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Maintaining Tenability of Exitways in Buildings in the Event of Fire – Literature Review

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Preface

This report was prepared as a result of a review of available literature on methods used to control smoke hazards and tenability in protected and safe paths of buildings during a fire event.

Acknowledgments

This work was funded by the Building Research Levy.

Note

This report is intended primarily for fire engineers, architects, code writers, regulators and researchers.

MAINTAINING TENABILITY OF EXITWAYS IN BUILDINGS IN THE EVENT OF FIRE – LITERATUE REVIEW

BRANZ Study Report SR 148 **A.P.R. Edwards and C.A. Wade**

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ABSTRACT

This report is a summary of a review of the current published literature on systems used to maintain the tenability of exitways in buildings in the event of a fire. There is commonly an over-reliance on the effectiveness of fire or smoke doors in keeping smoke out of exitways, and there are no quantitative smoke leakage criteria specified in the New Zealand Building Code Fire Safety Clauses (NZBC 2004) or the associated Compliance Documents (C/AS1 for NZBC 2005). An improved capability to predict the actual smoke leakage performance of construction elements would provide a more realistic assessment of the true hazards and provide a better basis for quantitative smoke leakage criteria or ventilation requirements to be included in the NZBC. Furthermore, the compartment of fire origin is the source of smoke for the entire building. Therefore a better understanding of the leakage of doorsets under similar conditions would be useful in the analysis of the conditions of the adjoining corridors etc.

Current door leakage criteria and exitway ventilation and pressurisation requirements for protection from smoke in building code requirements and standards for New Zealand, Australia, and various other countries and the associated published discussion papers are presented. A selection of statistics and summaries of case study fires that have involved smoke logging of exitways or general smoke inhalation fatalities and injuries is presented. Experimental and theoretical investigations of doorset leakage and pressurisation in exitways to maintain tenability conditions for safe egress, and general smoke movement through buildings, are summarised. Recommendations for potential future work are also included.

KEYWORDS

Smoke, smoke control doors, leakage, ventilation, pressurisation, tenable conditions, exitway, safe path, escape route, standards, regulations.

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Abbreviations

CO	carbon monoxide
Eq.	equation number
FRL	Fire-resistance Level (Australia)
FRR	Fire-resistance Rating (New Zealand)
HCN	hydrogen cyanide
ifsa	Intumescent Fire Seals Association
Temp.	Temperature

Nomenclature

ΔP	pressure difference across path (Pa)
A	flow area (m^2)
a	gap thickness perpendicular to the flow direction (m)
c	concentration in parts per million (ppm)
C	a dimensionless flow coefficient
C_e	a flow coefficient for the exponential flow equation ($m^3.s^{-1}.Pa^{-n}$)
D_h	effective hydraulic diameter of the flow path, $D_h = 2a$ (m)
F	dimensionless flow factor to account for bends in the leakage path (Klote and Milke 1992)
f	a general functional relation
g	gravitational acceleration (m/s^2)
h_r	relative humidity (%)
K	a flow coefficient (to account for frictional and dynamic losses)
L	length of the gap (m)
n	dimensionless flow exponent (0.5 to 1). For interior paths n is taken at 0.5 and for exterior walls n is taken at ~ 0.6 or 0.65
N	dimensionless number
P	pressure (Pa)

Q	volumetric flow rate through the doorset (m^3/h per metre of leakage path, per square metre of clear opening, or per leaf, which is measured at a specified cross-door pressure (Pa))
Q^*	dimensionless heat release rate, normalised with respect to density × specific heat × temperature × square root of gravitational acceleration × room height^(5/2) for ambient conditions (Karlsson and Quintiere 2000)
Re	Reynolds number
t	time (s)
T	temperature (K)
τ	dimensionless time, normalised with respect to the square of the ratio of room height to gravitational acceleration and the ratio of floor area to the square of room height (Karlsson and Quintiere 2000)
V	average velocity in the flow path (m/s)
x	distance of the gap in the flow direction (m)
y	dimensionless height of the lower layer in the fire room, normalised with respect to the room height (Karlsson and Quintiere 2000)
Z	elevation (m)
α	dimensionless exponent for calculating the non-dimensional flow in the region of transition between viscous and kinetic dominated leakage flow (Klote and Milke 1992)
μ	absolute viscosity (N.s/ m^2)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts

air	refers to the characteristics of air
i	refers to path inlet conditions
inc	refers to incapacitation
HCN	refers to hydrogen cyanide
o	refers to path outlet conditions
P	refers to pressure
Q	refers to volumetric flow

All units are consistent with the International System (SI), unless otherwise stated.

1. INTRODUCTION

1.1 Motivation

Parts of escape routes in buildings such as stair shafts and corridor enclosures are commonly constructed as ‘safe paths’, and are intended to protect occupants from the hazards of fire and smoke originating elsewhere in the building. These ‘safe paths’ commonly rely on construction elements and particularly doors to protect against the entry of smoke. Furthermore the major proportion of fatalities in structure fires are attributable to inhalation of smoke and toxic gases (NFPA 105 2003; Cunningham 1999; Holburn 2001).

1.2 Objective

The objective of this literature review is to summarise the current, available, building regulations and standards associated with maintaining the tenability of exitways during a fire event in conjunction with related research. Particular emphasis is laid on the leakage of doorsets, with a view to assessing the appropriateness of the current New Zealand Building Code requirements.

1.3 Summary of the topics included

Summaries of current standards associated with doorset leakage and ventilation and pressurisation of exitways are presented. A summary of the components of the current building code requirements for maintaining a safe escape route is also presented for a selection of countries, where information was available. A summary of the available published literature associated with the requirements, standards, usage and characteristics of smoke doors, as well as other information relating to experiments and models of smoke movement associated with leakage through doors, is presented. In addition, the criteria for tenable conditions are summarised. Requirements and standards for a variety of regions, other than New Zealand and Australia, are included for comparison. Furthermore, conclusions of the current state of the understanding, needs and development of smoke doors and recommendations for potential courses of future work are discussed.

2. NEW ZEALAND AND AUSTRALIAN SMOKE PROTECTION REQUIREMENTS FOR ESCAPE ROUTES

The safe path requirements for protection from smoke, as specified in the New Zealand Building Code (NZBC) Fire Safety Clause C2 (NZBC 2004), is to “safeguard people from injury or illness from a fire while escaping”. The means of escape must provide adequate time for people to reach a safe place and for fire service personnel to perform rescues. Escape routes are required to be “resistant to the spread of fire” and “easy and safe to use”. The resistance to fire spread is further described in NZBC Clause C3, as provided by the NZBC (2004). Fire is defined as “the state of combustion during which flammable materials burn producing heat, toxic gases, or smoke or flame or any combination of these”. Therefore any discussion of fire explicitly includes smoke and toxic gases. That is, protection from smoke is explicit in the statement requiring safeguards to protect people (NZBC Clauses C2 and C3) “from injury or illness from a fire”. Furthermore, fire separations are explicitly required to avoid smoke spread (Clause C3.3.2).

The definition of a protected path is the “portion of an exitway within a firecell which is protected from the effects of smoke by smoke separations” (C/AS1 2001). The definition of a safe path is the “part of an exitway which is protected from the effects of fire by fire separations, external walls, or by distance when exposed to open air” (C/AS1 for NZBC 2005).

A smoke separation is defined as “any building element able to prevent the passage of smoke between two spaces” (C/AS1 for NZBC 2005). Furthermore, smoke separations are required to:

- “Consist of rigid building elements capable of resisting without collapse:
    - a horizontal pressure of 0.25 kPa applied from either side, and
    - self weight plus the intended vertically applied live loads, and
    - Form an imperforate barrier to the spread of smoke, and
- Be of non-combustible construction or a flame barrier, or achieve a FRR of 10/10/-, except that non-fire-resisting glazing may be used if it is toughened or laminated safety glass.” (C/AS1 for NZBC 2005)

A fire separation is defined as “any building element which separates firecells or firecells and safe paths, and provides a specific fire-resistance rating” (C/AS1 for NZBC 2005). However fire-resistance ratings (tested according to AS 1530.4 1997 as required in C/AS1) do not include a quantitative measure of smoke resistance, but a safe path is to be protected from “the effects of fire”.

Similarly, the Building Code of Australia (BCA 2005), in general, requires evacuation routes to remain tenable for sufficient time for the occupants to escape to “safeguard occupants from illness or injury while evacuating during a fire” (EO2b, EF2.1b and EP2.2a of BCA 2005). The tenability requirements are qualitative, in that the specifications are that “… in the event of a fire in a building the conditions in any evacuation route must be maintained for the period of time occupants take to evacuate the part of the building so that –

- the temperature will not endanger human life, and
- the level of visibility will enable the evacuation route to be determined, and
- the level of toxicity will not endanger human life” (EP2.2a of BCA 2005).

A fire-isolated passageway is defined as “… a corridor, hallway or the like, of fire-resisting construction, which provides egress to or from a fire-isolated stairway or fire-isolated ramp or to a road or open space” (A1.1 of BCA 2005). A fire-isolated ramp is defined as “… a ramp within a fire-resisting enclosure which provides egress from a storey” (A1.1 of BCA 2005). Similarly, a fire-isolated stairway is defined as “… a stairway within a fire-resisting shaft and includes the floor and roof or top enclosing structure” (A1.1 of BCA 2005). Fire-isolated exits are to act as primary evacuation routes in the case of an emergency. It is noted that, in general, fire-isolated exists are required in buildings with three or more floors. Although exceptions include such situations where fire-isolated exists are required for four or more floors in residential buildings (class 2) and for all stairs and exits in residential aged care (class 9c) or patient care areas in hospitals.

General smoke management provisions for exitways, required by the Building Code of Australia, may include pressurised fire-isolated (horizontal or vertical) pathways, smoke lobbies, smoke-proof walls and/or zone smoke control systems, depending on the building and occupation.

Fire separations may require integrity, in terms of fire-resistance rating (FRR) or fire-resistance level (FRL) in Australia, which is a measure of the ability to resist the passage of flames and hot gases, as specified in AS 1530.4 2005 (C/AS1 for NZBC 2005; BCA 2005). However, this criteria is to prevent ignition by hot gases on the other side of the separation/assembly being tested. It is not a measure of leakage or smoke protection.

In all cases, the level of smoke protection required is described qualitatively. No limit or level of fire effects allowable, to ensure tenability, is quantitatively described.

The requirements of the NZBC, BCA and associated documents for the specific case of smoke doors is discussed in more detail in Section 3 and ventilation and pressurisation requirements are discussed in Section 4.

3. DOOR LEAKAGE STANDARDS

During a fire event door leakage rates at various conditions may affect the tenability of exitways. The current standard test methods and general requirements associated with smoke doors for New Zealand, Australia, the US, the UK and Germany, as well as ISO standards, are reviewed. A summary of other standards associated with general air leakage test methods and suggested acceptance criteria is also included. A summary of the requirements for smoke doors according to each respective country's building codes is presented. This is followed by a review of published literature on the discussion of smoke door standards.

3.1 AS/NZS 1530.7

AS/NZS 1530.7 1998 "Methods for Fire Tests on Building Materials, Components and Structures – Smoke Control Door and Shutter Assemblies – Ambient and Medium Temperature Smoke Leakage Test Procedure" describes laboratory tests for ambient (298 ±15 K) and medium (stabilised at 473 ± 20 K in 30 ± 5 minutes then maintained for 2 minutes while measuring the leakage rate) temperature smoke exposure at pressure differentials of 10, 25 and 50 Pa (or as specified by the sponsor). An example of the apparatus, based on the principles described in AS/NZS 1530.7, is shown in Figure 1. No stratification of smoke is assumed and smoke leakage rates are assumed to be the same as air leakage rates. Pre-test analysis records are to include specifications of the doorset material and dimensions, and measurements of all gaps through which air can leak, techniques used and measurements of forces required to open the door leaf(s) and closing moments. The leakage rate of the test apparatus must be less than 7 m^3/h at 50 Pa.

Pressure differentials are to remain constant for 2 minutes during leakage rate measurements. Deformations perpendicular to the door, during testing, are also to be measured. The pressure and temperature at which the seal significantly breaks down is to be recorded. Asymmetrical doorsets are to be tested from both sides, with and without the door sill blocked. For reporting, all leakage rates are adjusted to standard pressure and temperature conditions (assuming the adjusted leakage rate is directly proportional to test pressure and inversely proportional to test temperature) (AS/NZS 1530.7 1998).

No acceptable maximum leakage rate for smoke doors is specified. Although, in Appendix A, it is noted that rates between 20 and 25 m^3/h are used for life safety considerations, in other countries (AS/NZS 1530.7 1998). In addition, AS/NZS 1530.7 is not called up in the Building Code of Australia Specification C3.4.3 (BCA C3.4 2004; BCA C3.4 Guide 2004) or in the New Zealand Building Code Fire Safety Clauses (NZBC 2004) or the associated Compliance Documents (C/AS1 for NZBC 2005).

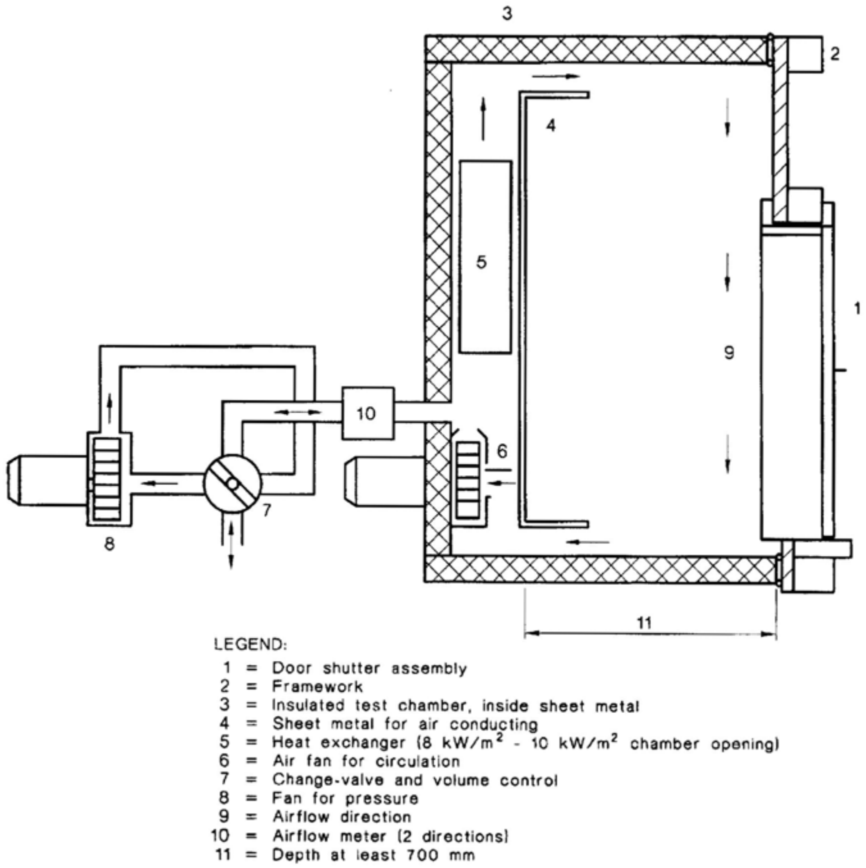


Figure 1: Schematic of the principal approach for an apparatus in accordance with AS/NZS 1530.7. Extracted from (AS/NZS 1530.7 1998).

3.2 AS 1905.3

An as yet unpublished Australian standard (AS 1905.3) for laboratory testing of smoke control doorsets for ambient (298 ± 15 K), medium (473 ± 20 K), and hot (> 473 K) smoke temperatures is currently under development (Soja 2005). A Smoke Resistance Rating, S = X/Y/Z, where X is the smoke temperature rating (A for ambient and M for medium), Y is the pressure differential (in Pa), and Z is the allowable leakage rate (in m^3/h per square metre of door opening), is also proposed. Permitted air leakage rates from the NFPA are suggested for the basis for life safety specifications. Classification and certification of smoke seals for resilience, durability and cycling are recommended. Pressure differences up to 75 Pa across doorsets are considered, similar to (ASTM E283 1999), to account for the possible effect of air handling systems, stack effects and outside wind conditions that could increase the pressure difference, in addition to pressure differences of 10 – 20 Pa that are typically developed in the upper parts of a room that is involved in a fire.

