Fire Safety Design Guidelines for Federal Buildings

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EXECUTIVE SUMMARY

Building codes in many countries around the world are shifting from prescriptive-based to performance-based due to economic and social reasons as well as a result of progress in fire safety technology and the development of engineering tools that are required to implement such codes. The approach used to develop performance-based codes follows a transparent, hierarchical structure in which there are usually three levels. The top level objectives usually state the functional requirements and the last level the performance criteria. Usually one middle level exists but more levels can be used in this hierarchical structure depending on the complexity of the requirements. The middle level outlines the fire safety design guidelines that must be used to satisfy the objectives.

The success of performance-based codes depends on the ability to establish the necessary fire safety design guidelines along with the performance criteria that are verifiable and enforceable.

The present study is part of a joint research project of the National Fire Laboratory, Institute for Research in Construction, National Research Council of Canada, partially funded by the Department of National Defence and Public Works and Government Services Canada. The purpose of the project is to develop fire safety design guidelines that can be used for the design of fire protection systems in Canadian federal buildings. These design guidelines will allow for the design of flexible and cost-effective fire protection systems without compromising the safety of the occupants.

The fire safety design guidelines contained in this document are based on the extensive literature survey on performance-based regulations undertaken at the National Fire Laboratory by Hadjisophocleous, Benichou and Tamim (1996), the New Zealand Design Guide (1994), the Australian Fire Engineering Guidelines (1996), the British Standards Institute Draft Code of Practice (1994), and the Nordic Building Regulations (1994). The document also provides guidance to designers in applying the fire safety design guidelines in order to protect building occupants and property from undesirable fires.

In addition, this document presents the performance criteria that can be used in designing fire protection systems in buildings and the models used to determine whether the design criteria are met by the proposed designs. The models are presented along with their limitations and availability. Furthermore, the policies and procedures used for fire safety management are also examined.

NOMENCLATURE

A_e	=	Area of an enclosing rectangle containing all of emitting openings, m^2
A_f	=	Area of the compartment floor, m^2
A_{fire}	=	Area of fire, m^2
A_o	=	Area of openings, m^2
A_{st}	=	Cross sectional area of the steel section, m^2
A_t	=	Surface area of the compartment including openings, m^2
A_T	=	Total area of the compartment enclosing surfaces, m^2
c	=	Specific heat capacity of the material, kJ/kg·K
c_i	=	Specific heat of insulating material, J/kg °C
c_p	=	Specific heat of gas at constant pressure, kJ/kg·K
c_{st}	=	Steel specific heat, J/kg °C
C_w	=	Pressure coefficient
CF	=	Conversion factor, min/MJ/m^2
CO(ppm)	=	Concentration of carbon monoxide in parts per million
Con_{co}	=	Concentration of carbon monoxide, kg/m^3
C_1	=	Radiation reduction factor
C_2	=	A value of 0.5 for sprinklered buildings and a value of 1.0 for all others
C_3	=	Importance factor
C_4	=	Proportionality constant for the detector
C_5	=	A factor
d	=	Distance between the fire and the detector, m
d_l	=	Distance between the incident light source and the point where the effective intensity is measured, m
D	=	Effective diameter of the fire source, m
D_m	=	Mass optical density, m^2/g
D_o	=	Occupant density, persons/m^2
E	=	Effective intensity, lumens/m^2
F_c	=	Actual flow of occupants, persons/s
F_f	=	Facade factor
F_s	=	Specific flow, persons/m·s
G	=	Length of the stair tread, m
g	=	Acceleration due to gravity, m/s^2
h	=	Heat transfer coefficient from exposure to steel member, W/m^2·K
h_c	=	Convective heat transfer coefficient, W/m^2·K
h_k	=	Effective heat transfer coefficient, W/m^2·K
h_r	=	Radiative heat transfer coefficient, W/m^2·K
H_c	=	Calorific value of the fuel or heat of combustion, MJ/kg
H_{comp}	=	Height of the compartment, m
H_d	=	Calorific value of the dry material, MJ/kg
H_o	=	Height of ventilation openings, m
H_p	=	Heated perimeter of the steel section, m
H_w	=	Average height of the openings weighted with respect to each individual opening area, m
I	=	Intensity of the incident light source, candela

I_o	=	Radiated power received without smoke
I_s	=	Radiated power received with smoke
k	=	Thermal conductivity, kW/m·K
k_g	=	Fire growth parameter, s/MW$^{1/2}$
k_i	=	Thermal conductivity of insulation material, W/m°C
l_c	=	The height of the continuous flame, m
l_i	=	The height of the intermittent flame, m
l_m	=	Mean flame height, m
L	=	Fire load, kg
L_{op}	=	Optical measuring length, m
L_t	=	Travel length, m
m_c	=	Total mass of each combustible material in the compartment, kg
m_f	=	Mass of fuel burnt, kg
$\dot{m}$	=	Mass flow rate, kg/s
$\dot{m}_{ent}$	=	Entrained mass flow rate in plume, kg/s
$\dot{m}_f$	=	mass rate of fuel burnt, kg/s
$\dot{m}_{smoke}$	=	mass rate of smoke produced, kg/s
M	=	Moisture content in percentage by dry weight
M_d	=	Moisture content, %
N	=	Number of storeys
NP	=	Number of persons passing through door or stairway
OD	=	Optical density, dB/m
P	=	Projection of the flame tip from the wall, m
P_d	=	Radiant power emitted by the detector, W
P_f	=	Perimeter of fire, m
P_w	=	Wind pressure, Pa
q_f	=	Fire load density per floor area, MJ/m^2
q_c	=	Convection heat flux, W/m^2
q_r	=	Radiation heat flux, W/m^2
q_{rc}	=	Critical received radiation, W/m^2
q_x	=	Heat flux in the x direction, W/m^2
Q	=	Heat release rate, kW
$Q(t_{act})$	=	Heat release rate at the activation time, kW
Q_c	=	Convective heat release rate (may usually be assumed as 0.7 Q), kW
Q_{com}	=	Rate of heat release in the compartment produced by combustion, kW
Q_{fo}	=	Rate of heat release at flashover, kW
Q_g	=	Rate of accumulation of heat in hot gases in the compartment, kW
Q_l	=	Rate of heat loss by convection through openings, kW
Q_{max}	=	Heat release during fully developed burning phase, kW
Q_{peak}	=	Peak heat output of the total fire area, kW
Q_r	=	Rate of heat loss by radiation through openings, kW
Q_w	=	Rate of heat loss by radiation and convection to the compartment walls, kW
Q"	=	Heat output per unit area of fire, kW/m^2

Q(t)	=	The heat release rate as a function of time t, kW
$Q(t-t_{act})$	=	Heat release rate after the activation time, kW
r	=	Radial distance between the axis of the fire and the detector, m
r_f	=	Ratio of the design action on the member under the design load for fire to the design capacity of the member at room temperature
R	=	Riser height of each step, m
RTI	=	Response Time Index, $(m \cdot s)^{0.5}$
s_1	=	Length between two detectors in a rectangle of four, m
s_2	=	Width between two detectors in a rectangle of four, m
S	=	Radiant power reaching the detector, W
S_t	=	Travel speed, m/s
SF	=	A safety factor
t	=	Time, s
t_a	=	Time from detection to alarm sounding, s
t_{att}	=	Fire attack time, min
t_{act}	=	Time at the sprinkler activation, s
t_b	=	Duration of burning period, s
t_c	=	Fire control time, min
t_d	=	Time from fire ignition to fire detection, s
t_{dis}	=	Dispatch time, min
t_e	=	Equivalent severity time of fire exposure to the standard test, min
t_{ed}	=	Design fire severity, min
t_{eva}	=	Travel or evacuation time, s
t_{ex}	=	Fire extinguishment time, min
t_{fb}	=	Duration of fully developed burning, s
t_{fd}	=	Time of fire discovery, s
t_i	=	Time to investigate, collect goods, fight the fire, etc., s
t_{inv}	=	Search and investigation time after arrival, min
t_{ls}	=	Life saving and rescue activities time, min
t_n	=	Time to notify the fire department of the emergency, min
t_o	=	Time from alarm to making a decision to respond, s
t_{od}	=	Time of onset of the decay phase, s
t_p	=	Thermal penetration time, s
t_{pas}	=	Passage time through an exit, s
t_{pm}	=	Pre-movement time, s
t_r	=	Fire resistance rating or time to reach a critical temperature, min
t_{res}	=	Response or reaction time, s
t_t	=	Travel time to arrive to the burning area, min
t_{tot}	=	Total required time, s
t_{tr}	=	Minimum traversal time to an exit, s
t_{unt}	=	Minimum time to reach untenable conditions measured from ignition, s
t_v	=	Time delay, min
Δt	=	Time step, s
Δt_f	=	Effective fire duration, s
T	=	Temperature, °C
T_d	=	Detector temperature, °C

T_e	=	Temperature of the emitting source/surface, K
T_f	=	Temperature of flames in smoke plume, K
T_g	=	Expected compartment temperature, K
T_l	=	Lower layer temperature, K
T_L	=	Limiting steel temperature, °C
T_o	=	Ambient temperature, K
T_r	=	Temperature of the receiving surface, K
T_s	=	Smoke temperature, °C
T_{st}	=	Steel temperature at time t, K
T_u	=	Upper layer temperature, K
ΔT	=	Temperature difference between the surface and fluid, K
ΔT_p	=	Temperature rise on plume centreline, K
ΔT_{st}	=	Temperature rise in steel for the duration Δt, °C
u	=	Instantaneous velocity of hot fire gases, m/s
u_o	=	Velocity of hot gases at which τ_o was measured, m/s
$\dot{V}_s$	=	Volume rate of smoke production at a specified temperature, m^3/s
V_t	=	Total volume of smoke generated at time t, m^3
V_w	=	Wind velocity, m/s
VF	=	Ventilation factor
Y	=	Distance between floor and bottom smoke layer under ceiling, m
Y_{co}	=	Carbon monoxide yield factor, kg/kg
w	=	Spray density, mm/s
W_e	=	Effective width, m
W_{min}	=	Minimum aisle width, m
W_o	=	Width of the window, m
W_{st}	=	Steel weight per unit length, kg/m
W_w	=	Width of the wall containing openings, m
x, y, z	=	Rectangular co-ordinates, m
z	=	Height above top of the fire source, m
z_o	=	Height of virtual origin above top of the fire source, m
Z	=	Flame height above the top of the opening of the burning floor, m

Greek Symbols

α	=	Thermal diffusity, $\alpha = k / (\rho c)$, m^2/s
δ	=	Thickness of compartment surface, m
δ_f	=	Thickness of the flame, m
δ_i	=	Thickness of insulation material, m
ε	=	Emissivity of the surface
ε_f	=	Emissivity of the flame
ε_{smoke}	=	Smoke mass conversion factor, kg/kg
ϕ	=	Configuration factor ($0 < \phi < 1$)
ρ	=	Material density, kg/m^3
ρ_i	=	Density of insulating material, kg/m^3

ρ_o	=	Ambient (outside) air density, kg/m^3
ρ_s	=	Density of air as smoke at a temperature T in °C, kg/m^3
σ	=	Stefan-Boltzman constant (5.67 x 10^{-8} W/m^2·K^4)
τ	=	Detector time constant, s
τ_o	=	Detector time constant measured at reference velocity u_o, s
ζ	=	Extinction coefficient of air

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1. INTRODUCTION

1.1 General - Purpose and Scope of the Study

This study is part of a joint research project of the National Fire Laboratory, Institute for Research in Construction, National Research Council of Canada, with the Department of National Defence and Public Works and Government Services Canada. The purpose of the project is to develop fire safety design guidelines that can be used for the design of fire protection systems in Canadian federal buildings. These fire safety design guidelines will permit the assessment of fire safety in buildings and the ability of the fire protection systems to achieve established objectives. Minimum objectives are those stated in the National Building Code (1995) and National Fire Code (1995) of Canada, however, the design team may state additional objectives. The design guidelines will also allow flexible and cost-effective fire safety designs without compromising the safety of the occupants. The document also provides the necessary guidance to designers in applying the fire safety design guidelines as a means to prevent undesirable fires.

The fire safety design guidelines contained in this document are based on the extensive literature survey on performance-based regulations undertaken at the National Fire Laboratory by Hadjisophocleous, Benichou and Tamim (1996), the New Zealand Design Guide (1994), the Australian Fire Engineering Guidelines (1996), the British Standards Institute Draft Code of Practice (1994), and the Nordic Building Regulations (1994).

1.2 Application of Fire Safety Design Guidelines

The fire safety design guidelines presented in this report are applicable to the following:

- Design of fire protection systems in existing buildings (renovations, change of use, etc.)
- Design of fire protection systems in new buildings especially those in which the National Building Code (1995) and National Fire Code (1995) of Canada are limited in application
- Establishment of equivalency to the requirements of the National Building Code (1995) and National Fire Code (1995) of Canada

1.3 Important Comments about the Fire Safety Guidelines

The fire safety design guidelines are neither a design code nor a document intended to replace the National Building Code (1995) and National Fire Code (1995) of Canada. Rather, it provides guidance that permits fire safety engineers to satisfy rationally the objectives set by the National Building Code (1995) and National Fire Code (1995) of Canada. This document may also be used to support the work being conducted by the Canadian Commission on Building and Fire Codes to develop objective-based building and fire codes by the year 2001 as outlined in their Strategic Plan (1994).

The procedures outlined in this document are intended to be used by competent and qualified fire safety engineers, i.e., engineers that are aware of the behaviour of building materials, structural components and occupants when exposed to fire. In addition, it must be emphasized that fire safety design requires the use of engineering and expert judgement, practical experience, and a thorough understanding of the limitations and assumptions involved in the methodologies used.

The fire safety design guidelines presented herein can also be used by code officials to assess designs submitted for approval. Building owners, architects, insurance companies and the fire department personnel could use these guidelines to provide valuable tips to fire safety designers.

The methodologies and equations presented in this document are not exhaustive. The use of alternative design approaches can be used provided they are technically sound and justified by the designer.

This document is open to improvement and expansion with new developments in fire research and with feedback from users, i.e., code officials, consultants and the fire community at large.

1.4 Outline of the Document

The fire safety design guidelines are comprised of a set of Sections that guide fire safety engineers in the preparation of detailed fire engineering designs. Code officials can also use the guidelines to verify the adequacy of the designs. Included in this document are the following Sections:

1. An introduction outlining the purpose, scope, applicability of the guidelines and an overview of performance-based fire safety design. This is followed by Sections on the qualitative fire safety goals, an overview of the fire safety design guidelines and a brief discussion on characterization of buildings and occupants.
2. Sections 5 to 12 present a detailed analysis for each component of the fire safety design guideline namely, fire initiation and growth, smoke production and movement, fire spread, fire resistance and structural stability, fire detection, fire suppression, fire department response, and safe evacuation. In each Section, methodologies,

procedures and equations are provided, as well as performance criteria for use in assessing the design.
3. Section 13 provides information on engineering fire models as well as a list of the computer models that are available.
4. Section 14 discusses fire safety management. This Section explains the responsibilities of the building manager/owner and the occupants vis-à-vis fire safety, the procedures that should be in place to prevent a fire from occurring as well as the actions to take in the event of a fire emergency.

1.5 Overview of Performance-Based Fire Safety Design

1.5.1 General - why the move?

In recent years, building codes, regulations and standards have been going through a transition from being prescriptive-based to being performance-based. Many countries are in the process of developing performance-based fire safety regulations and the engineering criteria required to support these regulations. The reasons behind the move towards the performance approach are the expected advantages that the performance-based fire safety design can offer over the prescriptive design, which can be summarized as follows:

- Establishing clear safety goals and leaving the means of achieving those goals to the designer
- Permitting innovative design solutions that meet the established performance requirements
- Eliminating technical barriers to trade for a smooth flow of industrial products
- Allowing international harmonization of regulation systems
- Permitting the use of new knowledge as it becomes available
- Allowing cost-effectiveness and flexibility in design
- Enabling the prompt introduction of new technologies to the marketplace
- Eliminating the complexity of the existing prescriptive regulations

1.5.2 Structure of performance-based fire safety design

The development of performance-based fire safety design follows a hierarchical structure in which there are usually three levels. The top level states the functional goals, the middle level gives the fire safety design guidelines, and the last level provides acceptance criteria. In the literature survey conducted at the National Fire Laboratory, Hadjisophocleous, Benichou and Tamim (1996), it was suggested that the approach used to develop performance-based fire safety design is as follows:

- Identification of qualitative goals,

- Identification of quantitative design guidelines and the establishment of fire safety acceptance criteria and safety factors that go along with these guidelines,
- Establishment of evaluation tools and methods for the quantification process.

2. QUALITATIVE FIRE SAFETY GOALS

2.1 General

The implementation of a rational fire safety design requires a definition of its operational goals. It is, therefore, important to establish goals that are clearly defined and accepted by society as a whole. In some situations, however, for the benefit of a community, additional goals may be specified by the community, insurance companies or the building owner.

2.2 Qualitative Goals

The overall objectives of the fire safety system in a building are:

1. *To protect the life and health of people from fires.*
   This includes, but is not limited to, incapacitation due to exposure to heat, smoke, toxic gases and structural instability.
2. *To protect the property in the building of fire origin and adjacent buildings.*
   This includes, but is not limited to, damage or loss to building contents, spread of fire of other compartments and other buildings, and structural failure of building.
3. *To limit the economic, social and environmental impacts from fires.*

Failure to meet the above qualitative goals implies losses to society in terms of human and physical resources. These goals and the fire safety design objectives stated in the following Section are based on the summary of objectives and requirements given in Appendix A. These objectives and requirements are based on the literature survey conducted by Hadjisophocleous, Benichou and Tamim (1996).

3. OVERVIEW OF FIRE SAFETY DESIGN OBJECTIVES

The qualitative goals outlined in Section No. 2 are very general and require further refinement. This refinement is achieved by sub-dividing each goal into a number of design objectives so that they can be easily quantified. These design objectives are not independent from each other and from any other part of the fire safety system such as the qualitative goals. Indeed, all components of one level of the design guidelines interact with each other and every level interacts with the one next to it in the structured fire safety system.

A number of factors, including building characteristics, occupant characteristics, means of safe evacuation, means of fire detection and suppression and structural stability, must be taken into account in establishing the fire safety goals. The following is a set of design objectives to be considered when conducting a fire safety design:

1. Avoidance of fire occurrence/outbreak;
2. Limitation of fire growth;
3. Avoidance of smoke spread;
4. Avoidance of fire spread;
5. Assurance of safe load-bearing structure;
6. Effective use of detection systems;
7. Effective use of suppression systems;
8. Effective use of fire fighting service;
9. Assurance of safe escape and evacuation;
10. Assurance of continuity of operations;
11. Assurance of environmental protection.

This wide range of possible building uses does not permit the development of a single set of design goals that can be applied to all buildings. In addition, the potential interactions between a fire and the building and its occupants give rise to a large number of possible fire scenarios. Appropriate fire scenarios must be selected for the design of the fire protection systems.

4. BUILDING AND OCCUPANT CHARACTERISTICS

4.1 General

A common and important factor in the quantification of fire protection systems is the characterization of buildings and occupants. Therefore, before getting into the details of the design guidelines, it is worthwhile introducing these characterizations.

The fire safety design objectives outlined in Section No. 3 depend on the characteristics of the building to be designed and the occupants of the building. Thus, prior to beginning any fire safety design, information about the building, its contents and its occupants must be gathered. This information will provide an indication of the probable occurrence of events such as fire development, fire spread and potential impact to humans and property. The data needed to assess the characteristics of the buildings and occupants is presented below.

4.2 Building Characteristics

Building characteristics affecting the design of fire safety systems include:

- Geographical position of the building;

- Dimensions of the building and its components (structural and non-structural);
- Properties of the materials forming the building;
- Locations of means of fire detection and fire suppression;
- Locations of routes of escape;
- Amount of combustible materials in the building;
- Monetary value of contents;
- Ways of storage of contents.

4.3 Occupant Characteristics

The characteristics of the occupants in a building affect their ability to avoid untenable conditions that may develop due to the occurrence of a fire. In order to appropriately design for life safety in buildings, it is of prime importance to have a detailed knowledge of the capabilities and behaviour of the occupants of a building. The capabilities and behaviour of the occupants in a fire emergency, in terms of response and evacuation, depend on many parameters. These include:

- Familiarity of the occupants with the building;
- Existence of proper signage for evacuation towards a safe place;
- Complexity of the construction of the occupancy;
- Number of occupants and occupants with disabilities;
- Training of occupants in evacuation process and the use of fire extinguishing means;
- Age of occupants.

5. FIRE INITIATION AND GROWTH

5.1 Purpose

- To provide methodologies for the evaluation of the rate of fire growth, the production of heat and toxic gases, the occurrence of flashover and the characteristics of post-flashover fires.
- To develop guidelines to minimize the likelihood of fire occurrence and the rate of fire growth and the occurrence of flashover.

5.2 Introduction

During its life, a fire goes through four distinct stages, usually characterized in terms of the average temperature of compartment gases: fire initiation or ignition which is defined as the onset of combustion; the pre-flashover or growth period during which the fire is localized to a few burning objects; the post-flashover or fully-developed stage during which the fire engulfs the whole compartment; and the decay stage. The transition from the growth stage to the fully-developed stage is known as flashover.

These typical fire stages are shown in Figure 5.1, which plots the fire heat release rate with time. Ignition, the rate of fire growth during the growth period, the time to flashover, the maximum heat release rate, the duration of the fully-developed period and the decay rate for different fires vary widely. It should be mentioned that the four stages cannot be identified for all fires. This Section will describe the parameters affecting the fire during each of these stages and provide evaluation methods to determine the fire and compartment characteristics.

5.3 Evaluation Procedures

5.3.1 Fire ignition

Fire is a chemical reaction known as combustion. It is defined by the rapid oxidation of a combustible material accompanied by release of energy in the form of heat. In order for ignition to occur, the presence of both a fuel and a heat energy source is required. When the two come together, with the appropriate proportions, either by a lack of separation or by some type of active interaction, a fire occurs. There are three modes of ignition:

1. Pilot ignition: Occurs when released flammable gases are ignited by a flame or an electrical spark.

2. Non-pilot ignition: Occurs when the temperature of the pyrolysis gases is such that the energy produced by the exothermic reaction of the pyrolysis is enough to ignite the volatile mixture of oxygen and the released gases.
3. Spontaneous ignition: Occurs when there is sufficient oxidation reaction energy to raise the temperature above the ignition point (in the absence of a flame or a spark).

The probability of occurrence of ignition within a room or a compartment depends upon a number of parameters, including:

1. Heat or ignition sources present and the available ignition energy;
2. Flash point of flammable liquids in the compartment;
3. Flammability limit of combustible vapours released from the fuel;
4. Ignitability characteristics of fuels that are near ignition sources;
5. Critical temperatures of materials in the compartment;
6. Separation or arrangement of fuels and heat sources;
7. Building management characteristics (housekeeping, maintenance, inspection, training and security of the building).

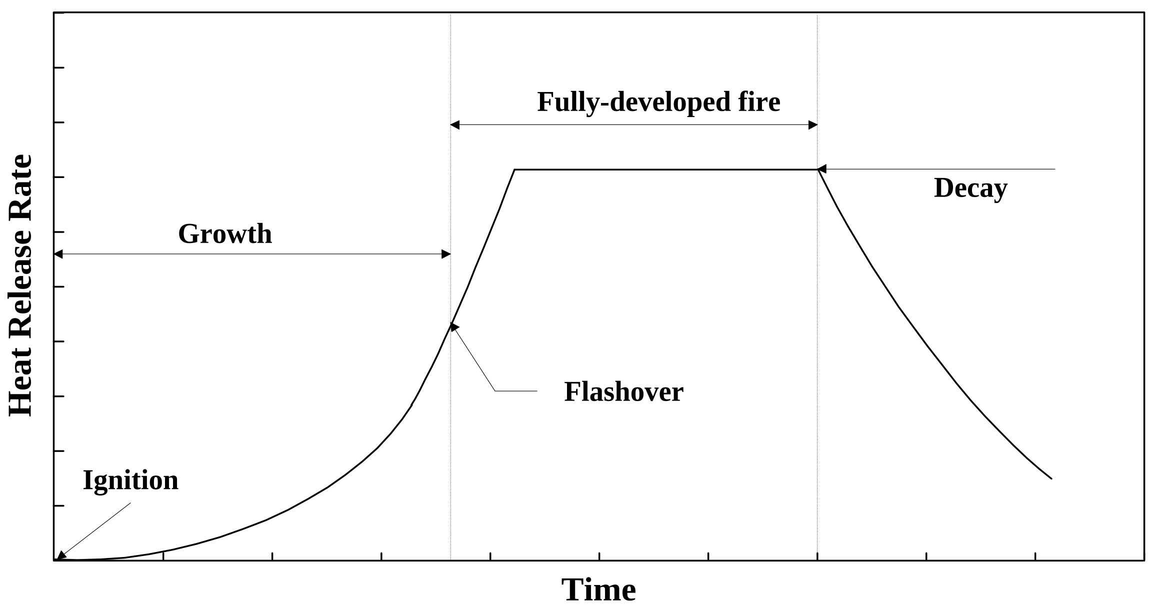

Figure 5.1. Typical stages of fire growth

5.3.2 Pre-flashover

Following ignition, fires may go through a smouldering phase before flames are initiated. Smouldering fires develop very slowly with periods of up to several hours. With lack of ventilation, smouldering fires may self extinguish. However, with increased ventilation, they may develop into flaming fires. Smouldering fires are a threat to life because of the generation of smoke and toxic gases such as carbon monoxide (CO) that can spread throughout the building. In addition to the influence of ventilation, the characteristics of smouldering fires depend on the nature of the burning material and the strength of the source of ignition.

The development of a fire during the pre-flashover flaming stage is very important as it determines the time when untenable conditions will be reached and the time when the detection and suppression systems will activate. For this reason, it is essential to predict the rate of fire growth, and the production of heat and toxic gases.

5.3.2.1 Rate of fire growth

The rate of growth of fires during the pre-flashover stage and the production of heat and toxic gases depend on fuel properties, such as ignitability, heat of combustion, fuel quantity and arrangement, proximity of first ignited item to other combustible items and the properties of the compartment lining materials, such as thermal absorptivity and ignitability and the compartment size, geometry and ventilation conditions.

The rate of fire growth can be determined using experimental results, computer models or empirical correlations. One of the most-used estimates for fire growth is the t-squared (t^2) fires.

For a t^2 fire, the heat output for an ignited item is assumed to increase according to a quadratic function of time. The fire growth rate is defined in terms of the fire growth parameter, k_g. The heat release rate, Q, is given by:

$$Q = 1000 \cdot (t / k_g)^2 \qquad (5.1)$$

where: Q = heat release rate, kW;
t = time, s;
k_g = fire growth parameter which is defined as the time (in s) for fire to reach a heat output of 1000 kW, $s/MW^{1/2}$ (see Table 5.1 for values).

Table 5.1 shows fire growth rates and their corresponding fire growth parameters as defined in the New Zealand Design Guide (Buchanan, 1994).

For t^2 fires, the fire is assumed to continue to grow until either the fuel is totally consumed or the heat release rate reaches a peak value. The peak heat release rate is dependent upon the burning object and may be estimated based on the fire area and the specific rate of heat release per unit area, if known, as:

$$Q_{peak} = Q'' \cdot A_{fire} \qquad (5.2)$$

where: Q_{peak} = peak heat output of the total fire area, kW;
Q'' = heat output per unit area of fire, kW/m^2;

A_{fire} = total area of fire, m^2.

Table 5.1. Typical fire growth rate parameters (Buchanan, 1994)

Rate of Fire Growth	k_g ($s/MW^{1/2}$)	Typical Equivalent or Real Fire
Slow	600	Solid wooden material with a horizontal orientation such as floors.
Medium	300	Solid wooden furniture such as desks; cotton/polyester spring mattress; etc.
Fast	150	Light wooden furniture such as plywood wardrobes; full mail bags; plastic foam; stacked timber pallets; etc.
Ultra Fast	75	Upholstered furniture; some pool fire; lightweight drapes; etc.

In the absence of data, the maximum heat release rate per unit area, Q" can be assumed as shown in Table 5.2. Then, knowing k_g and Q_{peak}, the time to reach the peak heat output of the fire can be estimated.

Table 5.2. Maximum design heat release rates (BSI, 1994)

Occupancy Type	Maximum Heat Release Rate (kW/m^2)
Offices, Schools, Dwellings, Hotels	250
Shops, Retail, Places of Assembly	500

5.3.3 Production of toxic gases and compartment temperature

Experiments have shown that conditions inside the room or compartment of fire origin become life-threatening for the occupants well before flashover due to the production of CO and other toxic gases and smoke, oxygen depletion and high temperatures. Evaluating these conditions in the compartment of fire origin during the pre-flashover stage is important to determine whether occupants have sufficient time to evacuate the building. Knowledge of these conditions is also needed to estimate the time of smoke detector and sprinkler activation.

5.3.3.1 Concentration of carbon monoxide

The principal toxic gas produced by a fire is carbon monoxide. The concentration in parts per million (ppm) of CO at 20°C in the combustion products can be estimated as follows:

$$CO\ (ppm) = \frac{0.858 \cdot 10^6 \cdot Y_{co} \cdot m_f}{V_t} \qquad (5.3)$$

where: Y_{co} = carbon monoxide yield factor, kg/kg (See Table 5.3 for values);

V_t = volume of smoke generated at time t, m^3;
m_f = mass of fuel burnt, kg.

Table 5.3. Typical product yield for flaming combustion (Australian Guidelines, 1996)

Material	Carbon Monoxide Yield Factor (Y_{co}) (kg/kg)
Timber	0.004
Polyvinyl chloride (PVC)	0.063
Polyurethane (flexible)	0.042
Polyurethane (rigid)	0.051
Polystyrene	0.060
Polypropylene	0.024
Generic building contents *	0.013

* The data for the generic building contents may be applied to residential, office and retail premises where there is a typical mixture of combustible contents.

5.3.3.2 Production of smoke

Although smoke generation does not greatly affect fire growth, it affects occupant safety as it reduces visibility causing disorientation of occupants. Smoke production varies from material to material as shown in Table 5.4, hence, it is important to limit smoke producing materials in exit ways. The production of smoke can be computed using:

$$\dot{m}_{smoke} = \varepsilon_{smoke} \cdot \dot{m}_f \qquad (5.4)$$

where: $\dot{m}_{smoke}$ = mass rate of smoke produced, kg/s;
$\dot{m}_f$ = mass rate of fuel burnt, kg/s;
ε_{smoke} = smoke mass conversion factor, kg/kg (see Table 5.4 for values).

5.3.3.3 Compartment temperatures

The temperature in the compartment of fire origin is another parameter that affects life safety. High temperature leads to ignition of nearby objects and eventually the onset of flashover. It also affects the integrity of fire barriers and structural elements of the building. McCaffrey, Quintiere and Harkleroad (1981) proposed the following relationship to predict temperature during pre-flashover:

$$T_g - T_o = 480 \cdot \left[\frac{Q}{\sqrt{g} \cdot c_p \cdot \rho_o \cdot T_o \cdot A_o \sqrt{H_o}} \right]^{2/3} \cdot \left[\frac{h_k \cdot A_T}{\sqrt{g} \cdot c_p \cdot \rho_o \cdot A_o \sqrt{H_o}} \right]^{-1/3} \qquad (5.5)$$

where:

T_g	=	temperature of the upper gas layer, K;
T_o	=	ambient temperature, K;
g	=	acceleration due to gravity, m/s^2;
c_p	=	specific heat of gas, kJ/kg·K;
ρ_o	=	ambient air density, kg/m^3;
Q	=	heat release rate of the fire, kW;
A_o	=	area of opening, m^2;
H_o	=	height of opening, m;
A_T	=	total area of the compartment enclosing surfaces, m^2;
A_T	=	$A_{walls} + A_{floor} + A_{ceiling} - A_{openings}$
h_k	=	effective heat transfer coefficient (see Equation (5.6)), kW/m·K.

$$\begin{cases} h_k = k / \delta & t > t_p \\ h_k = (k \cdot \rho \cdot c / t)^{1/2} & t \le t_p \\ t_p = (\rho \cdot c / k) \cdot (\delta / 2)^2 \end{cases} \qquad (5.6)$$

where:

k	=	thermal conductivity of compartment surface material, kW/m·K;
δ	=	thickness of compartment surface material, m;
ρ	=	density of compartment surface material, kg/m^3;
c	=	specific heat of the compartment surface material, kJ/kg·K;
t	=	time of exposure, s;
t_p	=	thermal penetration time, s.

