



ENGINEERS
AUSTRALIA
SOCIETY OF
FIRE SAFETY
NSW CHAPTER

Practice Note for Design Fires

Version 1.0, dated 22.03.12

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1 Introduction

Since the inception of the performance based building code in Australia, fire safety engineering as a discipline has grown significantly. Along with the advancement in fire safety science, fire safety engineering practice is also evolving. The process, the methodology and the data can be regarded as the three pillars of fire safety engineering, as noted in the International Fire Engineering Guidelines (IFEG)^[1]. A rational approach to fire safety engineering design relies on clarity in the process, as well as scientific rigor in the analysis and verifiable data. The process is an overarching framework within which engineering designs are carried out, and the design methodology and data are implemented. The development of the process is an essential part of advancing fire engineering science and it often stems from practitioners' experience and the need for consistent quality assurance in engineering practice.

On 16 June 2009, the Society of Fire Safety New South Wales chapter held a seminar on the topic of Design Fire. The issue of consistency in engineering design practice was discussed. The attendees felt that there was no specific guidance to practitioners on how to derive design fires, and that there were discrepancies found in fire engineering reports prepared by different consultants, or in some instances, by different offices of the same consultant, in terms of the design fire adopted for projects. As an outcome of the seminar, a consensus was reached that there is a need of clear guidance to practitioners on how to derive design fires to address the problem of discrepancies mentioned above.

According to the IFEG^[1], in order to specify the design fires that are to be used in a fire engineering evaluation, three steps should be undertaken:

1. Determine potential fire scenarios.
2. From these possibilities, select the design fire scenarios to be used for developing the design fires.
3. For each of these design fire scenarios, specify a design fire.

With respect to Step 3 above, the limitations of the tools available to fire safety practitioners to date do not allow prediction of the initiation and development of the design fire from first principles or even through complex Computational Fluid Dynamics (CFD) models, but require the fire safety practitioners to prescribe the design fire.

This Practice Note was drafted by a group of fire safety engineers on behalf of the Society of Fire Safety. It serves as a supplementary guide to the IFEG^[1] for fire safety engineers and aims to assist the fire safety engineers to derive design fires and design fire scenarios in a consistent manner. **However; the Society of Fire Safety does not claim that the proposed method in this practice note is the only method for derivation of design fire scenarios and design fires.**

This practice note is divided into seven sections. Section 1 provides the background of producing the note. Section 2 states the limitations of this note, the status of this note in regulatory regimes, and the responsibility of the users. Section 3 discusses the relationship between design fire scenarios and design fires, and the strategy to derive design fire scenarios. Section 4 describes the strategy to derive design fires. Section 5 provides information on the types and characteristics of design fires, and items to consider for derivation. Section 6 includes an example of how the practice note can be used to derive design fires, using a low rise shopping centre for illustration. Section 7 lists the literature referenced for producing this practice note. Appendix A describes the mathematical relationships within event trees.

2 Limitations of This Practice Note

This practice note has been prepared as a guide to practitioners on derivation of design fire scenarios and design fires, for the purpose of enhancing consistency in the fire engineering industry. **The proposed methodology should not be claimed to be the only means of derivation.** This practice note should be used in conjunction with the International Fire Engineering Guidelines.

Whilst the design fire scenario derivation methodology has employed a risk based approach, this practice note was predominantly prepared for the derivation of design fires to be used in fire modellings or calculations in a deterministic analysis. Where a semi-probabilistic or probabilistic approach is to be employed, relevant guidance from the fire engineering literature should be consulted.

This practice note has been prepared under the regime of the National Construction Code of Australia and may not be 100% applicable under building regulatory regimes in other countries.

The data presented in this practice note was based on the information in fire engineering literature available to the working group at the time of preparation. It is the onus of the practitioners to make sure that the data are accurate, up to date, and applicable to specific projects with which the practitioners are involved.

This practice note does not address acts of terrorism, explosions or multiple occurrences of arson.

3 Design Fire Scenario

3.1 Introduction

Fire safety engineering analysis is by and large a mixture of deterministic and probabilistic analyses. These types of approaches are undertaken in engineering assessment processes at different levels. In analysing a design fire scenario, the most common approach is deterministic, and most commonly used computational tools are of this type. However, the identification of the design fire scenarios for the engineering analysis relies on a probabilistic approach, either explicitly or implicitly.

It has long been recognised that fire safety engineering design parameters are associated with uncertainties due to the complex nature of reality^[2, 3]. The number of possible fire scenarios in reality may approach infinity and it would be extremely difficult to base a fire safety engineering design on the analysis of all possible fire scenarios^[4, 5]. Instead, a limited number of typical, or so called “worst credible”, scenarios may be used to carry out the analysis^[1].

The term ‘fire scenario’ is defined as a qualitative description of the course of a fire (event) with time. A design fire scenario is a specific fire scenario of which the sequence of events will be quantified and a fire safety engineering analysis will be conducted^[4].

A design fire is a quantitative description of assumed fire characteristics within the design fire scenario. Design fires are part of design fire scenarios and are inseparable from the design fire scenarios. The determination of design fires is an important step in fire engineering analyses.

Although design fire scenarios and design fires are intrinsically related, a differentiation is made in the current document. This chapter focuses on the selection of design fire scenarios. Detailed discussions on the determination of design fires are given in Chapter 4.

Design fire scenarios and design fires are also closely related to building occupancy and the fire safety design issues, or the proposed Alternative Solutions. There is no design fire scenario or design fire that will fit all building occupancies or can be used to assess all Alternative Solutions. For the purpose of discussion in this note, the building occupancy and the Alternative Solutions that are dealt with in a fire engineering project are referred to as *design occupancy* and *fire safety design issues*.

3.2 Selection of Design Fire Scenarios

The selection of design fire scenarios is part of the Fire Engineering Brief (FEB) process as outlined in the IFEG. The design fire scenarios should be agreed by all stakeholders of the project.

A systematic approach to the identification of significant fire scenarios and the selection of design fire scenarios for quantitative analysis in fire safety design is documented in ATS 5387.2^[4], ISO/TR-13387^[6] and the SFPE Handbook^[7], where the selections of design fire scenarios and design fires are combined. In the current document the selections of design fire scenarios and design fires are discussed separately.

The selection of design fire scenarios depends on the building classification, project issues and the relevant fire safety subsystems installed in the building. For example, the sprinkler system installed in a high rise apartment building means that its design fire scenario will be different from that for a low rise building of the same classification without sprinklers. Generally, multiple design fire scenarios need to be analysed as a requirement for sensitivity studies^[1].

Based on the SFPE Handbook^[5] and ISO/TR-13387^[6], a procedure for the derivation of design fire scenarios is outlined below:

1. Identify the design occupancy and the fire safety design issues;

2. Identify all subsystems related to the fire safety design issues;
3. Identify all possible statuses of each and every subsystem relevant to the fire engineering assessment;
4. Quantify the associated probabilities;
5. Use an event tree to establish the possible scenarios;
6. Calculate the probability of each scenario;
7. Estimate the potential consequences of all the scenarios using engineering or expert judgement;
8. Use risk ranking and / or probabilities to select the design fire scenarios for analysis.

Whilst the quantitative evaluation of risk relies on the outcome of the fire scenario analysis, it may be possible to combine the event tree analysis and expert judgement in risk ranking to determine the fire scenarios for engineering assessment. Whether such a process should be undertaken entirely, or partially, for a specific project is to be determined by the project stakeholders. It may depend on the scale of the project and the nature of the design solutions. In case insufficient data or experience or expertise is available for expert judgement, the selection of fire scenarios may be based on probability of an event.

The base case design fire scenario would be a fire scenario in which all proposed fire safety measures in the trial fire safety design are assumed to operate and achieve their design objectives. Other design fire scenarios would be fire scenarios where one or a combination of the proposed fire safety measures are assumed to fail or cannot achieve their design objectives; these scenarios are likely to include low probability/high consequences fires.

3.2.1 Simplified Analysis

For simple projects it may not be necessary to go through all the above steps. When steps 1 and 2 have been undertaken, existing guidelines such as CIBSE Guide E^[8] can be utilised to determine design fires. This approach may be appropriate:

- When only minor non-compliances with the Deemed-to-Satisfy Provisions are addressed.
- For comparative assessments where layout of building and possible consequences are similar to a Deemed-to-Satisfy compliant design.

