Ethylene	C_2H_4	2.72	0.013	0.005	0.043
Propylene	C_3H_6	2.74	0.017	0.006	0.095
1,3-Butadiene	C_4H_6	2.46	0.048	0.014	0.125
Acetylene	C_2H_2	2.60	0.042	0.013	0.096
Common liquids					
Methyl alcohol	CH_4O	1.31	0.001	-	-
Ethyl alcohol	C_2H_6O	1.77	0.001	0.001	0.008
Isopropyl alcohol	C_3H_8O	2.01	0.003	0.001	0.015
Acetone	C_3H_6O	2.14	0.003	0.001	0.014
Methylethyl ketone	C_4H_8O	2.29	0.004	0.001	0.018
Heptane	C_7H_{16}	2.85	0.010	0.004	0.037
Octane	C_8H_{18}	2.84	0.011	0.004	0.038
Kerosene	$C_{14}H_{30}$	2.83	0.012	0.004	0.042
Benzene	C_6H_6	2.33	0.067	0.018	0.181
Toluene	C_7H_8	2.34	0.066	0.018	0.178
Styrene	C_8H_8	2.35	0.065	0.019	0.177
Hydrocarbon		2.64	0.019	0.007	0.059
Mineral oil		2.37	0.041	0.012	0.097
Polydimethyl siloxane	$(C_2H_6OSi)_n$	0.93	0.004	0.032	0.232
Silicone	$CH_3O_{0.50}Si_{0.50}$	0.72	0.006	0.008	-
Solids – natural materials					
Wood (red oak)		1.27	0.004	0.001	0.015
Wood (Douglas fir)		1.31	0.004	0.001	-
Wood (pine)		1.33	0.005	0.001	-
Solids – synthetic materials					
Acrylonitrile butadiene styrene (ABS)		-	-	-	0.105
Polyoxymethylene (POM)		1.40	0.001	0.001	-
Polymethylmethacrylate (PMMA)		2.12	0.010	0.001	0.022
Polyethylene (PE)		2.76	0.024	0.007	0.060
Polypropylene (PP)		2.79	0.024	0.006	0.059
Polystyrene (PS)		2.33	0.060	0.014	0.164
Silicone		0.96	0.021	0.006	0.065
Polyester-1		1.65	0.070	0.020	0.091
Polyester-2		1.56	0.080	0.029	0.089
Epoxy-1		1.59	0.080	0.030	-
Epoxy-2		1.16	0.086	0.026	0.098
Nylon		2.06	0.038	0.016	0.075
Polyurethane (flexible) foams					
GM21		1.55	0.010	0.002	0.131
GM23		1.51	0.031	0.005	0.227
GM25		1.50	0.028	0.005	0.194
GM27		1.57	0.042	0.004	0.198

Fuel	Chemical Formula	Yields of species [kg/kg]			
		y_{CO_2}	y_{CO}	y_{HC}	y_{soot}
Polyurethane (rigid) foams					
GM29		1.52	0.031	0.003	0.130
GM31		1.53	0.038	0.002	0.125
GM35		1.58	0.025	0.001	0.104
GM37		1.63	0.024	0.001	0.113
GM41		1.18	0.046	0.004	-
GM43		1.11	0.051	0.004	-
Building products					
Particleboard (PB)		1.2	0.004	-	-
Fibreboard (FB)		1.4	0.015	-	-
Medium-density fibreboard (MDF)		1.2	0.002	-	-
Wood panel		1.2	0.002	-	-
Melamine-faced particleboard		0.8	0.025	-	-
Gypsum board (GB)		0.3	0.027	-	-
Paper on gypsum board		0.4	0.028	-	-
Plastics on gypsum board		0.4	0.028	-	-
Textile on gypsum board		0.4	0.025	-	-
Textile on rock wool		1.8	0.091	-	-
Paper on particleboard		1.2	0.003	-	-
Rigid polyurethane (PUR)		1.1	0.200	-	-

PART 5

A.4 Fire suppression

This section includes tables useful for determine the effect of fire suppression by an automatic water sprinkler system.