Table 5.4. Smoke production for wood and plastic (BSI, 1994)

Material	Smoke Mass Conversion Factor (ε_{smoke}) (kg/kg)
Douglas Fir	0.025
Hardboard	0.001
Fibreboard	0.010
PVC	0.120
Polyurethane (flexible)	0.035
Polyurethane (rigid)	0.090
Polystyrene	0.170
Polypropylene	0.010
PMMA	0.020
Polyoxymethylene	~ 0

5.3.3.4 Flame height

In order to determine the potential ignition of adjacent fuel, detect the flame and determine the severity of fire spread, it is important to calculate the flame height. The height of the continuous flame, l_c (m), can be evaluated by:

$$l_c = 0.08 \cdot Q^{2/5} \tag{5.7}$$

The height of the intermittent flame, l_i (m), can be estimated by:

$$l_i = 0.20 \cdot Q^{2/5} \tag{5.8}$$

Heskestad in the SFPE Handbook (1995), predicted the mean flame height, l_m (m), taken as a mean value above the fire source according to the following equation:

$$l_m = -1.02 \cdot D + 0.235 \cdot Q^{2/5} \tag{5.9}$$

where: D = effective diameter of the fire source (fire source area = $\pi D^2/4$), m.

5.3.3.5 Plume temperature

The mean plume temperature rise at the centreline of the flame can be estimated using the following equation (Heskestad, SFPE Handbook (1995)):

$$\Delta T_p = 9.1 \cdot \left[\frac{T_o}{g \cdot c_p^{\,2} \cdot \rho_o^{\,2}} \right]^{1/3} \cdot Q_c^{\,2/3} \cdot (z - z_o)^{-5/3} \tag{5.10}$$

where:

ΔT_p	=	temperature rise on plume centreline, K;
Q_c	=	convective heat release rate (may be assumed as 0.7 Q), kW;
z	=	height above top of the fire source, m;
z_o	=	height of virtual origin relative to the base of the fire source (see Heskestad, SFPE Handbook (1995), for detailed calculations), m.

5.3.3.6 Entrained mass flow rate in plumes

The plume generated by the fire carries the products of combustion towards the ceiling. As it moves upwards, it entrains air which is then mixed with the hot gases. The amount of entrained air depends on the fire size and the distance between the fire and the hot layer. The growth and properties of the smoke layer depend on the entrained mass flow rate of the plume. Heskestad in the SFPE Handbook (1995), proposed the following equation to predict the entrained mass flow rate:

$$\dot{m}_{ent} = 0.196 \cdot \left[\frac{g \rho_o^{\,2}}{c_p T_o} \right]^{1/3} Q_c^{\,1/3} (z - z_o)^{5/3} \left[1 + \frac{2.9 \cdot Q_c^{\,2/3}}{(g^{1/2} c_p \rho_o T_o)^{2/3} (z - z_o)^{5/3}} \right] \tag{5.11}$$

where: $\dot{m}_{ent}$ = entrained mass flow rate in plume, kg/s.

If the virtual origin correction is negligible, the entrained mass flow rate shown in Equation (5.11) can be written as (Klote, 1994),

$$\dot{m}_{ent} = 0.071 \cdot Q_c^{1/3} \cdot z^{5/3} + 0.0018 \cdot Q_c \quad (5.12)$$

In addition to Equations (5.11) and (5.12), Peacock et al (1993) state that for a plume where the height to the upper layer is large and the fire size is small, the mass flow rate entrained into the plume is limited by the following relation:

$$\dot{m}_{ent} < \frac{Q}{c_p(T_u - T_l)} \quad (5.13)$$

where: T_u = upper layer temperature, K;
T_l = lower layer temperature, K.

5.3.3.7 Emissivity of the flame

Radiation fluxes from the flames to other objects in the compartment and the compartment boundaries depend on the temperature of the flames and the flame emissivity. For a luminous flame, the emissivity can be estimated as follows:

$$\varepsilon_f = 1 - e^{(-0.3 \cdot \delta_f)} \quad (5.14)$$

where: ε_f = emissivity of the flame;
δ_f = thickness of the flame, m.

5.3.4 Flashover

As the fire continues to grow, the temperature in the compartment of fire origin increases and every part of the compartment is exposed to flame radiation that leads to an event called flashover. Flashover is also characterized by the rapid transition from a localized fire to combustion of all exposed fuel surfaces within a compartment. Because of the undesirability of the flashover event, it is of prime importance to know the likelihood and timing of flashover. Parameters influencing the time and likelihood of occurrence of flashover include:

- Fuel load in the compartment;
- Ignitability of the fuel;
- Compartment size, openings and ventilation;

- Temperature and thickness of the upper hot gas layer;
- Heat radiation from the flames;
- Distance between the fuel surface and the upper hot gas layer.

It is very unlikely to survive in a fire that has reached flashover. This is due to the high temperatures, lack of oxygen, high CO concentration and heavy smoke.

An important aspect of flashover is the rate of heat release once this key event has occurred. Thomas (1981) developed an empirical equation to estimate the rate of heat release necessary to cause flashover. This formula is given by:

$$Q_{fo} = 7.8\, A_T + 378\, A_o \sqrt{H_o} \qquad (5.15)$$

where: Q_{fo} = rate of heat release at flashover, kW.

In addition to Equation (5.15), McCaffrey et al (1981) proposed the relationship shown in Equation (5.16) to predict the rate release rate that causes flashover. The authors used the same method that was used to predict the temperature in a compartment during pre-flashover given by Equation (5.5).

$$Q_{fo} = \left[\sqrt{g} \cdot c_p \cdot \rho_o \cdot T_o^2 \cdot \left(\frac{T_g - T_o}{480} \right)^3 \right]^{1/2} \cdot \left(h_k \cdot A_T \cdot A_o \sqrt{H_o} \right) \qquad (5.16)$$

For design purposes, the rate of heat release at flashover can be taken as the minimum value obtained from calculations using Equations (5.15) and (5.16).

The determination of the time to flashover is very important. As an example of the time to reach flashover and the influence of the construction materials, Table 5.5 shows test results of flashover times for a variety of building materials performed at the Fire Research Station in the U.K. (Malhotra, 1986). The area of the rooms used for the tests was 4.27 m^2 and the height was 2.6 m. The rooms were constructed of brick walls with a concrete roof. As a fire source, mock-up timber furniture was provided as for a living room giving a fire load of 24 kg/m^2. In addition, the rooms were provided with a wood floor and the walls and ceilings were lined with a variety of materials.

5.3.5 Post-flashover - fully-developed fires

The fully-developed fire stage occurs after flashover. It is characterized by very high temperatures and heat release rates. Once the fire is fully developed, the elements of a building structure must have the necessary fire resistance to prevent spread of fire and eventual structural failure. This stage is of prime importance when trying to satisfy the objective of property protection as well as when considering stability of the structure and the likelihood of fire spread to adjacent properties.

There are two control mechanisms during fully-developed fires: ventilation control and fuel control. The governing mechanism is the one that yields the lower value of rate of heat release. For ventilation-controlled fires, the rate of heat release is dependent upon the available ventilation, ventilation changes (e.g., glass breakage), shape and location of ventilation openings, thermal characteristics of the compartment and the nature of the fuel. In this case, the burning rate is controlled by limiting the supply of oxygen. On the other hand, fuel-controlled fires are affected by the nature of the fuel, surface area of exposed fuel, dimension and thermal characteristics of the compartment. In this case, the burning rate is influenced by the combustible contents, separation of fuel by barriers and the action of making the fuel less likely to burn.

Table 5.5. Flashover times in room fires (Malhotra, 1986)

Walls	Ceiling	Density (kg/m^3)	Flashover Time (s)
Brick	Concrete	2000	1410
Brick	Fib painted	2000/100	1170
LW concrete	Dense concrete	80/2000	1020
Brick	Fib painted	2000/100	960
Fib+plaster	Concrete	200/2000	720
LW concrete	Fib painted	80/100	630
Hardboard+p	Concrete	100/2000	495
Mineral fib	Concrete	50/2000	480
LW concrete	Fib painted	80/100	405
Fib	Concrete	100/2000	405

Fib = fibre insulation board
LW = light weight concrete
+p = with a paint finish

The heat release rate of fully-developed fires can be calculated for the ventilation-controlled fires and fuel-controlled fires and the lesser of the two used for design purposes. The following formula can be used for the calculation of the steady rate of heat release, Q:

$$Q = \dot{m}_f \cdot H_c \tag{5.17}$$

where: H_c = calorific value of combustible material or heat of combustion, kJ/kg (see Equation (5.18) below and Table 5.6 for some values);

$\dot{m}_f$ = mass loss rate of fuel burning computed as shown below, kg/s.

$$H_c = H_d \cdot (1 - 0.01 \cdot M) - 0.025 \cdot M \tag{5.18}$$

where: H_d = calorific value of the dry material, MJ/kg;

M = moisture content in percentage by dry weight.

For ventilation-controlled fires, the mass loss rate of the fuel can be computed using:

$$\dot{m}_f = 0.02 \sqrt{(A_T - A_o) \cdot \frac{W_w}{H_{comp}} \cdot A_o \cdot H_o^{0.5}} \tag{5.19}$$

where: W_w = width of the wall containing openings, m;
H_{comp} = height of the compartment, m.

The mass loss rate can also be calculated using an alternative formula as follows:

$$\dot{m}_f = 0.092 \cdot A_o \sqrt{H_o} \quad \textit{valid for} \quad \frac{r_o \cdot g^{1/2} \cdot A_o \cdot H_o^{1/2}}{A_f} < 0.235 \tag{5.20}$$

where: A_f = area of the compartment floor, m^2.

For fuel-controlled fires, the fuel mass loss rate can be computed using:

$$\dot{m}_f = \frac{L}{\Delta t_f} \tag{5.21}$$

where: L = fire load, kg;
Δt_f = effective fire duration (a value of 1200 s may be used in the absence of data), s.

5.3.5.1 Fire compartment temperatures

Maximum compartment temperatures can be used to estimate impacts and consequences of fully-developed fires. The maximum compartment temperature can be determined as follows (Law, 1983):

$$T_g - T_o = 6000 \cdot \frac{(1 - e^{-0.10\,\Omega})}{\Omega^{0.5}} \cdot (1 - e^{-0.05\,\Psi}) \tag{5.22}$$

with

$$\Omega = \frac{A_T - A_o}{A_o \cdot \sqrt{H_o}}$$

$$\Psi = \frac{L}{\left[A_o \cdot (A_T - A_o)\right]^{0.5}}$$

where: T_g = maximum expected compartment temperature, K;
L = fire load (wood), kg.

Table 5.6. Calorific values of typical combustible materials (Buchanan, 1994)

Material	Combustion Heat (MJ/kg)	Material	Combustion Heat (MJ/kg)
Solids		**Solids (continued)**	
Anthracite	31-36	Polyurethane foam	23-28
Asphalt	40-42	Polyvinylchloride	16-17
Bitumen	41-43	Ureaformaldehyde	14-15
Cellulose	15-18	Ureaformaldehyde foam	12-15
Charcoal	34-35	Rubber foam	34-40
Clothes	17-21	Rubber isoprene	44-45
Coal, Coke	28-34	Rubber tire	31-33
Cork	26-31	Silk	17-21
Cotton	16-20	Straw	15-16
Grain	16-18	Wood	17-20
Grease	40-42	Wool	21-26
Kitchen refuse	8-21		
Leather	18-20		
Linoleum	19-21	**Liquids**	
Paper, Cardboard	13-21	Benzene	40.1
Paraffin wax	46-47	Benzyl alcohol	26.9
Particle board	17-18	Diesel oil	40-42
(chipboard and hardboard)		Ethyl alcohol	26.9
Plastics:		Gasoline	43-44
ABC	34-40	Isopropyl alcohol	31.4
Acrylic	27-29	Linseed oil	38-40
Celluloid	17-20	Methanol	19-20
Epoxy	33-34	Paraffin oil	40-42
Melamine resin	16-19	Spirits	26-28
Phenolformaldehyde	27-30	Tar	37-39
Polyester	30-31		
Polyester, fibre-reinforced	20-22		
Polyethylene	43-44	**Gases**	
Polystyrene	39-40	Acetylene	48.2
Petroleum	40-42	Butane	45.7
Polyisocyanurate foam	22-26	Carbon monoxide	10.1
Polycarbonate	28-30	Ethanol	26.8
Polypropylene	42-43	Hydrogen	119.7
Polytetrafluorethane	5.0	Methane	50.0
Polyurethane	22-24	Propane	45.8

5.3.6 Decay

After reaching a peak burning rate during the fully-developed fire, this rate decreases as the fuel is consumed and the fire fails to spread to neighbouring compartments. This is the start of the decay stage. Fire decay can also occur from the effects of suppression systems. In the case of fuel consumption without suppression systems intervention, the transition to the decay stage is generally assumed to have started when 80% of the fuel has been consumed by the fire. The heat release rate, Q(t), as a function of time, t, in a linear relationship, can be estimated as:

$$Q(t) = \left(1 - 1.75 \frac{(t - t_{od})}{t_{fb}}\right) Q_{max} \quad (5.23)$$

where: t_{fb} = duration of fully developed burning, s;
t_{od} = time of onset of the decay phase, s;
Q_{max} = heat release during fully developed burning phase, kW.

5.4 Input and Output for The Evaluation Procedures

Tables 5.7 and 5.8 summarize the input and output requirements for fire growth.

Table 5.7. Input requirements

Input Needed	Section Taken From
Possible fire scenarios	- Initial design parameters - Statistics on fires start, fuel arrangement etc.
Nature of building contents	- Initial design parameters
Arrangements of fuel in the compartments	- Initial design parameters
Effective fire load	- Initial design parameters
Compartment geometry	- Initial design parameters
Size and location of ventilation openings	- Initial design parameters
Thermal characteristics of linings	- Initial design parameters
Ambient conditions inside the compartment	- Initial design parameters
Wind conditions	- Initial design parameters
Volume of smoke produced	- Smoke spread
Change in ventilation through the creation of new openings	- Fire spread - Fire resistance of barriers and glazing
Starting of suppression systems	- Initial design parameters - Fire detection and suppression
Starting of fire fighting activity	- Fire detection - Fire department response
Hot layer temperature	- Smoke spread

Table 5.8. Output requirements

Output	Needed For Section

Heat release rate	- Smoke spread - Fire Spread - Fire fighting control of the fire
Production of toxic gases (CO)	- Smoke spread - Evacuation (measure of untenable conditions)
Production of smoke	- Smoke spread
Flame height	- Flame detector response - Fire spread - Impact on structural elements
Plume temperature	- Heat detector response - Smoke detector response - Measure of untenable conditions
Compartment temperatures	- Heat detector response - Structural resistance - Evacuation (measure of untenable conditions)
Flame emissivity	- Fire spread, barrier failure
Entrained mass flow rate in plumes	- Smoke spread
Time of occurrence of flashover	- Fire fighting response

5.5 Performance Criteria

In order for a fire safety design to be satisfactory, it must be judged against some acceptance or performance criteria. The minimum performance criteria are those established by the National Building Code (1995) and National Fire Code (1995) of Canada. The performance criteria can also be set by the fire safety design team based on the minimum performance criteria found in the National Building Code (1995) and National Fire Code (1995) of Canada.

5.5.1 Minimizing ignition and fire occurrence

To minimize ignition and prevent fire occurrence, it is necessary to address one or more of the following requirements:

1. Identify and remove/minimize the heat sources,
2. Identify and control the fuel ignition characteristics,
3. Identify and minimize/control the interactions between the fuel and the heat sources.

5.5.1.1 Ignition/heat energy sources

Ignition/heat energy sources may be small, however, they may produce sufficient energy to ignite a fuel and start a fire, provided the environment is satisfactory. Many heat and ignition sources may be found in a building including static sparks, hot surfaces, open flames/burner flames, electrical wiring, smoking, explosives/fireworks, fuel-powered equipment, chemical reactions, welding, and overheated materials (see also Appendix C for more details on ignition sources). To prevent ignition, these sources must be either controlled, isolated or removed.

5.5.1.2 Fuel ignition characteristics

The ignition of combustible materials is mainly affected by the radiant heat flux and surface temperature of the fuel. The BSI Draft Code of Practice (1994) identifies typical threshold values for ignition in terms of the radiant heat flux or surface temperature, for a variety of materials, as illustrated in Table 5.9. These proposed values can be used, as ignition criteria, to examine the possibility of ignition of a first item. Thus, knowing the ignitability of combustible materials in a compartment, the size of possible heat sources can then be limited to ensure no ignition.

To facilitate the process of determining the ignition criteria, solid fuels can be classified based on their ease of ignitability into groups such as those used by the National Fire Protection Research Foundation (NFPRF) Fire Risk Assessment Method (FRAM) (Bukowski et al, 1990). The proposed classification is shown in Table 5.10. The ignition sources are then limited to below the nominal values of the group representing the materials in a compartment.

Table 5.9. Threshold values for ignition (BSI, 1994)

Material	Radiant Heat Flux for Ignition (kW/m^2)		Surface Temperature for Ignition (°C)	
	Pilot	Spontaneous	Pilot	Spontaneous
Wood	12	28	350	600
Chipboard	18			
Hardboard	27			
PMMA (Perspex)	21		270	
Flexible PU	16		270	
Polyoxymethylene	17			
Polymethylene	12			
Polyethylene/42% Cl	22			

Table 5.10. Heat flux range for ignitability (Bukowski et al, 1990)

Ignitability	Heat Flux Range (nominal value) (kW/m^2)
Easy	≤ 14.1 (10)
Normal	14.1 - 28.3 (20)

Hard	> 28.3 (40)

5.5.1.3 Fuel/heat sources interactions

Ignition can be prevented by minimizing or removing, if possible, the interaction that may exist between a fuel and a heat source. The effectiveness of ignition prevention measures is affected by many factors, including fire safety management procedures, processes undertaken such as welding, chemical processing and experimentation, and storage and dispensing of hazardous materials, equipment in place such as furnaces and portable heating units, and nature of contents of a compartment.

The potential causes of fuel/heat sources interactions can be grouped into two groups:

1. Occupant-related interactions which include child play, cooking, heating, smoking, fuel spills, misuse of heat sources and misuse of fuel.
2. Non-occupant-related interactions which include arson, equipment deficiency such as non-properly insulated electrical wiring, operational deficiency such as the lack of appropriate fire safety policies, process failure such as leakage of stored hazardous material, and exposure/natural fire.

Minimizing or controlling the interaction between fuel and heat sources can be accomplished through a number of ways, including the following:

- Proper arrangement of equipment that produce heat,
- Control of the temperatures generated by the heat-producing equipment,
- Control of gases generated by the heat-producing equipment,
- Control of fire properties of combustible building materials,
- Conducting periodic inspection and maintenance of heat-producing equipment,
- Establishment and enforcement of in-house fire safety rules,
- Education of occupants in fire safety,
- Implementation of maintenance and good housekeeping measures,
- Implementation of an effective waste management program,
- Safeguarding fire risk areas from arson and vandalism,
- Separation between fuel and heat sources either by a distance or a physical barrier.

5.5.2 Control of fire growth

A fire can be controlled if the components influencing its growth are controlled. A first approach is to limit fire growth by specifying the appropriate materials to cover the walls, floors and ceiling, especially in the escape routes so that material ignitability is delayed in the compartment of fire origin. Table 5.9 provides ignition criteria which can be used to determine the ignition of neighbouring items. These threshold values for ignition can be used to determine whether a developing fire will spread to a second object in the fire room and if it is possible to limit ignition of adjacent combustibles.

A second approach for controlling fire growth is by allowing sufficient distance between a burning item and adjacent items so that the adjacent items will not ignite. The approach, detailed in Babrauskas (1981), is in terms of the radiant heat flux necessary to ignite an item. Babrauskas' procedure states that a burning item will ignite a distant non-burning item when the mass loss rate of the burning object attains a value necessary to produce the required flux at the distance between the two items. The relationship between the mass loss rate and ignition distance for the three ignitability levels, shown in Table 5.10, are presented graphically in Babrauskas (1981). Objects in a room can therefore be arranged in a manner that can limit fire spread from object to object.

There is also an equation, developed by Alpert and Ward (1984), used in NFPA 204M (1991) to estimate the minimum aisle width to prevent lateral spread by radiation. The minimum aisle width is based on the heat release rate and the minimum ignition flux of 20.4 kg/m^2 (assumed for most materials), given by:

$$W_{\min} = 0.042 \cdot Q^{1/2} \tag{5.24}$$

where: W_{min} = minimum aisle width, m.

5.5.3 Flashover

The determination of the time to flashover occurrence is very important in the design process. The following are three approaches for estimating this parameter:

- Temperature of the hot gas layer is equal to 600°C,
- Radiation at the floor from the hot gas layer is equal to 20 kW/m^2,
- Rate of heat release is equal to the required heat release that causes flashover.

5.5.4 Minimization of flashover

Since flashover is characterized by high heat outputs and temperatures, the most effective measure to minimize the probability of its occurrence is by minimizing heat output. This can be achieved by:

- Controlling the materials in the compartment of fire origin to limit the fuel load,
- Decreasing the ignitability of the fuel in the compartment, i.e., ensure that the heat flux required to ignite the materials in the compartment is high.

5.5.5 Control by detection and suppression

The growth of fire can be controlled if detected early and suppressed. Detection includes humans as detectors, smoke detectors, heat detectors and flame detectors. These means can be used to notify the occupants, control systems and the fire department of fire outbreak and growth. Suppression of the fire reduces the rate of heat release and the probability of the occurrence of flashover. Suppression can be achieved by automatic suppression (e.g., sprinklers), by fire service intervention or by trained occupants (e.g., manual fire extinguishers). The concepts and principles used to calculate the time and probability of fire detection and suppression are discussed in Sections No. 9 and 10 on Detection and Suppression.

6. SPREAD OF SMOKE

6.1 Purpose

- To provide methodologies for the evaluation of production and movement of smoke within the compartment of fire origin and other areas in the building.
- To evaluate the performance of smoke control systems.
- To provide methodologies to evaluate the properties of smoke that might cause untenable conditions and damage to a building's contents and property.

6.2 Introduction

6.2.1 General

Smoke is considered the main cause of death in fires. It is, therefore, of prime importance for the designer to provide adequate and efficient smoke control mechanisms especially in highly-populated buildings. Damage to contents and property by smoke is also a design issue. Smoke control measures can limit this damage by limiting the smoke spread and reduce risk to life by improving visibility.

6.3 Evaluation Procedures

6.3.1 Smoke movement

6.3.1.1 Movement of smoke within the compartment of fire origin

Smoke produced by a fire in a compartment moves upwards due to buoyancy forming a plume. This upward movement entrains fresh air into the plume, which cools and dilutes the plume gases but, at the same time, increases its volume. Once the gases in the plume reach the ceiling, they start moving horizontally along the ceiling creating a ceiling jet. Eventually, smoke fills the upper space of the compartment forming a hot upper layer. As more gases enter the hot layer, its thickness increases and, eventually, it occupies all the volume of the compartment threatening the occupants.

6.3.1.2 Movement of smoke outside the compartment of fire origin

From the compartment of fire origin, smoke may move to other areas in the building through openings, such as doors and windows or cracks and small leakage paths. The mechanisms causing smoke movement through the building include buoyancy forces, stack effect, wind effects and mechanical ventilation systems. As smoke moves away from the compartment of fire origin, it cools down. While hot smoke moves upwards forming a hot layer and leaving the lower compartment space relatively clear, cool smoke mixes with the air in the compartment resulting in untenable conditions and reducing visibility.

More details on smoke spread through the building can be found in the SFPE Handbook (1995), and the ASHRAE Design Guide (Klote and Milke, 1992).

6.3.1.3 Prediction of smoke movement

The prediction of the movement of smoke within and beyond the compartment of fire origin can be undertaken using engineering correlations or zone or field computer models. Discussion of these models is given in Section No. 13 on Fire Safety Engineering Design Tools.

6.3.2 Control of spread of smoke

6.3.2.1 General

The spread of smoke to adjacent areas in buildings is one of the causes of death and injuries in the event of a fire. Because of this, smoke control systems should be considered to:

- Reduce the spread of smoke to neighbouring areas,
- Maintain tenable conditions in the escape routes and neighbouring spaces,
- Increase visibility for the occupants and fire department personnel,
- Reduce heat and toxic gas exposure to the occupants and fire fighters,
- Enable smoke to be cleared from the building after the fire is under control.

6.3.2.2 Factors affecting control of smoke spread

The production rate and movement of smoke through the building is influenced by many factors, including:

- The materials used to construct and furnish a building and their contribution to smoke generation as they decompose,
- The manual and automatic barriers (doors, ventilation shutters, etc.) in place to reduce smoke spread,
- The active smoke control systems in place to exhaust and replace the polluted air or to limit smoke spread to other areas in the building (pressurization systems),
- The climatic conditions outside the building,
- The interaction between the smoke control systems and the means of detection and suppression.

6.3.2.3 Smoke control techniques

The spread of smoke can be controlled by different methods. Some of the techniques commonly used in designing smoke control systems include:

- Smoke exhaust/clearance: Continuous extraction of the smoke and replacing it by fresh air. This is achieved by natural or mechanical ventilation.
- Smoke dilution: Mixing fresh air with the smoke to increase the visibility and decrease untenable conditions.
- Smoke containment: Smoke can be contained in the area of fire origin using existing barriers (smoke doors, dampers in ventilation systems, etc.).
- Smoke pressurization/opposing airflow: This mechanism is implemented by producing pressure differentials to limit smoke from entering into adjacent compartments or spaces.

6.3.2.4 Smoke control systems and their design

6.3.2.4.1 Heating, Ventilation and Air Conditioning (HVAC) systems

Heating, Ventilation and Air Conditioning (HVAC) systems should be designed to limit smoke spread to other areas of a building.

The measures in HVAC systems to control the spread of smoke include smoke dampers and shutting off fans. For an optimum system, these measures must work together with the physical barriers and architectural components that constitute the building. A detailed description of smoke control measures for HVAC systems, can be found in the New Zealand Design Guide (Buchanan, 1994), NFPA 90A (1996), NFPA 92A (1996) and ASHRAE Design Guide (Milke and Klote, 1992).

6.3.2.4.2 Smoke management systems

Smoke management systems are usually employed in shopping mall atria and large assembly halls. These mechanical systems activate in the event of a fire and extract smoke from the hot layer, thus maintaining the smoke level above evacuation routes. Details on smoke management in atria, can be found in NFPA 92B (1995) and ASHRAE Design Guide (Milke and Klote, 1992).

Smoke exhaust inlets should be located so as to provide efficient smoke extraction. The fans extracting the smoke should have a capacity sufficient to exhaust the volume of smoke produced by the design fire. Moreover, the temperature rating for the fans must be greater than the temperature of the smoke or hot smoke gas layer. Table 6.1 shows some of the operational temperatures for smoke removal fans as well as their duration of operation in various countries around the world.

As the smoke extraction is being performed, there must be a supply of fresh air into the lower layer to replace the exhausted air. Supply of fresh air is usually through doors.

Table 6.1. Temperatures and duration of operation of smoke control fans in various countries (Buchanan, 1994)

Country	Temperature (°C)	Time (hours)	Comments
Austria	200	2	
Belgium	250	2 or 3	
	400	2	
Canada	-	-	Each consultant legally responsible for safety
Egypt	400	2	French consultant specifications adopted
Finland	350	1	
France	200	2	Certificate of independent test required by law
	400	2	
Hong Kong	250	1	
Italy	200	2 or 3	
	400	2	
Malaysia	250	2 or 3	Following U.K. practice
New Zealand	300	0.5 or 1	Likely to adopt U.K. practice
Saudi Arabia	-	-	No current specification
Singapore	150	1	
	250	1	
South Africa	-	-	Follow U.K., U.S.A.
U.K.	300	0.5 or 1	
U.S.A.	650	1	No national approach; State regulations vary
	260	1	
W. Germany	600	1.5	

6.3.2.4.3 Pressurization systems especially in escape routes

Escape routes are constructed so that, in the event of a fire, occupants can evacuate safely. Therefore, the conditions in these routes must remain tenable and useable by occupants. Protection of escape routes is done through fire resisting construction that prevents fire from spreading to the exit path, fire rated doors with automatic closing devices so that smoke cannot pass through and the use of pressurization.

Pressurization is performed by inducing air inside the designated area so that a higher pressure is maintained. This higher pressure prevents smoke from neighbouring spaces from entering the protected spaces. The pressurization systems that may be encountered are the stairwell pressurization system, the elevator smoke control system (less common), and the zoned smoke control system.

- Stairwell pressurization is performed by pressurizing the stairwells by one or more fans. The fans may be used exclusively for the pressurizing system or in addition to other purposes such as HVAC systems.
- Elevator smoke control is a system designed to supply air to the hoistway for the purpose of producing a pressure differential that will prevent smoke migration into the hoistway.
- Unlike stairwell pressurization and elevator smoke control which are intended to prevent smoke infiltration into shafts, zoned smoke control is intended to limit the smoke movement through cracks and unpressurized shafts within a building. For this system, the building is divided into smoke zones. At the outbreak of a fire, mechanical fans are used to produce pressure differences which prevent the spread of smoke to other zones. In general, a zone is defined as a floor.

In highly-populated buildings, it is expected that many stairwell doors will open during the evacuation process. This may create a large pressure drop and thus the stairwell pressurization systems should be designed to operate with a number of open doors. The National Building Code of Canada (NBCC, 1995) uses a system with constant-supply air rate and an exterior stairwell door that opens automatically upon system activation. This system eliminates pressure fluctuations by eliminating opening and closing of the exterior stairwell door during system operation. This system, called the Canadian system, is also used in sprinklered buildings.

In addition, the performance of a pressurized stairwell can be improved if the smoke is vented and exhausted from the fire floor. The removal of the smoke can be accomplished by exterior wall vents, smoke shafts, and fan-powered exhausts. The smoke venting from the fire floor can also help fire fighters in smoke purging after the fire has been extinguished.

Finally, during the design of the pressurization systems, parameters such as air leakage (door gaps, construction gaps, etc.), the number of doors opened simultaneously and opening door forces caused by pressurization must be taken into consideration. The steps to be considered in designing pressurization systems are detailed in the New Zealand Design Guide (Buchanan, 1994), NFPA 92A (1996) and ASHRAE Design Guide (Klote and Milke, 1992).

6.3.2.5 Probability of successful activation and reliability of control systems

Probability of successful activation must be calculated so that the reliability of the control systems in place is determined and verified against acceptable fire safety levels.

The reliability of a smoke control system mainly depends on the equipment used, the quality of the system's maintenance and inspection as well as the age of the system. In addition, smoke control equipment must be able to work in a hot smoky environment. The equipment used for smoke control must be successfully tested and rated by the manufacturer. The electrical supply for the operation of smoke control systems must be reliable and able to work in the fire emergency conditions. Table 6.2 shows the reliability and mean life of some smoke control systems as reported by Klote and Milke (1992).

Table 6.2. Reliability and mean life of smoke control systems (Klote and Milke, 1992)

System	No. of HVAC System Fans	No. of Other Components	Reliability of New System Before Commissioning	Mean Life of Commissioned System (months)
1	3	0	0.97	116
2	0	3	0.83	46
3	3	9	0.56	14
4	5	18	0.31	8
5	5	54	0.03	3

6.3.2.6 Time of failure of smoke control systems

Although, smoke control systems may have been well designed and function effectively during their operation, they may be rendered inoperative due to high temperatures or structural failure. The flashover event and integrity of the barriers affect the smoke control systems, i.e., the smoke control system can lose its function if there is loss of pressure due to formation of holes in the barriers and the extraction of smoke may be impossible if the fire is too large. In general, smoke control systems cannot be designed to cope with smoke generation in the post-flashover and fully-developed fire stages because of the high temperatures involved and the large quantity of smoke produced.

6.3.3 Environmental effects

The parameters affecting the movement of smoke include the exterior ambient conditions (temperature and wind).

Temperature effect. Temperature differentials between the ambient temperature and the building temperature affect the movement of smoke especially in high rise buildings. These temperature differentials create what is known as stack effect. Stack effect causes upward movement of smoke in buildings in the winter as the building temperature is higher than the ambient temperature. In the summer, the reverse stack effect occurs as the indoor temperature is lower than the exterior temperature. In the event of a fire, this air flow carries smoke from the compartment of fire origin and spreads it throughout the building.