More complex projects may also be suitable for a simplified analysis; however this would depend on the issues being assessed and would require agreement from stakeholders.

3.2.2 Complex Projects – Event Tree Analysis

The approach to the selection of design fire scenarios outlined in the existing literature, such as ATS 5387.2^[4], ISO/TR-13387^[6] and the SFPE Handbook^[7], consists of a number of steps. The core of the design fire scenario selection process is the event tree analysis. It is through this analysis that probabilistic description and evaluation of events is carried out.

In the event tree, the initiating event, namely the start of a fire, is the cause of the subsequent events which are represented by the nodes that branch off the previous event. Each branch in the event tree represents a scenario. Each event in the event tree will have an associated probability of occurrence and consequence. These probabilities will help the risk ranking process through which the design fire scenario can be selected^[5]. Figure 3-1 is an example of an event tree. A more detailed description of event trees can be found in Appendix A.

The probabilities for each event can be determined based on published statistical data or can be determined by using fault tree analysis^[9].

Note that the Fire Initiation and Development and Control subsystem (Sub-system A^[1]) occupies a special place in the event tree in that its status, or nodes, represent the initiating events. Each node represents an initiating design fire which can also be regarded as the descriptions of the status of this particular subsystem. Like any nodes in the event tree, initiating design fires have associated probabilities of occurrence. In that sense, each design fire defines an event in the fire initiation subsystem. More comprehensive discussions of design fires are given in Chapter 4 of this document.

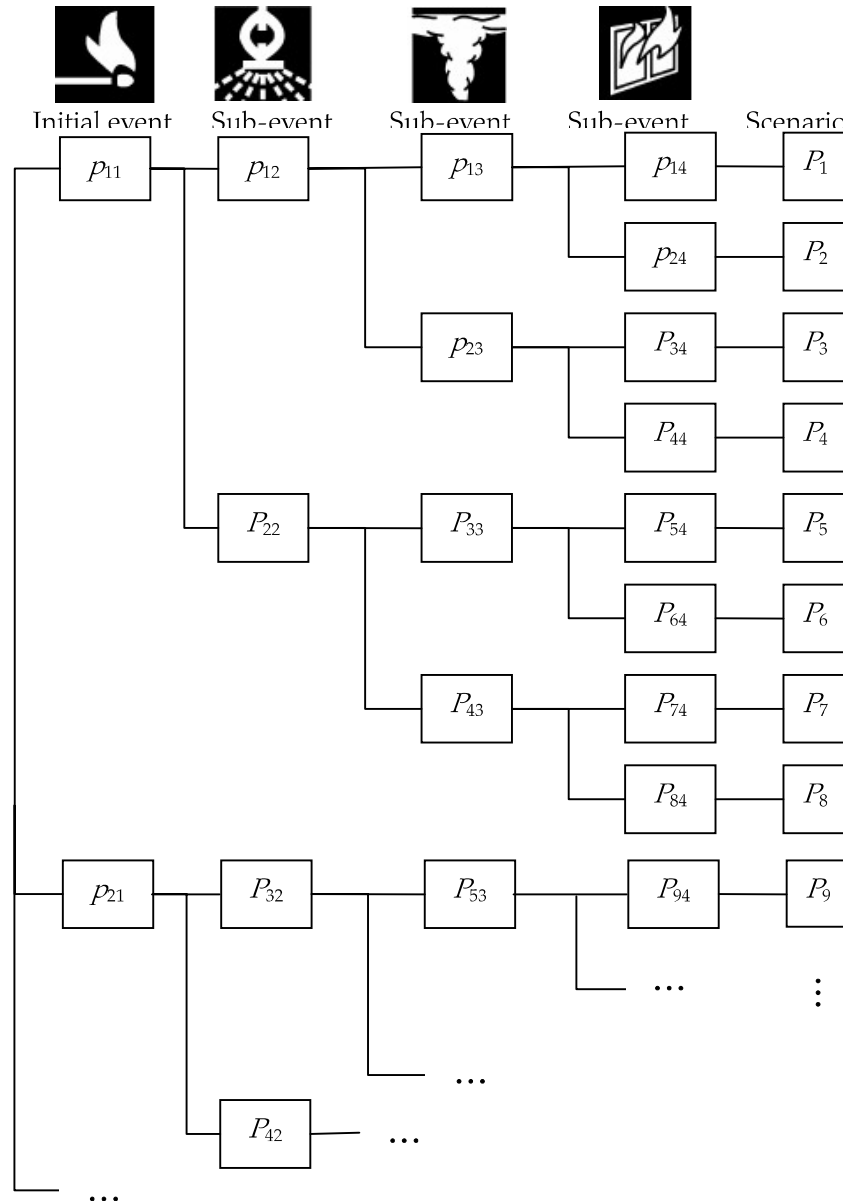


Figure 3-1: Example of an Event Tree¹

¹ “Sub-event” in the diagram means “subsequent event”

3.2.3 Risk Ranking

Risk ranking is an important step in the selection of design fire scenarios. Risk is defined as the expected loss, or the product of the probability of a scenario and the consequence of that scenario^[10]. For a particular scenario i ;

$$R_i = P_i C_i \quad (3-1)$$

where R_i , P_i and C_i are the risk, probability of occurrence and consequence of scenario i respectively.

It is seen that risk ranking requires not only the knowledge of probabilities associated with various possible scenarios, or the events that constitute scenarios, but also the knowledge of consequences of the scenarios, which is not usually *a priori* before the quantitative analysis is carried out. Engineering judgement may be employed in determining the possible consequences^[5]. If insufficient information or experience can be referred to, then risk ranking may be reduced to probability ranking and the scenario selection may be based on probability alone.

Fire incident statistics with reasonable qualities can be referred to as a source of information for identification of the initial set of possible ignition scenarios. More specifically, quality fire incident statistics can be used to determine (a) the most likely type(s) of ignition scenario; and (b) the most likely ignition scenario(s) with significant consequence.

The design fire scenarios can be determined on the basis of risk ranking. The scenarios with significant risks in the ranking or with high probabilities in the ranking should be considered for analysis.

3.3 Redundancy

Redundancy analysis examines the redundant measures of a trial design that essentially fulfils the same function. For example a smoke exhaust system may be activated manually, by detection or by sprinklers. It is not expected that each redundant component will deliver the exact same performance^[1].

Consideration should be made for redundancy in fire safety designs, particularly when the consequences of some of the scenarios may not be quantifiable for the risk ranking before the engineering assessment is carried out. Examination of redundancy can be carried out by rendering one or a combination of key fire safety systems to be ineffective in order to test the robustness of the design. It should however be noted that the safety margin can be relaxed in comparison to that used in the assessment of the trial fire safety design^[11].

Consideration of the following should be taken when determining if a redundancy analysis is required:

- Are there single points of failure?
- Is the consequence in case of failure comparable to a Deemed-to-Satisfy compliant design?
- Is the reliability of the system comparable to a Deemed-to-Satisfy compliant design?

If the risk is considered higher than a comparable Deemed-to-Satisfy compliant design or unacceptable, it can be lowered by reducing the probability of the scenario to occur (for instance through enhancing the reliability of key fire protection systems) or by modifying the fire protection systems to reduce the consequence. The IFEG^[1] states that 'Care and judgement should be used to avoid unnecessarily analysing events with a very low probability of occurrence, but where the scenario may have a very high adverse consequence, due consideration should be given if not for the primary analysis at least in the sensitivity studies'. It has been recognised that in the design of major commercial complexes it is better to attempt to reduce the probability of occurrence of catastrophic events than try to design for these events^[12].

3.4 Sensitivity

Sensitivity analysis measures the impact on the results of the fire engineering analyses by changing one or more key input variables. This is especially important if there is some doubt about their quantification or evidence that there is a heavy reliance on a particular fire safety measure. It allows the identification of those parameters that are most important to the outcome^[1].

3.5 Fire Brigade Intervention

A performance based Alternative Solution should account for, and facilitate, fire brigade intervention where it is deemed relevant to do so. In accounting for fire brigade intervention, fire fighters should be given a reasonable time to undertake search and rescue activities before conditions in the building or structure(s) become untenable or unsafe for fire fighters.