3.3 ISO 5925 Parts 1 & 2

ISO 5925/1 1981 "Fire tests – Evaluation of Performance of Smoke Control Door Assemblies – Part 1: Ambient Temperature Test" describes a method used to measure the ability to prevent smoke spread through a doorset at ambient temperature over a range of pressure differences across the specimen. A maximum leakage rate of 16 m^3/h per metre of leakage path is anticipated for any specimen tested. The maximum allowable leakage rate of the test apparatus is 1 m^3/h at 100 Pa, and is to be tested before and after each series of tests. Pre-test measurements of the clearances between the door edge and frame are to be recorded. Normal operation of the door is also to be ensured.

Test conditions of ambient temperature (298 ± 15 K), relative humidity of 40 – 60%, and a pressure difference across the doorset of 5 to 100 Pa ± 10% (with a maximum of ± 5 Pa and measurement accuracy of ± 1%, e.g. measurements at 5, 10, 20, 30, 50 ,70, 100, then 5 and finally 100 Pa) (ISO/DIS 5925/1 1981). The air leakage measurement should have an accuracy of better than ± 5%. Measurements are to be taken after 3 minutes of constant pressure difference across the door. Pressure measurements are to be taken inside the chamber at a distance of 100 ± 10 mm from the plane of a single leaf door, at the top and bottom of the vertical axis of the door, or for a double leaf door, at the centre top of one leaf and the centre bottom of the other. For reporting, air leakage rates are adjusted to standard reference conditions, using ratios of temperature, pressure and relative humidity, similar to (AS/NZS 1530.7 1998). Both sides of the doorsets are to be tested. A maximum air leakage rate is not specified. Future test methods are proposed for additional parts, including a medium temperature test method, which is currently under development, and a high temperature test method, which is an intended future project (ISO/DIS 5925/1 1981; Soja 2005).

Current developments of the incorporation of a medium temperature test method into ISO 5925/1 1981 (Soja 2005) suggest a test temperature of 473 ± 20 K. The maximum pressure difference may be reduced to 55 Pa, with tests at 10, 25 and 50 Pa. An increase of maximum allowable apparatus leakage rate of 7 m^3/h at ambient or medium temperatures is also suggested. The test equipment will be required to compensate for leakage rates through a specimen of up to 55 m^3/h. Again, a criteria for assessing the acceptability of an air leakage rate is not specified, as it is noted that the acceptable rate will be dependent on the controlling authority. However it is noted that a maximum leakage rate of 20 – 25 m^3/h has been used for life safety considerations in other countries, the same as stated in AS/NZS 1530.7 (1998).

In the commentary document, ISO 5925/2 (1997), it is noted that ISO 5925/1 (1981) may not be appropriate for use in situations where smoke control is by ventilation or pressurisation. ISO 5925/2 1997 states that, "… in a single storey enclosure, initially … elevated temperatures will only be imposed on seals in the upper part of the enclosure and may be applied to linear gap seals, glazing seals, or service penetration seals for which no smoke leakage tests currently exist, neither at ambient, nor elevated temperatures …" (ISO/TR 5925/2 1997). Furthermore, no times or other measurements are listed or suggested for levels of deterioration or degradation of components, e.g. door seals, etc. The test conditions of ISO 5925/1 (1981) are not intended to represent the range of conditions likely to occur in the situation of an actual fire. In addition, effective smoke management is not quantitatively defined. Instead, the laboratory tests are intended to provide an indication of the performance of a doorset. The possible benefits of a single test for measuring fire and smoke resistance properties of a doorset are briefly mentioned. The use of a tracer gas to measure the air leakage rate is suggested. In addition, adjustment of pressure conditions of ISO/DIS 834/1 is suggested to produce a positive pressure over the whole height of the door to prevent airflow from the unexposed side (ISO/TR 5925/2 1997).

Some factors suggested (ISO/TR 5925/2 1997) for consideration when applying the results of the smoke control assemblies test (ISO/DIS 5925/1 1981) include:

- actual pressure conditions expected, depending on doorset location within a building
- any smoke transferring through door gaps is likely to lose much heat energy and will reduce in temperature and buoyancy – it is noted that experimental work has demonstrated that smoke leaving via a small gap will soon become fully mixed with the air
- size of the protected space

- ventilation conditions in the protected space
- illumination in the protected space (e.g. a smoke concentration of 1% is proposed as an acceptable optical density)
- composition and nature of smoke, and
- time required for evacuation.

3.4 NFPA 105

NFPA 105 2003 "Standard for the Installation of Smoke-Control Door Assemblies" is used for controlling smoke leakage at door perimeters. Door performance in smoke temperatures up to 477 K is considered. Ambient temperature is 297 K. Tests at pressure differences of 25, 50 or 75 ± 1.25 Pa are required. It is expected that cross-door pressure differences of at least 10 Pa are developed in the upper parts of rooms involved in fire. Furthermore it is noted that in sprinklered buildings, it is anticipated that the pressure difference across a doorset would not exceed 12.5 Pa. In stair pressurisation systems it is noted that cross-doorset pressure differences may be as high as 62.5 to 125 Pa, and up to 250 Pa or more between the exterior and unvented shafts. Thus it is important to test a doorset to conditions representative of the intended use and location within a building.

Other requirements of NFPA 105 2003 include the testing of doorsets as they are intended to be installed, similar to other standards considered (ISO/DIS 5925/1 1981; AS/NZS 1530.7 1998). Air leakage of doorsets is required to be tested according to UL 1784, "Air Leakage Tests of Door Assemblies". A maximum air leakage rating of 54 m^3/h per square metre of door opening is stated. An "S" label is required on a smoke doorset to indicate a maximum air leakage rate of 180 m^3/h per square metre of door opening at a particular test pressure difference, which is also to be included on the label. In addition, it is noted that complete sealing of doors can cause difficulty when opening and it may be necessary for a seal to be broken in order to open the door.

A selection of allowable air leakage rates was presented for a range of door locations, as shown in Table 1 (NFPA 105 1999). This table was present in NFPA 105 1999 and removed from the 2003 version. It is not clear what information was used for the determination of the values for the maximum leakage rates (shown in Table 1).

Maximum pressure differences across doors (combined with the closer force) is suggested to be small enough so that the force required to begin opening the door is a maximum of 133 N (NFPA 92A 2000).

3.5 UL 1784

A copy of the Underwriter's Laboratories standard, UL 1784 2004 "Air Leakage Test for Door Assemblies", was not sighted in this study. However, from other literature (Rose 1997), UL 1784 requires that doorsets be tested at both ambient (297 K) and medium (477 K after 30 minutes of exposure) temperatures, or whichever presents the worst-case conditions for the particular specimen.

Table 1: Suggested allowable door leakage rates. Adapted from (NFPA 105 1999).

Door Installation	Pressure Difference (Pa)	Temperature (K)	Maximum Leakage ($m^3/h.m^2$)
Room to corridor [a,b]	25	477	54
Room to corridor (pressurised)	12.5	477	54
Area of refuge [a]	50	477	36
Elevator lobby [a]	25	297	54
Elevator-pressurised hoistway	25	477	108
Elevator without lobby separation (not pressurised)			
≤ 15 m	25	477	54
> 15 m and ≤ 30 m	50	477	54
> 30 m	75	477	54
Cross corridor [a,b]	12.5	477	18
Stair enclosure	25	297	54
Stair enclosure (pressurised)	75	297	204
Horizontal exit	12.5	477	18

[a] In fully sprinklered buildings, the pressure differential should be considered to be 12.5 Pa.

[b] Tested with artificial bottom seal. However, it was noted that in an actual installation, the bottom seal that was provided in the test may be omitted due to the neutral pressure plane being located in approximately one-third of the way up from the bottom of the door during fire conditions.

3.6 ASTM E2074, E283, E783 & E1424

ASTM E2074 2000 "Standard Test Method for Fire Tests of Door Assemblies, Including Positive Pressure Testing of Side-Hinged and Pivoted Swinging Door Assemblies" does not provide for a method of measurement of smoke leakage through a tested doorset. Instead, it is suggested that this may be an important consideration in terms of fire hazard or fire risk and "this information may be determined by other suitable fire test methods" (ASTM E2074 2000b). ASTM standard test methods for determining air leakage rate through doorsets are ASTM E283 1991 (1999) "Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen", ASTM E783 2002 "Standard Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors", and ASTM E1424 1991(2000) "Standard Test Method for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure and Temperature Differences Across the Specimen".

ASTM E283 describes laboratory tests to measure the air leakage rate associated with the assembly and not installation, similar to all other standards considered (ASTM E283 1999). Tests are to be performed at standard conditions (101.3 kPa, 294 K, 1.202 kg/m^3) on the outside of the specimen, with a static pressure across specimen (75 Pa if not defined). The air leakage rate is measured in m^3/h per metre length of operable crack perimeter and m^3/h per unit area (m^2) of outside frame dimension. It is noted that performing tests at non-ambient conditions or with a temperature difference across the doorset may affect the air leakage rate.

ASTM E783 describes field tests to measure the air leakage rate associated with the window or door assembly in situ, but is not designed to measure the leakage associated with the joining of the assembly and adjacent construction (ASTM E783 2002). It is noted that results from this test method may be affected by the age or physical condition of the specimen, the quality of installation, the local conditions (e.g. temperature, humidity, wind etc) and the attachment of the test apparatus to the specimen frame. It is stated that the estimated uncertainty of the air leakage determined by this test method would be in the order of 15% or less. The test apparatus is similar to and the test conditions are the same as those described in ASTM E283, with modifications for mobility and limited space.

ASTM E1424 describes laboratory tests to measure assembly air leakage rates for various cross-door pressures (27, 75 and 300 Pa if not defined) and temperatures (in the range considered reasonable for external seasonal changes: internal side 295 ± 2 K and external side warm 316 ± 2 K and cold 256 ± 2 K) (ASTM E1424 2000). The test apparatus is similar to, and the test conditions are the same as, those described in ASTM E283, with modifications for temperature control. That is, a heater is added to the ASTM E283 test apparatus and a chamber is attached to the other side of the door, so the conditions can be measured and controlled without interference from possible drafts, etc, in the laboratory. The measured leakage rate is adjusted to standard conditions, using ratios of air densities.

3.7 UBC 7-2/2

The Uniform Building Code, UBC 7-2/2 “Test Standard for Smoke- and Draft-control Assemblies of the International Conference of Building Officials” requires both a fire endurance test, of no less than 20 minutes, as well as a chamber leakage test, at ambient (297 K) and elevated (477 K) temperatures (UBCS 7-2/2 1997). The leakage rate of the apparatus is to be measured by sealing the specimen with an air-impermeable sheet, before conducting the ambient temperature tests. The fire endurance test is to be conducted as for a fire door, as specified in (UBCS 7-2/1 1994). The ambient and elevated temperature leakage tests are to be performed at cross-door pressures of 12.5, 25, 50 and 75 ± 1.25 Pa. The temperature for the elevated temperature test is to be increased from ambient to 450 K within 15 minutes, then from 450 to 477 K within 15 minutes. When the temperature is stabilised at 477 K, then the measured airflow is recorded.

3.8 DIN 18095

Smoke doors, according to the definition in DIN 18095/1 “Smoke Control Doors – Concepts and Requirements”, restrict the spread of smoke and are not fire barriers (DIN 18095/1 1988). A minimum of two identical specimens are to be tested for both durability and air leakage. The example test chamber for air leakage is designed to be able to provide both a positive or negative pressure to the sample (DIN 18095/2 1991). Doorsets are to be tested over a range of cross-door pressures from 0 to 50 Pa, at ambient (298 ± 15 K) and medium (473 ± 20 K) temperatures. It is noted that a cross-door pressure of 50 Pa is not intended to reproduce the actual pressure difference associated with a fire. The measured leakage rate, adjusted to standard reference conditions (the same as ISO/DIS 5925/1 1981 and BS 476/31.1 1983), is used as a primary assessment parameter. The maximum allowable apparatus leakage rate is 5 m^3/h at a cross-door pressure of 50 Pa at ambient temperature. At either test temperature, the maximum leakage rate allowable is 20 m^3/h and 30 m^3/h for single- and double-leaf doors, respectively. The durability and air leakage tests (DIN 18095/1 1988; DIN 18095/2 1991) were originally designed for single- and double-leaf hinged and pivoted doors only. However larger doors, shutter assemblies, folding and other types of doors have subsequently been satisfactorily tested using the same standard (DIN 18095/3 1999). Therefore the general leakage requirements for an assembly of clear opening 3 – 7 m wide and 3 – 4.5 m high is a maximum of 50 m^3/h, for an opening of 3 × 3 m is a maximum of 40 m^3/h, for other sizes of openings the maximum leakage rate is to be calculated from the ratio of area opening compared to the 3 × 3 m case. In addition, the minimum number of specimens to be tested is reduced to one. Deformations of the door or frame are also to be measured and recorded. Leakage rate values are adjusted to a 10 minute period, which is stated as an acceptable time for evacuation and rescue to occur within. The materials of the doorset must be chosen to ensure operation at 473 K, and immediately after the leakage test the door shall be operable, without tools. A name plate, at eye height, is required on the door, and is to include designation, manufacturer, number and date of issue of test certificate, testing agency and year of manufacture.

3.9 BS 476: Section 31.1

The current British Standard for smoke control doors, BS 476: Section 31.1 1983 "Fire Tests on Building Materials and Structures, Part 31. Methods for Measuring Smoke Penetration Through Doorsets and Shutter Assemblies, Section 31.1 Method of Measurement under Ambient Temperature Conditions" with Amendment No. 8366 (November 1994), only considers ambient temperature (298 ± 15 K) conditions. Static pressure measurements to be taken inside the chamber at a distance of 100 ± 10 mm from the plane of a single leaf door, at the top and bottom of the vertical axis of the door, or for a double leaf door, at the centre top of one leaf and the centre bottom of the other, as also specified in ISO/DIS 5925/1 (1981). The maximum allowable air leakage rate of the apparatus is 1 m^3/h adjusted to standard conditions at a cross-door pressure difference of 100 Pa. Test conditions must be held constant for 3 minutes before measuring the air leakage rate. Air leakage rates are measured at cross-door pressure differences of 5, 10, 25 and 50 Pa up to the maximum pressure difference required and then measured again at 5 Pa and the maximum pressure difference, similar to ISO/DIS 5925/1 (1981). The measured leakage rate is adjusted to standard conditions, using ratios of pressure, temperature and relative humidity, similar method to AS/NZS 1530.7 (1998) and using the same relationship as ISO/DIS 5925/1 (1981) and DIN 1895/2 (1991). Both sides of the doorset are to be tested, unless it can be ascertained that the doorset has been tested in the orientation that would achieve maximum air leakage rates. No acceptable air leakage rate limit is presented, although it is suggested that doors designed for smoke control purposes would not be expected to exceed an air leakage rate of 16 m^3/h per metre of the leakage path (BS 476/31.1 1983).

3.10 BS/EN 1634/3

The European Standard EN 1634/3 "Fire-resistance Tests for Door and Shutter Assemblies, Part 3: Smoke Control Doors and Shutters" describes the requirements for ambient (293 ± 10 K) and medium (473 ± 20 K) temperature smoke leakage tests for hinged or pivoted leaf, folding leaf or rolling shutter assemblies (BS/EN 1634/3 2001). The operation of each specimen is determined before testing by opening the leaf to 30° and closing 10 times. Leakage rate measurements are to be taken at cross-door pressure differences of 10, 25 and 50 Pa, or other values specified by the sponsor. Measurements are to be taken at the end of a 2 minute steady period. Observations and measurements of door deformation are to be recorded. The operation of the door is also assessed after the leakage test. The maximum allowable leakage rate of the apparatus is 10 m^3/h. No maximum value for an acceptable smoke door leakage rate is stated. (Note: the latest version of EN 1634/3 is 2004.)