Wind effect. The effect of wind on smoke movement can be expressed in terms of the wind pressure applied on the surface under consideration. This pressure, as reported in the New Zealand Design Guide (Buchanan, 1994), can be calculated as follows:

$$P_w = 0.5 \cdot C_w \cdot \rho_o \cdot V_w^2 \qquad (6.1)$$

where: P_w = wind pressure, Pa;
C_w = pressure coefficient, -0.8 (leeward walls) and 0.8 (windward walls);
ρ_o = outside air density, kg/m^3;
V_w = wind velocity, m/s.

In the case of broken windows or openings to the outside (e.g., stairways), wind effects will affect pressurization and may spread smoke throughout the building.

6.3.4 Interaction of smoke control systems with active systems

The operation of active fire protection systems, such as sprinklers and HVAC systems may influence the spread of smoke through the building, as well as the performance of smoke control systems.

The activation of sprinklers may cause cooling of the gases in the hot layer and mixing with the air in the lower layer. Although the fire intensity may be controlled by sprinklers, contamination of the lower layer may threaten the life of the occupants.

The operation of HVAC systems, both in normal conditions and in fire mode, should be examined to determine how it impacts smoke movement both within the compartment of fire origin and to other compartments.

In addition, as smoke control systems are usually activated upon detection by smoke, heat or flame detectors, the time of activation should be determined and used to evaluate the conditions at that time. Proper placement of such detectors is crucial to allow activation of smoke control systems in time to prevent the occurrence of untenable conditions.

6.3.5 Evaluation of properties of smoke

The calculation of smoke properties within the compartment of fire origin are an indication whether or not untenable conditions have been reached. The properties can be calculated using well established engineering equations or validated fire computer models. Below are the equations governing the calculation of some of the properties.

6.3.5.1 Temperature of smoke (average plume temperature)

Smoke temperature is important since it affects the time of activation of heat detectors and sprinklers. High smoke temperatures also create untenable conditions endangering the occupants and fire fighters. Smoke temperature (average plume temperature) can be calculated as follows:

$$T_s - T_o = \frac{Q_c}{\dot{m} \cdot c_p} \tag{6.2}$$

where:
- T_s = smoke temperature, °C;
- T_o = ambient temperature, °C;
- Q_c = convective heat output of the fire, kW;
- Q = total heat output of the fire, kW;
- c_p = specific heat of air, kJ/kg;
- $\dot{m}$ = mass flow rate (see Equation (5.11) in Section No. 5 on Fire Growth or the BSI (1994) for detailed calculations), kg/s.

6.3.5.2 Optical density of smoke and visibility through smoke

These parameters can be used to determine the activation time of smoke detectors and if the visibility has fallen below the acceptable conditions. Equations (6.3) and (6.4) below predict values of optical density and visibility, respectively:

$$OD = 10 \cdot \left(\frac{D_m \cdot m_f}{V_t} \right) \tag{6.3}$$

where:
- OD = optical density, dB/m;
- D_m = mass optical density, m^2/g (see Table 6.3 for some values);
- m_f = mass of fuel burnt, g;
- V_t = total volume of smoke generated at time t, m^3.

The visibility through smoke can be calculated from the optical density as:

$$Visibility\ (m) = \frac{10}{OD} \tag{6.4}$$

6.3.5.3 Concentration of carbon monoxide (CO)

The toxicity of the smoke produced by the fire depends on the fuel. The principal toxic element produced during the pre-flashover fire growth stage is CO. The concentration, in parts per million (ppm) of CO, at 20°C, is used to determine the tenability conditions in the compartment of fire origin and can be estimated as follows:

$$CO\ (ppm) = 0.858 \cdot 10^{6} \cdot Con_{co} = \frac{0.858 \cdot 10^{6} \cdot Y_{co} \cdot m_f}{V_t} \tag{6.5}$$

where: Con_{co} = concentration of carbon monoxide, kg/m^3;
Y_{co} = carbon monoxide yield factor, kg/kg (See Table 6.3 for some values);
m_f = mass of fuel burnt, kg;
V_t = volume of smoke, m^3.

Table 6.3. Typical product yield for flaming combustion (Australian guidelines, 1996)

Material	Carbon Monoxide Yield Factor (Y_{co})	Mass Optical Density (D_m) (m^2/g)
Timber	0.004	0.04
Polyvinyl chloride (PVC)	0.063	0.40
Polyurethane (flexible)	0.042	0.34
Polyurethane (rigid)	0.051	0.30
Polystyrene	0.060	1.00
Polypropylene	0.024	0.24
Generic building contents	0.013	0.30

6.3.5.4 Volume of smoke

The volume of smoke produced depends on the size of the fire and the nature of the fuel in the occupancy in which the fire occurred. The volume rate of smoke produced can be estimated, according to the BSI (1994), as follows:

$$\dot{V}_s = \dot{m} \cdot \frac{T_s}{\rho_o\, T_o} \tag{6.6}$$

where: $\dot{V}_s$ = volume rate of smoke production at a specified temperature, m^3/s;
$\dot{m}$ = mass flow rate, kg/s;
T_s = smoke temperature in smoke plume, K;
ρ_o = density of air under ambient temperature, kg/m^3;
T_o = ambient temperature of the space, K.

In addition, according to the New Zealand Design Guide (Buchanan, 1994), the volume of smoke can be evaluated based on the quantity of smoke produced. The quantity of smoke produced can be estimated as follows:

$$\dot{m}_{smoke} = 0.096 \cdot P_f \cdot \rho_o \cdot Y^{1.5} \cdot \left(g \cdot \frac{T_o}{T_f} \right)^{0.5} \tag{6.7}$$

where: $\dot{m}_{smoke}$ = mass rate of smoke production, kg/s;
P_f = perimeter of fire, m;
ρ_o = density of the ambient air, kg/m^3;
Y = distance between floor and bottom smoke layer under ceiling, m;
T_o = temperature of ambient air, K;
T_f = temperature of flames in smoke plume (about 1100 K), K;
g = gravitational acceleration, m/s^2.

The volume rate of production of smoke, $\dot{V}_s$, can be related to the mass rate by the following equation (6.8):

$$\dot{V}_s = \frac{\dot{m}_{smoke}}{\rho_s} \tag{6.8}$$

where: $\dot{m}_{smoke}$ = mass rate of smoke production, kg/s;
ρ_s = density of air as smoke at a temperature T in °C, kg/m^3;
ρ_s = $1.22 \cdot \left(\frac{290}{T + 273}\right)$.

6.3.5.5 Depth of the hot smoke layer

The depth of the hot layer provides an indication whether the smoke interface has descended to a level which could threaten the life of the occupants and fire fighters in the compartment. This parameter can be calculated using zone or field computer models. Also, for high spaces such as atria, the engineering correlations contained in NFPA 92A (1996) can be used.

6.4 Input and Output for the Evaluation Procedures

Tables 6.4 and 6.5 summarize the input and output requirements for smoke spread.

Table 6.4. Input requirements

Input needed	Section Taken from
Geometry of compartment	- Initial design parameters

Building characteristics	- Initial design parameters
Environmental effects	- Initial design parameters
Rate of heat release as a function of time	- Fire growth
Smoke yield	- Fire growth
Yield toxic substances	- Fire growth
Time of detector activation and smoke control systems activation	- Detection

Table 6.5. Output requirements

Output	Needed for Section
Smoke temperature	- Detection - Measure of untenable conditions
Smoke optical density	- Detection - Measure of untenable conditions
Concentration toxic substances	- Measure of untenable conditions
Depth of hot layer	- Detection - Measure of untenable conditions

6.5 Performance Criteria

Calculations for smoke control systems must be undertaken by the designer to determine whether the performance criteria are satisfied and whether untenable conditions are reached in the compartment of fire origin or in adjacent areas.

Smoke control systems must be activated by the detection system and should be activated well before untenable conditions are reached in the building.

The main criteria to be set by the design team is the activation time of the smoke control systems based on the calculated detection times and the reliability of the existing smoke control systems.

7. SPREAD OF FIRE

7.1 Purpose

- To provide guidelines for evaluating the potential for fire spread from the compartment of fire origin to other areas in the building and to adjacent buildings.

7.2 Introduction

7.2.1 General

Spread of fire is defined as the occurrence of ignition of nearby exposed items. The objective of building compartmentation is to contain a fire in the compartment of fire origin.

Spread can occur in two fashions: either within the compartment of fire origin only or beyond the compartment of fire origin. Spread within the compartment of fire origin is defined as the ignition of neighbouring items inside the compartment of origin. Spread outside the compartment of fire origin is assumed if an item outside the compartment is ignited and initiates fire growth in adjacent compartments.

7.2.2 Transmission of heat or means of fire spread

Heat can be transmitted throughout a burning building by one or more (combination) of the following four methods:

1. <u>Conduction</u>: The process of conduction is generally associated with heat transfer rather than flame. Heat may be conducted from one body to another by direct contact of the two bodies or by an intervening heat-conduction medium. The amount of heat that will be transferred and its rate of travel by this method depends on many factors including the conductivity of the material through which the heat is passing and the ignition temperature of the materials in the compartment.
2. <u>Radiation</u>: Radiated heat will travel through space until it reaches an object. As the object is exposed to the radiant heat flux and increases in temperature heat, it will, in return, radiate heat from its surface. Radiated heat is one of the major sources of fire spread and its importance demands an immediate defensive attack at points where radiation exposure is severe. When considering this mode of spread, factors to be considered include dimensions of the flame, emissivity of the flame, absorptivity of combustible materials, temperature of the flame, arrangement of combustible surfaces and ignitability of adjacent items.
3. <u>Convection</u>: The spread of fire by convection has more influence on the position for fire attack and ventilation than either of the previously discussed methods of heat

propagation. Convection is the transfer of heat by the movement of air or liquid. Heated air in a building will expand and rise. For this reason, fire spread by convection is mostly in an upward direction from floor to floor, from room to room and from area to area. The spread of fire through corridors, up stairwells and elevator shafts, through wall openings and through attics is mostly caused by convection. Factors affecting this mode of fire spread include the temperature of the flame and ignitability of adjacent items.

4. Direct flame contact: Fire also spreads along and through a material that will burn by direct flame contact. When a substance is heated to a point where flammable vapours are given off, these vapours may be ignited. Any other flammable material which is in contact with the flame may be heated to a temperature where it will ignite and burn.

The mode of ignition, during fire spread, may be either piloted (through direct flame) or non-piloted (radiant heat flux through an opening). The terms piloted ignition and non-piloted ignition were defined in Section No. 5 on Fire Initiation and Growth.

7.3 Evaluation Procedures

7.3.1 Heat transfer principles

Conduction. Conduction expressed as a steady state uni-directional heat flux is given by:

$$q_x = -k \frac{dT}{dx} \tag{7.1}$$

where:
- q_x = heat flux in the x direction, W/m^2;
- k = thermal conductivity, W/m·K;
- T = temperature, °C;
- x = distance in the x direction, m.

Non-steady state heat transfer can be determined, by numerical methods, using the following equation:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \cdot \frac{\partial T}{\partial t} \tag{7.2}$$

where:
- T = temperature, °C;
- x, y, z = directions of the heat flow;
- α = thermal diffusity (α = k / ρ c), m^2/s;
- k = thermal conductivity, W/m·K;
- ρ = material density, kg/m^3;
- c = specific heat capacity of the material, J/kg·K;
- t = time, s.

Convection. For a convection flow, the heat flux can be determined as:

$$q_c = h_c\,(\Delta T) \tag{7.3}$$

where: q_c = convection heat flux, W/m^2;
h_c = convective heat transfer coefficient, W/m^2·K;
ΔT = temperature difference between the surface and the fluid, K.

The quantification of the convective heat transfer coefficient, h_c, is difficult and the reader is referred to Drysdale (1985) for an estimation of h_c. A value of 25 W/m^2·K can be used in fully-developed fires.

Radiation. The radiant heat flux received by a remote surface can be estimated as follows:

$$q_r = \phi\,\sigma\,\varepsilon\,(T_e^4 - T_r^4) \approx \phi\,\sigma\,\varepsilon\,T_e^4 \tag{7.4}$$

where: q_r = radiation heat flux, W/m^2;
ϕ = configuration factor ($0 < \phi < 1$) (see SFPE Handbook (1995) for detailed calculations);
ε = emissivity of the surface;
σ = Stefan-Boltzman constant (5.67 x 10^{-8} W/m^2·K^4),
T_e = temperature of the emitting source, K;
T_r = temperature of the receiving surface, K (very small compared to T_e and can be neglected in calculations).

The above equations (7.2), (7.3) and (7.4) are based on experiments conducted in compartments with floor areas of 10 m^2 and less.

7.3.2 Spread of fire inside the compartment of fire origin

Spread of fire is directly related to the type and arrangement of material in the compartment. The fire propagates very rapidly through combustible materials. Therefore, spread can be controlled if the contents, structural elements, walls and ceilings of the compartment are not prone to rapid ignition, fire spread and emission of heat and toxic gases. One way of achieving this control is by adding physical or chemical fire retardants to combustible materials to delay combustion of the material during the early stages of ignition. Another way to minimize the likelihood of fire spread to an adjacent fuel is to reduce the radiation heat flux to a level that will not result in fuel ignition. This can be achieved by reducing radiation from the hot layer by venting the hot gases or by providing adequate horizontal separation between combustible materials.

One of the parameters affecting probable fire spread within large compartments are concealed spaces. A large compartment may contain a number of concealed spaces. These must be accounted for in the fire safety design and should be eliminated from the building construction, when possible. Concealed spaces include ceiling voids, spaces within hollow construction, under floors, under exterior cladding or any others where unseen spread of fire and smoke can occur. Concealed spaces within walls or floors should be sealed off at common junctions.

Another obstacle to fire spread inside a fire compartment is internal partitions. In general, internal partitions within a compartment are not fire resistant unless they are designed to protect a safe egress path. They do, however, limit fire spread.

In cases where the compartment size is large (greater than 150 m^2), such as open office areas, time for fire spread is usually large and high temperatures are not likely.

7.3.3 Spread of fire outside a fire compartment

7.3.3.1 Factors affecting fire spread

The factors influencing spread of fire beyond the compartment of fire origin include:

- Fire intensity;
- Fire load in the compartment of fire origin;
- Fire resistance of barriers;
- Fire suppression systems in-place;
- Fire dampers and air-handling systems;
- Concealed spaces such as ceiling voids, spaces with hollow construction, under floors and under exterior cladding through which hot gases may spread undetected (easy preheat and ignition of internal combustibles at weak points);
- Large open spaces with high ceilings (atriums and malls) where fires are likely to be fuel-controlled (spread occurs due to direct radiation from fires);
- Access to vertical shafts such as stairways, lift shafts and large service ducts.

7.3.3.2 Routes of fire spread

Fire spread beyond the compartment of fire origin is generally caused by excessive heat exposure and the formation of openings in the compartment boundaries. The following is a list of potential routes of fire spread that may exist or may be created by a fire in a compartment:

- Existing openings (e.g., open doors, open windows, open roofs, etc.);
- Formation of openings as a result of breakage of glass and glazing;

- Formation of openings as a result of deterioration of the compartment barriers from structural failure, formation of cracks or local excessive temperature rise on the unexposed face through heat conduction;
- Formation of openings as a result of failure at penetrations of building services in barriers from flow of hot gases through services or local hot spots at weak points.

Openings that are created as a result of a fire should be considered in fire safety design because they can change the development of a fire, e.g., change to the ventilation inside the fire compartment. The designer must, therefore, consider all possible openings that could be created as the fire develops and grows. The most probable reasons for fire spread should be determined. This includes the existing openings such as open doors and windows and the openings created due to glass breakage and/or barrier deterioration. For barriers, fire resistance time can be used to evaluate the deterioration of the assembly including the formation of holes. Window glass breakage, on the other hand, can be determined using the criteria defined in Subsection No. 7.5 on Performance Criteria. In addition, the time and nature of the breakage of glass is difficult to predict since it depends upon the material and the fire in the compartment.

7.3.3.3 Prevention of spread through fire compartmentation design

One way to minimize fire spread outside the compartment of fire origin is the use of compartmentation. Every fire compartment may include a room or a group of rooms depending on the building use. The separating function of the structural elements, also called fire separations, are fire resisting assemblies (walls or floor-ceiling systems) that prevent spread of fire from one compartment to another. In general, a fire separation should have a fire resistance rating that corresponds to the complete burn-out of the compartment, i.e., the fire resistance exceeds the expected severity of the fire. The design of the fire separations should include an assessment of the integrity and thermal resistance of these separations against the integrity and thermal resistance criteria set (see Subsection No. 7.5 on Performance Criteria). Finally, the structural load bearing members (beams, columns, walls) must have, at minimum, a fire resistance rating equivalent to that of the separations.

Weak elements in fire compartments are openings such as doors. An open door constitutes a breach of compartmentation which can provide a path for spread of fire and smoke to other compartments. Doors can be designed to stop smoke and fire movement. However, good housekeeping, occupant education to practice good fire safety habits (e.g., no wedging), and implementing new technology (e.g., doors held open by magnetic catches and released in fire emergencies, especially in public buildings) is required to ensure that they will perform their function. In addition, fire spread may be reduced by using fire resistant glazing to delay fire growth and allow safe evacuation of the occupants and by extinguishing the fire by means of suppression.

7.3.3.4 Prevention of spread through fire resisting barriers

Barriers have the potential to contain the fire within the compartment of fire origin and to protect combustibles against fire exposure and, therefore, prevent fire spread to other areas. One of the characteristics of barriers is their ability to withstand a fire, called fire resistance. The barrier fire resistance is a function of the level and duration of the expected fire severity. The level of fire severity is determined by the fire safety objectives to be satisfied. This could include highest fire severity during the complete fire duration, prior to fire department personnel intervention or during the evacuation period.

Fire barriers can be either structural or non-structural elements. The barriers which are also structural elements may fail earlier than anticipated and can affect the other structural elements and eventually the whole building, if not designed properly. It is, therefore, essential to assess the time of loss of stability for barriers which act as structural elements. In addition, the time at which openings develop in the barriers is a major factor in fire safety design. This time can be obtained using the criteria set for loss of integrity of the barriers. More details on structural adequacy of fire barriers are provided in Section No. 8 on Fire Resistance and Structural Stability.

7.3.3.5 Fire spread from one storey to another

In multi-storey buildings, the fire can spread from one floor to another. This situation is undesirable and the fire safety design should consider spread of fire from floor-to-floor which can occur through the paths described below.

Failure of floor or ceiling fire separations. The fire separations were described in Subsection No. 7.3.3.3 on fire compartmentation.

Concealed spaces. To prevent fire spread to other storeys in a building, the building design must include provisions for fire-stops in concealed spaces.

Service ducts and shafts. Service ducts and shafts must be properly fire proofed so that the fire resistance of fire separations is not weakened. A fire resistive wall can be constructed around the duct or the shaft so that fire cannot penetrate it. The fire resistance of the wall should be at least the same as the supported members in terms of stability and at least the same as that required for the fire separation in terms of thermal resistance and integrity. In addition, as an alternative, openings within the duct can be sealed at every floor level using fire dampers.

Stairways. Stairways represent the main fire escape route for the occupants. Therefore, the prevention of fire and smoke spread into stair shafts is of prime importance. This can be achieved by providing fire resistive doors with the same rating as the stairway walls. In addition, the doors must be closed at all times.

<u>External openings</u>. Calculation of the effects of radiant heat transfer on fire spread require the determination of the size, shape and temperature profile of the fire, as well as the horizontal projection distance from the openings. Exterior windows and openings are the main means of fire spread in multi-storey buildings, especially when easy-to-ignite materials are nearby. To determine the possibility of exterior fire spread, the radiation inside the window above the floor of fire origin should be calculated and compared to the radiation criteria. The radiation into the compartment is related to the shape and size of the flame coming out of the window of the fire compartment. The flame height can be estimated as follows (Drysdale, 1985):

$$Z = 12.8 \cdot \left(\frac{\dot{m}}{W_o} \right)^{2/3} - H_o \tag{7.5}$$

where:
- Z = flame height above the top of the opening of the burning floor, m;
- W_o = width of the window opening, m;
- H_o = height of the window opening, m;
- $\dot{m}$ = rate of burning in the room (see Equation (7.6) below), kg/s.

$$\dot{m} = \frac{1.5 \cdot Q}{H_c} \tag{7.6}$$

where:
- Q = average rate of heat release, MW;
- H_c = calorific value of the fuel, MJ/kg (see Equation (5.18) and Table 5.6 in Section No. 5 on Fire Initiation and Growth).

The projection, P (m), of the flame tip from the wall can be estimated as:

$$P = 0.314 \cdot H_o^{1.53} \cdot W_o^{-0.53} \tag{7.7}$$

The radiation through the opening above the floor of fire origin can be estimated using the area of the flame (Z and P) to determine whether or not spread is possible, with a flame temperature, T_e, of 600°C and emissivity, ε, of 0.5 applied to Equation (7.4). In general, fire spread is likely to occur if the radiation on combustible materials is greater than the radiation criterion of 12.5 kW/m^2 (see Subsection No. 7.5 on Performance Criteria) or any other rational value set by the design team.

Methods for calculating fire size, flame shape and temperature from external openings (windows and doors) can also be found in references such as Law and O'Brien (1981) and AISI (1983).

7.3.4 Fire spread to adjacent properties

The prevention of fire spread to neighbouring buildings can be satisfied by providing fire walls that possess fire resistance to withstand the duration of the fire, by limiting opening size to minimize the radiation to the exposed adjacent property, by separating the buildings by minimum distances and by reducing the potential for ignition adjacent buildings including roofs due to flying brands (use of external construction materials that are not easily ignited).

7.3.4.1 Fire resistance design of fire walls

The fire walls of a building must retain their stability and load-bearing capacity for the duration of a fire. They must also prevent fire spread during the entire period of the fire. Fire resistance is detailed in Section No. 8 on Fire Resistance and Structural Stability.

7.3.4.2 Radiation to adjacent buildings

The dominant mode of heat transfer outside the compartment of fire origin is radiation. The radiant heat intensity from a single opening of a building with a fire contained in a compartment to some distant receiving point can be estimated using Equation (7.4) and a reduction factor C_1, as follows:

$$q_r = C_1 \cdot \phi \cdot \sigma \cdot \varepsilon \cdot \left(T_e^{4} - T_r^{4} \right) \qquad (7.8)$$

where:

- q_r = radiant heat intensity, W/m^2;
- C_1 = radiation reduction factor;
- ϕ = configuration factor;
- ε = emissivity (a value of 1.0 gives a conservative design);
- σ = Stefan-Boltzman constant (5.67×10^{-8} $W/m^2 \cdot K^4$);
- T_e = temperature of the emitting surface, K;
- T_r = temperature of the receiving surface, K.

Preventing fire spread to exposed property is evaluated based on the critical values of received radiation outlined in Subsection No. 7.5 on Performance Criteria.

7.3.4.3 Glazing

Typical window glazing will break and fall out as the compartment reaches flashover. After breakage, an opening is created. Fire spread to floors above the fire or to adjacent structures can occur if the critical radiation intensity is exceeded. For normal glass, C_1 of Equation (7.8) takes the value of 1. If the glazing is fire resistant and remains in place during the fire, C_1 can be taken as 0.5.

7.3.4.4 Multiple emitting radiation openings

In the case of multiple windows on a facade of a burning building, an additional factor is introduced to the incident radiation. This factor can be calculated as follows:

$$F_f = A_o / A_e \tag{7.9}$$

where: F_f = facade factor;
A_e = area of an enclosing rectangle containing all emitting openings, m^2;
A_o = area of openings within the enclosing rectangle, m^2.

7.3.4.5 Separation distances between adjacent buildings

The main objective of separating buildings by a distance is to limit and hinder the spread of fire to neighbouring buildings. More details on the general principles and methods for evaluating the separation distances between buildings can be found in Read (1991), NFPA 80A (1996) and McGuire (1965).

7.3.4.6 Spread from flying brands

In the design process, it should be ensured that the roofing material is not subjected to radiation levels, from flying fire brands, that will initiate ignition and eventual fire. Methods used to evaluate the ignitability and fire characteristics of external surfaces of roofs under radiation from flying fire brands can be found in CAN/ULC-S107-M87 and ASTM E108-96.

7.4 Input and Output for the Evaluation Procedures

Tables 7.1 and 7.2 summarize the input and output requirements for fire spread.

Table 7.1. Input requirements

Input needed	Section Taken from
Building characteristics	- Initial design parameters
Geometry of compartment	- Initial design parameters
Separating distances between buildings	- Initial design parameters
Environmental effects	- Initial design parameters
Thermal characteristics of compartment boundaries and structural elements	- Initial design parameters
Performance criteria	- Initial design parameters
Rate of heat release as a function of time	- Fire growth
Time of flashover	- Fire growth

Table 7.2. Output requirements

Output	Needed for Section
Radiation from fire	
Enclosure temperature	- Measure performance criteria
Time of fire spread to other areas	
Time of structural failure	

7.5 Performance Criteria

7.5.1 Glass breakage

The following criteria can be used to define breakage of glass:

- The Australian guidelines (1996) provide guidelines based on the temperature differential ΔT between the two faces of the glass. Based on this criteria, ordinary glass breaks at ΔT= 80°C and tempered glass breaks at ΔT= 240°C.
- Quaglia (1992) set the temperature criteria for breakage of interior ordinary glass at 100°C and of tempered glass at 270°C. Frantzich et al (1993) used a single value of 300°C for the breakage of glass.
- Kim and Taber (1989) stated that critical temperatures on the exposed side of glazing were 150 to 175°C for plain glass and 350°C for both heat strengthened and tempered glass.

7.5.2 Radiation criteria

Preventing fire spread to exposed property is evaluated based on the critical values of received radiation q_{rc}. Tables 7.3 and 7.4 list these criteria for different building materials.

Table 7.3. Critical values of received radiation q_{rc} as listed in (Buchanan, 1994)

Condition of Neighbour's Wall	q_{rc} (kW/m^2)
Combustible • Plastic • Cellulose	 10.0 12.5
Non-combustible with non-fire resistant glazing	20.0
Non-combustible with fitted fire resistant glazing	50.0

Table 7.4. Critical values of received radiation q_{rc} as listed in (Quaglia, 1992)

q_{rc} (kW/m^2)	Outcome
> 9	Breakage of ordinary glass Ignition of fabrics if in contact with sparks or embers
≥ 21	Ignition of timber if in contact with sparks or embers
≥ 42	Spontaneous ignition of timber

Other researchers have also described typical threshold values for the critical radiation level at exposed structures from a neighbouring fire as a safety criterion.

- To determine the minimum separation distance necessary between two buildings so that pilot ignition of an exposed building or its contents is unlikely, McGuire (1965) used a maximum tolerable level of incident radiation at the facade of the unprotected exposed building of 12.5 kW/m^2. This radiation is also used as the basis for the exposure requirements in the NBCC (1995) and NFPA 80A (1996).
- Scherfig (1993) used 15 kW/m^2 as the acceptable threshold level for preventing spread from one structure to an adjacent exposed structure.
- Barnett and Simpson (1995) provide the following threshold levels: 10 kW/m^2 for plastic cladding, 12.5 kW/m^2 for wood cladding, and 25 kW/m^2 for spontaneous ignition of items just inside the windows of an exposed building.

8. FIRE RESISTANCE AND STRUCTURAL STABILITY

8.1 Purpose

- To give guidance regarding the design procedures for fire resistance and structural stability of a building so that, in case of fire, premature failure of load-bearing elements of the building will be prevented.

8.2 Introduction

8.2.1 General

Fire resistance and structural stability are major components in fire safety design. The fire safety design must ensure an adequate design because of the following reasons:

- Safety of the people during evacuation, rescue and fire fighting operations;
- Safety of people in neighbouring properties;
- Expenses (economic aspect) that may be incurred due to property loss, content loss and possible business loss;
- Social impact due to loss of income or loved ones.

8.2.2 Factors affecting structural stability

There are many factors that influence the structural stability of a building during a fire including:

- Fire resistance of a structure and its elements;
- Fire intensity;
- Properties of the structural materials, such as steel and concrete, in terms of critical temperatures;
- Degree of exposure or protection of the structural elements by other elements and suppression systems during a fire.

8.3 Evaluation Procedures

8.3.1 Fire severity

In order to evaluate the performance of barriers and structural elements, the fire severity in the compartment of fire origin is measured in terms of the temperature time profile or heat flux time profile. The peak values and time periods of these two parameters are important in determining the performance of barriers or structural elements. Temperature or heat flux time profiles can be determined using empirical/semi-empirical expressions, fire engineering models or experimental test results.

8.3.1.1 Compartment temperatures

For the calculation of fire severity during the post-flashover stage, the compartment temperatures can be calculated directly or be represented by a standardized heating curve. The following are some of the methods that can be used to determine the heating curves:

1. Characteristic temperature-time curves

A heat balance represented by Equation (8.1) can be used to determine temperature-time history for a compartment. Pettersson et al (1976) used this approach with some simplifications to derive gas temperature-time curves.

$$Q_{com} = Q_l + Q_w + Q_r + Q_g \tag{8.1}$$

where: Q_{com} = rate of heat release in the compartment produced by combustion, kW;
Q_l = rate of heat loss by convection through openings, kW;
Q_w = rate of heat loss by radiation and convection to the compartment walls, kW;
Q_r = rate of heat loss by radiation through openings, kW;
Q_g = rate of accumulation of heat in hot gases in the compartment, kW.

The rate of heat loss from radiation and convection through openings and to compartment boundaries, as well as the accumulation of heat in the hot gases of the compartment can be determined using Equations (7.2), (7.3) and (7.4) given in Subsection No. 7.3.1 on Heat Transfer Principles.

2. Maximum compartment temperatures

Maximum compartment temperature can be used to estimate impacts and consequences of fully-developed fires. The maximum compartment temperature can be determined as follows (Law, 1983):

$$T_g - T_o = 6000 \cdot \frac{(1 - e^{-0.10\,\Omega})}{\Omega^{0.5}} \cdot (1 - e^{-0.05\,\Psi}) \tag{8.2}$$

with

$$\Omega = \frac{A_T - A_o}{A_o \cdot \sqrt{H_o}}$$

$$\Psi = \frac{L}{\left[A_o \cdot (A_T - A_o)\right]^{0.5}}$$

where: T_g = expected maximum compartment temperature, K;
T_o = ambient temperature, K;
A_T = area of compartment enclosing surfaces, m^2;
A_o = area of the ventilation opening, m^2;
H_o = height of the ventilation opening, m;
L = equivalent total fire load of wood, kg.

3. Standard temperature-time curves

In order to obtain the performance of structural elements and fire-resisting barriers, the ISO 834, CAN/ULC-S101-M89 (Underwriters' Laboratories of Canada, 1989) and ASTM E-119 tests can be used. These tests utilize standardized time/temperature curves. Even though the temperature obtained from a test furnace may not realistically represent a compartment fire, it does provide a measure of a material's performance. The relationship representing the standard ISO 834 temperature-time curves, also referred to as the standard test, is given by

$$T_g = T_o + 345 \log_{10} (8t + 1) \tag{8.3}$$

where: T_g = average furnace temperature, °C;
T_o = ambient temperature, °C;
t = time, min.

The North American temperature-time curve as given by ASTM E-119 and CAN/ULC-S101-M89 can be approximated as follows:

$$T_g = T_o + 750 \cdot \left[1 - exp\left(-0.49\sqrt{t}\right)\right] + 22\sqrt{t} \tag{8.4}$$

4. Hydrocarbon heating curve

BS 476: Part 20 specifies the equation below to represent a hydrocarbon temperature-time curve. The equation can be used to predict fire conditions involving hydrocarbon fuels.

$$T_g = 1100 \left(1 - 0.325\, e^{-0.1667t} - 0.204\, e^{-1.417t} - 0.471\, e^{-15.833t}\right) \tag{8.5}$$

8.3.1.2 Equivalent time of fire exposure

Fire severity is defined as the equivalent time of exposure to a standard fire. Empirical relationships provide an easy solution for the determination of fire severity. The following is an empirical procedure prepared by CIB W14 (1986) to estimate the fire equivalent fire severity based on wood crib tests in standard compartments:

$$t_e = CF \cdot VF \cdot q_f \tag{8.6}$$

where: t_e = equivalent severity time of fire exposure to the standard test, min;
CF = conversion factor, min/MJ/m^2 (see Table 8.1 below or use 0.067 if the material properties are not known);
VF = ventilation factor (see Equation (8.7) below);
q_f = fire load density per floor area, MJ/m^2 (see Equation (8.8) below as well as Appendix B for a variety of occupancies).

$$VF = \frac{A_f}{(A_t \cdot A_o \cdot \sqrt{H_w})^{0.5}} \tag{8.7}$$

where: A_f = total interior area of the compartment floor, m^2;
A_t = surface area of the compartment including openings, m^2;
A_o = total area of the door and window openings, m^2;
H_w = average height of the openings weighted with respect to each individual opening area, m.

$$q_f = \frac{\Sigma\, m_c \cdot H_c}{A_f} \tag{8.8}$$

where: A_f = total internal area of the compartment floor, m^2;
m_c = total mass of each combustible material in the compartment, kg;
H_c = calorific value of the fuel for each combustible, MJ/kg (see Equation (5.18) in Section No. 5 on Fire Growth).