Consideration for fire brigade intervention and conditions against the tenability limit criteria for fire fighters needs to be evaluated at the anticipated arrival time. Given the nature and use of buildings, the model duration may also need to be extended to consider the time fire service personnel inside a building for search and rescue operations during which tenable conditions for fire fighters and structural stability may need to be maintained.

A performance based Alternative Solution should not use fire brigade intervention in isolation as a means or justification of the issues being addressed.

4 Design Fire Derivation

4.1 Introduction

This section illustrates the design fire derivation procedure. Whether a design fire is to be considered in a fire engineering assessment is dictated by the design fire scenario derivation procedure.

As illustrated in the previous chapter, a design fire constitutes the status of the Fire Initiation and Development and Control sub-system and is one of the determining factors of design fire scenarios. A design fire is characterised within the following sub-sections.

4.2 Design Fire Derivation Strategy

Figure 7-1 presents a recommended process for the derivation of design fires. Further illustrations of the process are presented in the subsequent sections.

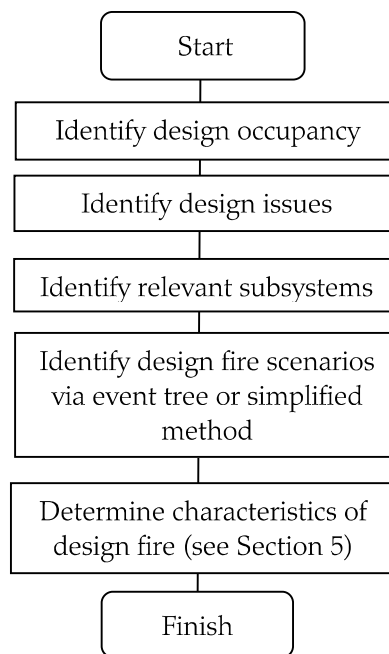


Figure 7-1: Design Fire Derivation Strategy

4.2.1 Identify Design Occupancy

Important items to consider here include:

- Building classification based on BCA classification
- Occupancy type
- Occupant characteristics
- Relevant hazards

4.2.2 Identify Fire Safety Design Issues

Important items to consider here include:

- Involvement of all relevant stakeholders
- Identification of applicable fire safety issues (i.e., issue relating to egress will result in a different fire scenario to an issue relating the structural capacity)

4.2.3 Identify Relevant Subsystems

Fire safety subsystems that could have an impact on the growth and development of fires should be identified. These subsystems typically include fire suppression or extinguishing systems, smoke control systems, and (failure of) building elements. Potential impacts of these subsystems on design fires are discussed in Section 5.7.4.

4.2.4 Determine Characteristics of Design Fire

See Section 5.

5 Characteristics of Design Fires

5.1 General

Design fires are usually characterised in terms of the following parameters:

- Location (e.g., at corner or middle of room, height of fire, near exit, in unoccupied room, in concealed space, or external),
- Type of fire or burning regime (e.g., smouldering, flaming or fully developed; fuel or ventilation controlled),
- Type and amount of fuel (material, configuration, fuel load ... etc),
- Radiative fraction,
- Soot and species (e.g., CO, CO₂, HCN, HCl etc) yields,
- Heat of combustion,
- Heat release rate (HRR) history,
- Interaction with other fire safety measures.

Other parameters such as HRR per unit area or volume, fuel ignition temperature, emissivity and fuel material chemical composition may be required as inputs to sophisticated fire models. An understanding of the building hazards will assist in determining relevant parameters.

All of the parameters listed above are interrelated. Some parameters are usually specified as functions of time^[4, 13]. The specifications of design fire parameters depend on the fire safety design issues at hand, building layout and the level of sophistication of fire simulation models used. Some of the design fire parameters are discussed in the following sections.

For the purpose of the present document, the burning behaviour of design fires can be categorised into two types; intervened and uninvolved. An intervened design fire will interact with other fire safety subsystems and its HRR will change according to the change in the status of other subsystems (see Section 5.7.4 and Figure 7-3).

Uninvolved design fires in this practice note refer to design fires that have not been subjected to any manual fire suppression (by occupants or fire brigade) or automatic fire suppression or change in mechanical ventilation conditions.

It is considered that in most cases an arson fire will be covered by the following process. Should the occupancy, contents or other building specifics result in a deliberately lit fire outside the design fire characteristics presented below, and this scenario is considered a likely event, a more detailed analysis may be required.

5.2 Location of Design Fire

The fire location is related to design occupancy and design issues. Variation of fire location may also be required as part of the sensitivity study in an engineering assessment. The selection of fire location can be aided by event tree analysis whereby the locations at which fires have either highest likelihood of occurrence or most adverse consequences may be selected. The selection list is likely to include, but may not be limited to^[14],

- Challenging fire – credible worst case scenario that will challenge the fire protection features of a building
- Blocked exit – fire located near primary exit

- Unoccupied room / concealed space
- Smouldering fire – in proximity to sleeping occupants
- Potential spread to neighbouring properties
- Fire source external to building

Moreover, precise fire source location in the room of fire origin may be required by some fire models to determine entrainment rate and detector or sprinkler activation time.

5.3 Type of Fire

Fire burning behaviour has been traditionally classified into smouldering, flaming and fully developed. With the sophistication of modern fire models, the need to distinguish flaming and fully developed fires in the design fire specification process is diminishing. However, smouldering fire is a special mode of burning and may need to be considered for certain design occupancies and fire safety design issues.

5.4 Type and Amount of Fuel

The first step to establish a design fire is to identify potential fuel and its form (gaseous, liquid and/or solid) in the design occupancy. The configuration of the fuel items is also an important parameter that may influence the burning behaviour.

5.5 Radiative Fraction

Radiative fraction of the heat released from fires depends on the type of fuel, combustion efficiency, soot concentration and the diameter of burning surface area. It may vary between 0.1 and 0.35^[15]. The lower bound represents clean fuel fires similar to alcohol fires whilst the upper bound represents smoky hydrocarbon fires where sooty smoke is released. Without further details on the characteristics of the fuel load, this fraction is typically assumed to be 0.3.

5.6 Soot and Species Yields and Heat of Combustion

The values of toxic species yields (e.g., CO and CO₂) and smoke/soot yield for a wide range of commonly encountered combustible materials are presented in the SFPE Handbook^[16]. Soot yield is a critical input to fire models for predicting visibility through smoke. However, there is little validation of such predictions of smoke visibility for real fires in large compartments. Therefore visibility predictions for real-scale fires using fire models should be treated with caution, using engineering judgement.

In particular, when these soot yield "data" are used in CFD simulations, the recent research findings^[17] as summarised below should be taken into account.

"The study showed that FDS significantly over-predicted smoke concentrations compared to the experiments. Exploratory findings indicate that soot deposits to the ceiling above the plume may be as high as 37 percent of the soot produced. Current versions of FDS do not account for this substantial soot loss.

Another important finding of this work was a large discrepancy between reported small-scale soot yields and yields from larger scale fires. Commonly used soot yields in the literature for a range of fuel materials have been obtained for small fires conducted in bench-scale calorimetry apparatus. This work has shown that measured soot yields for 100 kW fires range from 2 to 5 times smaller than the reported values. This finding is consistent with other data in the literature; however, there are minimal published studies that address this issue."

The values for yields of CO and CO₂ and smoke/soot for a few selected commonly encountered combustible materials are presented in Table 7-1. These values are taken from the SFPE Handbook^[16, 18] and represent data measured in the bench-scale ASTM E2058 fire propagation apparatus at FM Global, under well ventilated conditions with the sample material exposed to a constant external radiant heat flux. The conditions such as ventilation and exposure of materials to radiant flux in real-scale fires can vary substantially from those in the bench-scale measurement, and will affect the soot and species yield values.

The heat of combustion, ΔH_c , is the energy released as heat when a compound undergoes complete combustion with oxygen under standard conditions. The values for a selected few commonly encountered combustible materials are presented in Table 7-1. These values are taken from the SFPE Handbook^[18], the Fire Protection Handbook^[19] and the Fire Engineering Design Guide^[20]. The user of this practice note should always refer to the latest edition of the literature for the most current data.

The heat of combustion is one of the factors required to quantify the pre-and post-flashover fire. With other factors, it can be used to determine the total energy in the fuel (MJ), the ventilation controlled heat release rate, whether flashover occurs or not, the equivalent time of fire exposure and the duration of the burning period.