3.11 BS/EN Drafts

A new British Standard and European Standard for the requirements and classification of smoke control doorsets and shutter assemblies (BS/EN 14013 Draft 2000) is currently being developed. The testing required or concessions for alternative hardware, seals and glazing for tested doorsets are addressed. In addition, testing for durability of the doorset is described. Requirements for general safety of the doorset are also described. The air leakage of the specimen is to be determined by testing to BS/EN 1634/3 (2001) and reported in terms of the classifications defined in prEN 13501/2 (2003).

3.12 WFRA FSE 04.1

Warrington Fire Research developed and tested a provision of supplementary methods and procedures for testing smoke doors, based on a standard AS 1530.4 fire test furnace with a full-scale corridor (WFRA FSE 021 2000; WFRA FSE 04.1 2003). Advantages of this test approach for smoke door performance includes insights into the deterioration of the performance during fire exposure and the sensitivity of results to transient enclosure temperature changes. Based on test results, some values for maximum leakage rates have been suggested. For example, it was suggested that leakage rates of less than 15 m^3/h per leaf measured between 65 and 70 minutes after the commencement of heating "corrected to STP at a pressure differential of 25 Pa after more than 30 minutes exposure to 200ºC when subjected to a test in accordance with AS/NZS 1530.7 1998" (WFRA FSE 04.1 2003) in addition to the Warrington Fire Research Technical Specification for Air Leakage Testing to be satisfactory, according to BCA deemed-to-satisfy requirements. However, measuring the air leakage rate associated with the doorset and the total leakage from the attached corridor may require careful measurement, based on the length and construction of the corridor and the range of conditions within the corridor. This supplementary test method for smoke door air leakage measurements has been submitted to ISO for consideration as a possible test methodology for combined fire and hot smoke leakage of unit entry doors leading onto adjacent escape corridors (Rakic 2002).

3.13 Summary

A summary of the test methods of the standards that have been discussed in this section is presented in Table 2.

3.14 Standards for general door and window leakage and other smoke stopping assemblies test methods

A summary of a selection of standards associated with door or window leakage and smoke stopping assemblies, other than smoke doors, are presented.

NFPA 92A "Recommended Practice for Smoke-Control Systems" suggests that for a smoke barrier, in general, with a gas temperature of 1198 K on one side, the minimum design pressure difference across the smoke barrier for a sprinklered area should be 12.5 Pa (NFPA 92A 2000). For non-sprinklered areas, the minimum design pressure difference across the smoke barrier should depend on the ceiling height, ranging from 25 Pa for 2.7 m to 45 Pa for 6.3 m. Again, the basis for these values is not clear, i.e. air leakage rate magnitudes, or the size of the area to protect and the minimum tenability conditions over a specified time etc.

The Loss Prevention Standard for "Requirements and Tests for LPCB Approval of Fixed Fabric Smoke Curtains, Fixed Metal Smoke Curtains and Powered Smoke Curtains" (LPS 1882 1994) is primarily concerned with the manufacture, installation (BS 5750/1 1987, BS 5750/21987 and BS EN ISO 9000 2000) and fire resistance (BS 476/20 1987) of the assemblies. Smoke curtains are given a grade of A or B. For Grade A, the specimen is tested to (BS 7346/3 1990), which is specifically for smoke and heat control assemblies and uses a time temperature curve. For Grade B, the specimen is tested to (BS 476/7 1997), which is a reaction to fire test associated with flame spread, and must achieve class 1. However the gap integrity criteria is not used at the bottom of the curtain, or at the sides of the curtain, where side guides are not provided. No quantitative criteria for determining a success or failure is provided.

Table 2: Summary of the various smoke door leakage standards

Standard	Smoke Temp. (K)	Cross-door Pressures (Pa)	Leakage Criteria [a] (Max. for Apparatus)	Ratios for Adjustment of Leakage Rate [b]	Pre-test Information	Post-test Information
AS/NZS 1530.7 1998	298 ±15 473 ± 20	10, 25, 50	- [c] (7 m^3.h @ 298 or 473 K)	p, T	Force to open and closing moments. Apparatus leakage. [d]	(Deformations during the test.)
AS 1905.3 unpublished	298 ±15 473 ± 20 > 473	Up to 75	- [c]	-		Smoke Resistance Rating, S = X/Y/Z [g]
ISO 5925/1 1981	298 ± 15 (h_r = 40 – 60%)	5, 10, 20, 30, 50 ,70, 100, then 5 and finally 100	- [c] (1 m^3/h @ 100 Pa)	p, T, h_r	Apparatus leakage rate. Normal operation of doorset ensured. [d]	Apparatus leakage rate.
ISO 5925/1 future developments	298 ± 15 473 ± 20	10, 25 and 50	- [c] (7 m^3/h @ 293 or 473 K)			
NFPA 105 2003	297 477	25, 50 or 75 ± 1.25	54 m^3/h.m^2	-	[d]	"S" label for a max. leakage of 180 m^3/h.m^2
ASTM E283 1999	293.95	75, if not defined	- m^3/h.m	ρ_{air}		
ASTM E783 2002	Field conditions			ρ_{air}		
ASTM E1424 2000	internal side 295 ± 2, and external side warm 316 ± 2 and cold 256 ± 2	27, 75 and 300, if not defined		ρ_{air}		
UL 1784 2004	297 477		54 m^3/h.m^2	[h]		
UBC 7-2/2 1997	297 477	12.5, 25, 50 and 75 ± 1.25	54 m^3/h.m^2 @ 25 Pa	-	Apparatus air leakage	
DIN 18095/1 1988 DIN 18095/2 1991 DIN 18095/3 1999	298 ± 15 477 ± 20	0 to 50	dependent on opening size [e] (5 m^3/h @ 50 Pa)	p, T, h_r	Durability of specimen	Deformations Operation ensured Name plate
BS 476: Section 31.1 1983	298 ± 15	5, 10, 25, 50, max, 5, max	- (7 m^3/h @50 Pa)	p, T, h_r		
EN 1634/2 2001	293 ± 10 473 ± 20	10, 25 and 50, if not defined	- (10 m^3/h)	-	Operation of specimen	
WFRA FSE 021 2000	at AS/NZS 1530.7	25	15 m^3/h per leaf [f]	p, T		

Notes for Table 2:

[a] Air leakage criteria are either presented in units of m^3/h per unit area of door opening or m^3/h per unit length of gap, as listed. An absolute value for the maximum allowable air leakage of the test apparatus (in m^3/h) is included in parentheses.

[b] Ratios used for adjustment of the measured air leakage rate, where p denotes pressure, T denotes temperature, h_r denotes relative humidity, and ρ_{air} denotes air density.

[c] A general life safety limit of 20 – 25 m^3/h is suggested, but is not required.

[d] Doorsets are to be installed to the manufacturer's specifications. Pre-test records are to show material, dimensions and measurements of all gaps of the tested doorset.

[e] The maximum air leakage rate is 20 m^3/h and 30 m^3/h for single- and double-leaf doors, respectively. The maximum air leakage rate for an assembly of clear opening 3 – 7 m wide and 3 – 4.5 m high is a maximum of 50 m^3/h, for an opening of 3 × 3 m is a maximum of 40 m^3/h, for other sizes of openings the maximum leakage rate is to be calculated from the ratio of area opening compared to the 3 × 3 m case.

[f] Measured between 65 and 70 minutes after the commencement of heating.

[g] Smoke Resistance Rating, S = X/Y/Z = smoke temperature (ambient or medium)/cross-door pressure difference/allowable air leakage rate in m^3/h per square metre of door opening.

[h] As at the time of publishing, a full copy of this standard was not available.

Table 3: Typical leakage area for walls and floors of commercial buildings. Extracted from (NFPA 92A 2000).

Construction Element	Tightness	Area Ratio [h]
Exterior building walls (includes construction cracks and cracks around windows and doors)	Tight [i] Average [i] Loose [i] Very Loose [i]	0.5×10^{-4} 0.17×10^{-3} 0.35×10^{-3} 0.12×10^{-2}
Stairwell walls (includes construction cracks, but not cracks around windows and doors)	Tight [j] Average [j] Loose [j]	0.14×10^{-4} 0.11×10^{-3} 0.35×10^{-3}
Elevator shaft walls (includes construction cracks, but not cracks and gaps around doors)	Tight [j] Average [j] Loose [j]	0.18×10^{-3} 0.84×10^{-3} 0.18×10^{-2}
Floors (includes construction cracks and gaps around penetrations)	Tight [k] Average [l] Loose [k]	0.66×10^{-5} 0.52×10^{-4} 0.17×10^{-3}

[h] The area ratio is the area of the leakage through the element divided by the total area of the element (including leakage area).

[i] Values based on measurements from (Shaw, Reardon and Cheung 1993; Tamura and Shaw 1976; Tamura and Wilson 1966).

[j] Values based on measurements from (Tamura and Shaw 1976; Tamura and Wilson 1966).

k Values extrapolated from average floor tightness based on a range of other construction elements.

[l] Values based on measurements from (Tamura and Shaw 1978).

In addition to the ASTM standard test methods for measuring air leakage through doorsets (ASTM E283 1999; ASTM E1424 2000; ASTM E783 2002), there is an ASTM Work Group, WK4184, developing a standard test method for "Determining Air Flow Through the Face and Sides of Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen" (ASTM WK4184 initiated in 2004). Another ASTM Work Group, WK303, is developing a "Guide for Smoke Barrier Walls and Partitions" (ASTM WK303 initiated in 2003).

ICC Evaluation Services Inc. developed an acceptance criteria for evaluation of tight-fitting, smoke and draft control assemblies (AC77 2003) for the US building codes (2000 International Building Code Section® 714.2.3, 1997 Uniform Building Code™ Section 1004.3.4.2.1, or 1999 Standard Building Code© Section 705.1.3.2). Field tests are required after installation to ensure proper operation. Air leakage rates are to be recorded for cross-assembly pressures of 25, 50 and 75 Pa, to the performance requirement of UL 1784 or UBC 7-2, Part II. The maximum air leakage rate allowable is 54 m^3/h per square metre of opening at a cross-assembly pressure of 25 Pa. Other requirements include material types and thicknesses, expansion characteristics, durability and opening force.

A number of other standards exist for testing the air leakage of general door and window assemblies (primarily concerned with weathertightness), including NFRC 400 2001 "Procedure for Determining Fenestration Product Air Leakage", ASTM E1186-03 "Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems", ASTM E779-03 "Standard Test Method for Determining Air Leakage Rate by Fan Pressurisation", and associated discussion (Di Lenardo 2000).

3.15 Current building code requirements for smoke doors

Following are brief summaries of the requirements for smoke doors in the building codes of various countries.

3.15.1 New Zealand

The Acceptable Solution for the NZBC Fire Safety Clauses (C/AS1 for NZBC 2005) specifies locations where smoke control is required, elements of construction required and general performance criteria for purpose group interaction, rather than quantitative limits for achieving smoke control.

By definition, a smoke control door is a "doorset with close-fitting single or multi-leaves which are impermeable to the passage of smoke, fitted with smoke seals and installed within a smoke separation. In the event of smoke the door, if not already closed, will close automatically and be held closed" (C/AS1 for NZBC 2005). Smoke separations are required to simply "be able to prevent the spread of smoke between two spaces" (e.g. NZBC Clause C3.3.2, C3.3.4, C3.3.8). As part of a smoke separation, a smoke control door must resist collapse under self-weight and intended live loads, withstand a horizontal pressure of 250 Pa applied from either side (however this pressure requirement is "to ensure adequate rigidity and is not a smoke leakage requirement") and "form an imperforate barrier to the spread of smoke". Smoke separations, in general, are also required to "be of non-combustible construction or a flame barrier, or achieve a FRR of 10/10/-, except that non-fire-resisting glazing may be used if it is toughened or laminated safety glass". However there is no requirement for any closures forming a part of a smoke separation to meet this FRR.

Doorsets that are required to be smoke control doors are required to comply with the operational requirements listed in Appendix C 8.1, which include the maximum force required to open and self-closing provisions. There are exceptions for certain situations, as noted in P. 6.19.4 (C/AS1 for NZBC 2005), which include that smoke seals are not required for doorsets installed in fire separations where there is a pressurised safe paths or at the sill of doorsets on the ground floor or for any doorset in buildings less with than three floors. Doorsets require clear markings to show their FRR and including 'Sm' to indicate smoke stopping capability (P. 6.19.6 of C/AS1 for NZBC 2005). The smoke stopping capability (Sm rating) is usually achieved by fitting smoke seals at the head and all vertical edges in the gaps between the door leaf or leaves and the frame, and between leaves in multi-leaf doorsets (P. 6.19.2 of C/AS1 for NZBC 2005). There is no leakage requirement for doorsets with or without smoke seals. It is also noted that doorsets opening into shafts above the neutral plane should not have large gaps at the sill which would otherwise be acceptable in doorsets in escape routes, as there may be airflow from the shaft in through the doors.

There is no restriction on allowable area of glazing in smoke control doors. Fire-resisting glazing or toughened or laminated safety glass are required. The glazing is required to have at least the same smoke stopping ability as the smoke separation (P. 6.19.8, 5.8.11 of C/AS1 for NZBC 2005).

Smoke control door installation requirements cover human interaction considerations, such as hinging, self-closing mechanisms, locking devices, direction of opening, opening dimensions, vision panels, hold-open devices and locations (P. 6.19.5, 6.19.6, 3.17, 6.13 of C/AS1 for NZBC 2005).

It is stated that "smokecell effectiveness shall be maintained by ensuring continuity of fire and smoke separations at separation junctions, and around joints where doorsets, protected shafts and penetrations occur" (P. 6.12.4 of C/AS1 for NZBC 2005). Again, how the "effectiveness" is to be measured or assessed quantitatively is not specified.

Maximum gap size allowable and use of sealants specified for the smoke separations do not apply to smoke control doors (P. 6.12.9 of C/AS1 2001; C/AS1 for NZBC 2005).

3.15.2 Australia

Requirements for smoke doors, as specified by the Building Code of Australia Specification C3.4.3, is that the assemblies "must be constructed so that smoke will not pass from one side of the doorway to the other and, if they are glazed, there is minimal danger of a person being injured by accidentally walking into them [complying with AS 1288]" (BCA C3.4 2004). In addition, "the leaves are capable of resisting smoke at 200ºC for 30 minutes" and that "the leaves are fitted with smoke seals" (BCA C3.4 2004). However a standard is not specified for a test method or rating scheme for the leakage of a doorset (BCA C3.4 2004; BCA C3.4 Guide 2004).

3.15.3 Canada

Considering all buildings with major occupancies of Group A (assembly occupancies), Group B (care or detention occupancies), or Group F Division 1 (high hazard industrial occupancies) and all buildings with areas greater than 600 m^2 or more than three storeys and with major occupancies of Group C (residential occupancies), Group D (business and personal services occupancies), Group E (mercantile occupancies), or Group F Division 2 & 3 (medium and low hazard industrial occupancies), as specified in 2.1.2 of (NBCC 1999). Fire doors with a 20 minute fire rating must not have a clearance of more than 6 mm at the sill and 3 mm at the sides and top of the doorset, according to clause 3.1.8.10 of (NBCC 1999).

3.15.4 England and Wales

Smoke control doors must resist the passage of smoke at ambient temperature (i.e. in the early stages of a fire before intumescent seals have time to activate) (ODPM, Build. Reg. 2000, Approved Doc. B 2004).

Building Regulations Approved Document B, Appendix B, Table B1 specifies where smoke control doors are required, minimum fire-resistance ratings, and defines a maximum leakage rate of 3 m^3/h per metre of gap (for head and jambs only), when tested at 25 Pa according to BS 476: Section 31.1, unless compliance with BS 5588/4 (i.e. protecting by pressurisation) is demonstrated (ODPM, Build. Reg. 2000, Approved Doc. B 2004).