8.3.1.3 Fire duration versus fire severity

The duration of a fully-developed fire is different from fire severity, t_e. The former parameter is used to estimate fire spread and the latter is used to evaluate the fire resistance of structural elements. Below is the procedure to estimate the duration of the burning period.

Table 8.1. Conversion factor, CF, for ventilation

$(k\rho c)^{1/2}$ ($W\cdot s^{0.5}/m^2\cdot K$)	Typical construction	CF ($min/(MJ/m^2)$)
< 720	Insulating material	0.09
From 720 to 2500	Concrete or plasterboard	0.07
> 2500	Thin steel	0.05

k = thermal conductivity, W/m·K
ρ = density, kg/m^3
c = specific heat, J/kg·K

According to the New Zealand Design Guide (Buchanan, 1994), the maximum rate of burning in a fully-developed stage, for a ventilation-controlled wood crib fire, is given by:

$$\dot{m} = 0.092 \cdot A_o \cdot \sqrt{H_o} \qquad (8.9)$$

where: $\dot{m}$ = maximum rate of burning, kg/s (same as Equation (5.20));
A_o = total area of wall openings, m^2;
H_o = weighted average height, m.

The duration of the burning period, t_b, can be estimated as follows:

$$t_b = \frac{L}{\dot{m}} \qquad (8.10)$$

where: t_b = duration of burning period, s;
L = mass of the wood equivalent fuel load, kg.

The corresponding heat release rate, Q (MW), is given by

$$Q = \dot{m} \cdot H_c \qquad (8.11)$$

where: H_c = calorific value of the fuel, MJ/kg (see Equation (5.18) in Section No. 5 on Fire Growth).

8.3.2 Fire resistance of building elements

An evaluation of the fire resistance requirements is performed to determine whether the building elements are sufficiently strong to sustain structural stability, maintain load-bearing capacity, and prevent spread of fire to neighbouring areas (safe path, egress and rescue routes, adjacent buildings, etc.).

8.3.2.1 Fire resistance design based on equivalent time

As mentioned earlier, fire severity, determined from standard fire tests, is the equivalent exposure time to the standard fire. The fire resistance design is satisfied if:

$$t_r \geq t_{ed} \tag{8.12}$$

where: t_r = fire resistance rating, min (see Section No. 8.3.3 below);
t_{ed} = design fire severity, min (see Equation (8.13) below).

$$t_{ed} = C_2 \cdot C_3 \cdot t_e \tag{8.13}$$

where: t_e = equivalent fire severity, min (see Equation (8.6));
C_2 = a value of 0.5 for sprinklered buildings and a value of 1.0 for all others;
C_3 = importance factor applied to columns and members laterally restraining columns (Equation (8.14)), a value of 1.0 is used for members supporting roofs.

$$C_3 = 1 + \frac{N-2}{10} \qquad 1.0 \leq C_3 \leq 1.5 \tag{8.14}$$

where: N = number of storeys.

8.3.3 Determination of fire resistance

The calculation of the fire resistance rating, t_r, can be carried out using one of following procedures:

1. Calculation using a rational method: Designing a structure to resist fire loads follows the same steps as designing it when the fire is not considered. The additional parameters to be considered for fire resistance design are:
    - Thermal expansion and deformations in structural members caused by high temperatures;
    - Internal forces and restraints in structural members caused by high temperatures;
    - Change in mechanical properties of structural members caused by high temperatures;
    - Loss of cross section in structural members caused by high temperatures;
    - Existing loads on the structural members at the time of the fire.
2. By use of experiments (CAN/ULC-S101-M89).
3. By use of the design equations that exist in Appendix D of the NBCC (1995).
4. By correlation from experimental or analytical results.

8.3.4 Fire resistance of structural steel members

8.3.4.1 Methods of protection of structural steel members

Unprotected structural steel members are vulnerable to fire exposure. Indeed, high temperatures can cause structural failure of structural steel members unless they are oversized. This is, however, uneconomical. Another option is to protect the steel members so that their endurance and resistance to a fire can be increased. Many ways can be used to protect steel members including:

- Concrete encasement (full or partial);
- Spray-applied cement-based material;
- Board products (gypsum plaster, sodium silicate, etc.);
- Suspended ceiling assemblies (gypsum, perlite, mineral fibre) used as membranes;
- Water filling of hollow sections;
- Concrete filling of hollow steel sections (see Kodur and Lie (1995) for design);
- Intumescent paint.

It must be ensured that the protecting material provides the required increase in fire insulation performance and stays in place for the duration of the fire and throughout the change of behaviour of the structural steel member.

8.3.4.2 Critical steel temperatures

The evaluation of structural steel members can be conducted either by testing or by using simplified calculation methods such as the one outlined in the New Zealand Design Guide (Buchanan, 1994). This simplified method is based on determining the limiting steel temperature and the time to reach this temperature in the standard fire test. The limiting steel temperature can be estimated as follows:

$$T_L = 905 - 609 \cdot r_f \tag{8.15}$$

where: T_L = limiting steel temperature, °C;
r_f = ratio of the design action on the member under the design load for fire to the design capacity of the member at room temperature.

8.3.4.3 Temperature rise in structural steel members

Heat transfer analyses can be applied to determine the time required for structural steel elements to reach a critical temperature. The critical temperature, similar to that defined in the previous Subsection, defines the endurance of the structural member. Between the initial time and the time at which the critical temperature is attained, the rise in temperature can be computed. This computation is possible using numerical methods, graphical solutions or computers models. In the paragraphs below, the numerical methods are addressed for unprotected and protected steel members.

8.3.4.3.1 Unprotected steel members

The temperature rise, during a short period, in an unprotected steel member can be calculated, using a quasi-steady-state, lumped heat capacity procedure, as follows:

$$\Delta T_{st} = \frac{h}{c_{st}(W_{st} / H_p)} \cdot (T_g - T_{st}) \cdot \Delta t \qquad (8.16)$$

where:
- ΔT_{st} = temperature rise in steel for the duration Δt, °C;
- h = heat transfer coefficient from exposure to steel member, $W/m^2 \cdot K$ (see Equation (8.17) below);
- c_{st} = steel specific heat, J/kg°C;
- W_{st} = steel weight per unit length, kg/m;
- H_p = heated perimeter of the steel section, m (Milke, SFPE Handbook, 1995);
- T_g = fire temperature at time t, K (see Subsection No. 8.3.1.1 on Compartment Temperatures);
- T_{st} = steel temperature at time t, K;
- Δt = time step, s (not larger than $3.25 \cdot W_{st} / H_p$).

$$h = h_c + h_r \qquad (8.17)$$

where:
- h_c = convective heat transfer coefficient, $W/m^2 \cdot K$;
- h_c = ranges between 20 and 25 $W/m^2 \cdot K$;
- h_r = radiative heat transfer coefficient, $W/m^2 \cdot K$ (see Equation (8.18)).

$$h_r = \frac{5.77 \cdot 10^{-8} \cdot \varepsilon_f}{T_g - T_{st}} \cdot (T_g^4 - T_{st}^4) \qquad (8.18)$$

where: ε_f = flame emissivity (see Table 8.2 for values).

8.3.4.3.2 Protected steel members

The temperature rise, during a short period, in a protected steel member can be calculated, if the thermal capacity of the insulation layer is neglected, as follows:

$$\Delta T_{st} = \frac{k_i}{c_{st} \cdot \delta_i \cdot (W_{st} / H_p)} \cdot (T_g - T_{st}) \cdot \Delta t \tag{8.19}$$

where: k_i = thermal conductivity of insulation material, W/m°C;
δ_i = thickness of insulation material, m.

Table 8.2. Emissivity, ε_f, for different constructions (Milke, SFPE Handbook (1995))

Type of construction	Emissivity, ε_f
1. Column exposed to fire on all sides	0.7
2. Column outside facade	0.3
3. Floor girder with floor slab of concrete, only the underside of the bottom flange being directly exposed to fire	0.5
4. Floor girder with floor slab on the top flange	
Girder of I section for which the width-depth ratio is not less than 0.5	0.5
Girder of I section for which the width-depth ratio is less than 0.5	0.7
Box girder and lattice girder	0.7

The neglect of the thermal capacity of the insulation material is valid if the following equation is true:

$$c_{st} \cdot (W_{st} / H_p) > 2 \cdot c_i \cdot \rho_i \cdot \delta_i \tag{8.20}$$

where: c_i = specific heat of insulating material, J/kg°C;
ρ_i = density of insulating material, kg/m^3.

When the thermal capacity of the insulation material is taken into account, the temperature rise can be computed as follows:

$$\Delta T_{st} = \frac{k_i}{\delta_i} \cdot \left[\frac{T_g - T_{st}}{c_{st} \cdot (W_{st} / H_p) + 0.5 \cdot c_i \cdot \rho_i \cdot \delta_i} \right] \cdot \Delta t \tag{8.21}$$

8.3.4.4 Fire resistance rating for protected steel

In the absence of fire resistance tests, the time to reach the limiting steel temperature, T_L, can be estimated as:

$$t_r = 40 \cdot (T_L - 140) \cdot \left[\frac{k_i}{\delta_i} \cdot \frac{H_p}{A_{st}} \right]^{-0.77} \tag{8.22}$$

where: t_r = time for a steel member protected with light and dry insulation to reach T_L, min;
H_p = heated perimeter of the steel section, m;

A_{st} = cross sectional area of the steel section, m^2;
k_i = thermal conductivity of the insulation, W/m·K (see Table 8.4 for values);
δ_i = thickness of the insulation, m.

The application of the above Equation (8.22) is restricted according to Table 8.3.

Table 8.3. Restrictions of Equation (8.22)

Parameter	Lower Limit	Upper Limit
t (min)	30	240
T_L (°C)	400	600
H_p / A_{st} (m^{-1})	10	300
δ_i / k_i (m^2 °C /W)	0.1	0.3

For moist insulation, there is a time delay that must be added to the time t_r of Equation (8.22) in order to reach the limiting steel temperature, T_L. The time delay is given by:

$$t_v = \frac{M_d \cdot \rho_i \cdot \delta_i^2}{5 \cdot k_i} \qquad (8.23)$$

where: t_v = time delay, min;
M_d = moisture content, % (see Table 8.4 for some values);
ρ_i = density of the insulating material, kg/m^3 (see Table 8.4 for some values).

8.3.4.5 Fire resistance rating for unprotected steel

For unprotected steel members, the New Zealand Design Guide (Buchanan, 1994) reports the following two equations to determine the exposure time, t_r.

$$t_r = -5.2 + 0.0221 \cdot T_L + \frac{3.40 \cdot T_L}{H_p \;/\; A_{st}} \quad \text{(for a three-sided exposure)} \qquad (8.24)$$

$$t_r = -4.7 + 0.0263 \cdot T_L + \frac{1.67 \cdot T_L}{H_p \;/\; A_{st}} \quad \text{(for a four-sided exposure)} \qquad (8.25)$$

Table 8.4. Properties of insulating materials under fire conditions (Buchanan, 1994)

Material	Density (kg/m^3)	Thermal conductivity (W/m·K)	Equilibrium moisture content (%)
Sprayed mineral fibre	250-350	0.10	1.0

Perlite of vermiculite	300-800	0.15	15.0
plaster	450-900	0.15	3.0-5.0
Fibre silicate sheets	800	0.20	20.0
Gypsum plaster	120-150	0.25	2.0
Mineral wood slabs			

The application of the above Equations (8.24) and (8.25) are restricted according to Table 8.5.

Table 8.5. Restrictions of Equations (8.24) and (8.25)

Parameter	Lower Limit	Upper Limit
T_L (°C) *	500	800
H_p / A_{st} (m^{-1})	15	275

* under 500°C linear interpolation can be used

There are other methods that can be used to assess the fire resistance of building members, including:

1. Law and O'Brien (1983) design method of structural members outside a compartment, e.g., external beams and columns;
2. Milke, SFPE Handbook (1995), analytical methods for determining the fire resistance of steel members.

8.3.5 Fire resistance of reinforced concrete and masonry members

In general, reinforced concrete and masonry structures possess very good resistance to fires because of their non-combustibility. The main concern in the stability of the reinforced concrete and masonry structures is the stability of the reinforcement. Therefore, the more protection the reinforcement has (more depth of cover protection of steel) the more fire resistance the structure will exhibit.

The documents that are useful in designing reinforced and pre-stressed concrete structural members are those presented by Gustaferro and Martin (1977), Fleischmann (SFPE Handbook (1995)), Wade (1991), Appendix D of the NBCC (1995) and Lie (1992).

8.3.5.1 Temperatures and material properties

Wade (1991) presents graphs showing the behaviour of steel and concrete at elevated temperatures. The graphs show the temperatures at various depths within a slab or a wall, exposed to the standard fire. These graphs can be used to determine the level, in terms of time, of resistance of the structural element. Temperatures within reinforced concrete beams for a 60 minute and 90 minute exposure to the standard fire are also presented. In addition, the properties of reinforcing bars, pre-stressing strand as well as dense and lightweight concrete are illustrated graphically.

8.3.5.2 Structural calculation

The graphs presented by Wade (1991) can be used to determine the flexural capacity of a beam or a slab due to the load at the time of the fire and compared it with the actual capacity for an exposure of 60 or 90 minutes.

The easiest design procedure is to determine the steel limiting temperature within the concrete structural element at different stages of exposure and assume that the concrete is not contributing to the strength.

For simply supported T-beams where the compression zone is not affected by heat, only the reduction in steel strength needs to be considered. In the case of continuous beams where the compressive block of the concrete is heated, the effect of elevated temperatures can be considered by ignoring any concrete with a temperature greater than a critical value of 750°C and using the average temperature of the remaining concrete to obtain the compressive strength.

In addition, the fire resistance of reinforced concrete members can be greatly increased by flexural continuity and axial restraint.

Finally, in designing reinforced concrete columns, ACI suggests using the information illustrated in Table 8.6, developed by Hull and Ingberg (1925). Table 8.6 is based on results of a series of tests on concrete columns exposed to fire.

8.3.6 Fire resistance of structural timber members

Traditionally, fire resistance ratings for timber members were determined by testing the member or assembly in a furnace according to standard testing such as ASTM E-119 (1988). These ratings can also be found in the Fire Resistance Design Manual of the Gypsum Association (1988). Timber members can perform and resist well, when exposed to fire. This resistance to fire depends on four major items, namely:

- The size of the member (e.g., heavy timber);
- The performance of the protection membrane when provided;
- The extent of the charring of the structural wood member;
- The load-carrying capacity of the portion of the structural wood member that is left uncharred.

Table 8.6. Fire endurance of concrete columns (Hull and Ingberg, 1925)

Aggregate type	Minimum area of round or square cross section (cm^2)	Concrete cover (mm)	Fire endurance classification (h)
Siliceous	710	38	1.5
Siliceous	1290	38	2.5
Siliceous	1290 *	38	3.5
Siliceous	1613	64	3
Siliceous	1613 *	64	6
Traprock & slag †	1290	38	4
Carbonate	1290	38	6

* Mesh in cover
† Air-cooled slag

8.3.6.1 Protective membrane contribution to fire endurance

There are two common types of protective membrane: gypsum wallboard and plywood panelling. The fire resistance of protected wood members is mainly a function of the thickness and type of the protection membrane. The National Research Council of Canada (NRC) has developed a procedure to determine the fire resistance ratings of load-bearing light-frame wood floor and roof assemblies and load-bearing and non-load-bearing of wall assemblies, (See Appendix D of the National Building Code of Canada (1995) and Canadian Wood Council (1991)). The fire resistance rating is obtained by adding together the assigned times of the protective membranes, the framing and other factors. These times are shown in Tables 8.7, 8.8 and 8.9, respectively.

In addition to Tables 8.7 to 8.9 which give the values to calculate the fire resistance rating based on the cumulative effect of the finish, frame and additional protection, Appendix A of the NBCC (1995) provides the designer with detailed ready-to-use tables to determine the fire and sound resistance of building assemblies (see Tables A-9.10.3.1.A and A-9.10.3.1.B)

Table 8.7. Time assigned to wallboard membranes of fire-exposed side (Appendix D, NBCC, 1995)

Description of finish	Time (min)
11.0 mm Douglas Fir plywood phenolic bonded	10[1]
14.0 mm Douglas Fir plywood phenolic bonded	15[1]
12.7 mm Type X gypsum wallboard	25

15.9 mm Type X gypsum wallboard	40
Double 12.7 mm Type X gypsum wallboard	80[2]

[1] Non-load-bearing walls only, stud cavities filled with mineral wool conforming to CSA A101-M, "Thermal Insulation, Mineral Fibre, for Buildings" and having a mass of not less than 2 kg/m^2, with no additional credit for insulation according to Table 8.9.
[2] Applies to non-load-bearing steel framed walls only.

Table 8.8. Time assigned for contribution of wood frame (Appendix D, NBCC, 1995)

Description of frame	Time assigned to frame (min)
Wood studs 400 mm o.c. max.	20
Wood studs 600 mm o.c. max.	15
Wood floor and wood roof joists 400 mm o.c. max.	10
Wood roof and wood floor truss assemblies 600 mm o.c. max.	5

Table 8.9. Time assigned for additional protection (Appendix D, NBCC, 1995)

Description of additional protection	Time assigned (min)
Add to the fire resistance rating of wood stud wallboard, if the spaces between the studs are filled with preformed insulation of rock or slag fibres conforming to CSA A101-M and with a mass of not less than 1.22 kg/m^2 of wall surface[1]	15
Add to the fire resistance rating of non-load-bearing wood stud walls sheathed with gypsum wallboard, if the spaces between the studs are filled with preformed insulation of glass fibre conforming to CSA A101-M and having a mass of not less than 0.6 kg/m^2 of wall surface	5

[1] There is no test data to justify the 15 min additional protection for preformed glass fibre insulation.

8.3.6.2 Extent of charring of wood members

When exposed to fire, wood undergoes thermal degradation. The conversion of wood to char and gas results in a reduction of the density of the wood. The charring rate, a critical parameter in determining the fire resistance of a structural wood member, is defined as the linear rate at which wood is converted to char. Numerous empirical and theoretical models have been developed to account for the charring rate of wood exposed to fire. White, SFPE Handbook (1995), explains in detail the equations governing the rate of charring in the case of the ASTM E-119 fire exposure, in the case of nonstandard fire exposures as well as some of the theoretical modelling.

8.3.6.3 Load-carrying capacity of uncharred wood members

After charring of part of the wood, the uncharred portion of the wood member loses some of its strength and the temperature gradient increases rapidly in that portion. Further, the properties of the wood such as the modulus of elasticity, compressive strength and tensile strength are affected.

According to White, SFPE Handbook (1995), there are two methods to assess the load-bearing capacity of structural wood members: evaluation of the uncharred portion assuming a homogeneous section or proceed with layering the uncharred portion. These two methods along with the equations to determine the load-bearing capacity of the uncharred wood portion, for three-side exposure and four-side exposure, are detailed in White, SFPE Handbook (1995). This reference also presents the methods developed by Lie (1977) to obtain the fire resistance of wood beams and columns. The equations developed by Lie (1977) are the equations used in the National Building Code of Canada. The use of any of the above-mentioned equations must be in accordance with their limitations and assumptions.

More details on the fire resistance of wood members can be found in the SFPE Handbook (1995), Section 4 - Chapter 11, where White provides analytical methods for determining the fire resistance of timber members. Another source for the fire resistance design of timber members is the New Zealand Standard NZS 3603 (1993).

8.4 Input and Output for the Evaluation Procedures

Tables 8.10 and 8.11 summarize the input and output requirements for fire resistance and structural stability.

Table 8.10. Input requirements

Input needed	Section taken from
Building characteristics	- Initial design parameters
Geometry of compartment	- Initial design parameters
Thermal characteristics of compartment boundaries and structural elements	- Initial design parameters
Performance criteria	- Initial design parameters

Table 8.11. Output requirements

Output	Needed for Section
Fire severity time	- Fire spread
Fire resistance time	- Fire spread
Time of structural failure	- Fire spread

8.5 Performance Criteria

8.5.1 Structural performance

Under fire conditions, failure of a structural element is assumed to occur when its load-carrying capacity starts to decrease and the element can no longer support the load on the structure. The structure failure criteria, under elevated temperatures, can be determined using the appropriate standards for steel members, concrete members, masonry members and timber members, if available.

8.5.2 Existing criteria for barrier fire resistance

Building components separating compartments must be able to obstruct fire spread. In order to prevent fire spread, these components must satisfy the criteria for barrier failure. These criteria can be set in terms of stability, integrity and thermal insulation as follows:

- Stability: Stability failure is defined as the loss of load-bearing capacity of the member.
- Integrity: The building component must maintain its integrity during the time specified. Loss of integrity occurs when flames and hot gases can penetrate or pass through the component.
- Insulation: Temperatures on the unexposed face of the building component must be below the level that will cause ignition of nearby items or materials. Insulation failure is defined as an average temperature rise of 140°C or a local maximum of 180°C on the unexposed face.

The New Zealand Design Guide (Buchanan, 1994) lists the relevant criteria applying to common elements as illustrated in Table 8.12.

The fire resistance rating of structural elements is the common performance criteria used for barriers. The rating is dependent on the threshold values of surface temperature, plastic deformation, allowable stresses and ruptures. These threshold values are attained under critical conditions of fire duration and severity. The equivalent fire severity, or the equivalent time for barrier failure, is dependent on the existing fire load, building geometry and ventilation characteristics.

Table 8.12. Failure criteria for elements of building construction (Buchanan, 1994)

Building Element	Stability	Integrity	Insulation
Partition		x	x
Load bearing wall	x	x	x
Floor/ceiling	x	x	x
Beam	x		
Column	x		

Fire resistant glazing		x	

The threshold values, listed by CIB W14 (1986) to describe the criteria for thermal insulation of a separating structure or structural member, are a 200°C average temperature on the unexposed side of the separating structure or a maximum temperature of 240°C. Buchanan (1994) suggested using an average value of 140°C and a maximum value of 180°C. The values suggested by Buchanan (1994) are also the standard test criteria in CAN/ULC-S101-M89 (Underwriters' Laboratories of Canada, 1989).

Furthermore, O'Hara (1993) suggested, as property protection criteria, confining thermal damage to 100 m^2 in the area of fire origin with no primary structural member collapsing, and confining non-thermal damage, from smoke and water, to the floor of fire origin. For a steel roof structure, O'Hara proposed maintaining structural steel temperatures at less than 538°C.

9. FIRE DETECTION

9.1 Purpose

- To provide guidance on the techniques and principles to be used in the design of fire detection systems.
- To provide procedures for the evaluation of the effectiveness of fire detection systems.

9.2 Introduction

9.2.1 General

During a fire, many products of combustion are toxic and present life threatening conditions to occupants. Therefore, it is of prime importance to detect the fire as early as possible in order to:

- Proceed with the evacuation of occupants before conditions become untenable;
- Activate control systems (smoke control systems and fire suppression systems);
- Notify the fire department.

9.2.2 Fire detection systems

Fire detection systems are key features in fire prevention and protection of a building. Therefore, it should be ensured that, in the event of a fire emergency, these systems operate as required. Fire detection systems have three main components:

- Detection component: The part of the system that senses fire;
- Processing component: The part of the system that processes signals from the fire detection system;
- Signaling component: The part of the system that alerts the occupants and control systems after processing the signal from the detection component.

Fire detection can be achieved either through humans (i.e., occupants in place) or through automatic means (i.e., an alarm signal from a sensor system). In general, automatic fire detectors are located on the ceiling and are spaced in a manner to optimize the response to standard fires. Fire detection is affected by many parameters including the type and location of sensors, the occupants in-place and their sense of awareness, the periodic maintenance of the automatic detection systems in place and the reliability of these systems to perform as intended.

The installation, maintenance, testing and inspection of fire detection systems should be conducted according to existing Standards (National Fire Code of Canada (1995), NFPA 72 (1990), CAN/ULC-S524-M91, CAN/ULC-S537-M87, CAN/ULC-S553-M86).

9.2.3 Types of fire detectors

In general there are four types of fire detection: Smoke detection, heat detection (which includes sprinklers), radiation flame detection and human detection. Table 9.1, extracted from the SFPE Handbook (1995), shows fire signatures and commercially-available detector types.

Table 9.1. Fire signatures and commercially available detectors (SFPE Handbook, 1995)

Fire signature/ Detector type	Electromagnetic radiation wave length 170 to 290 nm	Electromagnetic radiation (thermal) 3.9 to 8.0 Microns	Visible products of combustion < 0.1 Micron	Visible smoke and products of combustion > 0.1 Micron	Rapid change in temperature	High tempera-ture
Ultraviolet detector*	x					
Infrared detector*		x				
Smoke detector						
- Photoelectric				x		
- Ionization			x			
- Photo-beam				x		
Rate-of-rise heat detector					x	
Rate anticipation heat detector						x
Fixed temperature heat detector						x

* Ultraviolet and Infrared detectors can be used separate or in combination

Table 9.2, taken from the Fire Engineering Design Guide (1994), illustrates what is expected from different types of fire detectors in terms of area covered, response time and fire size in a typical compartment and in the early stages of fire.

9.2.3.1 Heat detectors

The response of heat detectors is produced by the hot air that has elevated by convection to the location of the detector. There are two types of heat detectors: fixed temperature detectors operating when a pre-selected threshold temperature is reached and the rate-of-rise detectors which operate when there is rapid increase in temperature.

Table 9.2. Comparisons of various fire detector types (Buchanan, 1994)

Detector Type	Area cover (m^2)	Response time (min)	Fire size (kW)
Aspirating smoke detector	2000	1	0.01 - 0.1
Smoke detector	90	1 - 3	0.1 - 1
Heat detector	30	2 - 5	5 - 10
Normal sprinkler	20	5 - 10	10 - 15
Quick response sprinkler	35	2 - 5	5 - 10

9.2.3.2 Smoke detectors

Smoke detectors respond to the smoke contained in the products of combustion. The most commonly used smoke detectors are:

1. Ionization chambre smoke detectors
2. Optical scatter smoke detectors
3. Aspirating smoke detectors
4. Photo-beam detector - optical obscuration

9.2.3.3 Radiation flame detectors

Radiation detectors respond to the electromagnetic radiation emitted from the fire. The radiation emitted by a fire includes ultra-violet (UV), visible and infra-red (IR). In general, flame detectors include: UV, IR and combination UV/IR flame detectors. The selection of one type of detection depends upon many factors, including fuel characteristics, fire growth rate, ambient conditions, control means in-place and environmental conditions in the detection area.

9.2.3.4 Human detection

During the outbreak of a fire, the occupants in the room or compartment of fire origin may see the fire or smell smoke before the critical conditions for automatic detection are reached. Human detection is very difficult to quantify in terms of effectiveness and time and should not be relied on in the design of a fire protection system.

9.2.3.5 Time delays

Given that a detection system comprises a detection stage, a processing stage and a signaling stage, time delays associated with the activation of the fire alarm must be identified and considered by the fire safety engineer in the system design. These delays can be critical and the life of occupants may depend on them. Time delays include:

- Time for the production of conditions leading to fire detection;
- Time for the confirmation of detection and for the alarm to signal.

Since detection systems are frequently used to activate other fire protection systems, the fire safety designer must make sure that subsequent time delays are accounted for and included in the design. Such delays include those required for the initiation of protection systems such as smoke control and sprinkler activation, notification of the fire service, and notification of occupants.

9.3 Evaluation Procedures

9.3.1 Evaluation of fire detection times

In order to predict the activation time of a detector, the following factors must be considered: rate of fire growth, building geometry particularly the height of the ceiling above the floor, the response time index (defined below) of the detector, the distance between fire detectors, the distance between the fire detector and the seat of the fire and the characteristics of the fire detector especially its activation temperature.

9.3.1.1 Heat detectors

Time of activation of heat detectors can be estimated using hand calculations or computer models such as DETACT-QS (Evans and Stroup, 1986), DETACT-T2 (Evans et al, 1991), FPETOOL (Nelson, 1990), FASTLITE (Portier et al, 1996) and LAVENT (Davis and Cooper, 1991). These models are explained later in more detail and should be used according to their limitations and assumptions.

By hand calculations, Equation (9.1) can be used to determine the temperature of a fixed temperature heat detector or a sprinkler, treated as a lumped mass, exposed to hot fire gases.

$$\frac{dT_d}{dt} = \frac{u^{1/2}(T_g - T_d)}{RTI} \qquad (9.1)$$

where:

where:	T_d	=	detector temperature, °C;
	u	=	instantaneous velocity of hot fire gases, m/s;
	T_g	=	temperature of the hot fire gases, °C;
	RTI	=	Response Time Index, $(m\cdot s)^{0.5}$;
	t	=	time, s.

<u>Detection time</u>. The detector activation time is estimated, based on Equation (9.1), as the time necessary to reach the noted temperature for the detector. In order to determine the detector operation time, the values of T_g and u must also be known at the location of detector. The prediction of T_g and u requires information about rate of heat release, ceiling height, and distance from the plume to the detector. The temperature and velocity of gases can be predicted using fire plume models or ceiling-jet models.

Schifiliti, Meacham and Custer (SFPE Handbook, 1995) outline the correlations, developed by Heskestad and Delichatsios (1989), which can be used to determine the heat detector operation.

<u>The Response Time Index (RTI)</u>. The RTI used in Equation (9.1) is a measure of the sensitivity of a heat detector or a sprinkler and it is expressed as follows:

$$RTI = \tau_o \cdot u_o^{1/2} \approx \tau \cdot u^{1/2} \quad (9.2)$$

where: u_o = velocity of hot gases at which τ_o was measured, m/s;
τ = detector time constant (see Heskestad and Smith (1976)), s;
τ_o = detector time constant measured at reference velocity u_o, s.

Heskestad and Smith (1976) developed a test apparatus at Factory Mutual Research Corporation to determine the RTI for sprinklers. The test is referred to as the plunge test. Tables 9.3 and 9.4, taken from the Australian Guidelines (1996), give some values for the RTI of sprinklers and heat detectors, respectively.

Table 9.3. RTI for sprinkler heads (Australian Guidelines, 1996)

Sprinkler type	Typical RTI $(m\cdot s)^{0.5}$	Worst case RTI $(m\cdot s)^{0.5}$
Fast response	30	100
Soldered link	150	N/A
8 mm glass bulb	200	300

Table 9.4. Typical data for heat detectors (Australian Guidelines, 1996)

Type	Activation temperature (°C)	RTI $(m\cdot s)^{0.5}$
A and B	58 - 88	10 -20
C and D	88 - 132	10 -20

In addition, Portier, Peacock and Reneke (1996) presented an extensive list of RTI as illustrated in Tables 9.5 and 9.6.

Table 9.5. RTI values for fixed temperature heat detectors. RTI values shown are in $(ft\text{-}s)^{1/2}$ / $(m\text{-}s)^{1/2}$ (Portier et al, 1996)

UL Listed Spacing	UL Listed Activation Temperature						All FM Listed Temps.
(ft/m)	128°F	135°F	145°F	160°F	170°F	196°F	
10/3.1	894/494	738/408	586/324	436/241	358/198	217/120	436/241
15/4.6	559/309	425/235	349/193	246/136	199/110	101/56	246/136
20/6.1	369/204	302/167	235/130	158/87	116/64	38/21	157/87
25/7.1	277/153	224/124	174/75	107/59	72/40	---	107/59
30/9.2	212/117	179/99	136/75	81/45	49/27	---	81/45
40/12.2	159/88	128/71	92/51	40/22	---	---	---
50/15.3	132/73	98/54	67/37	---	---	---	---
70/21.4	81/45	54/30	20/11	---	---	---	---

Notes:
1. These RTI's are based on an analysis of the Underwriters Laboratories Inc. and Factory Mutual listing test procedures. Plunge test results on the detector to be used will give a more accurate response time index.
2. Since the original work was in English units, SI units are approximate.