In most cases it is considered reasonable to use average values to cover the likely contents. However; in situations where the contents are not well mixed, the values for the worst-case contents should be used.

In view of the above discussion, caution and good engineering judgement should be exercised in prescribing species yield values as inputs to fire models for prediction of parameters such as visibility through smoke.

Table 7-1: Species Yields and Heat of Combustion

Material	CO ₂ yield (g/g)	CO yield (g/g)	Soot Yield (g/g)	ΔH_c (MJ/kg)
Gasoline (Heptane/ Octane)	2.85	0.011	0.038	43.7 - 46.8
Kerosene	2.83	0.012	0.042	43.2 - 46.4
Wood / cellulose	1.3	0.004	0.015	16 - 22.5
PMMA	2.12	0.01	0.022	24.9
Polyethylene	2.76	0.024	0.06	43.3 - 47.7
Polystyrene foam	2.33	0.06	0.18- 0.21	39.7 - 42.2
Polypropylene	2.79	0.024	0.059	34.3 - 46.2
PVC	0.46	0.063	0.078- 0.172	16.4 - 26.8
Polycarbonate	1.5	0.054	0.112	29.7 - 31.5
Polyester	1.6	0.07	0.09	23.8
Polyurethane foam	1.5	0.01- 0.04	0.013- 0.23	22-28.64
Nylon	2.06	0.038	0.075	28-31.7

5.7 Heat Release Rate

One of the most important parameters to define a design fire is the HRR which is often specified as a function of time^[21]. Figure 7-2 illustrates an idealised HRR history for a compartment fire, from ignition through to complete burnout.

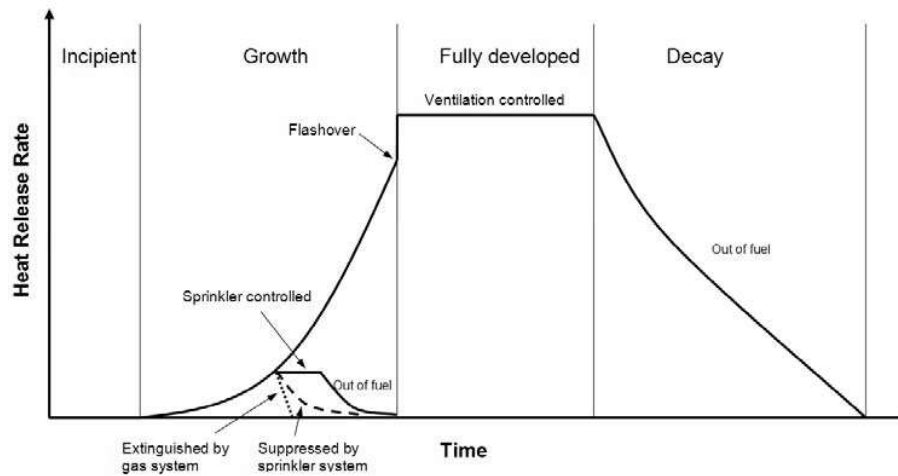


Figure 7-2: Idealised Heat Release Rate Curve

Note that fire brigade intervention has been ignored in the above curve. The resultant HRR may change at any stage of the fire curve due to fire brigade intervention.

The process of determining the HRR can be described by Figure 7-3.

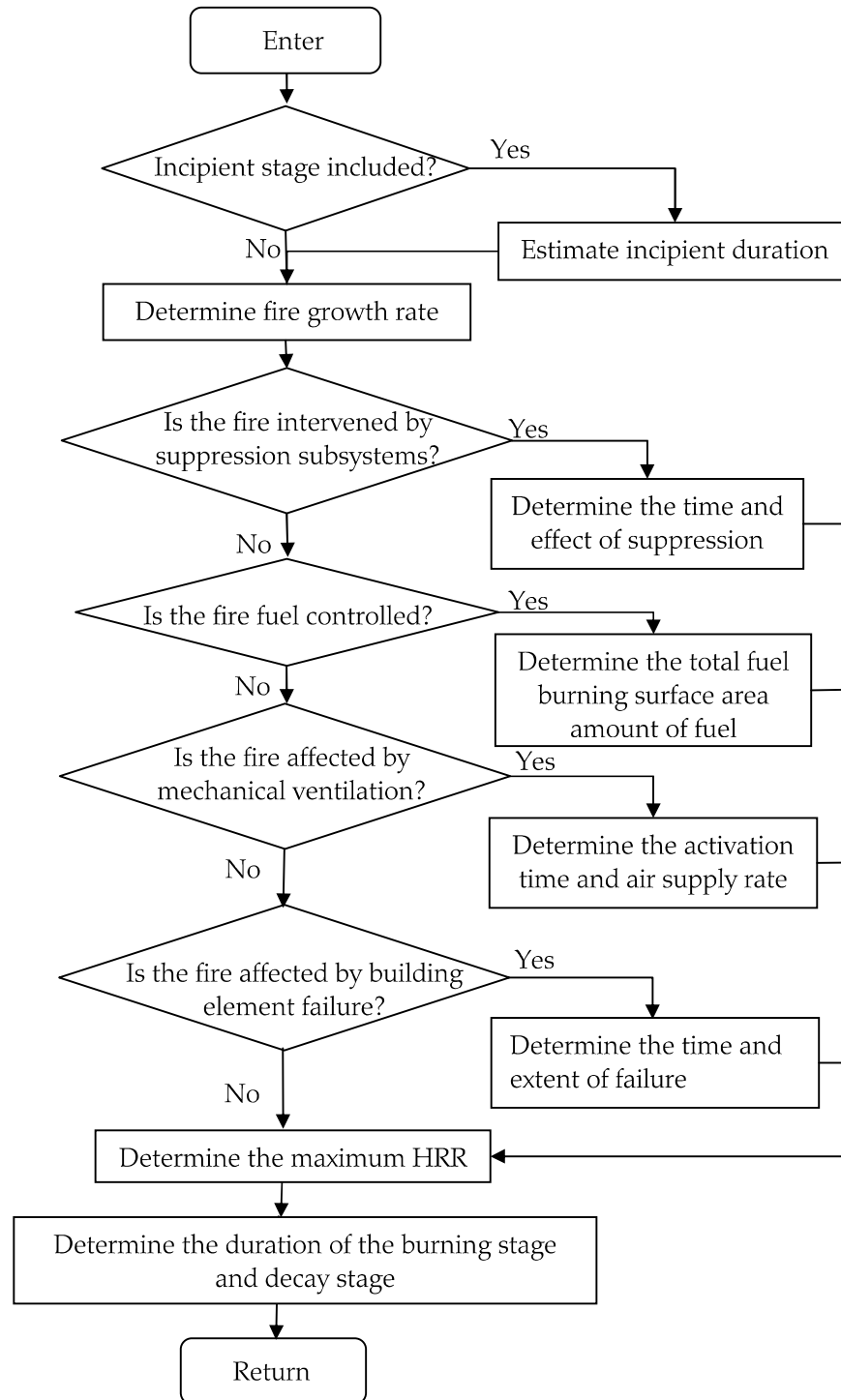


Figure 7-3: Determination of Heat Release Rate of Design Fires

5.7.1 Incipient Stage

The incipient stage is difficult to quantify. It depends on the ignition source, type of combustibles and ventilation conditions. Whether to include the incipient stage in the specification of HRR for a design fire is dictated by the design issue and the design occupancy. For example, in a large space where smoke control system capacity is a design issue, inclusion of the incipient stage is not critical. However, in a hospital where early detection is crucial, a design fire with incipient phase may be considered in one of the design fire scenarios.

5.7.2 Growth Stage

If large scale experimental data of HRR versus time is available and is deemed to be appropriate for the scenario being analysed, it can be used to describe the fire growth stage of the design fire. The HRRs of some furniture and appliances have been documented in the SFPE Handbook^[22].

When specific information about the combustible items is not available, the HRR of the fire growth phase is typically modelled using a t-squared growth rate, which depends on the type of combustibles and their configuration, e.g., horizontally distributed or stacked. The t-squared fire growth can be thought of in terms of a burning object with a constant HRR per unit area in which the fire is spreading in a circular pattern with a constant radial flame speed^[20].