3.15.5 United States of America

NFPA Building Construction and Safety Code (Section 11.2.1.1.4) (NFPA 5000 2003) and International Building Code (Section 710.5.2) (IBC 2003) specify that smoke control doorsets are required to be tested in accordance with UL 1784 Standard for Air Leakage Tests of Door Assemblies and that the maximum leakage rate of the door set is 54 m^3/h per square metre of door opening at 25 Pa for both ambient and elevated temperature tests.

As a side note, fire doors are required to be tested, according to UL10C, UBC 7-2 1997, IBC 2000 and ASTM 2074-00, under positive furnace pressure with the neutral plane maintained at approximately 1 m or less above the sill, and under negative furnace pressure according to UL10B, UBC 1994 or ASTM E-152.

3.15.6 Summary

The current smoke leakage requirements, according to the building regulation documents, is summarised in Table 4.

Table 4: Summary of the current building code requirements for leakage and sealing of smoke control doors

Country	Description of Type of Requirement	Maximum Leakage Rate	Details of Leakage Requirements
New Zealand	Qualitative – Performance	Impermeable to the passage of smoke	
	Qualitative – Prescriptive		Typically smoke seals are fitted at the head and all vertical edges Above the neutral plane, sills should not have a large gap
Australia	Qualitative – Performance	Impermeable to the passage of smoke	
	Qualitative – Deemed-to-Satisfy		Leaves resist smoke at 200 ºC for 30 min
England & Wales	Quantitative – Performance	3 m^3/h per metre of gap	Leakage measured at head and jambs, for a cross-door pressure of 25 Pa (BS 476: Section 31.1)
United States	Quantitative – Performance	54 m^3/h per m^2 of door opening	Leakage measured for a cross-door pressure of 25 Pa (UL 1784)

3.16 Published discussions of standards

Computerised literature searches show that the inclusion of smoke stopping assessment methods of smoke control doorsets in standards, with a similar level of detail as fire resistance, has been recommended since at least the early 1970s (Butcher 1974).

Rakic (2002) questioned the smoke control qualities of ‘tight fitting solid core doors’. It was pointed out that the fire resistance and smoke leakage performance of a ‘tight fitting solid core door’ was not established. In addition, it was noted that the terms ‘tight fitting’ and ‘solid core’ were not fully defined. Furthermore the ‘solid core’ referred to was made of blockboard, not solid timber. Rakic discussed the concept of a ‘life safety door’ (doorsets utilised in alternative solutions) versus traditional ‘fire doors’ and ‘smoke doors’ (doorsets complying to the Approved Solution) and the more recent ‘tight fitting solid core doors’. ‘Life safety’ doorsets, with performance for fire and smoke resistance, should require labelling and certification similar to the requirements outlined in AS/NZS 1905.1 (1997) and AS 1951.7 (1984). ‘Tight fitting solid core’ doorsets have been tested for fire resistance and significant smoke leakage was observed for both sprinklered (Rakic 2000) and non-sprinklered (WFRA FSE 021 2000) simulated conditions. However ‘tight fitting solid core’ doors were still being used in high-rise residential apartments, as an alternative design solution. The use of ‘tight fitting solid core’ doorsets are acceptable under the Building Code of Australia performance requirements CP2(a)(ii) for building elements that will, “to the degree necessary, avoid the spread of fire to adjoining sole-occupancy units and public corridors” in a class 2 or 3 building or class 4 part of a building (BCA 2005). Restriction of smoke or the effects of fire were not explicitly required. In addition, the lack of labelling on smoke doors was said to cause confusion in the marketplace. Rakic also recommended that provision for acoustic door seals and the design for fire and smoke protection should not be conducted separately.

According to IBC (Section 174.2.3) (IBC 2003), fire doors are required in fire-resistance rated corridors and smoke barrier walls. These doorsets are required to also be smoke and draft control doors, tested to UL 1784. However I-2 type occupancies (hospitals, nursing home facilities etc.) have an exception to certain corridors, thus allowing the use of non-fire rated doorsets. These doorsets are not required to comply with UL 1784, but “shall provide an effective barrier to limit the transfer of smoke”. Skold (2003) noted that smoke transfer is most effectively limited through a doorset that is gasketted with a product tested to UL 1784.

Horton (2004) questioned the standard requirements associated with means of escape and fire service access in high-rise residential buildings in the Approved Document B of the Building Regulations for the UK and BS 5588/5 1991, “Code of Practice for Firefighting Shafts and Lifts”. Revisions to BS 5588/5 in 1999 effectively removed the need for a separate firefighting lobby and that normal means of escape provisions for high-rise residential buildings would be sufficient for firefighting needs. No performance criteria are given for the ventilation of the common areas of a high-rise apartment building. A ventilation area is specified, but the acceptable conditions (e.g. optical density etc), for whom these conditions are provided (e.g. the length of time for conditions to be maintained – escape of occupants only, or for firefighting purposes as well), or what level of potential smoke logging is the system expected to perform under (e.g. if fire and smoke resistance of the fire room doorset fails) are not specified. The modelling of the impact of a fire behind a closed door was suggested as future work. The primary difficulty with modelling the behaviour of gases flowing through a gap of 2 – 3 mm was found to be integration of the scales associated with the gap and the room.

Pyatt (1990) states that “legislation and guidance on the specification of smoke-related building products, unlike that for fire, is dangerously inadequate”, based on the fact that lethal levels of smoke can be produced by a fire in minutes and the majority of fire-related deaths are attributed to smoke. Two particular points were raised for incorporation into future improvements of the regulations and standards. First, the acceptable level of smoke and, secondly, the creation of standards to outline how these levels could be met. It was noted that BS 476 only applied to ambient temperatures and that this does not represent real fire conditions. Hot swirling gases and pressure changes have different characteristics to smoke at ambient temperatures. In addition, distortion of the elements of the door under thermal load would change the door leakage characteristics. Without standards, manufacturers have to prove the smoke-stopping characteristics of their products using the few criteria specified.

In 1981, Gross (1981a) suggested air leakage tests at temperatures greater than ambient: at temperatures corresponding to the standard fire exposure for fire doors (ISO 3008 1976) and medium temperatures of 573 – 773 K. Concerns were raised regarding the differences of apparatus detail for air leakage, as the standards (in this particular case, ASTM E283-73 (1980)) only specified the measurement principle and required accuracy. At the time, no data from inter-laboratory testing was known. The units for recording air leakage rates for doors of volume per unit time per metre of gap ($m^3/h.m$) was suggested as a better measure than volume per unit of time per area of opening ($m^3/h.m^2$). Whole door air leakage rates were also briefly discussed. The lack of quantitative testing of the effectiveness of gaskets on doorsets was noted for UBC 43-2 1979. It is also suggested that quantitative performance levels would make general requirements and recommended practice more meaningful. There are now acceptance criteria of maximum leakage values at specified cross-assembly pressures for the US building codes (see Section 3.15.5).

4. VENTILATION AND PRESSURISATION OF EXITWAYS

During a fire event, ventilation and pressurisation of an exitway will affect the tenability of the protected space. Following are brief summaries of the requirements for the ventilation and pressurisation of exitways in the building codes of New Zealand and Australia. English, Welsh and Canadian practices are included, where information was available.

4.1 Prescriptive ventilation of exitways

4.1.1 New Zealand

For vertical safe paths, the ventilation rates required, according to the NZBC Acceptable Solution (C/AS1 for NZBC 2005), is to be achieved using roof-mounted ventilators or free vents. The ventilators must have a capacity equal to or greater than 0.7 m^3/s, or a total free vent area equal to or greater than 1.5 m^2. "Make-up air shall be provided using vents or grilles providing a total free vent area of no less than 0.7 m^2, and located no higher than 1.0 m above the lowest floor level" P.6.9.7 (C/AS1 for NZBC 2005). In addition, unpressurised vertical safe paths that are taller than 25 m in a building without a sprinkler system must be divided by smoke separations and smoke control doors at the landing nearest the mid-height of the building, P. 6.9.11 (C/AS1 for NZBC 2005).

For horizontal safe paths, the ventilation rates required, according to the NZBC Acceptable Solution (C/AS1 2001; C/AS1 for NZBC 2005), are to be achieved using roof-mounted ventilators or high-level free vents. The ventilators must have a capacity equal to or greater than 0.5 m^3/s, or the total free vent area must be equal to or greater than 1.0 m^2. Make-up air is to be provided using vents or grilles, with a total free vent area of no less than 0.5 m^2. The make-up air vents are to be located no higher than 1.0 m above the safe path floor level, P. 6.9.8 (C/AS1 for NZBC 2005). However if all the horizontal exitways leading to an enclosed stairway are naturally ventilated, then the stairway does not need not to be naturally ventilated, P. 6.9.10 (C/AS1 for NZBC 2005).

In the comments associated with this section (P. 6.9 (C/AS1 for NZBC 2005)), it is stated that permanent ventilation located in external walls should be by specific design. Furthermore, the design should take into account possible adverse wind effects and the tenability in the exitway. However the acceptable conditions (or limits) for tenability are not provided.

4.1.2 Australia

Fire isolated exits are required to be installed with either (Table E2.2a of BCA 2005):

- an automatic air pressurisation system (complying with AS/NZS 1668.1), or
- open access ramps or balconies (complying with D2.5).

The smoke hazard management requirements of an open access ramp or balcony (D2.5 of BCA 2005) are that:

- ventilation is achieved by openings direct to the outside air (where the total unobstructed ventilation area is not less than the floor area of the ramp or balcony and is evenly distributed along the length), and

- the openings are not enclosed above a height of 1 m (except if an open grille or similar is used where the open area is not less than 75% of its total area).

"In a Class 2 or 3 [residential] building, a public corridor, if more than 40 m in length, must be divided at intervals of not more than 40 m with smoke-proof walls …" (C2.14 of BCA 2005). The requirements for smoke-proof construction are specified in clause 2 of Specification C2.5 of BCA 2005. Specification C2.5 is also required for smoke-proof walls in class 9a (health-care) and 9c (aged care) buildings. The requirements for smoke stopping capabilities of this specification are qualitative and absolute.

A zone smoke control system, complying with AS/NZS 1668.1, is required for buildings of more than 25 m in effective height, in addition to sprinklers (Table E1.5 of BCA 2005), with occupancies of either (Table E2.2a of BCA 2005):

- class 5 (office), 6 (retail), 7b (storage/display), 8 (laboratory/process) and 9b (assembly) for either the whole or part of the building, or

- class 9a (health-care) (in addition to an automatic smoke detection and alarm system complying with Specification E2.2a).

A zone smoke control system, complying with AS/NZS 1668.1, is one of the options for buildings of less than 25 m in effective height with more than one fire compartment with occupancies of (Table E2.2a of BCA 2005):

- class 5 (office) or 9b school for either the whole or part of a building with more than three storeys, or

- class 6 (retail), 7b (storage/display), 8 (laboratory/process) or 9b other than a school for either the whole or part of a building with more than two storeys, or

- a class 5 (office) or 9b school part, and a class 6 (retail), 7b (storage/display), 8 (laboratory/process) or 9b other than a school part in a building with more than two storeys.

The alternative options to a zone smoke control system for these combinations of building heights and occupancies are (Table E2.2a of BCA 2005):

- an automatic air pressurisation system for fire-isolated exits (complying with AS/NZS 1668.1) in each required fire-isolated stairway and any associated fire-isolated passageways or fire-isolated ramps, or

- an automatic smoke detection and alarm system (complying with Specification E2.2a), or

- a sprinkler system (complying with Specification E1.5).

Either a zone smoke control system (complying with AS/NZS 1668.1) or a sprinkler system (complying with Specification E1.5 throughout the building with residential sprinkler heads in patient care areas) is required in a building less than 25 m in effective height with more than two storeys and an occupancy of class 9a (health-care) (Table E2.2a of BCA 2005).

Furthermore, "… in buildings less than 25 m in effective height, the necessary levels of protection may be achieved by measures other than zone smoke control, depending on the class and rise in storeys of the building. In buildings other than health-care buildings, zone smoke control may be substituted by either stairway pressurisation, smoke detection, or sprinkler protection. The rise in storeys before which the provisions become applicable depends on the building's classification and use. The above measures do not apply to the residential parts of a building because of the passive protection provided to such parts. However, where one or more fire-isolated exits join residential and non-residential parts, other than open-deck carparks, the fire-isolated exits must either be pressurised, or the non-residential parts provided with smoke detection or sprinkler protection. This is necessary to compensate for the potential additional hazard associated with the particular mix of Classes." (Guide to the BCA 2005)

Buildings serving class 7a (carpark, including a basement) are required to be provided with a mechanical ventilation system in accordance with AS 1668.2 and clause 5.5 of AS/NZS 1668.1 (Table E2.2a of BCA 2005). This requires the ventilation system to run in fire mode, but grants some exemptions from the construction requirement for the system under AS 1668.1. These systems are designed for car fumes (i.e. carbon monoxide). The system (running at 100% in fire mode) is intended only to extract smoke to assist with firefighting, not to maintain tenable conditions.

Either a zone smoke control system (complying with AS/NZS 1668.1 if the basement has more than one fire compartment), or an automatic smoke detection and alarm system (complying with Specification E2.2a), or a sprinkler system (complying with Specification E1.5) is required for basements (other than class 7a, carpark) that are not counted in the rise in storeys (according to C1.2 of BCA 2005) and are not more than two storeys below ground.

4.1.3 AS 1668.2

Minimum outdoor airflow rates required for general areas, such as corridors, lobbies, ramps and stairs is 1 l/s per m^2 of floor area (Table A1 of AS 1661.2 (1991)). However for these areas used as a means of egress during a fire, the performance requirements are that the fire-isolated exits are pressurised in accordance with AS/NZS 1668.1 (2002). This is discussed in more detail in Section 4.2.3.

4.1.4 Canada

Stairways that serve storeys above the lowest exit level must be vented to the outdoors, with an openable area 0.05 m^2 per door between the stairway and area of occupancy (with a minimum openable area to the outside of 1.8 m^2), according to 3.2.6.2(3) of the National Building Code of Canada (NBCC 1999). However, a ventilation rate is not specified. The specification for the ventilation of a stairway that serves storeys below the lowest level of exit is a minimum of 0.47 m^3/s for each storey served, according to B-3.2.6.2(2) of the NBCC (1999). Furthermore, as specified in paragraph 3.2.6.2 of the NBCC (1999), each exit stairway that serves storeys below the lowest exit level will not contain more than 1% (by volume) of "contaminated air from the fire floor" during the two hour period after the start of a fire.

4.2 Pressurisation of exitways

4.2.1 New Zealand

Pressurisation of exitways is required to comply with AS/NZS 1668: Part 1 Section 9, P. 6.21.2 (C/AS1 for NZBC 2005). It is also stated that "the ventilation system should not develop a negative pressure more than 0.5 Pa below atmospheric pressure otherwise the ratings of fire doors will be compromised. If mechanical ventilation is used the preferred position for the fan is at the bottom of the shaft to generate positive pressure." (Comments of P. 6.9 C/AS1 for NZBC 2005)

The required pressurisation specifications of AS/NZS 1668.1 are discussed in detail in Section 4.2.3.

4.2.2 Australia

To retain the fire-resisting performance of a fire-isolated exit, the number of entry points into a fire-isolated exit is limited. Doorways that open into a fire-isolated exit must be from a public area, a sole-occupancy unit (single owner/tenant/lessee or other type of occupier, to the exclusion of any other occupier) that occupies a whole floor, or a toilet (D1.7a of BCA 2005). If more than two access doorways are provided in the same storey, a smoke lobby or a pressurisation system (in accordance with AS/NZS 1668.1) is required to stop the entry of smoke into the fire-isolated exit (D1.7d of BCA 2005).