Table 9.6. RTI values for rate-of-rise heat detectors. RTI values shown are in $(ft\text{-}s)^{1/2}$ / $(m\text{-}s)^{1/2}$ (Portier et al, 1996)

UL Listed Spacing	UL Listed Activation Rate of Temperature Rise		
(ft/m)	15°F/min / 8°C/min	20°F/min / 11°C/min	25°F/min / 14°C/min
10/3.1	1834/1013	1308/722	984/543
12.5/3.8	1453/802	1073/593	805/445
15/4.6	1185/654	872/482	637/352
20/6.1	872/482	581/321	425/235
30/9.2	559/309	380/210	280/155
40/12.2	447/247	291/161	206/114
50/15.3	425/235	246/136	161/89

Note: Since the original work was in English units, SI units are approximate.

Radial distance. As mentioned earlier, the radial distance between a heat detector and the axis of the fire is an important parameter that is used in calculations. This radial distance can be calculated according to the following equation:

$$r = \sqrt{\left(\frac{s_1}{2}\right)^2 + \left(\frac{s_2}{2}\right)^2} \quad (9.3)$$

where: r = radial distance between the axis of the fire and the detector, m;
s_1 = length between two detectors in a rectangle of four, m;
s_2 = width between two detectors in a rectangle of four, m.

9.3.1.2 Smoke detectors

Because of the operating mechanism used for smoke detectors, there is no unique and easy procedure for determining detection time. At present only crude approximations exist for the prediction of activation time. Two prediction approaches are as follows:

9.3.1.2.1 Smoke detector temperature equivalence

Based on experiments undertaken by Heskestad et al (1978), smoke is detected at a temperature increase of about 13°C above ambient. Using this temperature differential and an RTI value of less than 10 $(m \cdot s)^{0.5}$, an estimate for the activation time of smoke detectors can be obtained using the same calculation method as that for heat detectors.

9.3.1.2.2 Smoke detector optical density

Smoke detector response can be estimated using the calculated optical density determined using Equation (6.3) in Section No. 6 on Spread of Smoke. The minimum levels of sensitivity as required by AS1603.2 (Australian Standard), for three sensitivity classes of detectors, are given in Table 9.7.

Table 9.7. Test limits for smoke detectors (Australian Guidelines, 1996)

Sensitivity class	Detector type		
	Photo-electric (optical)		Ionization
	%/m	O.D. (dB/m)	MIC_x
Normal	12 -20	0.55 - 0.97	0.35 - 0.55
High	3 - 12	0.13 - 0.55	0.1 - 0.35
Very high	0 - 3	0 - 0.13	0 - 0.1

For a conservative estimate for smoke detector activation, the upper values given in Table 9.7, for a photo-electric detector should be used. The MIC_x values for the ionization detectors can be related to the photo-electric detector values as follows:

- 0.55 MIC_x corresponds to about 40%/m obscuration or 2.20 dB/m optical density
- 0.35 MIC_x corresponds to about 20%/m obscuration or 0.97 dB/m optical density

9.3.1.2.3 Beam smoke detectors

The optical smoke density can be used to estimate the response time for an optical beam detector. The optical smoke density is given by:

$$OD = \frac{10}{L_{op}} \cdot \log_{10}\left(\frac{I_s}{I_o}\right) \tag{9.4}$$

where:
- OD = optical smoke density, dB/m;
- L_{op} = optical measuring length, m;
- I_o = radiated power received without smoke;
- I_s = radiated power received with smoke.

The response time may be estimated as the time at which the rated optical smoke density of the beam detector is exceeded.

9.3.1.2.4 Aspirating (sampling) smoke detectors

Aspirating smoke detectors are photo-electric detectors used to detect smoke in air sampled from various locations in the compartment using a system of sampling tubes. For design purposes, each sampling point is modelled as an imaginary point detector. The aspirating detectors are very sensitive and respond much quicker (about 10 times faster) than spot detectors (ionization or optical detectors).

9.3.1.3 Radiation flame detectors

A flame detector can be modelled as a point detector which receives radiation produced by flames. The intensity of radiation received by the detector can be determined using the principles outlined in Section No. 7 on Fire Spread. Schifiliti, Meacham and Custer (SFPE Handbook, 1995) reported that the standard practice for the design of radiant energy detection device is based on application of generalized fire size versus distance curves that are derived using the inverse square law (NFPA 72, 1993) as follows:

$$S = \frac{C_4 \cdot P_d \cdot e^{\zeta d}}{d^2} \tag{9.5}$$

where:
- S = radiant power reaching the detector, W;
- C_4 = proportionality constant for the detector;
- P_d = radiant power emitted by the detector, W;
- ζ = extinction coefficient of air;
- d = distance between the fire and the detector, m.

Equation (9.5) is used to determine the sensor response for specific fuels.

9.3.2 Fire alarm audibility and visibility

Fire detection and alarm systems are used to alert occupants of a developing emergency in the building so that they can start evacuating. Therefore, the alarm signal must be heard by all occupants otherwise the purpose of the system is not satisfied.

The transmission of sound from a source to a target is a function of various parameters, including humidity, air viscosity and temperature, the frequency of the signal, the location of the source relative to the target, the construction of walls, floors and ceilings, and the furnishing in the area.

Typical fire alerting systems consist of a combination of audible and visual signals activated by the fire detection systems. The audible devices are usually horns, bells or speakers. The visual devices consist of lights, lamps or beacons.

Audible fire alarms. In residential areas, fire alerting systems should be capable of awakening a sleeping occupant. Studies, by Nober et al (1980), have shown that a sound pressure level between 55 and 70 dBA will awaken a college-aged person with normal hearing. NFPA 72 (1993) requires signals to be 15 dBA above ambient in areas where people may be sleeping. British Standards require fire alarm signals to produce a sound pressure level of 65 dBA (5 dBA above ambient noise) in areas where occupants are awake and 75 dBA (15 dBA above ambient noise) in areas where people may be sleeping. Section 3.2.4.19 of the NBCC (1995) requires an audible fire alarm signal with a sound pressure level of not more than 100 dBA (measured at a distance of 3 m) in any normally occupied area. In addition, the NBCC requires, for sleeping areas that a sound pressure level from a fire audible signal device be not less than 75 dBA in a building of residential occupancy and in occupancies other than residential occupancies, the sound level must be not less than 10 dBA above ambient but with a minimum value not less than 65 dBA. For more details on the design of audibility of a fire alarm, the reader is referred to Schifiliti et al (SFPE Handbook, 1995) and to Butler, Bowyer and Kew (1981).

Visual signal alarms. Visual signals can be used to alert occupants in high background noise environments as well as people with hearing disabilities. They are not intended for sleeping people. The effective intensity required to alert a person is given by

$$E = \frac{I}{d_l^{2}} \tag{9.6}$$

where:
- E = effective intensity, lumens/m^2;
- I = intensity of the incident light source, candela;
- d_l = distance between the incident light source and the point where the effective intensity is measured, m.

For hearing impaired people, Underwriters Laboratories Inc. (UL, 1992) determined that an E value of 0.398 lumens/m^2 is the minimum requirement. For more details, see the SFPE Handbook (1995).

9.3.3 Fire detection probabilities

Table 9.8, taken from the Australian Design Guidelines (1996), shows the probabilities of success of detection systems. These values can serve as input data for fire risk assessment models.

Table 9.8. Probabilities of successful detector activation (Australian Guidelines, 1996)

Detector	Probability of successful activation		
	Smouldering fire	Non-flashover fire	Flashover fire
Heat detector	0	0.9	0.95
Sprinkler	0.5	0.95	0.99
Smoke detector			
• Smoke alarm	0.65	0.75	0.74
• AS 1630.2	0.70	0.80	0.85
• Sampling	0.90	0.85	0.95

In addition to the results in Table 9.8, data on the probabilities of failure of detection systems reported in the literature are as follows:

- Nash and Young (1991) reported that the failure rate for new sprinklers to operate correctly is estimated at $3.1x10^{-2}$ and for old sprinklers at $5.1x10^{-2}$.
- Thomas et al (1992) estimated the probability of failure of a sprinkler system in an office building to be 0.0184.
- Steciak and Zalosh (1992) reported that the rate of a smoke detector malfunctioning is estimated at 1.2×10^{-6} /h. On the other hand, the percentages of home smoke detectors not working in England and Wales are 7% and 11% after 18 and 36 months, respectively.

9.4 Input and Output for the Evaluation Procedures

Tables 9.9 and 9.10 summarize the input and output requirements for fire detection.

Table 9.9. Input requirements

Input needed	Section taken from
Characteristics of automatic detector: Type, location, and response time	- Initial design parameters
Characteristics of human detector: Ability to detect a fire	- Initial design parameters
Smoke characteristics: Optical density	- Smoke spread
Details on building geometry	- Initial design parameters
Velocity of smoke: For detailed calculations of heat transfer to sensing element	- Smoke spread
Flame size and temperature: Heat flux incident on detector	- Fire growth
Rate of heat release	- Fire growth
Plume temperature	- Fire growth
Compartment temperatures	- Fire growth
Flame emissivity	- Fire growth

Table 9.10. Output requirements

Output	Needed for Section
Activation time of alarm: Early awareness of occupants	- Evacuation and escape
Notification time of fire department	- Fire fighting activities
Activation time of control systems (smoke and suppression systems)	- Fire growth and spread - Smoke spread
Probabilities	- Fire risk assessment models

9.5 Performance Criteria

In order for a fire safety design to be satisfactory, it must be judged against some acceptance or performance criteria. The performance criteria can be set by the fire safety design team.

- Maintenance and inspection of systems;
- Reliability of systems;
- Detection time should be as early as possible so that people will not encounter untenable conditions.

10. FIRE SUPPRESSION

10.1 Purpose

- To provide guidance for evaluating the reliability and effectiveness of automatic suppression systems in order to reduce the rate of heat release and eventually control fires.

10.2 Introduction

10.2.1 Fire suppression systems

Once a fire is detected, the appropriate suppression system can be activated. The suppression system is effective if there is a reduction in the rate of heat release for the fire. There are two types of fire suppression:

1. Automatic suppression:

- Automatic sprinkler systems: Sprinklers are considered the most reliable systems for fire protection and suppression. They consist of a sprinkler for fire detection, a water flow alarm for giving a signal, and water for controlling or extinguishing the fire. In general, sprinklers are designed to operate at temperatures ranging between 57°C and 260°C.
- Gaseous suppression systems: These systems include chemical type agents (known as halocarbon agents) and inert gases.
- Water mist suppression systems: These systems utilize fine water sprays (i.e., water mist) as the extinguishing medium and are thought of as a hybrid of automatic sprinklers and gaseous suppression systems.
- Dry chemical extinguishing systems: These systems apply a dry chemical (fine particles usually sodium bicarbonate-, potassium bicarbonate-, ammonium bicarbonate-based) through a distribution system into a fire.

2. Manual suppression: Manual suppression consists of extinguishing a fire by the occupant or by the fire service. The occupants must have at hand the necessary tools for suppression such as portable extinguishers and hose reels. Also important for manual suppression are the hydrant main systems for use by the fire department once on site.

The maintenance, testing and inspection of automatic and manual fire suppression systems should be done in accordance with existing Standards (National Fire Code of Canada (1995), CAN/ULC-S503-M90, CAN/ULC-S504-M86, CAN/ULC-S507-92 CAN/ULC-S512-M97, NFPA 10 (1990), NFPA 13 (1996), NFPA 14 (1996), NFPA 17 (1994), NFPA 750 (1996), and NFPA 2001 (1996)).

10.2.2 Time delays in automatic suppression

As in the case of fire detection systems, time delays associated with the activation of fire suppression systems must be identified, estimated and incorporated in the design produced by the fire safety engineer.

10.3 Evaluation Procedures

10.3.1 General

The time to control a fire is related to the time required to activate the suppression system and the time required to stop further fire growth. The time for activating the suppression system can be estimated using the method in Section No. 9 on Fire Detection. The time for effective fire control is not easy to determine and, therefore, the fire safety designer should use conservative estimates for this time.

10.3.2 Automatic fire sprinkler systems

10.3.2.1 Reduction of heat release rate

For automatic fire sprinklers, analytical models for fire suppression have been developed for office fire scenarios. The reduction of heat release rate, in the case where the sprinkler can effectively suppress the fire, can be estimated by one of the following equations:

1. *Equation by Madrzykowski and Vittori (1992)*

$$Q(t - t_{act}) = Q(t_{act}) \cdot \exp[0.023 \cdot (t - t_{act})] \qquad (10.1)$$

where: $Q(t- t_{act})$ = heat release rate after the activation time, kW;
$Q(t_{act})$ = heat release rate at the activation time, kW;
t = any time following activation, s;
t_{act} = time of activation of sprinkler, s.

2. *Equation by Fleming (1993)*

$$Q(t - t_{act}) = Q(t_{act}) \cdot \exp[-(t - t_{act}) / 3.0 \cdot w^{-1.85}] \qquad (10.2)$$

where: w = spray density, mm/s.

The reduction of heat release rate given in Equations (10.1) and (10.2) are good estimates except in the case of shielded fires. A study to investigate the probability of occurrence and expected size of shielded fires in sprinklered buildings (Lougheed, 1997), indicated that shielded fires continue to burn for some time before the heat release rate begins decreasing. The results of the study show that, although the fire was controlled by sprinklers, a steady heat release rate of up to 100 kW can be sustained after the activation of sprinklers.

10.3.2.2 Probability of control of fires by sprinklers

The probability of success for an automatic suppression system is defined as the probability it will control and eventually extinguish a fire. The reliability of sprinklers is confirmed by the statistics collected by Marryatt (1988) from 1886 to 1986. Marryatt reported that 65% of the fires were controlled by one sprinkler, 92% were controlled by 1 to 5 sprinklers, 96.3% were controlled by 1 to 10 sprinklers, and only 3.7% required more than 10 sprinklers to operate. Marryatt's statistics are illustrated in Table 10.1.

Table 10.1. Percentage of fires controlled by sprinklers (Australian Guidelines, 1996)

No. of sprinklers required for control	Percentage (%)
1	65
2 - 5	27
6 - 10	4.3
> 10	3.7

Fire size can be used to measure the effectiveness of sprinklers to reduce the heat release rate. In the absence of experimental data to determine the maximum fire size to be expected in sprinklered buildings, statistical data can be used. Statistical data can be used by selecting a fixed size of fire that would cover almost all of the fire sizes likely to be found in a particular property class and then deduce a pessimistic heat output for that fire. Table 10.2, taken from Hansell and Morgan (1994), shows the heat release rates which are based on the statistical distribution of fire areas in the various occupancies based on the fire incident database.

Table 10.2. Steady-state design fires (Hansell and Morgan, 1994)

Occupancy	Sprinklered	HRR (MW)	Area (m^2)	Perimeter (m)
Retail	Yes	5	10	12
Office	No	6	47	24
Office	Yes	1	16	14
Hotel	No	1	Largest room	Largest room
Hotel	Yes	0.5	Bed	6

The reliability of sprinklers is an important parameter to control a fire. A number of studies have been carried out to determine the reliability of sprinkler systems. Table 10.3 lists these international studies.

Table 10.3. Reliability of sprinkler systems (Fire Prevention, 1993)

Source	Period	Reliability (%)
Industrial Risk Insurers	1975-92 fully-sprinklers 1975-92 part-sprinklers	98.0 92.0
Factory Mutual Research	1970-72 1970-77	85.0 86.1
NFPA	1897-1924 1925-59 1925-64 1925-69 1970-74	95.8 96.2 96.2 96.2 96.2
Oregon State Fire Marshall's Report	1970-78	85.8
New York City high-rise buildings	1969-72 1972-78	100 97.9
New York City high-rise - excluding offices	1969-72 1972-78	98.9 97.9
New York City low-rise buildings	1969-72 1972-78 1969-78	97.2 94.4 95.8
Australia and Yew Zealand	1886-1968 1886-1973 1886-1986 1968-73 1968-77	99.8 99.7 99.5 99.4 99.3
UK Fire and loss statistics	1965-69 1966-72 1970, '71 & '73 1982, '85 & '88	91.8 78.2 95.0 93.7*

* Weighted average

10.3.2.3 Hazard classification of occupancies

The design of a satisfactory sprinkler system necessitates knowledge of the fire hazard classes. Based on fire tests, statistics and past experience, NFPA 13 (1996) proposes the following main hazard classes in occupancies.

1. Light hazard (LH) occupancies: The amount and combustibility of contents are low and fires with relatively low rates of heat release are expected, for instance non-industrial occupancies such as offices.

2. Ordinary hazard (OH) occupancies: These occupancies include industrial and commercial premises involved in the handling and storage of ordinary combustible materials. These occupancies can be divided into two groups:

- Ordinary hazard (Group 1): Occupancies where combustibility is low, quantity of combustibles is moderate, stockpiles of combustibles do not exceed 2.4 m, and fires with moderate heat release rate are expected.
- Ordinary hazard (Group 2): Occupancies where quantity and combustibility of contents is moderate to high, stockpiles of combustibles do not exceed 3.7 m, and fires with moderate heat release rate are expected.

3. Extra Hazard (EH) Occupancies: These are industrial and commercial occupancies where quantity and combustibility of contents is very high and flammable and combustible liquids are present, introducing the probability of rapidly-developing fires with high rates of heat release. Extra hazard occupancies involve a wide range of variables that may produce severe fires. These occupancies can be divided into two groups:

- Extra Hazard (Group 1): Occupancies with little or no flammable or combustible liquids.
- Extra Hazard (Group 2): Occupancies with moderate to substantial amounts of flammable or combustible liquids or where shielding of combustibles is extensive.

More details on the basic design parameters for fire sprinklers such as area of operation, water storage, water flow, orifice size, etc. can be found in NFPA 13.

10.3.3 Inert gaseous flooding agents

Inert gaseous extinguishing systems can be designed in accordance with NFPA 2001. After detection, the discharge takes conservatively 3 min for fire extinguishment. In the design, a delay time of 30 seconds should be added to the activation time to account for the occupant evacuation of the area.

10.3.4 Chemical gaseous flooding agents

Chemical gaseous agents extinguishing systems can be designed using NFPA 2001. Chemical gaseous agents extinguish fires by chemical interaction with the process of combustion. The time taken between detection and activation of the suppression system ranges between 30 and 60 seconds. This allows occupants time to evacuate from the fire compartment. The time taken between activation and extinguishment ranges between 20 and 30 seconds.

10.3.5 Water mist suppression systems

Water mist extinguishing systems can be designed in accordance with NFPA 750. The small water droplets enable the water mist to control fires by cooling of the flame, fire plume, oxygen displacement by water vapour, and radiant heat attenuation. Water mist is an excellent alternative technology for fire suppression to replace the gaseous suppression agents. This is because water mist is not a toxic threat to the humans and the environment. The major problem with water mist is that it has difficulty extinguishing small and obstructed fires. Thus, to be effective as a fire suppressant, water mist must be carefully engineered.

10.3.6 Dry chemical extinguishing systems

Dry chemical extinguishing systems can be designed using NFPA 17. Dry chemical agents can efficiently suppress and extinguish fire by discharging micron-sized particles of certain salts from nozzles by various methods such as expellant gas. The type of dry chemical used must not be changed unless proved to be changeable by a testing laboratory, recommended by the manufacturer of the equipment, and approved by the Authority Having Jurisdiction. In addition, when using dry chemicals, the design must ensure prompt time for evacuation before discharge and appropriate protection of valuable equipment.

10.3.7 Manual suppression

In the presence of a fire emergency, occupants have two choices: either try to extinguish the fire or proceed to evacuate without interfering with the developing fire. Parameters affecting the successful manual suppression of a fire include the size of the fire, the training of the occupants in the use of fire fighting equipment, the manual suppression equipment available and the number of occupants attempting to suppress the fire.

10.3.7.1 Portable fire extinguishers

Hand-held fire extinguishers can be very helpful to control and suppress small fires which could become very hazardous if left growing. However, the use of fire extinguishers should be accompanied by the proper training.

The National Fire Code of Canada (NFCC, 1995) provides the minimum requirement for the installation, inspection, maintenance, recharging and testing of portable extinguishing equipment (Section 6.2 of the NFCC). In addition, portable fire extinguishers must be in conformance with Canadian Standards namely CAN/ULC-S503-M90, CAN/ULC-S504-M86, CAN/ULC-S507-92 and CAN/ULC-S512-M97, as well as with NFPA 10 (1990).

Portable extinguishers are classed by the type of fire they are used to extinguish. There are four categories of fire extinguishers:

1. Class A - Used for fires involving ordinary combustible materials such as food, cloth, wood, paper, plastic and textiles, where a quenching and cooling effect provided by water is used to extinguish the fire.
2. Class B - Used for fires involving flammable liquids, oils, tars, oil-based paints, lacquers and flammable gases, where a smothering effect is essential to put out the fire. Oxygen is kept away from the fuel using these fire extinguishers (carbon dioxide, dry chemical foam, vapourizing liquid type of extinguishing agent, or multi-purpose dry chemical).
3. Class C - Used for fires involving energized electrical equipment where the use of a non-conducting extinguishing agent is essential.
4. Class D - Used for fires involving combustible metals such as magnesium, titanium, zirconium, sodium, lithium and potassium. Extinguishment of such fires poses a special problem and requires materials and techniques approved for use on the specific combustible metal fire. Extinguishing materials include dry powder, sand or graphite.

Each fire extinguisher is labelled with a letter on its label to indicate the class of fire on which this extinguisher has been found effective. Some fire extinguishers can be used for more than one class of fire. They are then clearly marked to show the classes for which they can be used (e.g., type ABC extinguisher can be used on Class A, B and C fires).

10.3.7.2 Fire hose reels

Fire hose reels consist of a hose fixed on a reel to a wall inside a building. As in the case of hand held fire extinguishers, hose reels are for the use of the occupants in the event of a controllable fire.

10.3.7.3 Hydrant mains systems

Hydrant main and standpipe systems consist of permanently installed pipework for quick access and use of water by the fire department. These systems are very beneficial in multi-storey tall buildings.

10.4 Input and Output for the Evaluation Procedures

Tables 10.4 and 10.5 summarize the input and output requirements for fire suppression.

Table 10.4. Input requirements

Input needed	Section taken from

Characteristics of automatic suppression system: Type, location, and response time	- Initial design parameters
Activation time	- Detection systems
Rate of heat release	- Fire growth
Flame size and temperature: Heat flux incident on detector	- Fire growth
Smoke characteristics	- Smoke spread
Details on building geometry	- Initial design parameters
Plume temperature	- Fire growth
Compartment temperatures	- Fire growth

Table 10.5. Output requirements

Output	Needed for Section
Time to control or extinguish the fire	- Fire growth
Modified heat release rate	- Fire growth
Effectiveness of automatic suppression	- Fire risk assessment models

10.5 Performance Criteria

In order for a fire safety design to be satisfactory, it must be judged against some acceptance or performance criteria. The performance criteria can be set by the fire safety design team. Examples of these criteria include

- Maintenance and inspection of systems;
- Reliability of systems;
- Time to activate and suppress the fire is less than the time to reach flashover;
- Complete evacuation from the area of suppression should occur before activation of gaseous suppression systems.

11. FIRE FIGHTING RESPONSE

11.1 Purpose

- To rescue occupants and suppress the fire without endangering the life of the fire fighters.
- To give guidance on how to evaluate the different times that relate to the activities of the fire department.

11.2 Introduction

11.2.1 General

There are two main components for an effective suppression of a fire by the fire department service:

1. Effective communication of the fire to the fire department: This may include automatic fire detection and signalling to the fire department or reliance on occupant detection and alerting the fire department using manual means such as a telephone.
2. Effective response by the fire department to rescue occupants and extinguish the fire.

Between the notification stage and the complete extinguishment of the fire, a fire department goes through various response stages, including:

- Dispatch, departure from fire station and travel to the scene;
- Rescue and set-up;
- Extinguishment.

The control of a fire depends on many factors including access to the building, building geometry and existence of adequate water supplies. The control is also related to the fire growth stage of the fire, i.e., a fire that has not reached flashover can be controlled without considerable damage. On the other hand, control of a fire at or after flashover has occurred is very difficult and it is difficult to provide property protection and life safety.

As a conservative design approach, the occupants are assumed to evacuate completely the emergency area by themselves without the help of the fire service personnel. The fire service is supposed to concentrate on extinguishing the fire. This is generally not the case as the fire service's main objective is to rescue people and then control and extinguish the fire.

11.2.2 Time variables in fire fighting activities

There are many aspects that affect the activities of a fire fighting service and, therefore, quantification of different events and their required times is a complex process. If quantification is not feasible, expert judgement should be used. The key events and their appropriate times surrounding the work performed by a fire service are as follows:

- Time to notify the fire department of the emergency (t_n);
- Dispatch time (t_{dis});
- Travel time to arrive to the burning area (t_t);
- Search and investigation time after arrival (t_{inv});
- Life saving and rescue activities time (t_{ls});
- Fire attack time (t_{att});
- Fire control time (t_c);
- Fire extinguishment time (t_{ex}).

11.3 Evaluation Procedures

11.3.1 Notification time

This time is defined as the time when the alarm call (automatic or phone call) is received at the fire department station. This time can be taken as the fire detection time (through automatic means or by occupants) calculated based on Section No. 9 on Fire Detection, plus the delays required to make the notification.

11.3.2 Dispatch and arrival times

The dispatch time is defined as the time from the notification of alarm until the fire service vehicles leave the station. The arrival time is defined as the time from leaving the station to reaching the burning building. The arrival time is affected by travelling distance, traffic conditions, climate conditions and ease of access to the burning building. The combined time from the two events is estimated to be between 7 and 8 minutes in large cities. A longer time is assigned when dealing with country areas. In the absence of data, Table 11.1, taken from the Draft National Building Fire Safety Systems Code (NBFSSC) of Australia and based on 95% probabilities, can be used.

Table 11.1. Times for fire brigade arrival and set-up (Australian Guidelines, 1996)

Area	Arrival time (min)	Set-up time (min)
City	10	20
Country	20	15

11.3.3 Search and investigation time upon arrival

The search and investigation time is defined as the time taken to interrogate the building officer of the exact location of the fire and whether occupants are trapped inside. The time assigned to this event is very difficult to evaluate and input from the fire service can be valuable. Where no data is available, a value of 2 minutes can be used for a conservative design.

11.3.4 Life saving and rescue activities time

The time required for life saving and rescue depends on the activities taking place at the arrival of the fire service personnel at the fire. This time may be zero if the occupant evacuation is complete at the arrival time and could be a large value if the building is complex and people are not familiar with the area. There are no data or procedures available to determine the life saving and rescue activities time. Each fire case should be treated as a unique case. The fire department may be helpful in estimating this time. At this stage, provision for reliable communication with areas of refuge, where required, must be available.

11.3.5 Set-up time for fire attack

The set-up time is defined as the time required to position the vehicles, hoses and other equipment in order to start the extinguishment process. There are many factors that influence the fire attack time including:

- Access to the fire site;
- Fire fighting facilities in-place such as water supplies, fixed fire fighting facilities, etc.;
- Geometry of and access to the burning area;
- Volume of equipment in-place to attack the fire.

Quantification of the fire attack time relies mainly on information from the fire department and engineering judgement. In the absence of data, the set-up time shown in Table 11.1 may be used.

11.3.6 Fire control time

The fire control time is the time estimate to bring the fire under control, if possible. An estimate for this time is not straightforward as it is affected by many factors including:

- Most importantly, the size of the fire at the arrival of the fire service, i.e., pre-flashover or post-flashover;
- The fire fighting equipment and suppression systems available such as water;
- The number of fire fighters in-place;
- Fire fighters exposure to hazards, e.g., structural instability, toxic gases, explosions;
- Fire protection systems in-place, i.e., sprinklers, alarms for early notification, manual fire fighting by occupants.

The fire department may help in the estimate of the time to control a fire.

11.3.7 Fire extinguishment time

There are two options for extinguishing a fire: extinguishment after a complete burnout or extinguishment by the fire service upon arrival. The first option is, in general, undesirable. The time of extinguishment for the second option is not easily determined because it is affected by many factors including:

- Fire load in the building and its combustibility;
- Size of the building and its compartments;
- Fire resistance of barriers and structural members.

11.4 Input and Output for the Evaluation Procedures

Tables 11.2 and 11.3 summarize input and output for fire fighting activities.

Table 11.2. Input requirements

Input needed	Section taken from
Notification time	- Detection
Evacuation time	- Evacuation and escape
Rate of heat release	- Fire growth
Building geographical location	- Initial design parameters
Complexity of access within the building	- Initial design parameters
Complexity of access to area of the building	- Initial design parameters
Details on building geometry, size and layout	- Initial design parameters
Building occupancy, type and population	- Initial design parameters
Occupant characteristics	- Initial design parameters
Fire service facilities close by the building	- Initial design parameters

Table 11.3. Output requirements

Output	Needed for Section
Dispatch time	
Arrival time	
Complete investigation time	
Fire attack time	
Fire control time	
Fire extinguishment time	- Fire growth
Modified heat release rate	- Fire growth
Probabilities of arrival, set-up and extinguishment	- Fire risk assessment models

11.5 Performance Criteria

In order for a fire safety design to be satisfactory, it must be judged against some acceptance or performance criteria. The performance criteria can be set by the fire safety design team. Examples of criteria include:

- Arrival of the fire department on the fire scene before occurrence of flashover;
- If the fire service does not arrive before flashover, extinguish the fire before complete failure of the structure.

12. MEANS OF ESCAPE AND SAFE EVACUATION

12.1 Purpose

- To provide methodologies for the evaluation of the time required by the occupants to become aware of a fire and to evacuate to a safe place before untenable conditions are reached.

12.2 Introduction

12.2.1 General

The primary objective of most fire safety designs is to provide satisfactory levels of life safety for occupants of the building of fire origin and occupants of neighbouring buildings. Therefore, in the event of a fire, the existing means of escape must ensure that all occupants are able to evacuate the emergency area to a safe place without having their lives threatened by untenable conditions.

12.2.2 Evacuation sequence

To better understand the procedures for determining the movement of occupants as the evacuation process develops, Table 12.1, taken from BSI (1994), presents the sequence of events during an evacuation.

Table 12.1. Sequence of events in the evacuation process (BSI, 1994)

Event	Calculation Method/Comments
1. Ignition	Fire growth
2. Detection	Detection
3. Sounding of alarm	Detection and warning systems
4. Recognition of alarm sounding	Recognition and response time (Table 12.2)
5. Start of movement of all occupants	
6. Reaching of exits by occupants	Minimum travel period
7. Passage of all occupants through exits	Waiting period

12.3 Evaluation Procedures

12.3.1 Total escape/evacuation time

The total time required for the occupants to escape to a safe place without being overcome by untenable conditions can be estimated as follows:

$$t_{tot} = t_{fd} + t_{res} + t_{eva} \qquad (12.1)$$

where: t_{tot} = total required time, s;
t_{fd} = time of fire discovery, s;
t_{res} = response or reaction time, s;
t_{eva} = travel or evacuation time, s.

For design purposes, the total required time, t_{tot}, must be less than the time available to the occupants to reach a place of safety.

12.3.2 Fire discovery time

The time to discover a fire is defined as the time from the ignition of the fire to the time the alarm is given. This time can be estimated as:

$$t_{fd} = t_d + t_a \qquad (12.2)$$

where: t_d = time from fire ignition to fire detection, s. This time can be determined using a fire growth model;
t_a = time from detection to alarm sounding, s. This time can be determined using the detection calculations.

12.3.3 Response/reaction time

Response/reaction time is defined as the time from the alarm sounding until the occupant initiates movement to evacuate the emergency area. The response time is dependent upon the type of the building and the characteristics of the people inside, i.e., awake occupants who are familiar with a building react more quickly than occupants who are asleep and unfamiliar with the building. The response time can be represented as follows:

$$t_{res} = t_o + t_i \qquad (12.3)$$

where: t_o = time from the alarm sounding to making a decision to respond, s;
t_i = time to investigate, collect goods, fight the fire, etc., s.