The fire growth rates of various commonly encountered configurations of combustible materials are well documented in literature including but not limited to:

- BS EN 1991-1-2:2002^[23];
- PD 7974-1:2003: Application of fire safety engineering principles to the design of buildings. Part 1: Initiation and development of fire within the enclosure of origin (Sub-system 1)^[13];
- BS 9999:2008^[24];
- CIBSE Guide E: Fire Engineering^[8]; and
- NFPA 92^[25].

Typical growth rates for t-squared growth fires, as summarised from the above documentation are listed in Table 7-2. This table provides a general guide only and does not rule out other possible growth rates. The fire safety engineer should examine the fuel properties, ventilation conditions and even the possible ignition source to determine what is the appropriate growth rate.

Table 7-2: Fire Growth Rates for Typical Occupancies

Building Occupancies	Fire t-squared Growth Rate (α)
Residential	Medium
Hotel (Room)	Medium
Office	Medium
Retail	Fast
Kitchen	Fast
Picture gallery	Slow
Display area	Slow to medium
Storage and warehousing	Ultrafast
Teaching laboratories	Fast
Workshop	Medium to Fast

Building Occupancies	Fire t-squared Growth Rate (α)
Hospital (Room)	Medium
Library	Fast
Classroom of a school	Medium
Gymnasium	Medium
Assembly hall seating	Medium to Fast

Whether the condition inside the burning enclosure attains flashover depends on the enclosure geometry, HRR and ventilation condition^[15]. Modern sophisticated software packages are now capable of predicting if, and when, flashover will be attained and even the consequence of flashover in terms of variation in the HRR due to change of ventilation conditions with reasonable accuracy.

Fire growth rate may be simulated using sophisticated fire models with adequate sub-models for pyrolysis, flame and phase combustion. Caution, however, needs to be taken as fire growth models are not yet mature and validated to a stage where they can reliably predict the HRR of real fires. For most applications it is therefore recommended that the fire growth rate is determined by the user via the input variables.

Estimation of the HRR of a fuel controlled fire using Computational Fluid Dynamics (CFD) models such as Fire Dynamics Simulator (FDS) must be considered wisely because the model output is sensitive to minor changes in the input properties of bounding surfaces^[26].

5.7.3 Fully Developed Stage – The Maximum Heat Release Rate of Unintervened Design Fires

Unintervened design fires in this practice note refer to design fires that have not been subjected to any manual fire suppression (by occupants or fire brigade) or automatic fire suppression (by fixed fire suppression systems) or a change in mechanical ventilation.

Without intervention, fires may spread and continue to grow, depending on the availability of fuel and oxygen. At the early growth stage a fire is likely to be fuel controlled, whereas at the fully developed stage a fire is likely to be ventilation controlled if there is sufficient fuel available for combustion.

In the fully developed stage, the HRR may be assumed to attain a constant (maximum) value due to either fuel controlled or ventilation controlled burning. For unintervened ventilation controlled fires, there are empirical formulas in fire engineering literature for estimating the maximum HRR that can be supported by the ventilation available^[20]. The peak HRR of unintervened ventilation controlled design fires is recommended to be the maximum HRR estimated from these empirical formulas.

For unintervened fuel controlled fires, the peak HRR of the fire would depend on the maximum possible burning surface area and the HRR per unit surface area^[22]. Fuel composition and configuration (local ventilation) also influences the peak HRR of fuel controlled design fires. Fire science and engineering literature should be consulted on the burning characteristics of individual fuel items, such as furniture pieces, cars, stored product pallets, etc. Alternatively bench-scale to full-scale fire tests can be carried out to capture the HRR and species yield data of items that have not been documented in the literature.

The fire safety practitioners are recommended to consider the following when deriving unintervened fuel controlled design fires:

- Fire load density and distribution of fire load within the enclosure
- Characteristics of fuel packages (such as flame spread rate, HRR, percentage of heat loss through radiation, critical heat flux at ignition etc.) within the enclosure
- Arrangement of fuel packages (e.g. are packages stacked on top of each other and spatial distribution of fuel packages)
- Effect of radiant heat flux feedback from hot smoke layer

The Building Code of Australia (BCA) Deemed-to-Satisfy Provisions require the smoke exhaust rates for smoke hazard management purposes to be determined based on a peak heat release rate of 5 MW, 10 MW or 15 MW depending on the classification of the building^[27]. These may not be appropriate for every situation. If these fire sizes are to be used, justification of why they are considered appropriate for the design should be provided and agreement sought from stakeholders.

5.7.4 Impact of Fire Safety Systems

5.7.4.1 The Maximum Heat Release Rate of Intervened Design Fires

Fire suppression systems, either manual or automatic, could alter the HRR of a design fire. The maximum HRR can be determined by the time and effect of the system activation.

Manual intervention by occupants involves the use of devices such as fire hose reels and portable fire extinguishers. Manual intervention by the brigades may also occur at a later stage of the fire by fire hydrants, foam systems etc. When developing design fires on a deterministic basis, manual intervention is recommended to be ignored. If a probabilistic approach is applied, manual suppression can be considered and modelled by reducing the probability of larger fires occurring.

The most common automatic intervention system within buildings is a sprinkler system. Other automatic intervention systems include gas suppression systems, water mist systems and fire fighting foam systems etc.

The consequence of the intervention by suppression subsystems may be categorised as listed below and shown in Figure 7-2:

1. Controlled by a fire suppression system, i.e. the HRR remaining constant following sprinkler activation; or
2. Suppressed by a fire suppression system, i.e., the HRR decreasing following sprinkler activation;
3. Controlled or suppressed by fire brigade.

A sprinkler controlled fire is often defined by a constant HRR following the activation of sprinklers. The peak HRR is typically determined from the fire growth rate and time of the sprinkler activation using computer software and the following parameters^[28-31]

- Rate of fire growth (e.g., fast or ultra-fast t^2).
- Radial distance between the fire and the sprinkler(s). To provide a worst credible estimate for sprinkler activation time it is recommended that the fire is located in the middle between sprinkler heads.
- Sprinkler head activation temperature and the RTI value.
- Number of heads required for sprinkler control. It is recommended that this is based upon statistical data for the type of occupancy. If a deterministic approach is undertaken,

with appropriate safety factors applied, it is considered reasonable to use the number of heads controlling 90 % of the fires. This will determine if the radial distance to the first, second or third row of sprinkler is appropriate to use for sprinkler activation calculations.

- Height of base of fire to ceiling. For occupancies with the majority of the fuel load located above the floor level it may be appropriate to raise the base of the fire. If the configuration of fuel load is not known, the fire should be located at floor level.
- Location of fire – e.g. whether the fire is located in the middle of the room or located close to a corner / wall. Potential for the fire to be shielded should also be considered.
- Any heat transfer loss from sprinkler bulb to the sprinkler pipework, i.e. C-factor.
- Ambient temperature within area protected by the sprinkler system.

An automatic sprinkler system that is correctly designed is intended to control or suppress a fire. In many instances, the fire size will be reduced or suppressed following sprinkler activation. If specific data is not available or shielded fires are likely, it is recommended to assume that a sprinkler system controls the fire and that the fire remains at the fire size reached at the time of sprinkler activation for the purpose of developing a design fire. Otherwise, based on the reliability of modern sprinkler systems it is considered reasonable to assume suppression or a reduction in fire size. This is particularly relevant for systems such as storage (previously called ESFR) sprinkler systems that have been designed to suppress the fire. In some circumstances, such as spaces with very high ceiling heights (e.g. tall atrium voids) the sprinkler system may not control the fire size. The maximum fire size should then be determined based upon fuel and ventilation conditions.

There are several computer programs and empirical models available to predict sprinkler activation time and fire size upon sprinkler activation. The sprinkler activation time is the time when the sprinkler bulb reaches the activation temperature. Convective heat transfer from the gases in the ceiling jet to the sprinkler bulb is the primary heat transfer mechanism. However, for a small enclosure where the ceiling jet is immersed within a hot upper smoke layer, additional heat transfer from the hot upper layer to the sprinkler bulb also occurs. There are also heat transfer losses from the sprinkler bulb to the sprinkler pipework^[31]. Radiant heat transfer during the early stages of a fire, when sprinkler activation is expected, is generally neglected^[28].