Furthermore, smoke management provisions required by the Building Code of Australia includes pressurised fire-isolated stairways (or open access ramps or balconies in accordance with D2.5) for buildings higher than 25 m, more than two storeys below ground, with an atrium, a class 9a (health-care) building with a rise of more than two storeys, or a class 9c (aged care) building with a rise of more than two storeys (Table E2.2a of BCA 2005). A fire-isolated passageway or fire-isolated ramp, with a length of travel more than 60 m to a road or open space, must also be provided with either an automatic air pressurisation system for fire-isolated exits in accordance with AS/NZS 1668.1, or open access ramps or balconies in accordance with D2.5 of the Building Code of Australia (Table E2.2a of BCA 2005). Smoke lobbies need only be pressurised if they form part of an exitway that is required to be pressurised (D2.6d of BCA 2005).

Buildings that are effectively taller than 25 m and of class 5 (office), 6 (retail), 7b (storage/display), 8 (laboratory/process), 9a (health-care) and 9b (public assembly), or a part of the building which is of one of these classes, are required to be provided with a zone smoke control system, also in accordance with AS/NZS 1668.1 (Table E2.2b of BCA 2005).

An automatic air pressurisation system in accordance with AS/NZS 1688.1 (E2.2a of BCA 2005) is required for a fire-isolated stairways and any associated fire-isolated paths that serve classes 2 or 3 (residential) in addition to areas serving classes 5 (office), 6 (retail), 7 (storage, not including open deck carparks), 8 (laboratory/process) or 9b (assembly) (where these other areas are neither sprinklered nor have an automatic smoke detection and alarm system complying with Spec. E2.2a of BCA 2005).

Buildings or parts of buildings serving class 5 (office) or 9b school (with a rise of more than three storeys), class 6 (retail), 7b (storage/display), 8 (laboratory/process) or 9b (assembly, other than a school) (with a rise of more than two storeys), or buildings with two or more storeys and containing areas serving class 5 (office) or 9b school and class 6 (retail), 7b (storage/display), 8 (laboratory/process) or 9b (other than a school) are required to have one of the following options:

- "in each required fire-isolated stairway, including any associated fire-isolated passageway or fire-isolated ramp, an automatic air pressurisation system for fire-isolated exits in accordance with AS/NZS 1668.1", or

- "a zone smoke control system in accordance with AS/NZS 1668.1, if the building has more than one fire compartment", or

- "an automatic smoke detection and alarm system complying with Specification E2.2a", or

- "a sprinkler system complying with Specification E1.5" (Table E2.2a of BCA 2005).

Buildings, or part thereof, serving class 9a (health-care) or class 9c (aged care) are required to be installed throughout with (Table E2.2a of BCA 2005):

- an automatic smoke detection and alarm system (complying with Specification E2.2a), and

- automatic shutdown of any air-handling system that is not part of a zone smoke control system, and

- for buildings serving class 9a (health-care), with more than two storeys and not more than 25 m in height, a zone smoke control system in accordance with AS/NZS 1668.1 or a sprinkler system throughout with residential sprinkler heads in areas serving patient care.

In addition to the general building smoke management requirements, a basement (other than class 7a carpark and with a total floor area greater than 2000 m^2) that is not counted in the rise in storeys (as specified in C1.2) must be provided with a sprinkler system. However, if the basement is less than two storeys below ground level, the area must be installed with (Table E2.2a of BCA 2005):

- a zone smoke control system in accordance with AS/NZS 1668.1, if the basement has more than one fire compartment, or

- an automatic smoke detection and alarm system, or

- a sprinkler system.

Buildings serving class 6 (retail), with a floor area greater than 2000 m^2 and containing an enclosed common walkway or mall serving more than one shop, must have smoke management systems installed that include (Table E2.2b of BCA 2005):

- an automatic smoke exhaust system, or

- automatic smoke-and-heat vents, if the building is only a single storey high, or

- a sprinkler system, if the floor area of the fire compartment is less than 3500 m^2 and the building has no more than two storeys.

4.2.3 AS/NZS 1668.1 Section 9

In accordance with AS/NZS 1668.1, a vertical fire-isolated exit pressurisation system is required to maintain an average air velocity of 1 m/s or greater through open doorways of the fire compartment, when the main discharge doors and all doors to the fire compartment are fully open. For a purge system or system shutdown, all doors of the compartment immediately above and adjacent to the fire-affected compartment must also be fully open. It is noted that the performance criteria must be achieved for the most "demanding practical situation likely to occur in the early stages of fire development". The flow through the top two-thirds of the openings between a fire-isolated exit and the fire compartment must be in the direction away from the fire-isolated exit, unless it can be demonstrated that any reverse flow would not be "detrimental to the safe operation of the fire-isolated pressurisation system" (AS/NZS 1668.1 2002).

Pressurised horizontal fire-isolated exits are required to maintain an average air velocity of 1 m/s or greater through open doorways of the largest compartment served by the exitway, when the main discharge doors and all doors to the fire compartment are fully open.

For vertical and horizontal fire-isolated exits the cross-door pressure difference, in combination with any self-closing mechanism installed, must not exceed 110 N for the door opening force and must not prevent the door from closing and latching.

4.2.4 Canada

The specification for the mechanical pressurisation of stairways is a minimum of 12 Pa, according to B-3.2.6.2(3) of the National Building Code of Canada (NBCC 1999), for a sprinklered high-rise building with two doors assumed open. A maximum door opening force of 130 N is suggested for pressurised areas (which is higher than the recommended 90 N in other parts of the code), to allow the pressure difference to be achieved.

4.2.5 BS 5588 Part 4

Pressurisation of protected escape routes, which includes stairways, lobbies and possibly corridors, is specified in the British Code of Practice for Fire Precautions in the Design of Buildings (BS 5588/4 1998). For class A residential buildings (non-combustible construction), pressurised protected pathways require a pressure difference of 50 Pa (with all doors closed) between the inside and outside of a protected pathway, and an airflow of 0.75 m/s through an open doorway of the fire room. For class B residential buildings (traditional construction), the requirements are similar to that of class A occupancies, except that when considering firefighting shafts, pressurised stairways require a pressure difference of 50 Pa (with all doors closed). In addition, lobbies and lift shafts must be pressurised to ensure that an airflow of 2.0 m/s through the lobby to the fire room, with 5 stair- or lobby-doors open. For commercial occupancies with simultaneous evacuation (class C), pressurised stairways require a pressure difference of 50 Pa to be maintained when all doors are closed and 10 Pa when the bottom door of the stairway is open, and a minimum flow of 0.75 m/s through the doorway to the fire room, when open. For institutional occupancies (class D), the requirements are similar to that of class C, however the flow of air through the doorway of the fire room must be a minimum 0.75 m/s when the door at the bottom of the stairway is also open. For commercial occupancies with staged evacuation (class E), the pressurisation requirements are similar to that of the firefighting shafts of class B. However the airflow into the fire room, when five stairway or lobby doors are open, is only 0.75 m/s.

If a pressurisation system is used to replace protected paths that would have otherwise been required, then the requirement is a minimum flow through the fire room doorway of 0.75 m/s when the door at the bottom of the stairway is also open.

Where the stairway and lobby are pressurised and the lobby is not a simple lobby, then the lobby should have a separate air supply to the stairway. The pressure in the lobby is required to be the same or up to 5 Pa less than the pressure in the stairway. Similarly, where the stairway, lobby and corridor are pressurised and form part of the protected escape route, and the corridor is constructed for 30 minute fire resistance or more, then the corridor should have a separate air supply to the stairway and lobby. The pressure in the corridor is required to be the same or up to 5 Pa less than the pressure in the lobby.

4.3 Published discussions of standards

Simmons (2005) discussed the concerns with methods used to validate the smoke venting of shafts used for firefighting in buildings. For example, the English and Welsh building regulations Approved Document B requires a 1.5 m^2 vertical vent for natural venting in residential lobbies and firefighting shafts. It is recommended that stairways and lobbies be adjacent to the external elevation of a building, so that an opening at each level may be installed. However, testing of vertical windows in internal stairways and the recommendations of BS 5588/4 for vertical shafts have been shown to have limited performance, “unless the opening into the shaft is located fully above the top of the stair door” (Simmons 2005). A BRE Report (No. 79204, Smoke Shafts Protecting Firefighting Shafts: Their Performance and Design) recommended a single 3 m^2 natural shaft as means of egress, but this has not yet been tested for full-scale residential buildings (only scale models have been tested).

Simmons noted that although there are problems with the methods of ventilation and pressurisation provided in the approved document, the requirements of the codes are still met. That is, the prescribed methods are ‘deemed-to-satisfy’, but are not necessarily ‘proven-to-satisfy’. Simmons questioned the definition of the acceptable criteria for an alternative solution. The argument was raised that an alternative solution that provides better results than a prescribed method that has been proven not to work, may lead to a very low standard. It was suggested that new alternative methods be treated as concepts, until they have been validated using ‘realistic-scale’ or full-scale model results or validated computational fluid models of the installation, in alignment with the specifications of other countries’ performance-based building codes (e.g. Section A of BCA 2005) and fire engineering guidelines (e.g. international fire engineering guidelines, ABCB, 2005).

Butcher and Parnell (1998) reviewed the changes implemented in 1998 to the original 1978 version of BS 5588:Part 4. In general, the 1978 version of the code required a pressure difference of 50 Pa (with all doors closed) between the inside and outside of a protected pathway, and an airflow of 0.75 m/s through an open doorway of the fire room. Furthermore, if a lobby and/or corridor adjacent to a pressurised stairway is also to be pressurised, the lobby or corridor pressure is to be the same or less (but no more than 5 Pa less) than the stairway pressure (4.2.2 of BS 5588/4 1978). The pressurisation level required stairways, for all building heights, during emergency operation is to be 50 Pa or greater with all doors to the pressurised space closed (5.2.2 of BS 5588/4 1978). It is noted that special considerations may be required to ensure that all occupants can operate the doors at these pressure differences. These requirements were consistent across the various occupancies. Whereas the 1998 version of BS558/4 varied with occupancy and in all cases the requirements were either similar or more severe than the 1978 version. For instance the requirements for a class B occupancy were increased from an estimated flow rate of 2 m^3/s (which would be achieved with a 5 kVA capacity fan) to 14 m^3/s (which would require a 72 kVA, three phase, capacity fan).

Butcher and Parnell cited several post-fire investigations of buildings with pressurisation systems designed and successfully operated to the requirements of the 1978 version of BS 5588. In addition, the results from full-scale testing that was performed to establish data and an understanding for the basis of the 1978 version were also cited. Based on their analysis, Butcher and Parnell suggested that increases in airflow rates into the fire room would unnecessarily add to the fire event. Therefore they postulated that there was no satisfactory reason for the increase in the severity of the requirements for the 1998 version of BS 5588.

5. TENABILITY CONDITIONS

During a fire event it is imperative that the tenability of exitways is maintained to allow for escape and/or other functions as required. However the parameters for describing tenability, acceptable levels and duration must be defined to reflect the level and type of protection required for the space. The parameters typically associated with smoke management are presented. Where available, the levels of these parameters determined or estimated to be toxic to humans is also presented. Results of experiments investigating the response of humans or animals to smoke are summarised.

5.1 General

Basic parameters of tenability conditions for consideration in a smoke management system design include (NFPA 92B 2000; Buchanan 2001):

- convective and radiant heat flux
- visibility
- smoke toxicity (including narcotic and irritant gases), and
- smoke temperature.

The evaluation of smoke toxicity typically includes analysis of concentrations and movement of carbon monoxide, and fuel-dependent toxic gases. Tenability limits for smoke toxicity and smoke temperature are typically considered in terms of exposure time (NFPA 92B 2000). The time taken to reach untenable conditions, compared to the time required to alert the occupants and for the occupants to escape, is an important consideration in fire safety design (Purser 2002).

Incapacitating effects of the exposure to toxic smoke include (Purser 2002):

- impaired vision from optical opacity of smoke, irritation or heat.
- respiratory pain or breathing difficulties from irritation or heat.
- asphyxia (confusion or loss of consciousness) from toxic gases.
- skin pain, upper respiratory tract pain, burns or hyperthermia from heat.
- lung inflammation and oedema (that may occur and persist after the fire) from irritants.

The toxicity of an environment to an occupant is dependent on the dose of the particular toxin that the occupant receives, and not necessarily the concentration of the toxin in the environment, i.e. the amount of toxin allowed to build up in the body of the occupant and the time that toxic levels remain in the body determines the level of harm. For example, concentration of an asphyxiant product in the cerebral blood supply or inside brain cells, concentration of an irritant product in the lining of the nose, throat or lung, concentration of carboxyhaemoglobin in the blood. However the irritant effects of smoke can occur on exposure, increasing severity with concentration. Furthermore, the body can adapt to the stimuli and the pain may decrease with the duration of exposure (Purser 2002).

5.2 Toxicity levels in humans

Difficulties in determining limits for acceptable tenability conditions include the wide variety of reactions of individuals to the same conditions. This is particularly evident when considering groups and individuals with prior conditions, especially respiratory or pulmonary conditions. Figure 2 shows the range of lethal carboxyhaemoglobin concentration for fire-related and non-fire-related deaths (Purser 2002). Many of the fire fatalities occurred at lower carboxyhaemoglobin concentrations than for cases where CO poisoning alone occurred.

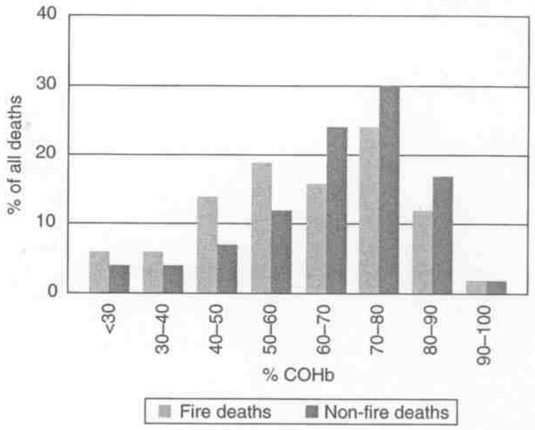


Figure 2: Range of lethal post-mortem carboxyhemoglobin concentrations in humans for CO fatalities in the US. Extracted from (Purser 2002).

The lethal level of toxins that cause asphyxia and lung irritation in rats is considered to be similar to that for humans (Purser 2002). Figure 3 shows the lethal concentrations of breathable toxins produced by burning various materials, as tested on rats. Furthermore, different fire conditions produce different levels of toxic products.

The physiological effect of carbon monoxide on cynomolgus monkeys sitting at rest was investigated. Respiration, cardiovascular (ECG) parameters and brain (EEG) parameters were recorded over a period of pre-exposure, exposure to an atmosphere containing 1850 ppm CO (produced from wood pyrolysed at 1173 K) and recovery, as shown in Figure 4(a). A monkey at rest and exposed to an atmosphere containing 147 ppm HCN was also investigated, as shown in Figure 4(b). The rate of carboxyhemoglobin accumulation in the blood depends on the rate of respiration, and therefore is linked to the level of activity, as shown in Figure 5. In primates, it was shown that subjects at rest were unaffected at carboxyhemoglobin concentrations of up to 40%, whereas those performing light exercise were seriously affected in at 25 – 35%. Similarly, a human subject at rest was capable of writing at a carboxyhemoglobin concentration 55%, but collapsed and fell unconscious when attempting to rise and walk (Purser 2002).

Unlike CO, the effects of HCN on the subject occur very rapidly from the start of exposure. HCN is carried by the blood, but accumulates in the brain. The most important factor in incapacitation from HCN appears to be the rate of absorption. Tests on animals showed that exposure to atmospheres with 80 – 180 ppm HCN resulted in hyperventilation and loss of consciousness at some time during 30 minutes. However exposure to atmospheres with more than 180 ppm HCN resulted in immediate hyperventilation and unconsciousness occurring within a few minutes (Purser 2002).