Values of the response time, extracted from the BSI (1994), to an alarm and the start of movement toward an exit are provided in Table 12.2.

Table 12.2. Design values for pre-movement time (BSI, 1994)

Occupancy	Pre-movement Time t_{pm} (s)		
	Alarm Bell	Non-directive P.A.*	Directive P.A.*
Hospitals	480	300	180
Residential	360	240	120
Nursing homes	360	240	120
Hotels	300	240	120
Places of assemblies	300	180	120
Sports stadia	300	180	120
Shopping complexes	300	180	120
Shops	300	180	120
Underground stations	240	180	60
Offices	240	180	60

* P.A. = Public Address System

12.3.4 Travel/evacuation time

After movement towards an exit starts, the main factor which must be considered in the design is the mobility and speed of occupants converging to a place of safety. The travel time is defined as the time from the commencement of the evacuation process until all occupants have reached a place of safety. The travel or evacuation time is dependent upon the number of people likely to exit, number of in-place exits, the existence of evacuation procedures, occupant density, and occupant characteristics such as knowledge of building, age, physical and mental health (see Section No. 4 for more details on Occupant Characteristics). The travel time includes time required to traverse the escape route to the exit, way finding and queuing. For design purposes, the travel time must be such that conditions in the area affected by the fire does not become life threatening due to smoke and flames.

Once evacuation has started, the travel time can be estimated as:

$$t_{eva} = t_{tr} + t_{pas} \tag{12.4}$$

where: t_{tr} = minimum traversal time to an exit, s;
t_{pas} = passage time through an exit, s.

12.3.4.1 Minimum traversal time

The minimum traversal time is a function of the travel distance and the travel speed as shown in Equation (12.5). The travel distance and the travel speed are defined in Subsections No. 12.3.4.2 and 12.3.4.3, respectively.

$$t_{tr} = \frac{L_t}{S_t} \tag{12.5}$$

where: L_t = travel distance, m
S_t = travel speed, m/s

12.3.4.2 Travel distance

It is defined as the distance from the point of departure of the occupant to the nearest exit. For a conservative design, the travel distance should be the longest possible found in the building.

12.3.4.3 Travelling speed

The travel speed is a function of a number of factors including the occupant density, physical conditions of the occupants and their age. When the density of population in a building is between 0.54 and 3.8 persons/m^2, the travel speed can be calculated using the following expression from Nelson and MacLennan (SFPE Handbook, 1995):

$$S_t = C_5 \cdot (1 - 0.266 \cdot D_o) \qquad (12.6)$$

where: D_o = occupant density (for level travel or stairways), persons/m^2;
C_5 = a factor given by $\begin{cases} C_5 = 1.4 & \text{for level corridors or doorways;} \\ C_5 = 0.86 \cdot (G / R)^{0.5} & \text{for stairs.} \end{cases}$

where: G = length of the stair tread, m;
R = riser height of each step, m.

For an occupant density less than 0.54 persons/m^2 (considered as uncongested flow), the people will move at their own pace and the maximum speed can be taken as 1.2 m/s for level travel (corridors, aisles, ramps and doorways) and between 0.85 and 1.05 m/s for stairways. The maximum speed on stairways, for various tread and riser dimensions, are given in Table 12.3. When the density is greater than 3.8 persons/m^2, the flow is very congested and no movement will take place until enough of the crowd has passed from the crowded area to reduce the density (Nelson and MacLennan (SFPE Handbook, 1995)). In addition, Portier et al (1996) reported that the Americans with Disabilities Act (ADA) suggests a speed of 0.47 m/s for disabled evacuees. This represents a speed 37% of that assumed for an able person. However, after every 30.5 m of travel, the ADA further suggests that the evacuee will pause for 2 minutes, presumably to rest.

Table 12.3. Travel speed on stairways (Nelson and MacLennan, SFPE Handbook, 1995)

Riser (m)	Tread (m)	Constant C_5	Max. Speed S_t (m/s)	Max. Specific Flow F_s* (persons/m.s)
0.20	0.25	1.00	0.85	0.94
0.18	0.25	1.10	0.95	1.01
0.17	0.30	1.15	1.00	1.09
0.17	0.33	1.25	1.05	1.16

* F_s = Specific flow given by Equation (12.9) below.

12.3.4.4 Passage time

The passage time for a number of people to go through a door or a stairway can be evaluated by:

$$t_{pas} = \frac{NP}{F_c} \qquad (12.7)$$

where: NP = number of persons passing through door or stairway;
F_c = actual flow of occupants, persons/s (see Equation (12.8) below).

The number of persons in an area can be calculated by multiplying the net area of occupation by the occupant density appropriate to the activity and the use of the space. The occupant density is given in Table 12.4 along with the travel speeds and the travel distances in a time of 2.5 minutes.

The actual calculated flow, F_c, of escaping people through a door or a stairway can be estimated as:

$$F_c = F_s \cdot W_e \qquad (12.8)$$

where: W_e = effective width calculated as the door or stairway width minus the boundary layer width shown in Table 12.5, m;
F_s = specific flow, persons/m·s (see Equation (12.9) below).

The specific flow, F_s, is the flow rate of evacuating occupants past a point in the escape path per unit time and unit of effective width. For a given occupant density value and its corresponding travel speed, a unique value for the specific flow rate can be calculated as:

$$F_s = S_t \cdot D_o \qquad (12.9)$$

Table 12.4. Occupant densities, speeds and distances (Buchanan, 1994)

Activity of any Floor or Compartment	Occupant Density (persons/m^2)	Travel Speed (m/min)	Distance in 2.5 min (m)
Crowd activities			
Standing space	2.6	26	65
Bar standing areas	2.0	39	98
Stadia and grandstands	1.8	44	110
Space with loose seating	1.3	55	137
Areas without seating	1.0	62	154
Exhibition areas	0.7	68	171
Lobbies, foyers	1.0	62	154
Bar sitting areas	1.0	62	154
Dance floors	1.7	46	115
Stages for theatrical	1.3	55	137
Spaces with loose tables	0.9	64	160
Restaurants, dining rooms	0.9	64	160
Dining, beverage etc.	0.8	66	165
Indoor games, bowling	0.1	73	182
Classrooms	0.5	73	182
Reading or writing rooms	0.5	73	182
Teaching laboratories	0.2	73	182
Training rooms in schools	0.1	73	182
Gymnasia	1.7	46	115
Supermarkets, bazaar	0.5	73	182
Sales - ground, basement	0.4	73	182
Sales - upper floors	0.2	73	182
Showrooms	0.2	73	182
Sleeping activities	< 0.5	73	182
Working, storage etc.	< 0.5	73	182
Intermittent activities	< 0.5	73	182

Table 12.5. Boundary layer widths (Nelson and MacLennan, SFPE Handbook, 1995)

Escape Route Element	Boundary Layer (m)
Stairways, wall or side of tread	0.15
Railings, handrails *	0.09
Theatre seats, stadium benches	0.00
Corridors, ramp wall	0.20
Obstacles	0.10
Wide concourse, passageway	0.46
Door, archways	0.15

* Where handrails are present, this value should be used only if they protrude more than 0.06 m from a wall

12.3.5 Additional concepts

12.3.5.1 Escape route geometry

In order for occupants to easily find their way out of the building in the case of a fire, the escape route geometry should be kept simple. Whenever possible, a minimum of two escape routes should be provided in all areas. When two or more escape routes are provided, their locations should be such that a fire cannot block all of them at the same time.

12.3.5.2 Basis for escape route design

As outlined in the previous Subsections, the main factors affecting the design of escape route designs include:

- Activities undertaken;
- Familiarity with the area;
- Occupant characteristics such as their number and location;
- Evacuation time;
- Travel speed;
- Travel distance;
- Flow rate;
- Physical and mental conditions of occupants;
- Time to reach untenable conditions;
- Fire detection and alarm.

For a successful evacuation design, the evacuation time must be less than the time to reach life threatening (untenable) conditions, as shown in Equation (12.10). To account for uncertainties in the calculation of the time required for evacuation, a safety factor should be used. Typically, a safety factor of 2 should be used for able-bodied adults. A larger safety factor should be used if the occupants include disabled people and children.

$$SF \cdot t_{tot} < t_{unt} \qquad (12.10)$$

where: SF = a safety factor;
t_{tot} = calculated evacuation time measured from ignition, s (see Equation (12.1));
t_{unt} = minimum time to reach untenable conditions measured from ignition, s.

12.3.5.3 Minimum time to reach untenable conditions

Evacuation must be completed well before fire conditions become life threatening. The time at which conditions become life threatening can be estimated using fire growth models. This time corresponds to the time when tenable limits, listed in Section No. 12.5 on Performance Criteria, are exceeded. In the absence of methods of calculation, Table 12.12, extracted from Malhotra (1986), can be used. In addition, the New Zealand Design Guide (Buchanan, 1994) suggests using a life threatening conditions time of 2.5 min (see Table 12.5 for travel distances in 2.5 min) when two escapes routes are in-place and 1 min when only one escape route exists. For large spaces, the New Zealand Design Guide suggests using a time of 4 to 6 min for spaces with high roofs or spaces with smoke control systems, and as much as 10 min in sprinklered buildings with smoke control systems.

12.3.5.4 Signage and evacuation plan

Signage indicating routes to exits and exit signs should be available and illuminated for facilitating the escape process. The exit doors should open in the direction of flow of exit. They should not be wedged open in order to retard the fire growth and spread. Finally, a written emergency plan should be in place. The plan should provide for safe evacuation, training for occupants, degree of evacuation assistance required and how the plan will be managed, maintained and audited.

12.4 Input and Output for the Evaluation Procedures

Tables 12.6 and 12.7 summarize the input and output requirements for escape and evacuation activities.

Table 12.6. Input requirements

Input Needed	Section Taken From
Ignition time	- Fire growth
Detection time	- Detection
Response/reaction time	- Initial design parameters
Performance required time, i.e., time for conditions to become untenable	- Fire growth, Smoke
Tenability limits	- Initial design parameters
Building characteristics	- Initial design parameters
Occupant characteristics	- Initial design parameters

Table 12.7. Output requirements

Output	Needed For Section
Occupant total evacuation time	- Fire fighting response, Life safety
Number of occupants evacuated with time	- Fire fighting response

12.5 Performance Criteria

In order for a fire safety design to be satisfactory, a number of performance criteria must be met. The performance criteria can be set by the fire safety design team to ensure effective occupant response to detection alarm and to ensure occupants are not trapped in untenable conditions.

12.5.1 Tenability limits criteria

The tenable limits within the compartment of fire origin should not be exceeded before occupants are able to reach a protected zone or a safe place. Below is information that was gathered from different sources to define life safety criteria. The criteria are mainly in terms of hot layer height, heat radiation, convected heat, toxicity and visibility or smoke obscuration.

In the SFPE Handbook of Fire Protection Engineering (1995), Purser summarized the toxicity levels of combustion products and presented a procedure for assessing fire effects on humans. The tables listed tenability limits for incapacitation, death and sensory irritation. The criteria include levels of carbon monoxide (CO), hydrogen cyanide (HCN), oxygen (O_2), carbon dioxide (CO_2), heat flux, air temperature and smoke optical density. The New Zealand Design Guide (1994) adopted the criteria shown in Table 12.8. These are based on the SFPE Handbook (1995).

Table 12.8. Tenability criteria (Buchanan, 1994)

Tenability Type	Tenability Limit
Convection Heat	Temperature of the relevant gas layer ≤ 65°C (time to incapacitation for 30 min exposure)
Smoke Obscuration	Visibility in the relevant layer should not fall below 2 m
Toxicity	CO ≤ 1400 ppm (small children incapacitated in half the time) HCN ≤ 80 ppm O_2 ≥ 12% CO_2 ≤ 5% (the above critical values lead to incapacitation in approximately 30 min)
Radiation Heat	Radiant flux from upper layer ≤ 2.5 kW/m^2 (this corresponds to a gas layer temperature of about 200°C; above this, the tolerance time is less than 20 s)

The British Standards Institute (BSI) Draft Code of Practice (1994) adopted the limits for tenability caused by toxic products of combustion, smoke obscuration and heat shown in Tables 12.9, 12.10 and 12.11. These limits are based on values reported in the SFPE Handbook (1995).

Table 12.9. Limits for tenability caused by toxic products of combustion (BSI, 1994)

Chemical Products	5 min Exposure		30 min Exposure	
	Incapacitation	Death	Incapacitation	Death
Carbon Monoxide	6000 ppm	12000 ppm	1400 ppm	2500 ppm
Low Oxygen	< 13 %	< 5 %	< 12 %	< 7 %
Carbon Dioxide	> 7 %	> 10 %	> 6 %	> 9 %

Table 12.10. Limits for tenability caused by smoke obscuration (BSI, 1994)

Location	Minimum Visibility within Room
In a small room	2 m
Other rooms	10 m

Table 12.11. Limits for tenability caused by heat (BSI, 1994)

Mode of Heat Transfer	Symptom	Exposure Level
Radiation	Severe skin pain	2.5 kW/m^2
Conduction	Skin burns 1 s of contact (metal)	60°C
Convection	Skin/lungs affected by hot gas in > 60 s	120°C
Convection	Skin/lungs affected by hot gas in < 60 s	190°C

Malhotra (1986) cited the critical times shown in Table 12.12 for reaching untenable conditions.

Table 12.12. Critical times for reaching untenable conditions (Malhotra, 1986)

Type of Zone	Critical Time to Reach Untenable Conditions in Means of Escape (min)
A. Unprotected fire zone	
• Normal sized room (≤ 100 m^2)	2 - 2.5
• Larger compartments or room (height > 4 m)	4 - 6
B. Partially protected zone	
• Natural smoke expulsion	5
• Pressurization or extraction system	10
C. Fully protected zone	
• Natural smoke expulsion, no lobby	30
• Natural smoke expulsion, lobby	45
• Pressurization or extraction system	60

In addition, the following are other criteria presented by other researchers:

- O'Hara (1993) gave a full outline of the performance objectives for a low-rise office building. For life safety, the author suggested limiting the CO level to less than 1700 ppm and the O_2 level in egress routes to more than 15%.
- For the smoke control system, O'Hara (1993) set the performance criteria as keeping the toxic fire product layer at not less than 3 m above the floor. For means of egress, O'Hara set, as the performance criteria, an evacuation time of 6 min or less.
- Tamura (1994) reported Table 12.13 which lists acceptable visibility in terms of distance and the corresponding optical visibility per metre suggested by various researchers. The criterion of 25 m of visibility and 0.043 Optical density/m suggested by Wakamatsu (1968) was introduced in the National Building Code of Canada, 1970 edition, for specifying tenability requirements in escape routes and refuge areas in high-rise buildings.
- Scherfig (1993) defined the safety criteria for evacuation in terms of visibility thresholds. The author set a rule that persons under egress must have a visibility of at least 3 m in the primary fire compartment and 10 m in escape routes.
- Johnson and Timms (1995) suggested that the life safety criteria in shopping mall atria were to limit the hot layer to not less than 1.9 m from the floor and to limit the hot layer temperature to not more than 183°C

Table 12.13. Visibility ranges and optical density limits (Tamura, 1994)

Researcher(s)	Visibility range (m)	Optical density (OD/m)
Jin (1976)	15 - 20 (unfamiliar occupant)	0.045
	3 - 5 (familiar occupant)	0.17 - 0.3
Kawagoe (1967)	20	0.45
Wakamatsu (1968)	25	0.43
Los Angeles Fire Dept. (1961)	14	0.076
Rasbash (1967)	4.5 (dash to safety)	0.21
Malhotra (1967)	4.5 (dash to safety)	0.21

13. FIRE SAFETY ENGINEERING DESIGN TOOLS

13.1 Purpose

- To describe the advantages, disadvantages, limitations, assumptions and availability for use of a number of computer fire engineering models that can be used by a designer to develop a fire safety design for buildings.

13.2 Introduction

Fire safety in buildings is an interaction between all the components of the fire safety system which includes fire outbreak, fire growth, fire and smoke spread, the response of building elements to fire, the occupant response to fire and the fire service response to fire. In order to develop a building fire safety design, it is necessary to determine the behaviour of a fire in a fire compartment from ignition to decay. Therefore, it is essential that the designers have at their disposal the means to predict the level of life safety for any particular design. The means are, in general, in the form of fire engineering computer models that can be used to estimate the performance of building fire safety systems and evaluate the compliance with the performance criteria set initially by the design team.

Over the past few years, considerable effort has been put into the development of fire engineering computer models. Many of these models are available for use by designers in evaluating the development and effects of fire and the movement of people.

13.3 Categories of Fire Engineering Models

Fire modelling can be grouped into two categories: probabilistic or stochastic fire models and deterministic fire models.

13.3.1 Probabilistic fire models

Probabilistic fire models involve the evaluation of the probability of risk due to fire based on the probabilities of all parameters influencing the fire such as human behaviour, formation of openings and distribution of fuel load in the compartment of fire origin. The probabilities are usually time dependent and are determined through experimental data and fire incident statistics. Laws of physics are generally not included in the equations used by the models. The results of the models are in terms of probabilities including fire likelihood. Little or no information is given on the production and distribution of combustion products (e.g., toxic products, smoke movement and temperatures).

13.3.2 Deterministic fire models

In contrast to the probabilistic fire models, deterministic fire models are based on physical, chemical and thermodynamic relationships and empirical correlations used to calculate the impact of fire. Deterministic models can be very simple requiring a short computing time or highly complex requiring hours of computation. Typically, deterministic models can be classified as zone models and fields models.

13.3.2.1 Zone models

Zone models are one- or two-dimensional models which divide a compartment into a number of distinct zones. Each zone is considered homogeneous and is characterized by a set of time-dependent parameters describing its physical state. The number of zones ranges typically from three to five. Possible zones include the hot layer, the cool layer and the rising thermal plume and ceiling jet. Zone models are easy to use, fast to run and practical. Because of their simplicity, zone models can achieve first order approximations to real fire behaviour. The accuracy of their results may, however, suffer in predicting complex fire situations.

13.3.2.2 Field models

Field models are two- or three-dimensional models. For these models, the compartment is divided into a grid or a mesh of small volume elements. These models solve the governing equations for mass, momentum and energy of each element of a compartment. Field models calculate the variables (e.g. temperature) at the point in a compartment. General purpose Computational Fluid Dynamic (CFD) models are frequently used to solve the governing equations. The advantage that field models can offer is the accuracy and the detail of the results. On the other hand, field models are still under development, require a great deal of experience in their use and place a high demand on computing resources and time.

13.4 Selection of Fire Models

There is no fire model that is comprehensive for all fire applications. The selection of a fire model to be used for an application depends on a number of factors including understanding the limitations and assumptions used in the model, validation of the model, documentation accompanying the model and ease of use.

13.4.1 Limitations and assumptions in fire models

The decision to use a particular fire model should be based on the understanding of its limitations and assumptions. The applicability of a fire model must be clearly stated. The user must ensure the model is used within the limits for which the model was verified.

13.4.2 Validation of fire models

Computer fire models are still in their infancy and users should be careful in selecting a model. To make the right decision in the selection process, the issue of the validation of the fire model must be addressed. The results of the model must be compared against experimental data to determine the predictability of the model. In addition, the model should be checked against simple hand calculations for consistency between input and output. Finally, the result should be verified using the judgement of an experienced fire protection engineer.

13.4.3 Documentation of fire models

The documentation accompanying the model provides a good indication of the quality of the model. The documentation should include the technical documentation for the model and a guide on how to use the model. The technical documentation includes the computer software (source code, if available, and information regarding installation of the model) and the theoretical basis for the calculations. The latter can be used to determine the level of confidence which can be placed in the fire model.

13.5 Sensitivity Analysis

When using a fire model, it is wise to determine the sensitivity of the output to changes in the input to determine if changes in the data or the model assumptions and applicability will lead to a different decision. The sensitivity analysis will determine the most dominant and significant variables. It will also determine whether the user should pay careful attention to particular input values that might significantly affect the results.

13.6 Uncertainty in Fire Models

Fire engineering models can provide a good estimate of the effects of fire, however, the randomness of fire is such that the results may not be precise. When a user has some doubts about a model, the user should establish from the literature (especially experimental research) the appropriateness of the results of the model. Further, when dealing with uncertainty associated with data for models, it is usually required to apply adequate factors of safety to ensure a conservative design. Furthermore, when uncertainty exists, it is appropriate to conduct a sensitivity analysis.

13.7 Available Fire Engineering Models

A survey carried out by Friedman (1992) has shown that a large number of computer fire models have been developed in recent years. A complete listing of these fire models is reported in the above cited reference (Friedman, 1992). Table 13.1 presents a list of computer fire engineering models along with their type, intended use, computer requirements and their availability.

Table 13.1. Computer fire engineering models

Model (type)	Intended use	Requirements	Availabl e	Comments
ARGOS (zone)	Prediction of fire development and the resulting conditions	Runs on PC	Yes	- Multi-compartments
ASCOS (other)	Prediction of smoke movement	Runs on PC	Yes	
ASET (zone)	Calculation of temperature, position of the hot layer and onset of hazardous conditions	Runs on PC	Yes	- Single room with closed doors and windows
ASET-B (zone)	Calculate of temperature and position of the hot layer	Runs on PC	Yes	- Single room with closed doors and windows
BF3D (field)	Buoyant convection induced by a heat source in a room	Main frame or super computer	No	
BRI2 (zone)	Prediction of the development of a fire	Runs on PC	Yes	- Multi-compartments
CFAST (zone)	Prediction of fire development and the resulting conditions	Runs on PC	Yes	- Multi-rooms (up to 10)
COMPBRN - III (zone)	Assessment of risk in the nuclear power industry	Runs on PC		- Single room
COMPF2 (zone)	Calculation of characteristics of a post-flashover fire	Runs on PC		- Single fire compartment
CONTAM-96 (other)	Prediction of smoke movement	Runs on PC	Yes	
CRISP2 (other)	Fire risk assessment	Runs on PC	No	
DETACT-QS (other)	Calculation of detection times for heat detectors	Runs on PC	Yes	- For arbitrary fires
DETACT-T2 (other)	Calculation of detection times for heat detectors	Runs on PC	Yes	- For t^2 fires
EXODUS (other)	Evacuation model for the safety industry	Runs on PC or workstations	Yes	
FASBUS II (other)	Estimation of fire resistance of steel-framed floor systems	Runs on PC	Yes	- Nonlinear finite element program - Program uses iteration procedure in calculation
FASTLITE	Estimation of fire growth and	Runs on PC	Yes	

Model (type)	Intended use	Requirements	Availabl e	Comments
(zone)	smoke movement			
FIRECALC (zone)	Prediction of the development of a fire, resulting conditions, the response of fire protection systems and time to escape	Runs on PC	Yes	- Based on FPETOOL - Single room
FIREDESIG N (other)	Evaluation of structural response of heated concrete or steel beams and columns	Runs on PC	Yes	- Finite element analysis to determine load-bearing capacity of structural members - Program interfaces with TEMPCALC program
FiRECAM (other)	Risk assessment and cost evaluation from fires	Runs on PC	No	
FIRES-T3 (other)	Analyzes heating of structural members exposed to fire	Runs on PC	Yes	- Finite element program
FIRST (zone)	Prediction of the development of a fire and the resulting conditions	Runs on PC	Yes	- Single room
FISCO-3L (field)	Fire development	Runs on PC	Limited	- Single compartment
FLOW-3D (field)	General purpose fluid dynamic code	Main frame or super computer	Yes	
FPETOOL (zone)	Prediction of the development of a fire, resulting conditions and the response of fire protection systems	Runs on PC	Yes	- Includes FIREFORM, MAKEFIRE and FIRE SIMULATOR - Single room
FRAME-WORKS (other)	Fire risk assessment	Runs on PC	Yes	
HAZARD I (zone)	Prediction of the development of a fire, resulting conditions, tenability conditions and time for people to escape	Runs on PC	Yes	- Includes FAST, EXITT and TENAB - Multi-compartment
JASMINE (field)	Analysis of smoke movement in a compartment	Vax	Yes	
KAMELEON FIRE E-3D (field)	Transient calculation of pool fires in a compartment	Runs on PC and UNIX X-windows	Limited	- Single room
KAMELEON II (field)	Calculation of smoke and toxic gas movement in complex geometries	Runs on PC and UNIX X-windows	Limited	- Multi-compartment
KOBRA-3D (field)	Determination of the hydrodynamic flow	Runs on PC	Yes	- Single compartment
LAVENT (zone)	Simulation of environment and response of sprinklers in compartment fires	Runs on PC	Yes	
MAGIC (zone)	Prediction of fire development and the resulting conditions		Yes	- Multi-compartment
PHOENICS (field)	General purpose transient fluid dynamic code	Main frame or super computer	Yes	

Model (type)	Intended use	Requirements	Availabl e	Comments
RMFIRE (field)	Transient calculation of smoke movement in room fires	Silicon graphics personal IRIS	No	
SPLASH (field)	A quasi-model describing the interaction of sprinkler sprays with fire gases	Vax	Limited	
SUPER-TEMPCALC (other)	Analyzes conduction of heat transfer through assemblies with air gaps	Runs on PC	Yes	- Finite element program
TASEF (other)	Analyzes conduction of heat transfer through assemblies	Runs on PC	Yes	- Finite element program
UNDSAFE (field)	Prediction of fire environment in open spaces and enclosures	Mainframe	Yes	
WPI - 2 (zone)	Prediction of the development of a fire and the resulting conditions	Runs on PC	Yes	- Single room

14. FIRE SAFETY MANAGEMENT

14.1 Purpose

- To provide guidelines for the development of a fire safety manual in which fire safety management procedures are explained.

14.2 Introduction

The management of a building must always be ready to face the possible occurrence of a fire emergency and the main fire safety rule should be preparedness rather than improvization. In general, fire casualties occur when occupants experience escape problems. Therefore, in the event of a fire, discovered through automatic detection or by visual means, the occupants should know the correct course of action to take in order to be safe and reach a place of safety. The correct actions can only be acquired through the implementation of effective fire safety management procedures that lead to the minimum number of fire fatalities and fire occurrences.

Fire safety management is an integral part of the fire safety system and can be regulated by the Occupational Health and Safety Act.

14.3 Fire Safety Manual

14.3.1 Purpose of the manual

The adoption of fire safety management procedures can be implemented through a fire safety plan. The plan, which is in the form of a manual, is a set of rules and procedures, developed by the building management, for use by occupants to establish and maintain a high fire safety standard. The manual can be used to ensure each occupant is aware of potential fire hazards and to provide procedures on how to deal with and eliminate them from the work environment. Building occupants should be urged to become familiar with the contents of the manual.

14.3.2 General description of the contents of the manual

The detailed contents of the fire safety manual depend on the building, its occupants and its function. The general structure of the manual should include the following topics:

- Responsibilities;
- Procedures upon discovery of a fire emergency;

- Emergency procedures;
- Housekeeping procedures;
- Maintenance and inspection procedures;
- Information and training.

14.3.2.1 Responsibilities

The fire safety manual should state the responsibilities of the building manager and occupants. These responsibilities provide designated people with authority and accountability. The occupants should also know the duties of key staff in the event of an emergency, e.g., who has the duty to contact the fire department or the duty to facilitate evacuation.

14.3.2.2 Fire action procedures upon discovery of a fire emergency

There are a number of actions and procedures that the occupants should perform if they see or sense a fire developing in the building. Actions that need to be taken include notifying the fire department for a quick response, starting the evacuation process, fighting the fire to control if not too dangerous, and showing the fire department personnel access to the area of emergency and providing other details requested by the fire fighters.

14.3.2.3 Emergency procedures

These procedures are an illustration of the step-by-step procedures that should be followed in order to minimize the occurrence of a fire, to evacuate an emergency building, or rescue an occupant. Example procedures include a general evacuation procedure, fire emergency procedures, hazardous material spill procedure, natural gas leakage procedure, procedure when occupants become aware of the existence of odours, and people caught by fire. Along with these procedures, a list of emergency phone numbers should be included to facilitate, for the occupants, the contact of the appropriate emergency service.

14.3.2.4 Housekeeping procedures

The housekeeping procedures need to be part of the fire safety manual. They are used to ensure that, in the case of fire outbreak, the fire does not propagate easily and that evacuation routes are not obstructed. Housekeeping procedures include fire prevention practices to make occupants aware of the proper habits, procedures for safe storage of hazardous materials especially combustible and flammable materials, and procedures for safe waste disposal particularly hazardous waste.

14.3.2.5 Maintenance and inspection procedures

Maintenance is crucial in fire prevention. Without proper maintenance programs, there is a high probability that a fire will develop unnoticed and consequently the damage, in terms of lives and contents, could be devastating. Maintenance procedures include periodic verification and testing of active and passive fire protection systems, i.e., fire alarm and detection systems, manual and automatic fire suppression systems, smoke control systems, door closing mechanisms, and the integrity of the fire and smoke barriers. Maintenance should be performed by competent individuals.

Inspection procedures are different from maintenance procedures. Inspections may be performed by the occupants and can include more details. Problems noted during inspections should be reported to the appropriate individuals for immediate action.

14.3.2.6 Information and training

An integral part of the fire safety manual is programs for providing occupants with information and training. Information includes postings and data for the occupants regarding fire hazards and how to avoid them.

Training is in the form of exercises or lectures which show occupants how to react to an emergency. Training includes how to react to a fire alarm (e.g., notifying the fire department, alerting others and evacuating), regular drills for evacuation practices and avoidance of panic, how to perform good housekeeping, use of manual fire suppression systems, and handling of hazardous materials. Training should be conducted by certified and competent individuals.

14.3.3 Review and update of the manual

The fire safety manual should be maintained over the lifetime of a building. However, it should be reviewed and updated as necessary, especially when there is change in personnel or usage of the building. Any changes in the manual must be communicated immediately to all building occupants.

14.4 Example of a Typical Fire Safety Manual

Every building should have its own fire safety manual adapted to its occupants and activities. However, in order to illustrate a typical fire safety manual, the following Subsections detail specific material that could be included in the fire safety manual.

14.4.1 Fire safety responsibilities

The management of a building is responsible for establishing fire safety standards. Once these standards are established, the maintenance of safe fire conditions in the building becomes a shared responsibility between the building management and its occupants. One of the main elements for a successful implementation of fire safety practices is the establishment of clear lines of communication, responsibilities and accountability. Another element is the maintenance of fire safety systems. Below is a list of responsibilities of the management and the occupants.

The management should:

- Ensure that individuals under their management have the authority to implement fire safety practices.
- Ensure that areas under their management are in compliance with fire safety practices.
- Provide safety instructions and encourage safe work habits by all employees.
- Discipline, when necessary, employees who refuse to abide by fire safety rules.
- Be aware of fire hazards and inform employees of these hazards.
- Ensure that passive measures are repaired when damaged including proper functioning of door closers and the repair of gaps in the door openings and other barriers.
- Ensure that the active fire protection measures are maintained and kept in working order. Fire detection and alarm systems, sprinkler installations, portable extinguishers and hose reels should be regularly checked and properly maintained.
- Ensure that alternates are designated in the case that the person with the primary responsibility is absent.
- Appoint a group of employees (fire safety officer and assistants) to act as a liaison with the fire department and to call and inform in the event of a fire emergency.
- Assist the fire department when they arrive to the fire scene. This includes guiding them to the fire location, informing them about the available facilities and giving them any other tips which may help them control the fire.
- Provide training to the staff (use of first aid, fire fighting, evacuation, etc.), especially those exposed regularly to fire hazards and those dealing with fire emergencies.

Each occupant should:

- Use maximum care and good judgement in preventing fire emergency incidents.
- Understand fire hazards and unsafe conditions and know the procedures for reporting observed fire hazards immediately to management.
- Abide by all fire safety rules.

14.4.2 Fire action procedures

Fire action procedures are well-defined actions which have to be undertaken when a fire is observed. These actions should be prepared by the management to show the duties and tasks of different members of staff as soon as a fire is detected. The main actions are:

1. Informing the fire department.
    - Once a fire is reported, by automatic detection or visually, the local fire department must be informed regardless of the fire size.
    - Management has the responsibility to appoint a group of staff to do this task (fire safety officer and assistants).

2. Assembling and evacuating occupants to a place of safety.
    - Once a fire is detected, occupants should evacuate the building.
    - Staff should encourage and assist non-staff members in responding to an alarm.
    - Designated members of a building should check that no one is left behind.
    - In high rise buildings, the evacuation should start with the affected floor first.
    - In areas with people with disabilities, special provisions must be made available.