The most appropriate model to use will depend on the building being assessed. An important factor is the geometry of the area being protected by sprinklers. For an enclosed room the upper hot layer will significantly impact on the time for sprinkler activation. For enclosed rooms the use of equations developed for unconfined ceilings may therefore significantly over-estimate the time for sprinkler operation^[31].

The location of the sprinkler below the ceiling should also be considered. Some models assume that the sprinkler head is located at the highest temperature and velocity of the ceiling jet while others considers the actual location of the sprinkler head below the ceiling. Sprinkler activation models are generally not developed for flush mounted or recessed sprinkler heads^[32].

It should also be noted that experiments indicate the sprinkler activation time is hard to predict when the sprinkler head activation temperature is close to the ceiling jet temperature^[30].

Consideration of ceiling obstructions such as beams should also be taken into account, as they may delay sprinkler activation.

5.7.4.2 Impact of a Smoke Control System

The impact of a smoke control system on the HRR must be considered during the design process because additional air provided by a smoke control system could potentially increase the rate of air entrainment into a fire plume. Research has shown that the burning rate may be increased by a factor of two or three, which could have an impact on the HRR^[34]. In tunnels, the HRR of a heavy goods vehicle could increase in value by a factor of 4 to 10 depending on the ventilation flow rate^[34].

Examples of smoke control systems that could have an impact on the HRR include, but not limited to:

1. Activation of longitudinal jet fans in tunnels to prevent back-layering;
2. High velocity make-up air near the fire origin.

If Storage Sprinklers are installed in the building to provide fire suppression in high challenge fire risks, special consideration must be given to the smoke control system, if installed. This sprinkler system has special design requirements and limitations in respect to the building structure and the system application may potentially have an impact on the smoke control system, i.e. delaying the activation time of smoke control system. Similarly, activation of the smoke exhaust system may negatively impact on the sprinkler system.

5.7.5 Impact of Building Element Failure

Building element failure may alter the HRR of a fire. A typical building element failure is window glass breaking. The consequence of this is the creation of additional ventilation which increases the HRR of ventilation controlled fires. In other cases, such as failure of a fire door, additional fuel may be involved in the fire development.

Depending on the sophistication of the models used for fire simulation, if separate models have to be used to predict window breaking time and extent, then the specification of the change of ventilation boundary condition relies on an iterative approach. A trial run of a fire model may be needed to evaluate time and extent of failure. Then the impact on the HRR can be estimated and the design fire modified for the subsequent fire simulations.

5.7.6 Duration of Burning Stage

The fully developed fire is most important when considering property protection and structural stability. During this stage the fire is usually ventilation controlled. The duration depends on the total amount of fuel and the available ventilation. Time temperature curves and empirical calculations are available to determine the duration of the burning stage.

5.7.7 Decay Stage

The requirement to assess the decay phase is dependent on the design issue. The fire duration may need to be determined to cover the required safe egress time, structural stability of the building or time for fire brigade intervention, with an adequate and appropriate margin.

Decay occurs as the fuel becomes consumed, and the HRR declines. Normally this is assumed to being when 70-80 % of the fuel has been consumed^[35]. The fire may change from ventilation controlled to fuel controlled during this period. So far, rates of decay of temperature can only be established empirically or by making conservative or highly idealized assumptions^[22].

6 Example Application on a Low Rise Shopping Centre

The building is a single storey retail mall with a basement level carpark. The building is a large isolated building greater than 3,500 m² of Type C construction with Deemed-to-Satisfy compliant perimeter access. The building does not exceed 18,000 m² in floor area nor 108,000 m³ in volume.

The retail area contains a number of speciality shops < 1,000 m² in area with one major tenancy > 2,000m² in area. The shops are connected by a mall with a number of kiosks within the mall. See Figure 6.1. The basement carpark contains more than 40 vehicles and is connected to the retail level by a travelator separated at basement level by drencher protected glass.

The building is fully sprinkler protected on both levels. The major tenancy and the mall are provided with automatic smoke exhaust systems, activated by smoke detectors installed in accordance with AS/NZS 1668.1. Basement level is provided with mechanical carpark exhaust ventilation only.

BCA Deemed-to-Satisfy non-compliances to be addressed are:

- Extended travel to point of choice, nearest exit and between alternative exits in the retail mall, major tenancy and carpark.
- Engineered smoke exhaust rate and no smoke baffle in the major tenancy and the mall.
- Glazed lobby between retail / carpark – i.e. lack of fire separation between classifications.

For this stage of the Practice Note, the event trees are provided as a guide to the process only. Therefore, the quantification of probabilities has not been included.