Purser (2002) stated that it is the objective of fire safety engineering to ensure that essentially all occupants, including the elderly, children and those with respiratory or pulmonary conditions, should be able to escape safely without experiencing or developing serious health effects. Therefore, safe levels for exposure of the human population to fire-related toxins must be significantly lower than the limits determined from experiments that use uniformly healthy animals or human surrogates, as these to do not simulate the heterogeneous nature of the general population well.

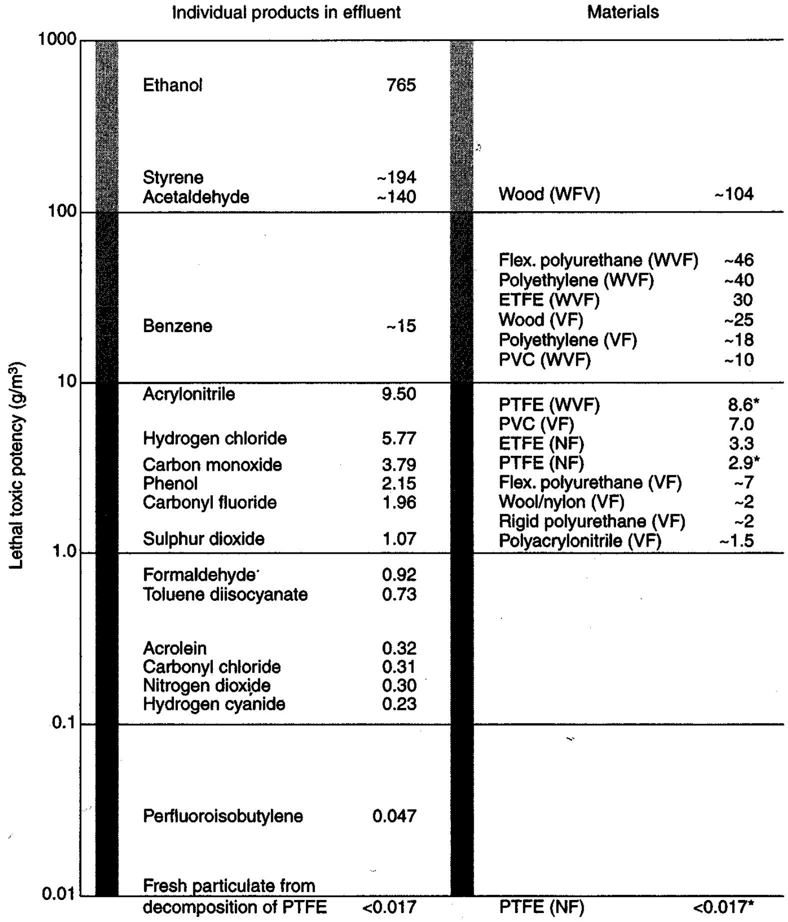
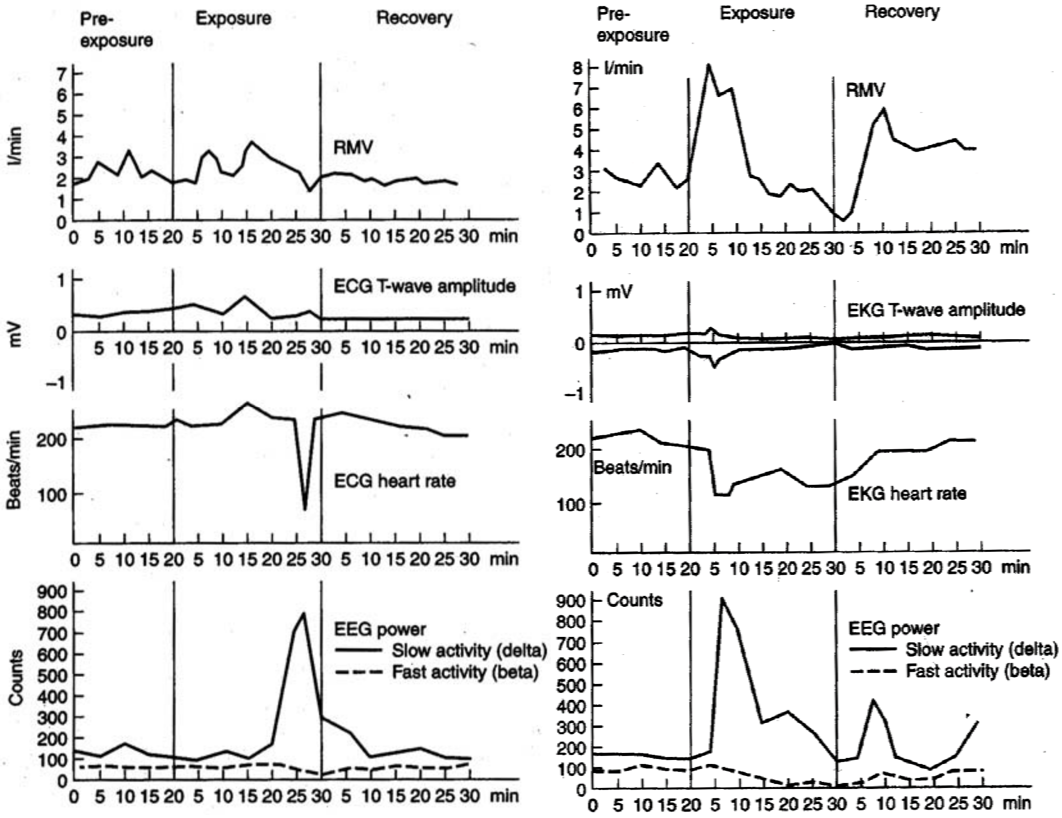


Figure 3: Lethal toxic concentrations (in g/m^3), for rats, for original materials and individual combustion products. Extracted from (Purser 2002).



(a) (b)

Figure 4: Physiological effects on cynomolgus monkeys in an atmosphere containing (a) 1850 ppm carbon monoxide, and (b) 147 ppm hydrogen cyanide. Extracted from (Purser 2002).

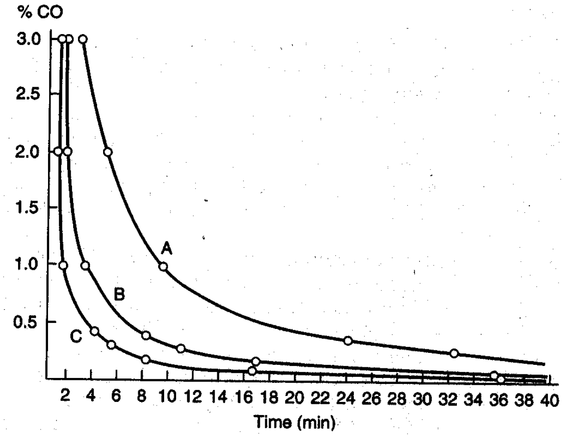


Figure 5: Calculated time to incapacitation by CO poisoning for a 70 kg human a) at rest (RMV 8.5 l/min), b) performing light work (RMV 25 l/min), and c) performing heavy work (RMV 50 l/min). Extracted from (Purser 2002).

5.3 Estimating/calculating toxicity levels of gaseous irritants

Two equations are primarily used for calculations of accumulated levels of inhaled gaseous toxins: Haber's rule and the Coburn-Forster-Kane equation. Haber's rule assumes that the concentration is a constant and the dose is the concentration times the duration of exposure and that no toxin in excreted by the lungs or broken down by the body (i.e. a linear relationship between dose and time). The Coburn-Forster-Kane equation accounts for the two-way transport of some toxins by the lungs, such as carbon monoxide. For high concentrations of carbon monoxide for short exposure times the proportion of carboxyhemoglobin in the blood is approximately linear, which Haber's rule predicts well, as shown in an example for a 70 kg human at rest in Figure 6. However lower concentrations of carbon monoxide over longer exposure times deviate from the approximately linear relationship, such that Haber's rule would over-estimate the level of carboxyhemoglobin in the blood after 4 hours at 840 ppm based on the toxin level after 1 hour for 2200 ppm (Purser 2002).

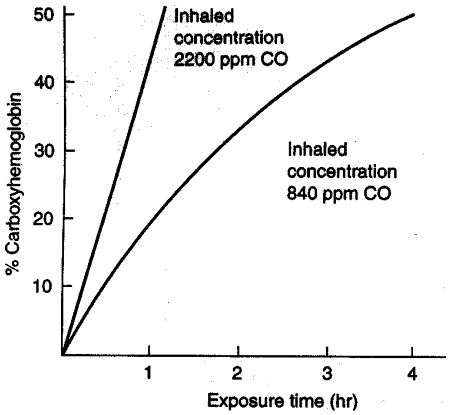


Figure 6: Proportion of carboxyhemoglobin saturation calculated for a 70 kg human at rest, using the Coburn-Forster-Kane equation, for various carbon monoxide concentrations. Extracted from (Purser 2002).

Using experimental results for animal subjects and limited human subjects, the time to incapacitation by CO is estimated to be:

$$t_{inc} = \frac{c_{inc,COHb}}{\left(3.315\times10^{-5} c_{CO}^{1.036} \dot{V}_b\right)}$$

Equation 1

where t_{inc} denotes the time to incapacitation (in minutes) and c_{CO} denotes concentration of CO in the atmosphere (in ppm), $c_{inc,COHb}$ denotes the concentration of carboxyhemoglobin in the blood to cause incapacitation (in %) and $\dot{V}_b$ denotes the rate of ventilation (in l/min) (Purser 2002).

Using experimental results for animal subjects and limited human subjects, the time to incapacitation by HCN is estimated to be (Purser 2002):

- up to concentrations of 80 ppm, the effects are considered to be minor for periods of up to 1 hour

- for concentration of 80 – 180 ppm, the time to incapacitation is:

$$t_{inc} = \frac{(185 - c_{HCN})}{4.4} \quad \text{Equation 2}$$

where t_{inc} denotes the time to incapacitation (in minutes) and c_{HCN} refers to the concentration of HCN (in ppm).

- For concentrations of > 180 ppm, the time to incapacitation is:

$$t_{inc} = e^{(5.396 - 0.023 c_{HCN})} \quad \text{Equation 3}$$

Using experimental results for animal subjects and limited human subjects, the time to incapacitation due to hypoxia is estimated to be:

$$t_{inc} = e^{-(3.156 + 0.54 c_{O2})} \quad \text{Equation 4}$$

where t_{inc} denotes the time to incapacitation (in minutes) and c_{O2} denotes concentration of O_2 in the atmosphere (%). For oxygen percentages of 11.8 – 14.4, maximum work capacity is reduced, ventilation and heart rate are increased and complex psychomotor performance is slightly reduced (Purser 2002).

Using experimental results for animal subjects and limited human subjects, the time to incapacitation by carbon dioxide is estimated to be:

$$t_{inc} = e^{(6.16723 - 0.5189 c_{CO_2})} \quad \text{Equation 5}$$

where t_{inc} denotes the time to incapacitation (in minutes) and c_{CO2} denotes concentration of CO_2 in the atmosphere (%) (Purser 2002).

The combined effects of these fire-related product gases are not well known. However, it is assumed that the hyperventilation effect of CO_2 would increase the uptake of other gases. For example, while the concentration of CO_2 is below 3%, little effect would be expected. However for carbon dioxide concentrations of 3%, respiration rate doubles and therefore the time to incapacitation by CO would be halved (of the estimation shown in Eq. 1). For carbon dioxide concentrations of 5%, respiration rate triples and, similarly, the time to incapacitation by CO would be a third (of the estimation shown in Eq. 1). This approach would also be the same for the effect of CO_2 on incapacitation times due to HCN uptake. Furthermore, studies have shown that CO and HCN have a slightly additive effect for close to lethal CO levels. Therefore estimating the effect of the combination of CO and HCN as additive is assumed to be a conservative estimate. Similarly, the interaction between CO and hypoxia is also assumed to be additive (at least for severe CO saturation in an active subject). In the absence of detailed information, all narcotic effects that would contribute to incapacitation are assumed to be additive (Purser 2002).

Other air borne fire-related irritants are more dependent on the concentration of the exposure rather than the dose (Purser 2002). A selection of estimated concentrations of such irritants that may incapacitate or impair the escape of half the population, based on available experimental data and assuming a normal distribution of the effect on the population, is presented in Table 5.

ISO/TS 13571 “Life-threatening Components of Fire – Guidelines for the Estimation of Time Available for Escape using Fire Data” provides guidelines for the analysis of model output for the initiation and development of fire, fire spread, smoke formation and movement, chemical species generation, transport and decay and people movement, as well as fire detection and suppression with regards to exposure of occupants trying to escape to hazardous components of fire (ISO 13571 2002).

Table 5: A selection of common fire-related irritants that is dependent on concentration more than an accumulated dose. Adapted from (Purser 2002).

Gas	Concentration Estimated to Impair Escape of Half the Population (ppm)	Concentration Estimated to Incapacitate Half the Population (ppm)
HCl	200	900
HBr	200	900
HF	200	900
SO_2	24	120
NO_2	70	350
CH_2CHO (acrolein)	4	20
HCHO (formaldehyde)	6	30

5.4 Tenability experiments

There are few experimental results from room-size fires that included the yields of narcotic and/or irritant gases. Even fewer investigations specifically focused on a quantitative level of protection (or lack there of) provided by any smoke protection system or physical arrangement of the system. A selection of tenability experiments that investigated conditions of an adjacent space to the room of fire origin or a corridor is summarised.

5.4.1 Experiments involving response of test subjects

Grand, Kaplan, Beitel, Switzer and Hartzell (1985) performed two tests to assess the toxic effects of pre-flashover and flashover conditions. A fully furnished 3.7 × 5.5 m room × 2.4 m high was set up to simulate a typical hotel/motel arrangement. These were ignited and allowed to proceed to past flashover.

The burn room was attached to a corridor via a doorway (0.9 m wide by 2 m high) and another room was attached approximately 4.9 m from the burn room via a closable doorway that extended to the ceiling (0.9 m wide by 2.4 m high), which was open 25 mm at the start of the test and then closed 5 minutes after flashover. The second room contained laboratory animals (rats), to assess the toxic effects of both pre-flashover and flashover. The rooms and corridor were instrumented with thermocouples, heat flux radiometers, smoke meters, gas sampling trains, and in the burn room only were located smoke detectors and sprinkler heads. Ventilation was only provided by the open end of the corridor. Six different sample sites were sequentially tested (each 2 minutes, i.e. 20 s per location) for concentrations of carbon monoxide, carbon dioxide, oxygen, hydrocarbons, and nitrogen oxides during each test. Hydrogen cyanide and hydrogen chloride were sampled with dry soda lime absorption tubes for subsequent wet-chemical analyses. A carbon dioxide analyser monitored the animal room constantly. Reduction of light transmission resulting from smoke development was measured vertically across the upper 1 m of the rooms or corridor at four locations (Grand et al 1985).

Results confirmed different smoke toxicity from fires burning in different situations (e.g. laboratory tests versus full-scale scenario). Significant toxic smoke hazards did not occur until 650°C was reached at 2.1 m from the floor in the burn room. After this point, tenability decreased very rapidly in the burn room, the corridor and the adjacent animal room. Carbon monoxide was attributed as the major cause of death. Carbon monoxide, hydrogen cyanide and oxygen depletion were assumed to be the major cause of incapacitation (Grand et al 1985).

Experiments recorded the levels of carbon monoxide and carbon dioxide in the room of fire origin for various stages of fire development (Purser 2002). A summary of the concentrations of CO, CO_2 and O_2 in the fire room are presented in Table 6.

Table 6: Summary of the general concentrations of CO, CO_2 and O_2 in a fire room. Adapted from (Purser 2002).