3. Attacking the fire.
    - A fire attack should only be undertaken by trained staff.
    - Untrained occupants should be strongly discouraged from fighting a fire.
    - Attacking a fire may only control it. This, however, gives the fire department a better chance to extinguish it.

4. Assisting the fire department once on the fire scene.
    - When the fire department is on the fire scene, the building officer should give all the necessary information with regard to the details of the fire, any special risk areas, facilities available and location of hydrants.

14.4.3 Emergency procedures

14.4.3.1 Useful phone numbers in case of emergencies

A list of emergency phone numbers should be prepared and communicated to all building occupants. The list should include phone numbers for the following:

- City Emergency
- On-Site Emergency
- Fire Department
- On-Site Fire Prevention Service
- Hospital

- Health and Safety Service
- Maintenance Service
- Waste Management Service
- On-Site Information Service
- Telephone Repair Service

14.4.3.2 Evacuation procedure

The following evacuation procedure should be followed in case the building must be evacuated:

- When the signal to evacuate the building is heard, alert others around you.
- Shut down any operations which may create additional hazards if left unattended without endangering yourself.
- Take your coat and keys with you. Close your doors.
- Proceed to the nearest exit if it is safe. Walk, do not run and DO NOT USE ELEVATORS.
- Once outside, move away from the building. Provide any information observed about the emergency condition on your way out.
- Occupants may re-enter the building only when given the "All Clear" signal.

14.4.3.3 Fire emergency procedure

In case you see a fire, proceed as follows:

- Pull nearest fire alarm.
- Alert occupants in the area of the fire.
- Confine the fire, if possible to do so, without endangering yourself or others.
- If the fire is small, you may wish to use a fire extinguisher. However, remember:
    1. Do not use a fire extinguisher unless you have been trained in their use.
    2. Do not use an extinguisher unless you think it is safe to do so.
    3. Use the "**PASS**" method: **P**ull the pin, **A**im at the base of the fire, **S**queeze the handle completely, **S**weep side to side.
- Evacuate the immediate area if the fire spreads, and close doors as you leave.
  DO NOT USE AN ELEVATOR.
- If dense smoke is evident, crawl on the floor to avoid smoke during evacuation.
- Once outside, remain outside the building until officials authorize re-entry.
- If evacuation is not possible, remain inside your area, seal all the gaps to obstruct the penetration of smoke and call for help.

14.4.3.4 Hazardous material spill procedure

Spills of flammable materials may present a fire hazard to those in the area of the spill. In case of a spill, proceed as follows:

- Alert every one in the immediate vicinity.
- Clean up spills, if trained and safe to do so, and properly dispose of waste.
- Confine the spill to the smallest possible area, if safe to do so.
- Close doors to prevent spread of vapours into adjoining rooms and corridors.
- Shut off ignition sources and avoid unplugging equipment.
- Evacuate the emergency area.
- Notify the emergency service immediately and provide detailed information.
- Re-enter the area only after the cleanup has been completed.

14.4.3.5 Natural gas leak procedure

If you smell or detect a leak of natural gas, proceed as follows:

- Cease all operations.
- DO NOT turn "on" or "off" a light switch or any electrical equipment.
- Follow the evacuation procedure and call the emergency service.

14.4.3.6 Odours

If you see or smell smoke or chemical odour coming from the ventilation system or somewhere else, immediately notify the emergency service.

14.4.3.7 First aid - clothes on fire

First aid is essential, in many cases, while you wait for trained personnel to arrive. In case a person's clothes are on fire, proceed as follows:

- Stop the person from running.
- Drop the person to the floor to prevent flames from rising to the face and head.
- Roll the person to snuff out the flames (blankets can be effective if readily available).
- Cool the person by removing smouldering clothing that has not adhered to the skin, and by using water and ice packs.
- Get medical assistance.

IN CASE OF ANY EMERGENCY, HELP DISABLED PERSONS AND THOSE WHO NEED ASSISTANCE IMPLEMENTING THE ABOVE PROCEDURES

14.4.4 Housekeeping procedures

14.4.4.1 Fire prevention practices

Fires do happen from time to time. Be prepared before the fire occurs. Be familiar with the evacuation procedures and know your evacuation plan and the location of the emergency equipment in your area. Every occupant should remember the following:

- Evaluate and analyze your own areas. What is the most likely thing to cause a fire and what can you do about it (see Appendix C for a list of potential fire hazards)?
- Smoking is not allowed near sources of ignition.
- Be alert to unsafe conditions and see that they are corrected when detected.
- Practice good housekeeping.
    1. Keep the work area clean and avoid clutter that permits fire to spread rapidly.
    2. Keep products and equipment properly labelled and stored.
    3. Clean up the work area on completion of an operation.
    4. Small spills (including water) should be cleaned up immediately.
    5. Exits, utility controls, and fire safety equipment must be free from any obstruction preventing access and use.
- Make sure corridors and stairwells are free of obstructions and combustibles so that escape can be rapid and safe.
- All exits and routes to exits must be conspicuously marked so that they will be obvious to all occupants.
- Keep all doors to stairwells closed at all times. DO NOT WEDGE OR BLOCK OPEN FIRE DOORS.
- Control all sources of ignition and keep ignition sources, fuel, and oxidizers separate. Potential ignition sources should be examined by competent persons (see Appendix C for a list of potential sources of ignition).
- All receptacles and any electrical conductors must be properly grounded.
- Separate all combustible materials from electrical equipment.
- Cylinders containing compressed gases (used for welding or other activities) can pose a fire and explosion hazard. They must be stored, transported, handled and used appropriately. They must also be regularly inspected for obvious signs of defects or leakage.
- Know the procedures for safe handling and storage of hazardous materials.
- Deposit hazardous waste in appropriately labelled containers and follow all waste disposal procedures.
- When transferring flammable liquids, static-generated sparks should be avoided by using of ground straps. When metal containers are used, bond the ground straps to the container.
- Removal of ordinary trash and recyclable material from designated receptacles should be scheduled regularly.

14.4.4.2 Safe storage of hazardous materials

There are four key elements in the safe storage of hazardous materials:

1. Maintenance of an inventory of hazardous products in the facility.
2. Proper labelling of all hazardous products. The need for adequate labelling extends far beyond the immediate requirements of the individual user, since the individual user may not be present in case of fire or explosion when containers are broken or spilled. Labels must be available for use by all occupants.
3. Separation of incompatibles. Hazardous materials must be stored according to their associated hazards and amount stored. Accidental contact between incompatible hazardous products can result in an explosion or fire. The following storage precautions should be followed:
    - Flammable and combustible products must not be stored in the same cabinet as oxidizers or strong acids.
    - Keep flammable products in approved safety containers or cabinets.
    - Separate acids from bases.
    - Never store corrosives with solvents.
4. Adequate storage environment
    - Ensure that access to hazardous products is limited to authorized people.
    - Stored hazardous products should be examined periodically for deterioration and integrity of the container.
    - Keep fire safety equipment such as fire extinguishers handy and in good working order.
    - Hazardous products must not be stored in traffic areas.

14.4.4.3 Hazardous waste disposal

Hazardous wastes include hazardous residues of experiments, outdated hazardous materials, and materials used to clean up spills. The general guidelines are:

- It is the responsibility of every employee generating hazardous wastes to dispose of them in compliance with the regulations.
- Hazardous wastes placed in the same collection container must be compatible with all other wastes in the container.
- Collection containers must be kept securely closed except when adding hazardous materials.
- To prevent the mixing of waste which could create an incompatible reaction, all materials must be clearly identified.
- All safety precautions required for handling and storage of chemicals also apply to waste material.

14.4.5 Maintenance/inspection procedures

14.4.5.1 Maintenance

Maintenance procedures are provided to ensure that protection systems operate effectively when required. Maintenance of protection systems (see Appendix D for a list of manual and automatic fire protection systems) should be conducted regularly by competent personnel and all maintenance work recorded and kept in a file. Maintenance should include the following:

1. Maintenance of passive systems to an acceptable level.
   - Keeping all escape routes available at all times.
   - Not storing any materials in corridors, on stairs or against doors.
   - Keeping all escape doors unlocked and in good working condition.
   - Repair of damages that may have been caused to fire barriers (doors or walls).
2. Maintenance of active systems to an acceptable level.
   - Regular maintenance programs for portable extinguishers, fire hoses, detection and alarm systems, sprinkler installations, emergency lighting, door closing mechanism for fire doors, and smoke ventilation systems.
   - In case of repair on a sprinkler system, a back up facility must be in-place to make sure that a fire will be controlled.
3. Preparation and maintenance of information and plans: posting of plans showing essential fire safety and fire control information. Evacuation routes are to be posted in buildings at every stairway and elevator landing. Posting of signs providing telephone numbers for emergency services, location signs for exits, extinguishers and other fire safety equipment, and warnings at areas where fire hazards exist.

14.4.5.2 Safety inspections

- All employees should perform periodic inspections of their work areas and report fire hazards and concerns to upper management.
- The inspections include functionality of the active and passive fire safety systems, housekeeping, etc. See Appendix E for an example of a checklist.
- Inspections also include verifying whether or not the building has been changed from its original design parameters.
- Formal fire safety inspections must be held at least annually.

14.4.6 Information and training

14.4.6.1 Information

The management should ensure that employees under their supervision are informed about and have access to the information on fire hazards, safe handling, storage and disposal of hazardous materials and emergency procedures in the work place.

14.4.6.2 Staff training

Employees should be provided with necessary training to ensure that they know how to control exposure to fire hazards. The extent of training depends on the activities undertaken in the facility and the potential fire risks. Staff training should be provided by competent personnel and should include the following:

- Fire safety practices and recognition of fire safety hazards.
- Action to be taken by the staff upon discovery of a fire or hearing an alarm, and procedures to call the fire department.
- Designation and training of a fire safety officer responsible to management for fire prevention. The fire safety officer has the mandate to oversee the execution of regular fire drills, to ensure the installation, maintenance, and inspection of fire protection systems, to investigate incidents involving fires, and to inspect buildings and provide recommendations with regard to fire safety.
- Appointment and training of fire safety assistants on each floor of a building. The training of the fire safety assistants is to ensure that they can complete their role of guiding occupants to a safe place, making sure that all occupants have been accounted for, and helping occupants overcome panic.
- Training of fire safety staff in the use and handling of fire safety equipment to extinguish a fire. Fire fighting appliances are of no use if there is no trained personnel available to use them. This is particularly the case with portable fire extinguishers. Trained personnel should receive refresher courses periodically.
- Practice of evacuation procedures through fire exit drills. The purpose of fire exit drills is to make occupants conscious of the actions they have to take in case of a fire, to ensure the efficient and safe use of the exit facilities and to ensure orderly exit under control and no panic. Fire drills should be varied by making some of the escape routes unavailable by simulating different fire scenarios.
- Training to practice good housekeeping, especially when hazardous materials are present (handling procedures, storage guidelines and waste disposal procedures).
- Practice of emergency procedures.

As the need arises, extra training or special training should be provided. The management should keep records of all training sessions.

15. REFERENCES

Alpert, R.L. and Ward, E.J. (1984), Evaluation of Unsprinklered Fire Hazards, Fire Safety Journal, Vol. 7, pp. 127-143.

American Iron and Steel Institute (1983), Fire Safe Structural Steel - A Design Guide, Washington, USA.

ASTM E-108-96 (1996), Standard Test Methods for Fire Tests of Roof Covering, American Society for Testing and Materials, Philadelphia, PA, USA.

ASTM E-119-88 (1988), Standard Test Methods for Fire Tests of Building Construction and Materials, American Society for Testing and Materials, Philadelphia, PA, USA.

Australian Fire Engineering Guidelines (1996), First Edition, Fire Code Reform Centre Ltd., Sidney, Australia.

Babrauskas, V. (1981), Will the second item ignite?, Report NBSIR 81-2271, National Bureau of Standards, Gaithersburg, MD, USA.

Barnett, C. and Simpson, M.R. (1995), Fire Code Review: New Zealand's Performance-based Fire Code, Proceedings of the First International ASIAFLAM Conference 1995, InterScience Communications Ltd., Hong Kong, March, pp. 27-40.

Beck, V.R. (1994), Performance-based Fire Safety Design - Recent Developments in Australia, Fire Safety Journal, Vol. 23, No. 2, pp. 133-158.

Boring, D.F., Spencer, J.C. and Wells, W.G. (1981), Fire Protection Through Modern Building Codes, American Iron and Steel Institute, 5th Ed., Washington, DC, USA.

BSI Standards (1994), Draft British Standard Code of Practice for The Application of Fire Safety Engineering Principles to Fire Safety in Buildings, Panel FSM/-/5 and Technical Committee FSM/24 Fire Safety Engineering, London, UK

Buchanan, A.H. (1994), Fire Engineering Design Guide, Centre for Advanced Engineering, University of Canterbury, New Zealand.

Building Industry Authority (1994), Approved Documents C1, C2, C3, C4, New Zealand Building Code, New Zealand.

Bukowski, R.W. and Babrauskas, V. (1994), Developing Rational, Performance-Based Fire Safety Requirements in Model Building Codes, Fire and Materials, Vol. 18, No. 3, pp. 173-191.

Bukowski, R.W., Clarke, F.B., Hall Jr., J.R. and Stiefel, S.W. (1990), Fire Risk Assessment Method: Description of Methodology, National Fire Protection Research Foundation, Quincy, MA, USA.

Bukowski, R.W. and Tanaka, T. (1992), Toward the Goal of a Performance Fire Code, "International Fire Safety Engineering Conference: The Concepts and the Tools", Conference Papers, Forum for International Cooperation on Fire Research, CSIRO, Sydney, Australia.

Butler, H., Bowyer, A. and Kew, J. (1981), Locating Fire Alarm Sounders for Audibility, Building Services Research and Information Association, Bracknell, UK.

Canadian Commission on Building and Fire Codes (1994), Draft Strategic Plan Final Report of the CCBFC Strategic Planning Task Group, National Research Council of Canada, Ottawa, ON, Canada.

CAN/ULC-S101-M89, Standards Methods of Fire Endurance Tests of Building Construction and Materials, Underwriters' Laboratories of Canada, Scarborough, ON, Canada.

CAN/ULC-S107-M87, Standards Methods of Fire Tests of Roof Coverings, Underwriters' Laboratories of Canada, Scarborough, ON, Canada.

CAN/ULC-S503-M90, Carbon Dioxide Hand and Wheeled Fire Extinguishers, Underwriters' Laboratories of Canada, Scarborough, ON, Canada.

CAN/ULC-S504-M86, Dry Chemical and Dry Powder Hand and Wheeled Fire Extinguishers, Underwriters' Laboratories of Canada, Scarborough, ON, Canada.

CAN/ULC-S507-92, 9 Litre Stored Pressure Water Type Fire Extinguishers, Underwriters' Laboratories of Canada, Scarborough, ON, Canada.

CAN/ULC-S512-M97, Halogenated Agent Hand and Wheeled Fire Extinguishers, Underwriters' Laboratories of Canada, Scarborough, ON, Canada.

CAN/ULC-S524-M91, Installation of Fire Alarm Systems, Underwriters' Laboratories of Canada, Scarborough, ON, Canada.

CAN/ULC-S537-M89, Verification of Fire Alarm Systems, Underwriters' Laboratories of Canada, Scarborough, ON, Canada.

CAN/ULC-S553-M86, Installation of Smoke Alarms, Underwriters' Laboratories of Canada, Scarborough, ON, Canada.

CIB Workshop W14 (1986), Design Guide Structural Fire Safety, Fire Safety Journal, Vol. 10, No. 2, pp. 75-137.

Custer, L.P. (1993), Selection and Specification of the "Design Fire" for Performance-Based Fire Protection Design, "Performance-Based Fire Safety Engineering", Proceedings, SFPE Engineering Seminars, Phoenix, AZ, USA, November, pp. 17-22.

Davis, W.D. and Cooper, L.Y. (1991), A Computer Model for Estimating the Response of Sprinkler Links to Compartment Fires with Draft Curtains and Fusible Link-Actuated Ceiling Vents, Fire Technology, Vol. 27, pp. 113-127.

DiNenno, P.J., Editor-in-Chief (1995), SFPE Handbook of Fire Protection Engineering, 2nd Edition, Society of Fire Protection Engineers, Boston, MA, USA.

Drysdale, D. (1985), An Introduction to Fire Dynamics, John Wiley and Sons, Chichester, UK.

Evans, D.D. and Stroup, D.W. (1986), Methods to Calculate the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings, Fire Technology, Vol. 22, pp. 54-65.

Evans, D.D., Stroup, D.W. and Martin, P. (1986), Evaluating Thermal Fire Detection Systems, NBS SP 713, National Institute of Standards and Technology, Gaithersburg, MD, USA.

Fire Prevention (1993), Sprinklers - The Real Story, No. 257, pp. 18-28.

Fire Resistance Design Manual (1988), Gypsum Association, Evanston, IL, USA.

Fleischmann, C. (1995), Analytical Methods for Determining Fire Resistance of Concrete Members, Chapter 4-10, SFPE Handbook of Fire Protection Engineering, Society of Fire Protection Engineers, Quincy, MA, USA.

Fleming, R. (1993), International Sprinkler Scene, National Fire Sprinkler Association Inc., Vol. 2, No. 3.

Frantzich, H., Jonsson, R. and Rantatalo, T. (1993), The Swedish Regulatory Approach, International Symposium and Workshop on Engineering Fire Safety in the Process of Design: Demonstrating Equivalency, Proceedings Part 3, CIB W14: Fire Safety Engineering, University of Ulster at Jordanstown, Antrim, Northern Ireland, September 13-16, pp. 71-109.

Friedman, R. (1992), An International Survey of Computer Models for Fire and Smoke, Journal of Fire Protection Engineering, Vol. 4, No. 3.

Gustaferro, A.H. and Martin, L.D. (1977), PCI Design for Fire Resistance of Precast Prestressed Concrete, Prestressed Concrete Institute, Chicago, IL, USA.

Hadjisophocleous, G.V., Benichou, N. and Tamim, A.S. (1996), Development of Performance Requirements for Fire Safety - Literature Review of Performance-Based Fire Codes and Design Environment, National Fire Laboratory, Institute for Research in Construction, National Research Council of Canada, Client Report, Contract No. 4409, Ottawa, ON, Canada.

Hansell, G.O. and Morgan, H.P. (1994), Design Approaches for Smoke Control in Atrium Buildings, Building Research Establishment, BR 258, Garston, UK.

Haviland, D.S. (1978), Toward a Performance Approach to Life Safety from Fire in Building Codes and Regulations, NBS-GCR-78-118, Center for Fire Research, National Bureau of Standards, Gaithersburg, MD, USA.

Heskestad, G. (1995), Fire Plumes, Chapter 2-2, SFPE Handbook of Fire Protection Engineering, Society of Fire Protection Engineers, Quincy, MA, USA.

Heskestad, G. and Delichatsios, M.A. (1978), The Initial Convective Flow in Fire, 17th International Symposium on Combustion, Combustion Institute, Pittsburgh, PA, USA.

Heskestad, G. and Delichatsios, M.A. (1989(B)), Update: The Initial Convective Flow in Fire, Fire Safety Journal, Vol. 15, pp. 471-475.

Heskestad, G. and Smith, H. (1976), FMRC Serial Number 22485, Factory Mutual Research Corp., Norwood, MD, USA.

Hull, W.A. and Ingberg, S.H. (1925), Fire Resistance of Concrete Columns, NBS Technological Papers, No. 272, National Bureau of Standards, Gaithersburg, MD, USA.

Jin, T. (1976), Visibility Through Fire Smoke (Part 5: Allowable Smoke Density for Escape from Fire), No. 42, Report of Fire Research Institute of Japan, Tokyo, Japan.

Johnson, P. and Timms, G. (1995), Performance-based Design of Shopping Centre Fire Safety, Proceedings of the First International ASIAFLAM Conference 1995, InterScience Communications Ltd., Hong Kong, pp. 41-50.

Kawagoe, K. and Saito, H. (1967), Measures to Deal with Smoke Problems Caused by Fire (translated title), Journal of Japan Society for Safety Engineering, Vol. 6, No. 7, pp. 108-114

Kim, A.K. and Taber, B.C. (1989), The Effect of Sprinkler Location and Activation Time on the Protection of Glazing Systems, International Fire Protection Engineering Institute - V, Ottawa, ON, Canada, May 21-31.

Klote, J.H. (1994), Method of Predicting Smoke Movement in Atria With Application to Smoke Management, NISTIR 5516, National Institute of Standards and Technology, Gaithersburg, MD, USA.

Klote, J.H. and Milke, J.A. (1992), Design of Smoke Management Systems, American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Atlanta, GA, USA.

Kodur, V.K.R. and Lie, T.T. (1995), Fire Performance of Concrete-filled Hollow Steel Columns, Journal of Fire Protection Engineering, Vol. 7, No. 3, pp. 89-98.

Law, M.(1983), Structural Engr., Vol. 61A, No. 1, p 25.

Law, M. and O'Brien, T. (1981), Fire Safety of Bare External Structural Steel, Steel Construction Institute, Berkshire, UK.

Law, M. and O'Brien, T. (1983), Fire Safe Structural Steel - A Design Guide, American Iron and Steel Institute, Washington, DC, USA.

Lie, T.T. (1977), Canadian Journal of Civil Engineering, Vol. 4, p 161.

Lie, T.T., ed. (1992), Structural Fire Protection, Manuals and Reports on Engineering Practice, No. 78, ASCE, New York, NY, USA.

Los Angeles Fire Dept. (1961), Operation School Burning, No. 2, National Fire Protection Association, Quincy, MA, USA.

Lougheed, G.D. (1997), Expected Size of Shielded Fires in Sprinklered Buildings, ASHREA Winter Meeting, Philadelphia, PA, USA (to be published).

Madrzykowski, D. and Vittori, R. (1992), A Sprinkler Fire Suppression Algorithm, Journal of Fire Protection Engineering, Vol. 4, p. 151-164.

Malhotra, H.L. (1967), Movement of Smoke on Escape Routes, Instrumentation and Effect of Smoke on Visibility, FR Note Nos. 651, 652, 653, JFRO, Borehamwood, UK.

Malhotra, H.L. (1986), Fire Safety in Buildings, Department of the Environment, Building Research Establishment, Report 987 (K), Borehamwood, UK.

Marryatt, H.W. (1988), Fire: A Century of Automatic Sprinkler Protection in Australia and New Zealand 1886 - 1986, Australian Fire Protection Association Ltd., Hawthorn, Australia.

McCaffrey, B.J., Quintiere, J.G., and Harkleroad, M.F. (1981), Estimating Room Fire Temperatures and the Likelihood of Flashover using Fire Test Data Correlations, Fire Technology, Vol. 17, No. 2, pp. 98-119.

McGuire, J. H. (1965), Fire and the Spatial Separation of Buildings, Fire Technology, Vol. 1, No. 4, Nov., pp. 278-287.

Milke, J.A. (1995), Analytical Methods for Determining Fire Resistance of Steel Members, Chapter 4-9, SFPE Handbook of Fire Protection Engineering, Society of Fire Protection Engineers, Quincy, MA, USA.

Nash, P. and Young, R.A. (1991), Automatic Sprinkler Systems for Fire Protection, 2nd Edition, Paramount Publishing International, Hernal Hampstead, Herts, UK.

National Building Fire Safety Systems Code of Australia (1991), Building Regulation Review Task Force, Sydney, Australia.

National Building Code of Canada (1970), National Research Council of Canada, Ottawa, ON, Canada.

National Building Code of Canada (1995), Canadian Commission on Buildings and Fire Codes, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON, Canada.

National Fire Code of Canada (1995), Canadian Commission on Buildings and Fire Codes, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON, Canada.

Nelson, H.E. (1990), FPETOOL: Fire Protection Engineering Tools for Hazard Estimation, NISTIR 4380, National Institute of Standards and Technology, Gaithersburg, MD, USA.

Nelson, H.E. and MacLennan, H.A. (1995), Emergency Movement, Chapter 3-14, SFPE Handbook of Fire Protection Engineering, 1st Edition, Society of Fire Protection Engineers, Boston, MA, USA.

NFPA 10 (1996), Portable Fire Extinguishers, National Fire Protection Association, Quincy, MA, USA.

NFPA 13 (1996), Standard for the Installation of Sprinkler Systems, National Fire Protection Association, Quincy, MA, USA.

NFPA 14 (1996), Standard for the Installation of Standpipe and Hose Systems, National Fire Protection Association, Quincy, MA, USA.

NFPA 17 (1994), Standard for Dry Chemical Extinguishing Systems, National Fire Protection Association, Quincy, MA, USA.

NFPA 72 (1996), National Fire Alarm Code, National Fire Protection Association, Quincy, MA, USA.

NFPA 80A (1996), Recommended Practice for Protection of Buildings from Exterior Fire Exposures, National Fire Protection Association, Quincy, MA, USA.

NFPA 90A (1996), Standard for the Installation of Air Conditioning and Ventilating Systems, National Fire Protection Association, Quincy, MA, USA.

NFPA 92A (1996), Recommended Practice for Smoke Control Systems, National Fire Protection Association, Quincy, MA, USA.

NFPA 92B (1995), Guide for Smoke Management Systems in Malls, Atria, and Large Spaces, National Fire Protection Association, Quincy, MA, USA.

NFPA 101 (1997), Code for Safety to Life from Fire in Buildings and Structures, National Fire Protection Association, Quincy, MA, USA.

NFPA 204M (1991), Guide for Smoke and Heat Venting, National Fire Protection Association, Quincy, MA, USA.

NFPA 750 (1996), Standard for Water Mist Fire Protection Systems, National Fire Protection Association, Quincy, MA, USA.

NFPA 2001 (1996), Standard on Clean Agent Fire Extinguishing Systems, National Fire Protection Association, Quincy, MA, USA.

Nober, E.H., Pierce, H., Well, A. and Johnson, C.C. (1980), NBS-GCR-83-284, National Bureau of Standards, Gaithersburg, MD, USA.

Nordic Building regulations (1994), Mandatory Provisions and General Advisory Notes, Boverket, Building Division, Karlskrona, Sweden,

New Zealand Standard NZS 3603 (1993), New Zealand Timber Design Code.

O'Hara, M. A. (1993), Prior Knowledge, The Construction Specifier, Vol. 46, No. 9, pp. 94-102.

Peacock, R.D., Forney, G.P., Reneke, P., Portier, R. and Jones, W.W. (1993), CFAST, The Consolidated Model of Fire Growth and Smoke Transport, NIST Technical Note 1299, National Institute of Standards and Technology, Gaithersburg, MD, USA.

Pettersson, O., Magnusson, S.E., and Thor, J.(1976), Fire Engineering Design of Steel Structures, Swedish Institute of Steel Construction, Publication No. 50, Stockholm, Sweden.

Portier, R.W., Peacock, R.D. and Reneke, P.A. (1996), FASTLITE: Engineering Tools for Estimating Fire Growth and Smoke Transport, NIST SP899, National Institute of Standards and Technology, Gaithersburg, MD, USA.

Purser, D.A. (1995), Toxicity Assessment of Combustion Products, Chapter 2-9, SFPE Handbook of Fire Protection Engineering, Society of Fire Protection Engineers, Quincy, MA, USA.

Quaglia, C. (1992), Deterministic Design, International Fire Safety Engineering Conference: The Concepts and the Tools, Conference Papers, Forum for International Cooperation on Fire Research, CSIRO, Sydney, Australia.

Rasbash, D.J. (1967), Smoke and Toxic Products Produced at Fires, Transactions and Journal of Plastic Institute, pp. 55-61.

Read, R.E.H., (ed.) (1991), External Fire Spread: Building Separation and Boundary Distances, BRE Report 187, Building Research Establishment, Borehamwood, UK.

Schifiliti, R.P., Meacham, B.J. and Custer, R.L.P. (1995), Design of Detection Systems, Chapter 4-1, SFPE Handbook of Fire Protection Engineering, Society of Fire Protection Engineers, Quincy, MA, USA.

Scherfig, S. (1993), Development of a Performance Fire Code and a Design System for Fire Safety in Buildings, Nordic Fire Safety Engineering Symposium, "Development and Verification of Tools for Performance Codes", Fire Technology Laboratory, Technical Research Centre of Finland and Forum for International Cooperation on Fire Research, Espoo, Finland, August 30-September 1.

Steciak, J. and Zalosh, R.G. (1992), A Reliability Methodology Applied to Halon 1301 Extinguishing Systems in Computer Rooms, Fire and Hazard Risk Assessment, ASTM STP 1150, ASTM, Philadelphia, PA, USA.

Supplement to the National Building Code of Canada (1990), National Research of Canada of Canada, Ottawa, ON, Canada.

Tamura, G.T. (1994), Smoke Movement and Control in High-Rise Buildings, National Fire Protection Association, Quincy, MA, USA.

Tanaka, T. (1990), A Performance-based Design Method for Fire Safety of Buildings, "11th Joint Panel Meeting of the UJNR Panel on Fire Research and Safety", NISTIR 4449, Jason, N.H., Cramer, D.M., Eds., Center for Fire Research, National Institute of Standards and Technology, October, pp. 269-291.

Tanaka, T. (1993-1994), Concept and Framework of a Performance-based Fire Safety Design System for Buildings, Journal of Applied Fire Science, Vol. 3, No. 4, pp. 335-358.

Thomas, P.H. (1981), Testing Products and Materials for their Contribution to Flashover in Rooms, Fire and Materials, Vol. 5, No. 3, pp. 103-111.

Thomas, I., Bennetts, I., Poon, S.L. and Sims, J. (1992), The Effect of Fire in the Building At 140 William Street, The Broken Hill Proprietary Company Limited, Melbourne, Australia.

UL 1971 (1992), Standard for Safety Signaling Devices for the Hearing Impaired, Underwriters Laboratories, Inc., Northbrook, IL, USA.

Wade, C.A. (1991a), Method for Fire Engineering Design of Structural Concrete Beams and Floor Systems, BRANZ Technical Recommendation No. 8, Building Research Association of New Zealand.

Wade, C.A. (1991b), Fire Engineering Design of Reinforced and Prestressed Concrete Elements, BRANZ Study Report No. 33, Building Research Association of New Zealand.

Wakamatsu, T. (1968), Calculation of Smoke Movement in Buildings, Building Research Institute Research Paper No. 34, Japan.

Wakamatsu, T. (1988), Development of Design System for Building Fire Safety, Fire Safety Science Proceedings of the Second International Symposium, Wakamatsu T. et al Eds., International Association for Fire Safety Science, Tokyo, Japan, June 13-17, pp. 881-895.

White, R.H. (1995), Analytical Methods for Determining Fire Resistance of Timber Members, Chapter 4-11, SFPE Handbook of Fire Protection Engineering, Society of Fire Protection Engineers, Quincy, MA, USA.

Wood and Fire Safety (1991), Canadian Wood Council, Ottawa, ON, Canada.

Appendix A - Fire Safety Objectives

Table A1. Fire Safety Objectives and Requirements (Hadjisophocleous et al, 1996)

Author	Objectives and/or Requirements
Haviland (1978)	The objectives are: • Protection of life of users of the building, the people in the community outside the building and fire fighters • Protection of property including the building itself and the adjoining properties
Boring, Spencer and Wells (1981)	The objectives are: • To provide for the safety of occupants of the buildings and to make provision for their evacuation or refuge during a fire or other emergency • To provide for the safety of fire fighters fighting a fire • To provide for the safety of adjoining property and to prevent the spread of fire • To provide for the preservation of the property itself
Malhotra (1986)	Building fire safety objectives are: • life safety • prevention of conflagration • property protection. These objectives are related to a set of functional requirements including: • Providing adequate means of escape • Preventing rapid growth of fire • Preventing internal fire spread by fire containment • Preventing external fire spread • Providing means to control and extinguish a fire
CIB W14 Workshop (1986)	The general objectives are: • limiting individual life and societal fire risks • limiting fire spread to buildings Functional requirements for attaining the general objectives are: • Reducing the frequency of fire occurrence • Control of fire (smoke and flames) at an early stage • Ensuring a safe evacuation of people • Preventing fire spread (smoke and flames) to other building areas or buildings • Avoiding structural failure or limiting structural damage
Wakamatsu (1988)	The general fire safety objectives are: • Prevention of fire outbreak due to inappropriate use of fire or heating apparatus • Human safety • Prevention of public troubles • Prevention of property losses

Table A1. Fire Safety Objectives and Requirements (Hadjisophocleous et al, 1996) con't.