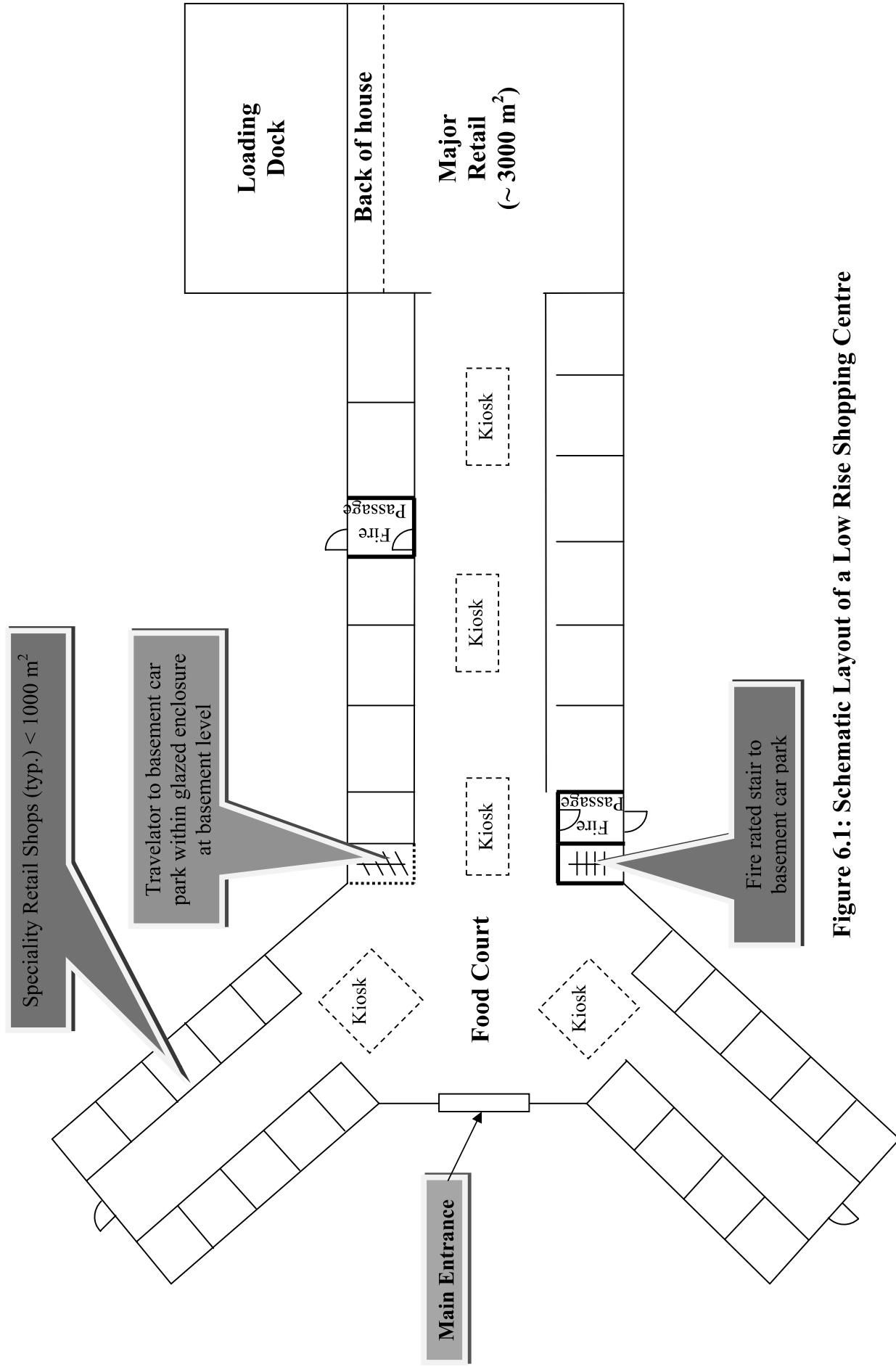


Figure 6.1: Schematic Layout of a Low Rise Shopping Centre

Table 7-3: Low Rise Shopping Centre Example

	Egress	Smoke exhaust	Compartmentation
Step 1 – identify design occupancy	Class 6 retail and Class 7a carpark.		
Step 2 – identify design issues	Extended travel to point of choice, nearest exit and between alternative exits in the retail mall, major tenancy and carpark	Engineered smoke exhaust rate and no smoke baffle in major tenancy and mall	Glazed lobby between retail / carpark
Step 3 – identify relevant subsystems	A (fire initiation, development and control), B (smoke development, spread and control), D (fire detection, warning and suppression), E (occupant evacuation and control) and F (Fire Services intervention)	A (fire initiation, development and control), B (smoke development, spread and control), D (fire detection, warning and suppression), E (occupant evacuation and control) and F (Fire Services intervention)	A (fire initiation, development and control), C (fire spread, impact and control) and D (fire detection, warning and suppression)
Step 4 – identify design fire scenarios	Event tree, see Figure 7-4 and Figure 7-5	Event tree, see Figure 7-4	Event tree, see Figure 7-6
Step 5 – determine characteristics of design fire			
Step 5a – location	Major – centre of tenancy and corner of tenancy Mall – in a speciality shop and middle of mall Carpark – centre of carpark	Major – centre of tenancy, and corner of tenancy (blocking exit) Mall – in a speciality shop and mall food court (main exit blocked) -	- - Carpark – adjacent to travelator
Step 5b – type of fire	Flaming t^2 growth until sprinkler activation Redundancy (sprinkler failure) – t^2 growth to peak HRR	Flaming t^2 growth until sprinkler activation Redundancy (sprinkler failure) – t^2 growth to peak HRR	Flaming t^2 growth until sprinkler activation Redundancy (sprinkler failure) – t^2 growth to peak HRR

	Egress	Smoke exhaust	Compartmentation
Step 5b – type & amount of fuel	Retail – mix of plastic and cellulosic materials up to 1300 MJ/m ² Carpark – car fire up to 200 MJ/m ²	Mix of plastic and cellulosic materials up to 1300 MJ/m ²	Car fire up to 200 MJ/m ²
Step 5c – radiative fraction	0.3	0.3	0.3
Step 5d – soot & species yields & heat of combustion	Retail – average value based on mix of plastic and cellulosic materials; CO ₂ – 1.8 g/g CO – 0.04 g/g Soot – 0.06 g/g ΔH_c – 30 MJ/kg Car – average value based on mix of plastic materials and gasoline; CO ₂ – 2.0 g/g CO – 0.04 g/g Soot – 0.08 g/g ΔH_c – 34 MJ/kg	Average value based on mix of plastic and cellulosic materials; CO ₂ – 1.8 g/g CO – 0.04 g/g Soot – 0.06 g/g ΔH_c – 30 MJ/kg	Average value based on mix of plastic materials and gasoline; CO ₂ – 2.0 g/g CO – 0.04 g/g Soot – 0.08 g/g ΔH_c – 34 MJ/kg

	Egress	Smoke exhaust	Compartmentation
Step 5e – heat release rate	Retail – <ul style="list-style-type: none"> • no incipient growth • fast t^2 growth • extinguished by sprinkler activation • no impact from the smoke exhaust • no building failure • HRR decay based on sprinkler activation • redundancy – fast t^2 growth to peak HRR based on available fuel Carpark – <ul style="list-style-type: none"> • no incipient growth • medium t^2 growth • controlled by sprinkler activation to one car • no building failure • HRR constant until occupant egress and fire brigade arrival • redundancy – fast t^2 growth to peak HRR based on available fuel 	<ul style="list-style-type: none"> • no incipient growth • fast t^2 growth • extinguished by sprinkler activation • no impact from the smoke exhaust • no building failure • HRR decay based on sprinkler activation • redundancy – fast t^2 growth to peak HRR based on available fuel 	<ul style="list-style-type: none"> • no incipient growth • medium t^2 growth • controlled by sprinkler activation to one car • no building failure • HRR constant until occupant egress and fire brigade arrival • redundancy – fast t^2 growth to peak HRR based on available fuel