Fire Development	**Ratio of CO to CO_2 Concentrations**	**CO Conc. (%)**	**CO_2 Conc. (%)**	**O_2 Conc. (%)**	**Irritants**
Smouldering/ non-flaming	~1	0 – 0.15	0 – 0.15	15 – 21	irritants smoke
Small vitiated flaming	< 10	0.2 – 4	1 – 10	< 12	irritants heat smoke
Flaming	1000 – 50	0 – 1	0 – 10	10 – 21	irritants heat smoke
Fully-developed	<10	0 – 3	-	-	HCN: 0 – 500 ppm Some irritants heat smoke

Sugawa, Kawagoe, Ozaki, Sato and Hasegawa (1985) performed full-scale tests on a residential high-rise building. It was noted that the upper level of smoke concentration that began to seriously worry the residents was about 0.1 – 0.15 /m. In addition, smoke concentrations of 0.7 – 0.8 /m decreased walking speed to 0.3 – 0.7 m/s.

Jin and Yamada investigated the human response to a smoke-filled environment by asking subjects to walk down a smoke-logged corridor (Jin 1978, 1981; Jin and Yamada 1990). Walking speed decreased with increased smoke density. Irritant and non-irritant smoke was tested. Walking speed decreased from approximately 1.2 m/s in the clear corridor to 0.3 m/s (and feeling their way along the walls) for a non-irritant smoke of an optical density of 0.55 /m and for an irritant smoke of an optical density of approximately 0.2 /m (and the experience was reported to be more distressing). Furthermore, full-scale building testes showed that 30% of people would rather turn back than continue to search for an exit at an optical smoke density of 0.33 /m (Jin 1978, 1981; Jin and Yamada 1990; Purser 2002).

5.4.1.1 Extrapolation of animal results to humans

The inflammation of tissues and pain response of mammals, in general, to irritant stimuli is considered to be consistent with the expected response in humans, based on the similarity of the physiological nerve structure and response for all mammals (Purser 2002). The response to upper respiratory irritants for non-primates and primates (including humans) may differ. For example, nasal structure of a rodent is much more complex, with a larger surface area than a primate's, therefore a rodent would be more susceptible to irritation of the upper respiratory tract than a human. In primates the lungs tend to be the target organ of irritants, with a characteristic transient respiratory rate reduction (breath-holding) followed by an increased respiratory rate (with deep breathing).

5.4.2 Experiments measuring fire effluent

The distribution of smoke particle size has been investigated for a range of burning materials (e.g. incense and smouldering cellulosic insulation) (Mulholland 1982, 2002). The optical density for a range of materials under various burning conditions has also been investigated using small-scale tests (Mulholland 2002). Drysdale and Abdul-Rahim (1985) also investigated the smoke production of various burning materials.

Gann, Babrauskas, Peacock, and Hall (1994) investigated the potential toxicity in the room of fire origin and an attached open-ended corridor of both pre- and post-flashover fires using room-scale testing. In addition, the extent of reactive gases reducing in concentrations as they travel from the fire vicinity (possibly due to absorption on particulate matter) was also of interest. Concentrations of CO2, CO, HCl, HCN, and carbonaceous soot were measured using Fourier transform infrared (FTIR) and non-dispersive infrared (NDIR) (for only CO2 and CO) spectroscopy. Other toxins (such as NO2, formaldehyde or acrolein) were not found, however concentrations below the detection limits were considered to be of limited toxicological importance relative to the detected toxins. Higher uncertainty of the measurements associated with pre-flashover than post-flashover was attributed to lower concentrations and the distribution of the fire effluent. Reductions in the concentrations of the gases measured at the two ends of the corridor were found to be dependent on the material tested, as shown in Table 7. Over the length of the corridor, the ratio of downstream to upstream concentration varied from unity for some fuels to a fifth for others. It was concluded that the thermal conditions would be the first to make the room of fire origin untenable and that lethal or incapacitating toxin exposures could precede intolerable thermal conditions in rooms remote from the fire room.

Table 7: Ratios of downstream to upstream (over the length of the corridor) concentrations for post-flashover conditions. Adapted from (Gann et al 1994).

Gas	Analyser	Material Tested			
		Sofa	**Bookcase**	**Cable**	**Bookcase and PVC Sheet**
CO_2	NDIR	0.65 ± 0.05	0.48 ± 0.05	0.58 ± 0.01	0.60 ± 0.04
CO	NDIR	0.54 ± 0.21	0.41 ± 0.09	0.57 ± 0.02	0.75 ± 0.26
CO_2	FTIR	0.41 ± 0.14	0.73	0.35 ± 0.02	0.25 ± 0.24
CO	FTIR	0.07 ± 0.04	0.57	0.12 ± 0.01	0.10 ± 0.02
HCl	FTIR	0.08 ± 0.05	0.53 ± 0.50	0.21 ± 0.02	0.11 ± 0.09
HCN	FTIR	0.17 ± 0.09	0.43	0.45 ± 0.02	0.39 ± 0.18
Smoke	Filter	0.47 ± 0.10	0.45 ± 0.22	0.18 ± 0.04	0.39 ± 0.18

5.4.3 Models investigating human exposure

Peacock, Jones and Forney (2004) used CFAST to model a number of types of buildings (a ranch house, a hotel, and an office building with high ceilings) to investigate the relative times at which smoke inhalation and heat exposure would result in incapacitation during pre-flashover conditions. The sub-lethal effects of smoke, before thermal effects occurred, were of particular interest. The yields of gas species (CO, CO_2, HCN and HCl), and rates of heat release for these design fires, were based on the results from real-scale fire test data available. The criteria for incapacitation was based on equations for heat exposure and gas concentrations from ISO

13571. The baseline fire scenario that was chosen for the investigation was that the door to the fire room was fully open with a linearly increasing heat release rate (by 10 kW/s) until reaching 90% of the calculated minimum heat release rate necessary for room flashover. A selection of other fire scenarios were also investigated, including growth characteristics of steady, linearly increasing and increasing as t^2, with fire size from 5 to 90% of the calculated minimum heat release rate required to cause flashover for each geometry considered.

The model was also run for a partially closed fire room door scenario, however the CFAST model only includes the effect of the oxygen limitation on the heat release rate of the fire. That is, the species generation rates remain unchanged unless the model input is changed to account for such effects. Peacock et al assumed that species generation rates remained unchanged with the decreased ventilation, and only discussed the change in heat generation for this scenario. However, it was noted that recent testing had shown that severe reduction of ventilation had little effect on species generation rates (Gann 1992; Gann et al 2003).

Similar to the conclusions of previous post-flashover experimental work (Gann et al 1994) in the room of fire origin, the thermal effects would generally cause incapacitation before narcotic gas concentrations reach even 1% of lethal conditions. This is except for smouldering fires, since little heat is generated and, thus, can readily generate incapacitating exposures, especially for occupants in the room of fire origin. For buildings with large rooms adjacent to the fire room, the smoke is diluted rapidly, and incapacitation from heat is expected well before exposure to the threshold to produce significant smoke inhalation effects.

For residential buildings and other buildings with ordinary sized rooms, it was suggested that "incapacitation from smoke inhalation would rarely occur before incapacitation from heat and thermal radiation or escape or rescue" (Peacock et al 2004). Incapacitation from smoke was expected to take place only remote from the room of fire origin, occurring long after ignition. Furthermore, the exposure threshold for significant sub-lethal effects in remote rooms may well be exceeded for fires that do not proceed to flashover. It was noted that the model predictions were reliant on experimentally determined fire-generated gas yield rates, which are "almost non-existent", especially for irritant gases in room-scale scenarios. It was stated that it would be beneficial to compare these results with experimental data when it becomes available in the future. However it was noted that the model results agreed with US fire incident statistics, in that fire-related deaths attributed to smoke inhalation typically occur after a fire has progressed beyond flashover.

In general, the results from the modelling indicated that the yield of HCl would need to be 5 to 10 times higher (than real-scale test measurements) before the incapacitation effect of HCl would surpass the incapacitation effects of narcotic gases (including CO, CO_2, HCN and reduced O_2). Based on the model results, Peacock et al suggested that occupancies in which sub-lethal effects from free burning fires could affect escape and survival include multi-room residences, medical facilities, schools and correctional facilities. In addition, fires originating in concealed spaces in any occupancy would pose such a threat (Peacock et al 2004).

5.5 Tenability limits for life safety

Zero door leakage was considered by Smith (1982) to be unnecessarily over-cautious. Furthermore, it was suggested that an airtight door would be undesirable in some circumstances. This was based on the possibility of a fire developing unnoticed behind such a door until failure of the door or opening of the door that may then induce flashover, causing an uncontrollable fire.

Gross (1981b) suggested that a limiting value of 1% of the smoke density at the source throughout the rest of the building, which had been previously determined based on a review of data for smoke generation and visibility in smoke-filled room, may be extended to limiting air leakage rates. That is, requiring the air leakage rate of a closed doorset to be 1% of the flow through the open door.

Although it is the gaseous combustion products that are lethal, when considering the use of exitways, Smith (1982) suggested that it is the limitation of visibility by smoke that is considered the greatest concern. When visibility was reduced to 10 m, experiments showed that approximately 10% of people would turn back rather than continue through the smoke (Smith 1982). Ten metres was suggested as a minimum visibility requirement for escape routes, which is approximately a cold smoke concentration of 1% (units were not specified).

Suggested tenability limits, in terms of optical smoke density, were 0.2 /m (visibility 5 m) (Buchanan 2001; Jin 1978, 1981; Jin and Yamada 1990; Purser 2002) for small enclosures with short travel distances and 0.08 /m (visibility 10 m) (Jin 1978, 1981; Jin and Yamada 1990; Purser 2002) for large enclosures with long travel distances. Buchanan (Buchanan 2001) suggested an optical smoke density of 0.1 /m (visibility 10 m) for all rooms, other than small enclosures.

For irritant gases, such as those presented in Table 5, a safety factor of 0.3 is recommended to be used with the concentration likely to impair the escape of half the population to account for nearly all susceptible individuals (Purser 2002). Furthermore an optical density of greater than 0.2 /m (visibility of 5 m) was suggested to be a conservative limit for which irritant gases would be unlikely to exceed tenability limits (Buchanan 2001). A more conservative criteria, suggested by the Fire Code Reform Centre (FCRC, Fire Engineering Guidelines 1996), was an optical density of 0.1 /m (visibility of 10 m) (Buchanan 2001).

Buchanan (2001) also suggested conservative tenability criteria for convective exposure, which corresponded to a gas temperature of 333 K, and radiative exposure, which corresponded to approximately 473 K for the upper layer (i.e. less than 2.5 kW/m^2 at head height).

6. CASE STUDIES AND STATISTICS

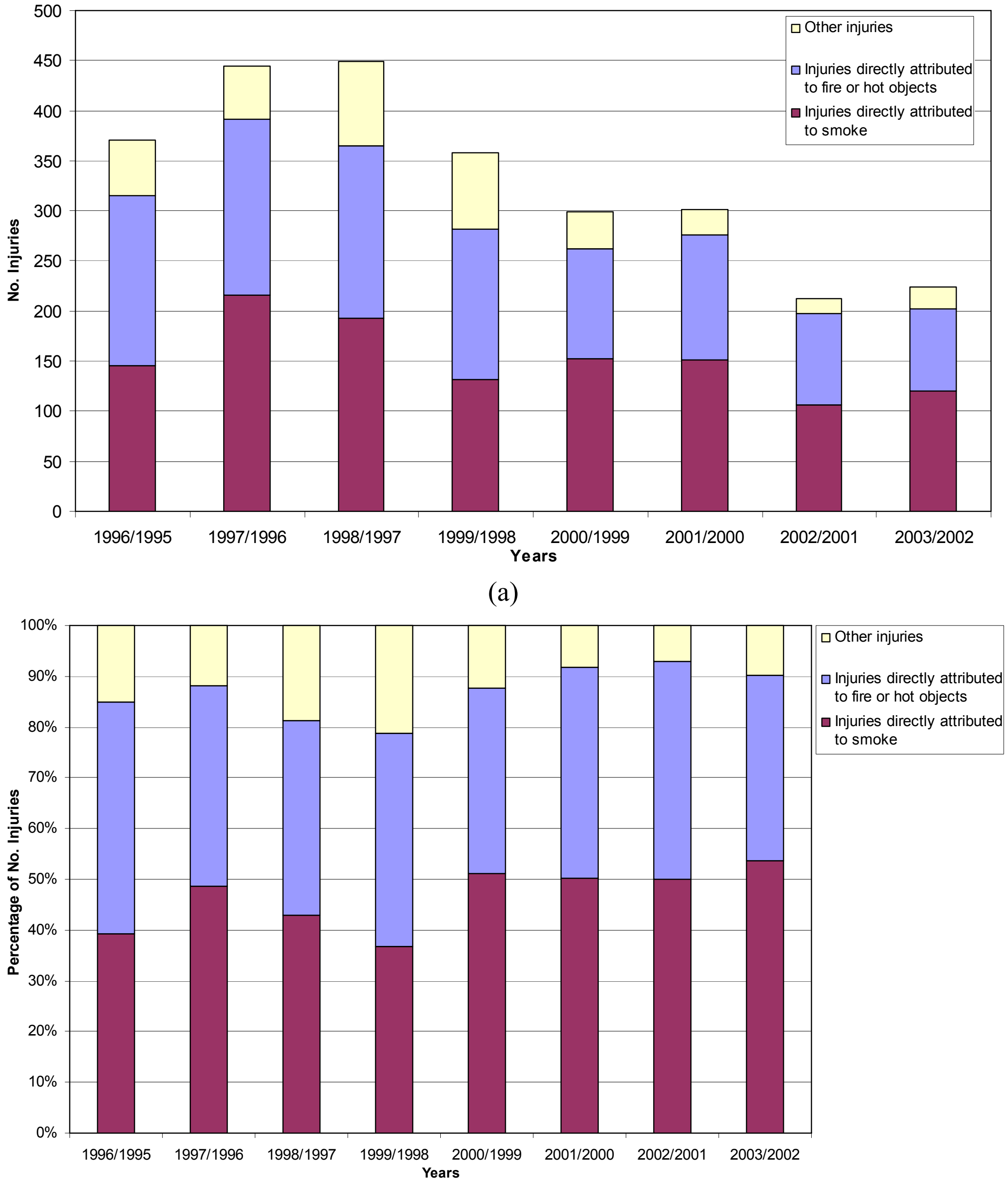
To highlight the importance of protecting occupants from smoke, a selection of statistics and summaries of case study fires that have involved smoke logging of exitways or general smoke inhalation fatalities and injuries are presented in this section. Unfortunately in most cases the details of the reasons for the smoke contamination, such as deficiencies in the current building codes, standards, maintenance or design or other reasons such as misuse, etc, are not available.

6.1 Fire death statistics – general

Approximately 60% of fire-related deaths in the UK each year are attributed to smoke (Smith 1982). For residential buildings, on average, 65% of fire-related deaths occur in the room of fire origin. Furthermore, for 50% of the fire-related deaths, the fire spread to less than one-third of the room of fire origin (Purser 2002).

Fire-related deaths, in general, in the US declined from 1979 through to 1994. However, the ratio of the number of deaths attributed to smoke inhalation to the total number of fire-related deaths increased by approximately 1% per year (Welty 1998). One attributing factor was suggested to be the increased toxicity of the composition of furnishings, finishings and other common materials. The ratio of smoke-inhalation-attributed deaths to the total number of fire-related fatalities increased from approximately 2:3 (based on old autopsy reports) to 3:4 (based on more recent statistics). Furthermore, autopsy results have also shown that the vast majority of the fire victims have carboxyhemoglobin levels in their bloodstreams sufficient to induce incapacitation or death (Pitts 2001). In the US, more than 50% of fire-related deaths occur remote from the room of fire origin, for fires that have spread beyond the room of fire origin (Purser 2002).

In New Zealand, the proportion of fire-related injuries attributed to smoke, from 1995 to 2003, was approximately 46% of the total number of injuries, as shown in Figure 7 (NZFS 1999, 2001, 2003). Fire (including burns from flames or hot objects, or scalds) was attributed to approximately 40% of the total number of injuries.



(a)

(b)

Figure 7: (a) Numbers and (b) percentage of types of civilian injuries sustained during structure fires with damage. Adapted from (NZFS 1999, 2001, 2003).