A.4.1 Automatic water sprinkler systems

The required minimum water spray density within the area of sprinkler operation for automatic water sprinkler systems according to Swedish Standard SS-EN 12845:2004 is given in Table A.16.

The occupancy classifications used in Table A.16 are defined as [52]:

- LH – Light Hazard
- OH – Ordinary Hazard
- HHP – High Hazard Process

The occupancies classified as OH and HHP is also divided into four sub-groups 1-4.

Table A.16. Required minimum water spray density within the area of sprinkler operation for automatic water sprinkler systems, depending on occupancy classification. Adapted from Swedish Standard SS-EN 12845:2004 [52]

Occupancy classification	Water spray density [mm/s]	Area of sprinkler operation [m²]	
		Wet pipe or pre-action system	Dry pipe or combined
LH	0.0375	84	Not allowed. Use OH1.
OH1	0.083	72	90
OH2	0.083	144	180
OH3	0.083	216	270
OH4	0.083	360	Not allowed. Use HHP1
HHP1	0.125	260	325
HHP2	0.167	260	325
HHP3	0.208	260	325
HHP4	Need special assessment. This occupancy is not covered by the standard.		

A.5 Fuel becoming consumed

This section includes tables useful for estimating when the fuel becomes consumed.

A.5.1 Heat of combustion

Table A.17. Complete heat of combustion, ΔH_c, for some common fuels [59].

Solids		Liquids	
Material	ΔH_c [MJ/kg]	Material	ΔH_c [MJ/kg]
Anthracite	31-36	**Gasoline**	43-44
Asphalt	40-42	**Diesel oil**	40-42
Bitumen	41-43	**Linseed oil**	38-40
Cellulose	15-18	**Methanol**	19-20
Charcoal	34-35	**Paraffin (kerosene)**	40-42
Clothes	17-21	**Spirits**	26-28
Coal, coke	28-34	**Tar**	37-39
Cork	26-31	**Benzene**	40.1
Cotton	16-20	**Benzyl alcohol**	32.9
Grain	16-18	**Ethyl alcohol**	26.9
Grease	40-42	**Isopropyl alcohol**	31.4
Kitchen refuse	8-21	Plastics	
Leather	18-20	Material	ΔH_c [MJ/kg]
Linoleum	19-21	**Acrylonitrile butadiene styrene (ABS)**	34-40
Paper, cardboard	13-21	**Acrylic**	27-29
Paraffin wax	46-47	**Celluloid**	17-20
Foam rubber	34-40	**Epoxy**	33-34
Rubber isoprene	44-45	**Melamine resin**	16-19
Rubber tyre	31-33	**Phenol formaldehyde**	27-30
Silk	17-21	**Polyester**	30-31
Straw	15-16	**Polyester, fibre-reinforced**	20-22
Wood	17-20	**Polyethylene**	43-44
Wool	21-26	**Polystyrene**	39-40
Particle board	17-18	**Petroleum**	40-42
Gases		**Polyisocyanurate foam**	22-26
Material	ΔH_c [MJ/kg]	**Polycarbonate**	28-30
Acetylene	48.2	**Polypropylene**	42-43
Butane	45.7	**Polytetraflourethylene**	5.0
Carbon monoxide	10.1	**Polyurethane**	22-24
Hydrogen	119.7	**Polyurethane foam**	23-28
Propane	45.8	**Polyvinyl chloride**	16-17
Methane	50.0	**Urea formaldehyde**	14-15
Ethanol	26.8	**Urea formaldehyde foam**	12-15

A.5.2 Fire load density

Table A.18. Fire load densities for different occupancies [22]. Notice that the values are the 80-percentile of the observed cases [22].

Type of occupancy	Fire load density, $E''_{load,t}$ [kJ/m²]
Dwelling, 2 rooms and kitchen	168 000
Dwelling, 3 rooms and kitchen	149 000
Offices	709 000[a]
Schools	96 300
Hospitals	147 000
Hotels	81 600

[a]Per floor area, not total surface area of enclosure.