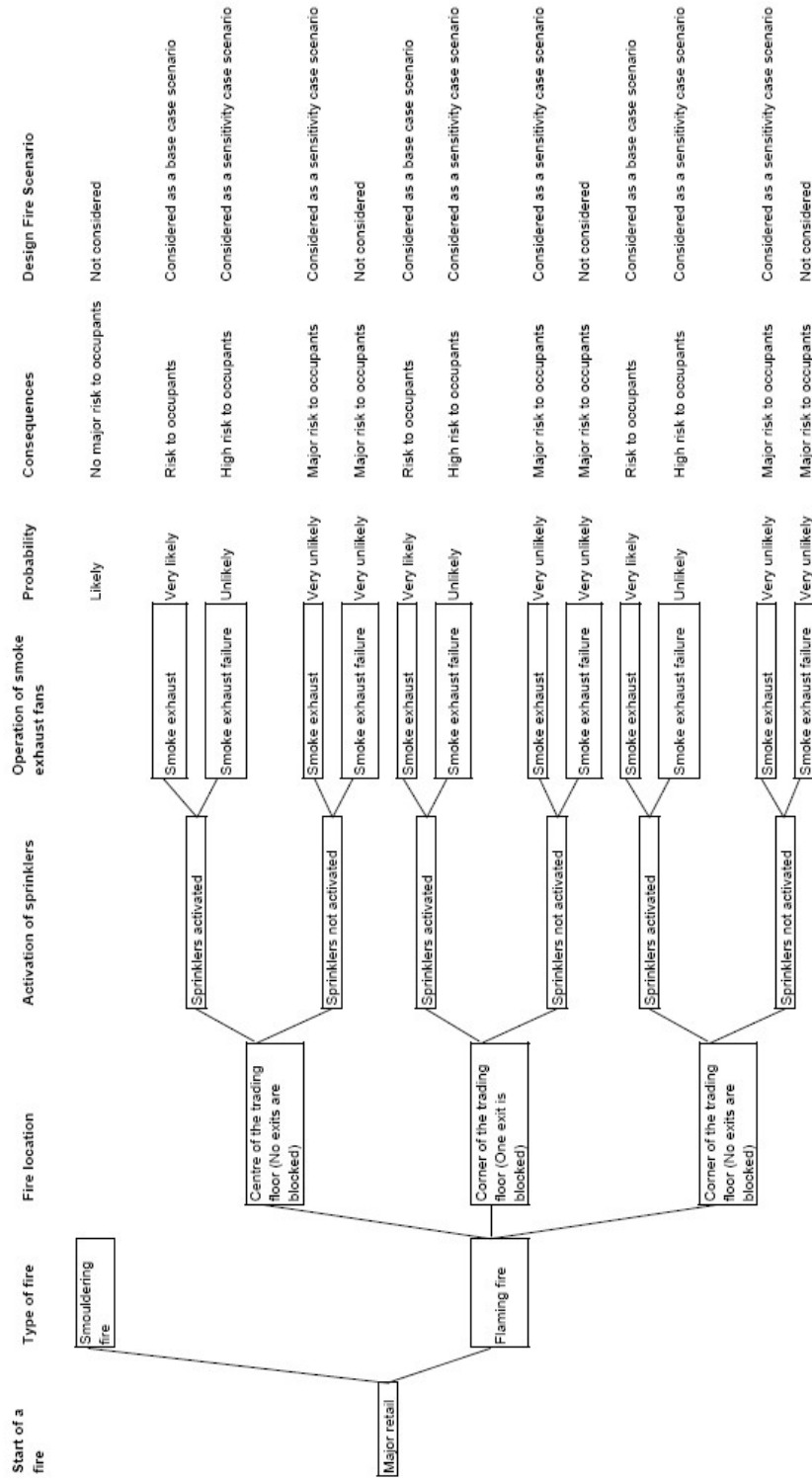


Figure 7-4: Event Tree in Major Retail Tenancy

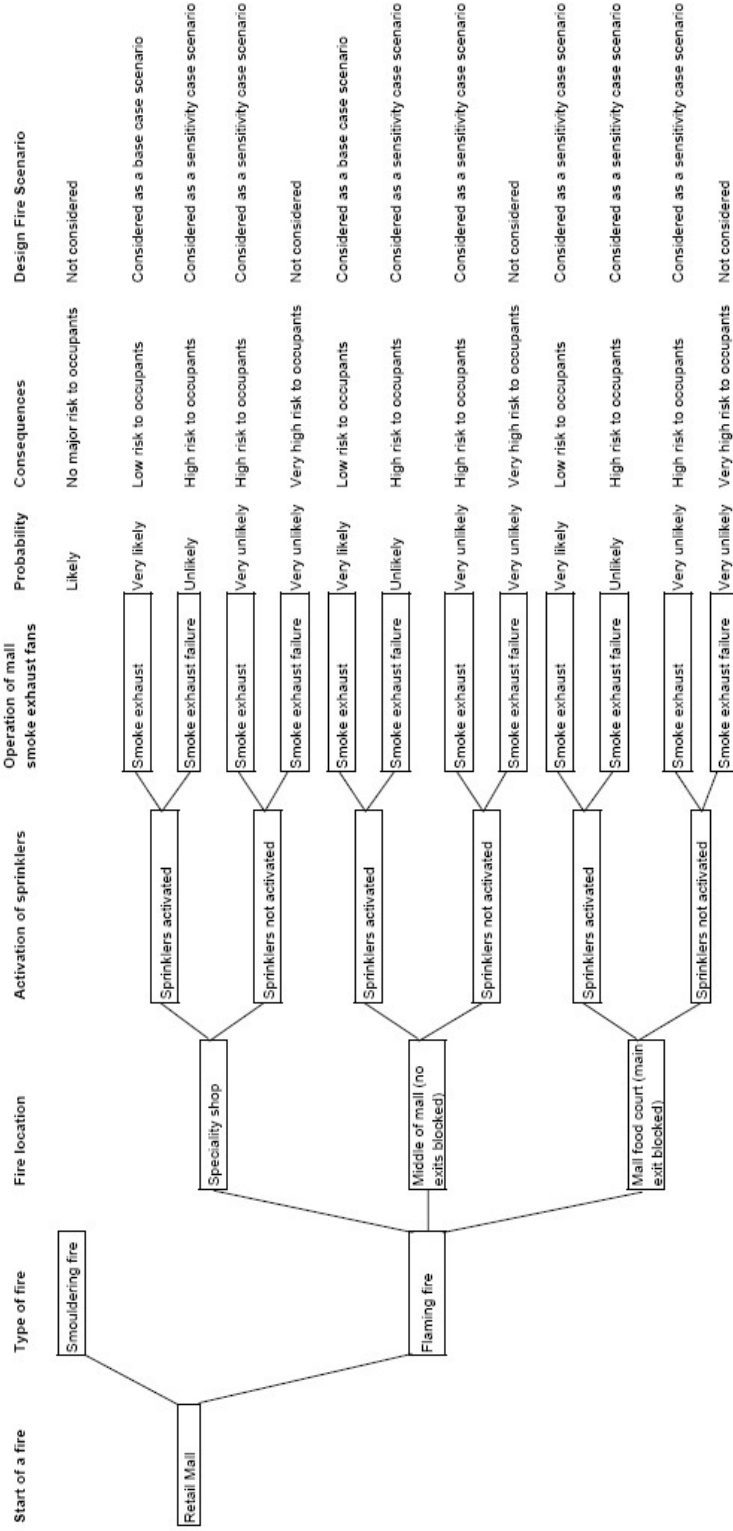


Figure 7-5: Event Tree in Mall

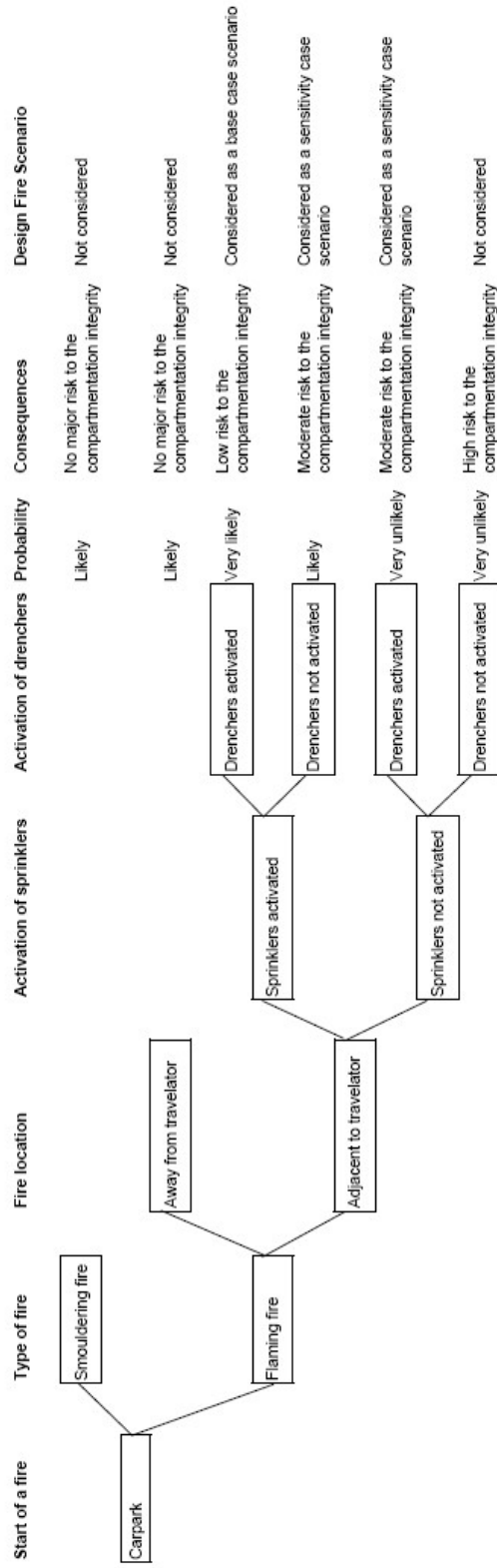


Figure 7-6: Event Tree in Carpark

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Appendix A Event Trees

In fire safety engineering analysis, the events in the event tree can be associated with the fire safety subsystems as described in the IFEG. The status of a subsystem defines an event, or a node, in the event tree (see Figure 2-1), and each event has the associated probability of attainment, p_{ij} ($i=1, 2, \dots, m_j$, and $j=1, 2, \dots, N$), where i and j are indices of a node, m_j is the number of possible status of the j th subsystem and N is the total number of subsystems involved. The probability of a scenario P_k ($k=1, 2, \dots, M$) can be calculated by:

$$P_i = \prod_{\text{All } k, j \text{ in the } i\text{th branch}} p_{kj} \quad (\text{A-1})$$

where M is the total number of scenarios and

$$M = \prod_{j=1}^N m_j \quad (\text{A-2})$$

In the event tree, as depicted in Figure 3-1, the subsequent events represent the outcomes of the bi-valued subsystems, or the subsystems that attain either the status of operation or failure, with associated probabilities. The probability of operation is also referred to as reliability. If the reliability of a subsystem is independent of the status of its predecessor or precursor, some of the probability values at the same level of the event tree may be equal. For example, it is possible that:

$$p_{13} = p_{33} \quad \text{and} \quad p_{23} = p_{43} \quad (\text{A-3})$$

Furthermore:

$$p_{13} + p_{23} = p_{33} + p_{43} = 1 \quad (\text{A-4})$$

Generally, Eq (A-3) may not hold and the status of a subsystem may depend on the status of its predecessor and so may the probabilities. For example, if the sprinkler subsystem has successfully suppressed a fire, the probability of the fire spreading to adjacent compartments diminishes.

It is possible for a subsystem to have more than two outcomes. For example, the interaction between a fire and a sprinkler subsystem may be suppression, control or failure. Each of these outcomes will define a scenario and have the associated design fire and probability.

Generally, the sum of the probabilities of all possible status of a subsystem should be unity:

$$\sum_{i=1}^{m_j} p_{ij} = 1 \quad (\text{A-5})$$

For the entire event tree, the following constraint must be satisfied

$$\sum_{k=1}^M P_k = 1 \quad (\text{A-6})$$

Equations (A-5) and (A-6) can be used to verify the event tree analysis.