Author	Objectives and/or Requirements
Custer (1993)	The basic fire protection goals are: • To provide life safety • To protect property • To provide for continuity of operations • To control any adverse environmental effects of fire protection
Tanaka (1990 & 1994)	The objectives are expressed in terms of fundamental requirements as follows: 1. Fundamental Requirements for Individual Buildings • Prevention of fire • Exclusion of hazardous areas • Assurance of safe evacuation - Evacuation planning Plans prepared in advance Plans include all potential occupants Plans consider all important building uses Plans are practicable - Restrictions on the use of certain materials - Assurance of safe refuge Adequate refuge(s) provided Location of refuge Safe refuge is provided Appropriate conditions for staying in the building Alternate refuge depending on fire location - Assurance of safe paths of egress Assurance of at least one exit Exits are clear and continuous Proper capacity and design for egress movement Exits are protected from fire Special protection for unique circumstances • Prevention of damage to third parties - Prevention of spread to other buildings - Prevention of collapse onto other buildings - Prevention of fire spread to other spaces - Re-use of buildings of multiple ownership • Assurance of fire fighting activities - Bases of operation Sufficient bases provided Bases are safe Arrangement of bases to cover rescue/suppression range - Access to bases Speedy access to bases Access to bases is safe from fire - Limitation of fire size 2. Prevention of Urban Fires • Buildings in designated urban fire districts • Buildings in designated quasi-urban districts

Table A1. Fire Safety Objectives and Requirements (Hadjisophocleous et al, 1996) con't.

<table>
<tr><th>Author</th><th>Objectives and/or Requirements</th></tr>
<tr><td>NFPA 101
(1994)</td><td>The two main objectives are:
• To provide minimum requirements, with due regard to function, for the design, operation and maintenance of buildings and structures for safety to life from fire and similar emergencies
• To protect the occupants not intimate with the initial fire development from loss of life and to improve the survivability of those who are intimate with the fire developments</td></tr>
<tr><td>New Zealand Building Code
(1994)</td><td>The objectives are stated as functional requirements as follows:
Clause C1 – OUTBREAK OF FIRE
1. Objective
To safeguard people from injury or illness caused by fire
2. Functional Requirement
In buildings, fixed appliances using the controlled combustion of solid, liquid or gaseous fuel, shall be installed in a way which reduces the likelihood of fire
Clause C2 – MEANS OF ESCAPE
1. Objective
• To safeguard people from injury or illness from a fire while escaping to a safe place
• To facilitate fire rescue operations
2. Functional Requirement
Buildings shall be provided with escape routes which:
• Give people adequate time to reach a safe place without being overcome by the effects of fire
• Give fire service personnel adequate time to undertake rescue operations
Clause C3 – SPREAD OF FIRE
1. Objective
• To safeguard people from injury or illness when evacuating a building during a fire
• To provide protection to fire service personnel during fire fighting operations
• To protect adjacent households and other property from the effects of fire
• To safeguard the environment from the adverse effects of fire
2. Functional Requirement
Buildings shall be provided with safeguards against fire spread so that:
• Occupants have time to escape to a safe place without being overcome by the effects of fire
• Fire fighters may undertake rescue operations and protect property
• Adjacent household units and other property are protected from damage
• Significant quantities of hazardous substances are not released to the environment during fire</td></tr>
</table>

Table A1. Fire Safety Objectives and Requirements (Hadjisophocleous et al, 1996) con't.

Author	Objectives and/or Requirements
	Clause C4 – STRUCTURAL STABILITY 1. Objective • To safeguard people from injury due to loss of structural stability during a fire • To protect household units and other property from damage due to structural instability during a fire 2. Functional Requirement Buildings shall be constructed to maintain structural stability during fire to: • Allow people adequate time to evacuate safely • Allow fire service personnel adequate time to undertake rescue and fire fighting operations • Avoid collapse and consequential damage to adjacent household units or other property
Quaglia (1992)	The Australian Building Code main safety objectives are: • Safety to the occupants – safe egress from the building • Effective intervention of the fire brigade • Prevention of conflagration The above list should be adjusted for some buildings to account for objectives such as: • Prevention of structural damage in a building of strategic importance • Prevention of damage to the fabric of a historic building • Prevention of fire and/or water damage to contents of a museum, art gallery or computer room
Scherfig (1993)	The performance objectives are: • Securing escape routes during egress from the building, i.e., requirements for limiting values of smoke, heat and carbon monoxide • Safety of fire fighting personnel • Limiting rapid fire development, i.e., surface requirements • Provisions for limiting fire and smoke spread to other fire compartments in the building • Safeguarding against spread of fire to adjoining buildings • Fire extinguishing, such as requirements for portable extinguishing equipment and for conditions of access for the fire brigade • Minimizing the risk of outbreak of fire • Securing load-bearing construction
Beck (1994)	The main objectives for the proposed performance-based building code are: • Life safety of occupants of the building of fire origin • Life safety for occupants of adjoining buildings • Life safety for fire brigade personnel

Table A1. Fire Safety Objectives and Requirements (Hadjisophocleous et al, 1996) con't.

Author	Objectives and/or Requirements
BSI Draft Code of Practice (1994)	The general and functional objectives are outlined as follows: 1. Limiting the Probability of Outbreak of Fire. The potential for ignition of combustible materials should be minimized as far as is reasonably practicable. 2. Life Safety Objectives. The occupants of a building, fire fighters and members of the public who are in the vicinity of a building can, potentially, be put at risk by a fire. The main life safety objectives are to ensure that: • Occupants are ultimately able to leave the building without being subject to hazardous or untenable conditions • Fire fighters are safely able to effect rescue and to prevent extensive fire spread • Collapse does not endanger people (including fire fighters) who are likely to be near the building 3. Loss Prevention. The effects of a fire on the continuing viability of a business can be substantial and consideration should be given to the limitation of damage to: • The structure and fabric of the building • The building contents • Ongoing business viability • Public image 4. Environmental Protection. A conflagration involving several buildings or the release of quantities of hazardous materials may have an environmental impact that is out of proportion to the size of the original fire. Consideration should, therefore, be given to the limitation of: • The effects of fire on adjacent buildings or facilities • The release of hazardous materials into the environment
Bukowski et al (1992 & 1994)	Common international basis for performance objectives as follows: 1. Prevent the fire or retard its growth and spread • Control fire properties of combustible items • Provide adequate compartmentation • Provide for suppression of the fire 2. Protect building occupants from fire effects • Provide timely notification of the emergency • Protect escape routes • Provide areas of refuge where necessary 3. Minimize the impact of fire • Provide separation by tenant, occupancy or maximum area • Maintain the structural integrity of the building • Provide for continued operation of shared properties 4. Support fire service operations • Provide for identification of fire location • Provide reliable communication with areas of refuge • Provide fire department access, control, communication and water

Appendix B - Fire Load Densities

Table B1. Fire Load Density in Different Occupancies, BSI Code of Practice (1994)

Densities in MJ/m^2				
Occupancy	Average (MJ/m^2)	Fractile*		
		80%	90%	95%
Dwelling	780	870	920	970
Hospital	230	350	440	520
Hospital Storage	2000	3000	3700	4400
Hotel bedroom	310	400	460	510
Offices	420	570	670	760
Shops	600	900	1100	1300
Manufacturing	300	470	590	720
Manufacturing and Storage ** < 150 kg/m^2	1180	1800	2240	2690
Libraries	1500	2250	2550	-
Schools	285	360	410	450

Notes:

* The 80% fractile is the value that is not exceeded in 80% of the rooms or occupancies
** Storage of combustible materials

The values given in Table B1 include only the variable fire loads (i.e., building contents). If significant quantities of combustible materials are used in the building construction this should be added to the variable fire load to give the total fire load

Table B2. Fire Load Density q_t per unit area of the Surface Bounding the Fire Compartment - Swedish Data, CIB W14 Design Guide (1986)

Type of Fire Compartment	Average (MJ/m^2)	Standard Deviation (MJ/m^2)	Characteristic Value (0.8 fractile) (MJ/m^2)
1. Dwellings *			
a. two rooms and a kitchen	150.0	24.7	168.0
b. three rooms and a kitchen	139.0	20.1	149.0
2. Offices **			
a. technical offices	124.0	31.4	145.0
b. administrative offices	102.0	32.2	132.0
c. all offices investigated	114.0	39.4	138.0
3. Schools **			
a. schools - junior level	84.2	14.2	98.4
b. schools - middle level	96.7	20.5	117.0
c. schools - senior level	61.1	18.4	71.2
d. all schools investigated	80.4	23.4	76.3
4. Hospitals	116.0	36.0	147.0
5. Hotels **	67.0	19.3	81.7

Notes:

* Floor covering excluded

** Only variable fire loads included

Table B3. Average Fire Load Density q_f - Swiss Data, CIB W14 Design Guide (1986)

Type of Occupancies	Fabrication (MJ/m^2)	Storage (MJ/m^2/m)	Type of Occupancies	Fabrication (MJ/m^2)	Storage (MJ/m^2/m)
Academy	300		Boiler house	200	
Accumulator forwarding	800		Bookbinding	1000	
Accumulator mfg	400	800	Bookstore	1000	
Acetylene cylinder storage	700		Box mfg	1000	600
Acid plant	80		Brick plant, burning	40	
Adhesive mfg	1000	3400	Brick plant, clay reparation	40	
Administration	800		Brick plant, drying kiln with wooden grates	1000	
Adsorbent plant for combustible vapours	> 1700		Brick plant, drying room with metal grates	40	
Aircraft hangar	200		Brick plant, drying room with wooden grates	400	
Airplane factory	200		Brick plant, pressing	200	
Aluminum mfg	40		Briquette factories	1600	
Aluminum processing	200		Broom mfg	700	400
Ammunition mfg	Special		Brush mfg	700	800
Animal food preparing, mfg	2000	3300	Butter mfg	700	4000
Antique shop	700		Cabinet making (without wood yard)	600	
Apparatus forwarding	700		Cable mfg	300	600
Apparatus mfg	400		Café	400	
Apparatus repair	600		Camera mfg	300	
Apparatus testing	200		Candle mfg	1300	22400
Arms mfg	300		Candy mfg	400	1500
Arms sale	300		Candy packing	800	
Artificial flower mfg	300	200	Candy shop	400	
Artificial leather mfg	1000	1700	Cane products mfg	400	200
Artificial leather processing	300		Canteen	300	
Artificial silk mfg	300	1100	Car accessory	300	
Artificial silk processing	210		Car assembly plant	300	
Artificial stone mfg	40		Car body repairing	150	
Asylum	400		Car paint shop	500	
Authority office	800		Car repair shop	300	
Awning mfg	300	1000	Car seat cover shop	700	
Bag mfg (jute, paper, plastic)	500		Cardboard box mfg	800	2500
Bakery	200		Cardboard mfg	300	4200
Bakery sale	300		Cardboard products mfg	800	2500
Ball bearing mfg	200		Carpenter shed	700	
Bandage mfg	400		Carpet dyeing	500	
Bank, counters	300		Carpet mfg	600	1700
Bank, offices	800		Carpet store	800	
Barrel mfg, wood	1000	800	Cartwright's shop	500	
Basement, dwellings	900		Cast iron foundry	400	800
Basketware mfg	300	200	Celluloid mfg	800	3400
Bed sheeting production	500	1000	Cement mfg	1000	
Bedding plant	600		Cement plant	40	
Bedding shop	500		Cement products mfg	80	
Beer mfg (brewery)	80		Cheese factory	120	
Beverage mfg, nonalcoholic	80		Cheese mfg (in boxes)	170	
Bicycle assembly	200	400	Cheese store	100	
Biscuit factories	200		Chemical plants (rough average)	300	1000
Biscuit mfg	200		Chemist's shop	1000	
Bitumen preparation	800	3400	Children's home	400	
Blind mfg, venetian	800	300	China mfg	200	
Blueprinting firm	400				
Boarding school	300				
Boat mfg	600				

Table B3. Average Fire Load Density q_f - Swiss Data, CIB W14 Design Guide (1986) con't.

Type of Occupancies	Fabrication (MJ/m^2)	Storage (MJ/m^2/m)
Chipboard finishing	800	
Chipboard pressing	100	
Chocolate factory, intermediate storage	6000	
Chocolate factory, packing	500	
Chocolate factory, tumbling treatment	1000	
Chocolate factory, all other specialties	500	
Church	200	
Cider mfg (without crate storage)	200	
Cigarette plant	300	
Cinema	300	
Clay, preparing	50	
Cloakroom, metal wardrobe	80	
Cloakroom, wooden wardrobe	400	
Cloth mfg	400	
Clothing plant	500	
Clothing store	600	
Coal bunker	2500	
Coal cellar		10500
Cocoa processing	800	
Coffee-extract mfg	300	
Coffee roasting	400	
Cold storage	2000	
Composing room	400	
Concrete products mfg	100	
Condiment mfg	50	
Congress hall	600	
Contractors		500
Cooking-stove mfg	600	
Coopering	600	
Cordage plant	300	600
Cordage store	500	
Cork products mfg	500	800
Cosmetics mfg	300	500
Cotton mills	1200	
Cotton wool mfg	300	
Cover mfg	500	
Cutlery mfg (household)	200	
Cutting-up shop, leather, artificial leather	300	
Cutting-up shop, textiles	500	
Cutting-up shop, wood	700	
Dairy	200	
Data processing	400	
Decoration studio	1200	2000
Dental surgeon's laboratory	300	
Dentist's office	200	
Department house	400	
Distilling plant, combustible materials	200	
Distilling plant, incombustible materials	50	
Doctor's office	200	

Type of Occupancies	Fabrication (MJ/m^2)	Storage (MJ/m^2/m)
Door mfg, wood	800	1800
Dressing, textiles	200	
Dressing, paper	700	
Dressmaking shop	300	
Dry-cell battery	400	600
Dry cleaning	300	
Dyeing plant	500	
Edible fat forwarding	900	
Edible fat mfg	1000	18900
Electrical appliance mfg	400	
Electrical appliance repair	500	
Electrical motor mfg	300	
Electrical repair shop	600	
Electrical supply storage H < 3 m	1200	
Electro Industry	600	
Electronic device mfg	400	
Electronic device repair	500	
Embroidery	300	
Etching plant glass/metal	200	
Exhibition hall, cars including decoration	200	
Exhibition hall, furniture including decoration	500	
Exhibition hall, machines including decoration	80	
Exhibition of painting including decoration	200	
Explosive industry	4000	
Fertilizer mfg	200	200
Filling plant/barrels		
• liquid filled and/or barrels incombustible	< 200	
• liquid filled and/or barrels combustible:		
Risk Class I	> 3400	
Risk Class II	> 3400	
Risk Class III	> 3400	
Risk Class IV	> 3400	
Risk Class V	> 1700	
(if higher, take into consideration combustibility of barrels)		
Filling plant/small casks		
• liquid filled and casks incombustible	< 200	
• liquid filled and casks combustible:		
Risk Class I	< 500	
Risk Class II	< 500	
Risk Class III	< 500	
Risk Class IV	< 500	
Risk Class V	< 500	
(if higher, take into consideration combustibility of casks)		

Table B3. Average Fire Load Density q_f - Swiss Data, CIB W14 Design Guide (1986) con't.

Type of Occupancies	Fabrication (MJ/m^2)	Storage ($MJ/m^2/m$)	Type of Occupancies	Fabrication (MJ/m^2)	Storage ($MJ/m^2/m$)
Finishing plant, paper	500		Hardware mfg	200	
Finishing plant, textiles	300		Hardware store	300	
Fire works mfg	Special	2000	Hat mfg	500	
Flat	300		Hat store	500	
Floor covering mfg	500	6000	Heating equipment room,		
Floor covering store	1000		wood or coal firing	300	
Flooring plaster mfg	600		Heat sealing of plastic	800	
Flour products	800		High-rise office building	800	
Flower sales	80		Homes	500	
Fluorescent tube mfg	300		Homes for aged	400	
Foamed plastics fabrication	3000	2500	Hosiery mfg	300	1000
Foamed plastics processing	600	800	Hospital	300	
Food forwarding	1000		Hotel	300	
Food store	700		Household appliances, mfg	300	200
Forge	80		Household appliances, sales	300	
Forwarding, appliances partly					
made of plastic	700		Ice cream plant (including		
Forwarding, beverage	300		packaging)	100	
Forwarding, cardboard goods	600		Incandescent lamp plant	40	
Forwarding, food	1000		Injection molded parts mfg (metal)	80	
Forwarding, furniture	600		Injection molded parts mfg		
Forwarding, glassware	700		(plastic)	500	
Forwarding, plastic products	1000		Institution building	500	
Forwarding, printed matters	1700		Ironing	500	
Forwarding, textiles	600				
Forwarding, tinware	200		Jewelry mfg	200	
Forwarding, varnish, polish	1300		Jewelry shop	300	
Forwarding, woodware (small)	600		Joinery	700	
Foundry (metal)	40		Joiners (machine room)	500	
Fur, sewing	400		Joiners (work bench)	700	
Fur store	200		Jute, weaving	400	1300
Furniture exhibition	500				
Furniture mfg (wood)	600		Laboratory, bacteriological	200	
Furniture polishing	500		Laboratory, chemical	500	
Furniture store	400		Laboratory, electric, electronic	200	
Furrier	500		Laboratory, metallurgical	200	
			Laboratory, physics	200	
Galvanic station	200		Lacquer forwarding	1000	
Gambling place	150		Lacquer mfg	500	2500
Glass blowing plant	200		Large metal constructions	80	
Glass factory	100		Lathe shop	600	
Glass mfg	100		Laundry	200	
Glass painting	300		Leather goods sales	700	
Glass processing	200		Leather products mfg	500	
Glassware mfg	200		Leather, tanning, dressing, etc.	400	
Glass store	200		Library	2000	2000
Glazier's workshop	700		Lingerie mfg	400	
Gold plating (of metal)	800	3400	Liqueur mfg	400	800
Goldsmith's workshop	200		Liquor mfg	500	800
Grainmill, without storage	400	13000	Liquor store	700	
Gravestone carving	50		Loading ramp including goods		
Graphic workshop	1000		(rough average)	800	
Greengrocer's shop	200		Lumber room for miscellaneous		
			goods	500	
Hairdressing shop	300				
Hardening plant	400				

Table B3. Average Fire Load Density q_f - Swiss Data, CIB W14 Design Guide (1986) con't.

Type of Occupancies	Fabrication (MJ/m^2)	Storage ($MJ/m^2/m$)	Type of Occupancies	Fabrication (MJ/m^2)	Storage ($MJ/m^2/m$)
Machinery mfg	200		Photographic store	300	
Match plant	300	800	Photographic studio	300	
Mattress mfg	500	500	Picture frame mfg	300	
Meat shop	50		Plaster product mfg	80	
Mechanical workshop	200		Plastic floor tile mfg	800	
Metal goods mfg	200		Plastic mfg	2000	5900
Metal grinding	80		Plastic processing	600	
Metal working (general)	200		Plastic products fabrication	600	
Milk, condensed, evaporated,			Plumber's workshop	100	
mfg	200	900	Plywood mfg	800	2900
Milk, powdered, mfg	200	10500	Polish mfg	1700	
Milling work, metal	200		Post office	400	
Mirror mfg	100		Potato, flaked, mfg	200	
Motion-picture studio	300		Pottery plant	200	
Motorcycle assembly	300		Power station	600	
Museum	300		Precious stone, cutting, etc.	80	
Musical instrument sales	281		Precision instrument mfg (containing		
			plastic parts)	200	
News-stand	1300		(without plastic parts)	100	
Nitrocellulose mfg	Special	1100	Precision mechanics plant	200	
Nuclear research	2100		Pressing, metal	100	
Nursery school	300		Pressing, plastics, leather, etc.	400	
			Preparation briquette production		
Office, business	800		Printing, composing room	300	
Office, engineering	600		Printing ink mfg	700	3000
Office furniture	700		Printing, machine hall	400	
Office, machinery mfg	300		Printing office	1000	
Office machine sales	300				
Oilcloth mfg	700	1300	Radio and TV mfg	400	
Oilcloth processing	700	2100	Radio and TV sales	500	
Optical instrument mfg	200	200	Radio studio	300	
			Railway car mfg	200	
Packing, food	800		Railway station	800	
Packing, incombustible goods	400		Railway workshop	800	
Packing material industry	1600	3000	Record player mfg	300	
Packing, printed matters	1700		Record repository, documents		
Packing, textiles	600		see also storage	4200	
Packing, all other combustible			Refrigerator mfg	1000	300
goods	600		Relay mfg	400	
Paint and varnish mfg	4200		Repair shop, general	400	
Paint and varnish, mixing plant	2000		Restaurant	300	
Paint and varnish shop	1000		Retouching department	300	
Painter's workshop	500		Rubber goods mfg	600	5000
Paint shop (cars, machines, etc.)	200		Rubber goods store	800	
Paint shop (furniture, etc.)	400		Rubber processing	600	5000
Paper mfg	200	10000			
Paper processing	800	1100	Saddlery mfg	300	
Parking building	200		Safe mfg	80	
Parquetry mfg	2000	1200	Salad oil forwarding	900	
Perambulator mfg	300	800	Salad oil mfg	1000	18900
Perambulator shop	300		Sawmill (without wood yard)	400	
Perfume sale	400		Scale mfg	400	
Pharmaceutical, packing	300	800	School	300	
Pharmaceutical mfg	300	800	Scrap recovery	800	
Pharmacy (including storage)	800		Seedstore	600	
Photographic laboratory	100		Sewing machine mfg	300	

Table B3. Average Fire Load Density q_f - Swiss Data, CIB W14 Design Guide (1986) con't.

Type of Occupancies	Fabrication (MJ/m^2)	Storage ($MJ/m^2/m$)	Type of Occupancies	Fabrication (MJ/m^2)	Storage ($MJ/m^2/m$)
Sewing machine store	300		Turning section	200	
Sheet mfg	100		TV studio	300	
Shoe factory, forwarding	600		Twisting shop	250	
Shoe factory, mfg	500				
Shoe polish, mfg	800	2100	Umbrella mfg	300	400
Shoe repair with manufacture	700		Umbrella store	300	
Shoe store	500		Underground garage, private	> 200	
Shutter mfg	1000		Underground garage, public	< 200	
Silk spinning (natural silk)	300		Upholstering plant	500	
Silk weaving (natural silk)	300				
Silverware	400		Vacation home	500	
Ski mfg	400	1700	Varnishing, appliances	80	
Slaughter house	40		Varnishing, paper	80	
Soap mfg	200	4200	Vegetable, dehydrating	1000	400
Soda mfg	40		Vehicle mfg, assembly	400	
Soldering	300		Veneering	500	2900
Solvent distillation	200		Veneer mfg	800	4200
Spinning mill excluding			Vinegar	80	100
garnetting	300		Vulcanizing plant (without storage)	1000	
Sporting goods store	800				
Spray painting, metal goods	300		Waffle mfg	300	1700
Spray painting, wood products	500		Warping department	250	
Stationery store	700		Washing agent mfg	300	200
Steel furniture mfg	300		Washing machine mfg	300	40
Stereotype plate mfg	200		Watch assembling	300	40
Store masonry	40		Watch mechanism mfg	40	
Storeroom (workshop, storeroom,			Watch repair shop	300	
etc.)	1200		Watch sale	300	
Synthetic fibre mfg	400		Water closets	~ 0	
Synthetic fibre processing	400		Wax products forwarding	2100	
Synthetic resin mfg	3400	4200	Wax products mfg	1300	2100
			Weaving mill (without carpets)	300	
Tar coated mfg	1700		Welding shop (metal)	80	
Tar preparation	800		Winding room	400	
Telephone apparatus mfg	400	200	Winding, textile fibres	600	
Telephone exchange	80		Window glass mfg	700	
Telephone exchange mfg	100		Window mfg (wood)	800	
Test room, electric appliances	200		Wine cellar	20	
Test room, machinery	100		Wine merchant's shop	200	
Test room, textiles	300		Wire drawing	80	
Theatre	300		Wire factory	800	
Tin can mfg	100		Wood carving	700	
Tinned goods mfg	40		Wood drying plant	800	
Tinware mfg	120		Wood grinding	200	
Tire mfg	700	1800	Wood pattern-making shop	600	
Tobacco products mfg	200	2100	Wood preserving plant	3000	
Tobacco shop	500				
Tool mfg	200		Youth hostel	300	
Toy mfg (combustible)	100				
Toy mfg (incombustible)	200				
Toy store	500				
Tractor mfg	300				
Transformer mfg	300				
Transformer winding	600				
Travel agency	400				
Turnery (wood working)	500				

Appendix C - Fire Hazards and Ignition Sources

Table C1. Potential fire hazards

Potential Fire Hazard	Examples and/or Comments
Wood Products	• Although most buildings contain large amounts of concrete and steel, many buildings contain finish materials that are wood products. Furniture, bookcases, cabinets, shelves, and similar fixtures may also contain significant amounts of wood. Paper is the most common wood product.
Textiles & Fibres	• Clothing: Many types of clothing are easily ignited. Fire hazards are increased if clothing has absorbed flammable vapours or has had flammable liquids spilled on them. • Curtains, draperies, wall coverings and decorative materials. • Upholstered furniture and mattresses. • Carpeting.
Flammable & Combustible Liquids	• Many flammable and combustible liquids will float on water. This is important to remember since fighting a flammable or combustible liquid fire with water may spread the fire. Ignition sources should be eliminated in the proximity and in the areas where flammable and combustible liquids are to be used. • All facilities that may involve the use of flammable or combustible liquids are allowed to store only a specified amount of a given material. The purpose of these limitations is to reduce the development of excess quantities that if involved in a fire could contribute to the loss of life and property.
Flammable Aerosol Sprays	• Aerosol sprays (WD-40, spray paint, etc.) contain flammable propellants. These sprays should be used only in well ventilated areas and stored where they will not be exposed to high temperatures. Before using, the area should be checked to assure that there are no ignition sources present.
Flammable & Combustible Gases	• Besides flammability, additional fire hazards are present for compressed and liquefied gases. In the heat of a fire, the container pressure may increase and rupture a container.
Water Reactive Materials	• Water reactive materials are materials which explode, violently react, produce flammable gases, or evolve enough heat to cause self-ignition or ignition of nearby flammable or combustible materials upon exposure to water or moisture.
Oxidizers	• Although oxidizers do not usually burn themselves, they promote burning of other flammable and combustible materials. Oxidizers may promote burning sufficient as to cause explosions or fires without the introduction of ignition sources.

Table C2. Ignition sources and control measures

Ignition Source	Control Measures
Smoking: Smoking is a potential cause of fire almost everywhere.	• Smoking is strictly prohibited except in designated areas.
Hot Surfaces: Examples of hot surfaces include heat from boilers, furnaces, hot ducts and pipes, electric lamps, hot plates, and space heaters, all of which have the potential to ignite flammable and combustible material.	• Design and maintain ample clearances. • Allow air circulation between hot surfaces and combustibles.
Burner Flames: Burner flames could provide an ignition source for flammable and combustible materials. Examples include portable torches, water heaters, dryers, ovens, furnaces, portable heating units, etc.	• Use tools and equipment with burner flames only for tasks which the tools or equipment is designed and operate in accordance with manufacturer's instructions. • Ensure regular maintenance and adequate ventilation. • Keep open flames away from flammable and combustible materials.
Static Sparks: Static sparks may ignite flammable vapours, dusts and fibres by a discharge of accumulated static electricity on equipment, materials, or on the human body.	• Ensure proper grounding and bonding.
Overheated Materials: Abnormal process temperatures, especially resulting from heating flammable liquids or combustible materials in ovens, autoclaves, heated baths and reaction vessels, have the potential to cause fires.	• Temperature controls should be checked regularly and well maintained. • Special safeguards should be developed for unattended heating operations.
Spontaneous Ignition: Oily waste and rubbish, deposits in dryers, ducts and flues, and some wastes may ignite spontaneously.	• Ensure good housekeeping and proper process operation. • Remove waste daily, frequently clean ducts, flues and isolated storage subject to spontaneous heating.
Welding: Potential fire hazards arise when sparks, arcs and hot metal from metal grinding, cutting and welding operations occur.	• Ensure that the area is clear of combustibles before beginning work.
Chemical Reaction: Fires may be caused when chemical processes get out of control, chemicals react with other materials, or unstable chemicals decompose.	• Carefully supervise and ensure personnel understand safe procedures. • Ensure that instrumentation and controls for the chemicals involved are used. • Properly store and ensure adequate separation of incompatible materials. • Never change the proportions or scale of an experiment without proper authorization.

Appendix D - Fire Protection Systems and Equipment

1. Fire Alarms and Detection
   Most buildings are provided with a fire alarm system designed to alert the building occupants of emergency conditions. The fire alarm system includes manual fire alarm pull stations and automatic detection systems (e.g., heat detectors or smoke detectors) which are intended to protect special hazards or equipment. Upon hearing the alarm system, all building occupants should evacuate the building from the nearest exit.

2. Automatic Sprinkler Systems
   Recently constructed buildings and portions of older buildings are provided with automatic fire sprinkler systems, in addition to alarm systems. A fire sprinkler system is designed to automatically apply water to a fire within a building. The sprinklers respond to heat in immediate proximity of the ceiling above a fire. Only the sprinklers over the fire will open and spray water to extinguish or reduce the spread of the fire.

3. Fire Hose Stations
   Many of the buildings are provided with fire hose stations for occupant use. They are connected to the buildings water supply. It is important to not block these cabinets with equipment, storage or other obstructions.

4. Fire Extinguishers
   The most common fire protection devices are portable fire extinguishers. Only those individuals who have had training should attempt to use a portable extinguisher to put out a fire. One should be aware of the location of the nearest two fire extinguishers within their work space. Extinguishers should be visually checked monthly to assure that it has not been tampered with and is readily available for use. The extinguishers are the "type class" to handle the type of hazard that occupants would normally be subjected to by the structure and its contents.

   - CLASS A - For those fires involving paper, wood, cloth, etc. The extinguishing agent is normally water.
   - CLASS B - For those fires involving flammable liquids. The extinguishing agent is normally carbon dioxide.
   - CLASS C - For those fires involving A and B materials in the presence of electrical equipment, motors, switches, and wires. The extinguishing agent is normally dry chemical.
   - CLASS D - For those fires involving combustible metals such as magnesium.

All fire safety systems should be installed, maintained, and inspected by competent personnel in accordance with standards in-place.

Appendix E - Safety Checklist

Building: ____________________ Date: ______________
Inspector: ____________________ Room(s): ______________

Yes No N/A

Exiting

☐ ☐ ☐ a. Exits and exit ways clearly marked.
☐ ☐ ☐ b. Exit ways are clear of slip, trip, and fall hazards.
☐ ☐ ☐ c. Doorways are unobstructed and door is usable as an exit.

Fire safety

☐ ☐ ☐ a. Are fire extinguishers adequate for your area and readily available?
☐ ☐ ☐ b. Fire extinguishers are unobstructed and have been serviced within the last year.
☐ ☐ ☐ c. Trash and combustible materials are removed on a regular basis.
☐ ☐ ☐ d. Are flammable materials properly used and stored?
☐ ☐ ☐ e. Do employees know what to do in case of fire or explosion?
☐ ☐ ☐ f. Are fire doors kept closed?
☐ ☐ ☐ g. Is electrical equipment in good repair and grounded?

Housekeeping

☐ ☐ ☐ a. Equipment not placed so as to create a fire hazard.
☐ ☐ ☐ b. Are corridors and aisles well lit, clean, and unobstructed?
☐ ☐ ☐ c. Are storage areas properly designated and maintained?
☐ ☐ ☐ d. Are floors in your area in good condition and free of hazards?
☐ ☐ ☐ e. Are walls and ceilings in good repair and all fixtures properly secured?
☐ ☐ ☐ f. Are windows clean and not broken?
☐ ☐ ☐ g. Are stairways in good condition?

Hazardous materials

☐ ☐ ☐ a. All containers of hazardous substances are properly labelled.
☐ ☐ ☐ b. Compressed gas cylinders are upright and properly secured.
☐ ☐ ☐ c. Flammable and oxidizers are stored separately.
☐ ☐ ☐ d. Strong acids and strong bases are separated.
☐ ☐ ☐ e. Containers (waste or others) are in good condition.
☐ ☐ ☐ f. Spill kit available for clean up.
☐ ☐ ☐ g. Containers for collecting hazardous wastes are properly labelled and kept closed.

Other hazards noted during inspection:

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