In Australia, for the period 1 July 1991 to 20 June 1996, the ratio of deaths caused by smoke inhalation to total fire-related deaths was similar to the US findings of over 3:4, for all of the Australian States and Territories (as shown in Figure 8), except for Queensland (QLD Dept of

ES 1998). Fire-death statistics for Queensland indicated that only half of the deaths are attributed to smoke inhalation, however the majority (54%) deaths attributed to burns or incineration were either young children (0 – 4 years) or elderly (> 65 years). Furthermore, people aged 65 years and over represented 26% of all fire-related deaths, but only account for 11% of the total population. In addition, children between 0 and 4 years represented 16% of the fire-related deaths, but only 7% of the total population. In general, these two demographic groups were over represented for fire-related deaths in all States and Territories. For New South Wales, the cause of 48 fire-related deaths was unknown, 81 were directly attributed to smoke inhalation, 46 were attributed to burns or incineration and 41 were attributed to a combination of smoke inhalation and burns or incineration. The two fire-related deaths, attributed to burns or incineration in South Australia, were both elderly people with limited mobility who were also in the room of fire origin. For the Australian Capital Territory, five (56%) of the fatalities were classified as being accidental or preventable and the remaining four (44%) victims died in fires that were reported as being deliberately lit.

In Scotland (Scottish Executive 2004), there were a total of 80 fire-related deaths in 2003. Sixty two percent (48 fatalities) of the total fatalities were attributed to gas or smoke inhalation, 13% were attributed to a combination of smoke and burns, and 22% were attributed to burns alone, as shown in Figure 9.

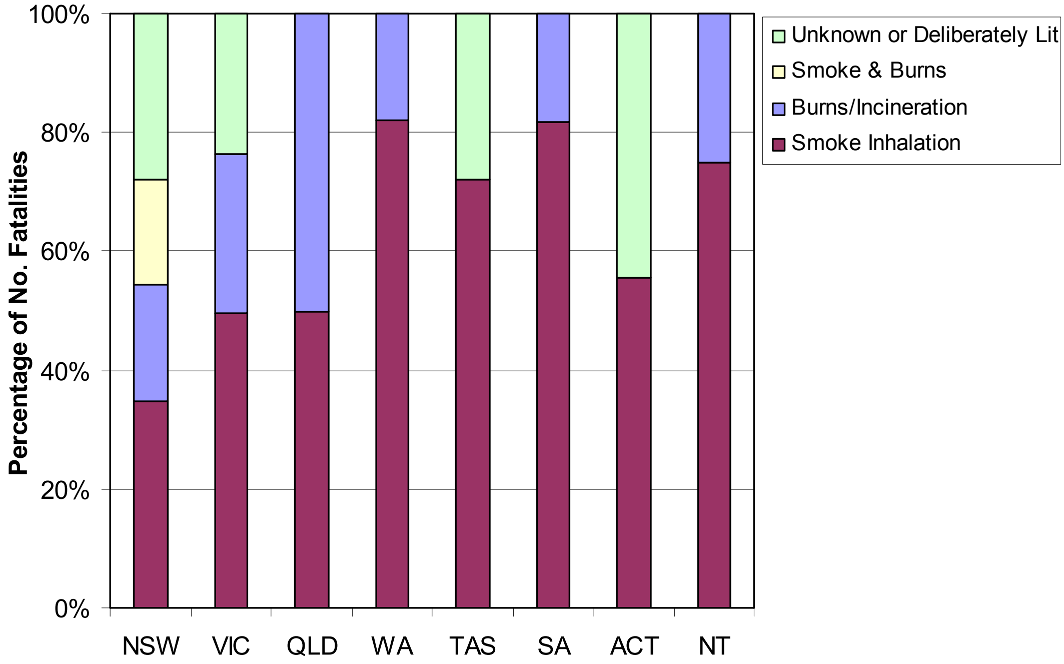


Figure 8: Fire-attributed deaths in the States and Territories in Australia between 1 July 1993 and 30 June 1996. Adapted from (QLD Dept of ES 1998).

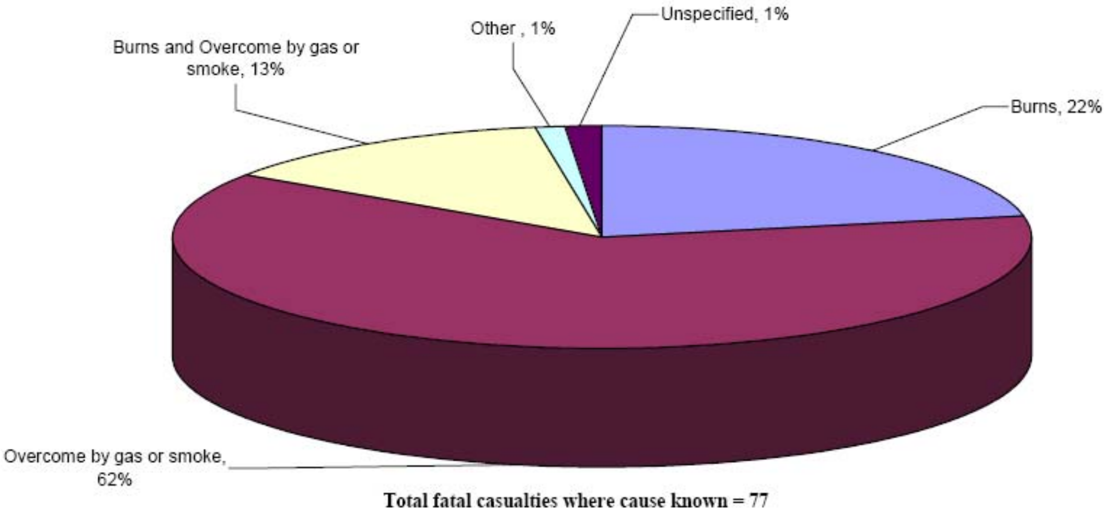


Figure 9: Proportions of the total fire-related fatalities that occurred in Scotland in 2003. Extracted from (Scottish Executive 2004).

In the United Kingdom, the majority of fire-related fatalities were consistently attributed to smoke inhalation for reported causes (for 1990 – 2002, (National Statistics UK 2002; National Statistics UK 2004)), as shown in Figure 11. Smoke inhalation alone was attributed to 45% of all the fire-related civilian fatalities that occurred between 1990 and 2002, as shown in Figure 10. Burns alone were attributed to 27% of all cases and a combination of burns and smoke inhalation was reported as the cause of 17% of fatalities. Similarly, smoke inhalation was consistently the most common cause of fire-related civilian injuries that occurred in the period from 1990 to 2002, as shown in Figure 12. Smoke inhalation was also the most common cause of fire-related injuries (61%), as shown in Figure 13. Whereas burns alone were attributed to 25% of all injuries and a combination of burns and smoke inhalation made up only 5%.

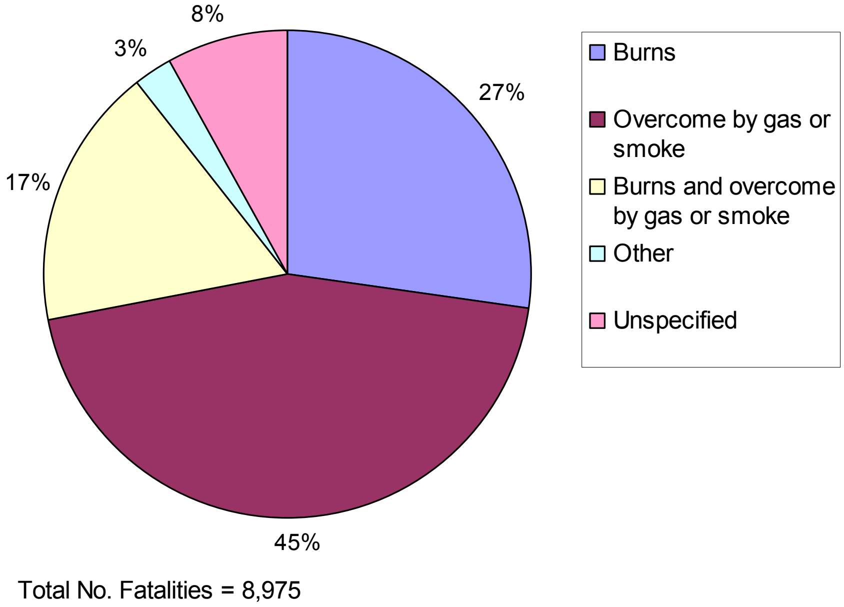
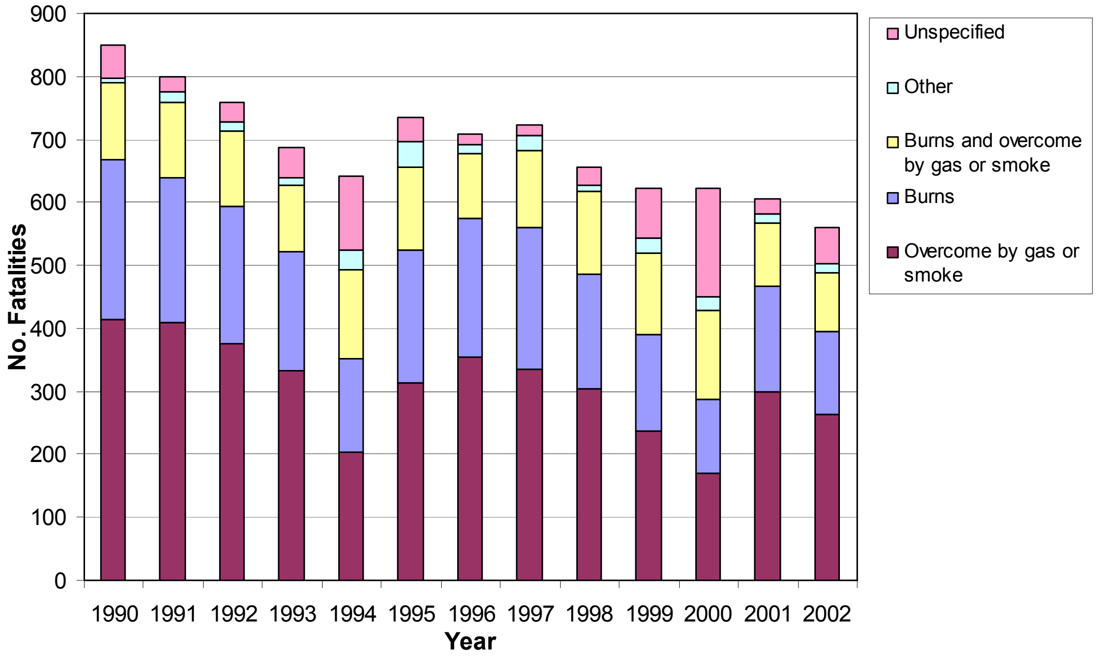
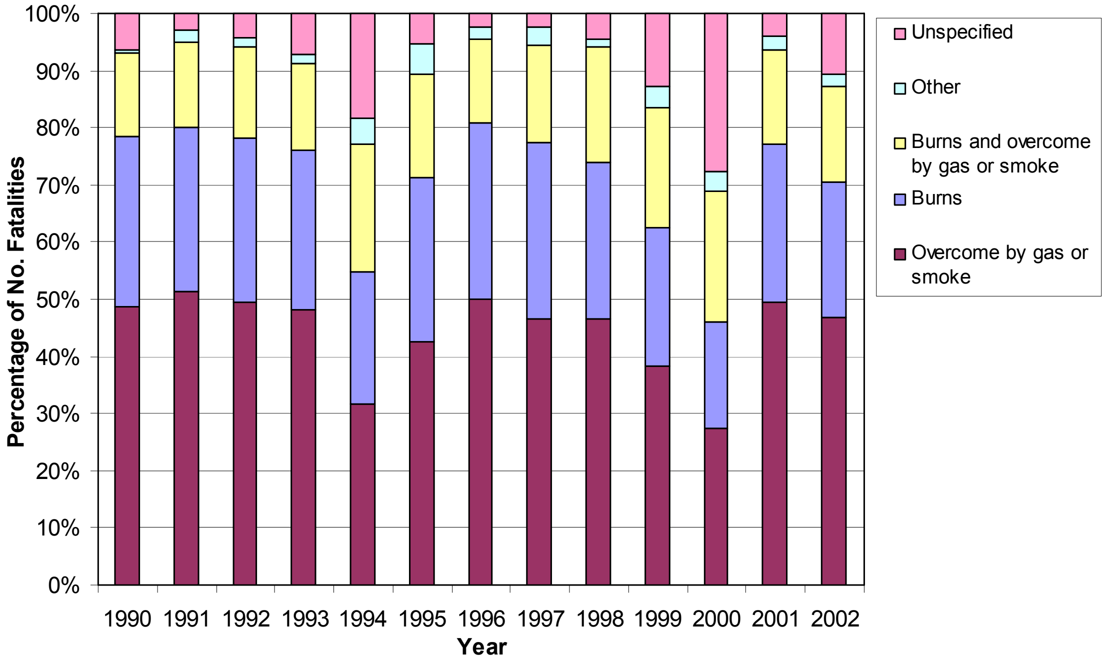


Figure 10: Overall proportions of the cause of death for all fire-related fatalities that occurred in the UK in 1999 – 2000. Adapted from (National Statistics UK 2002; National Statistics UK 2004).

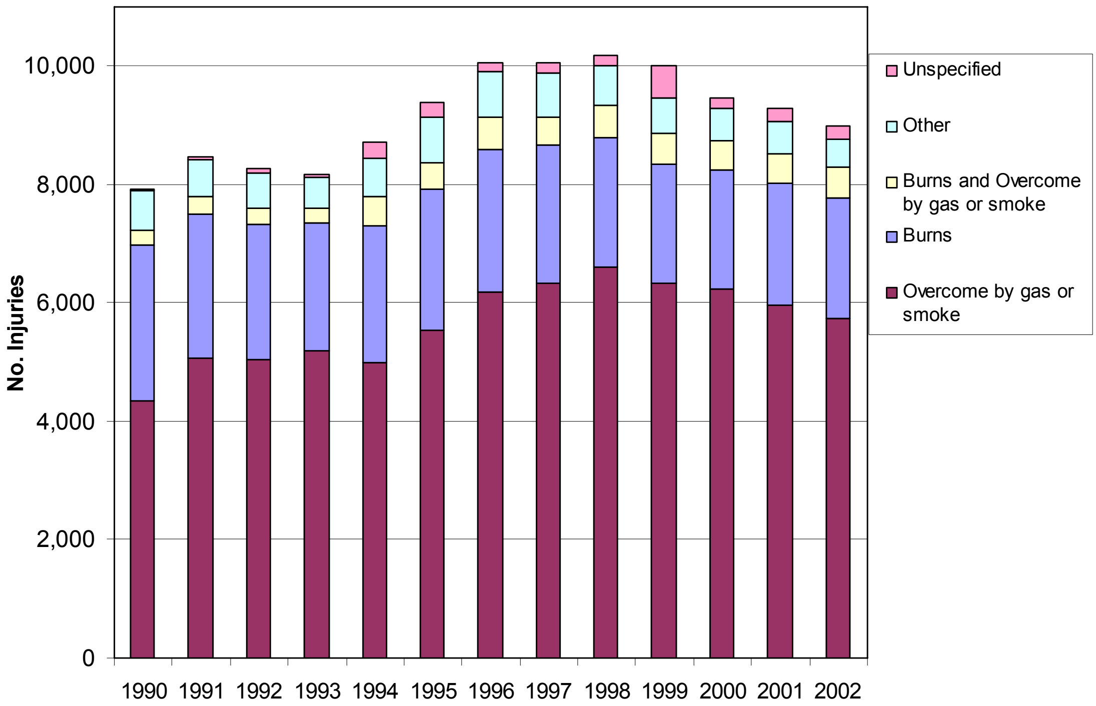


(a)

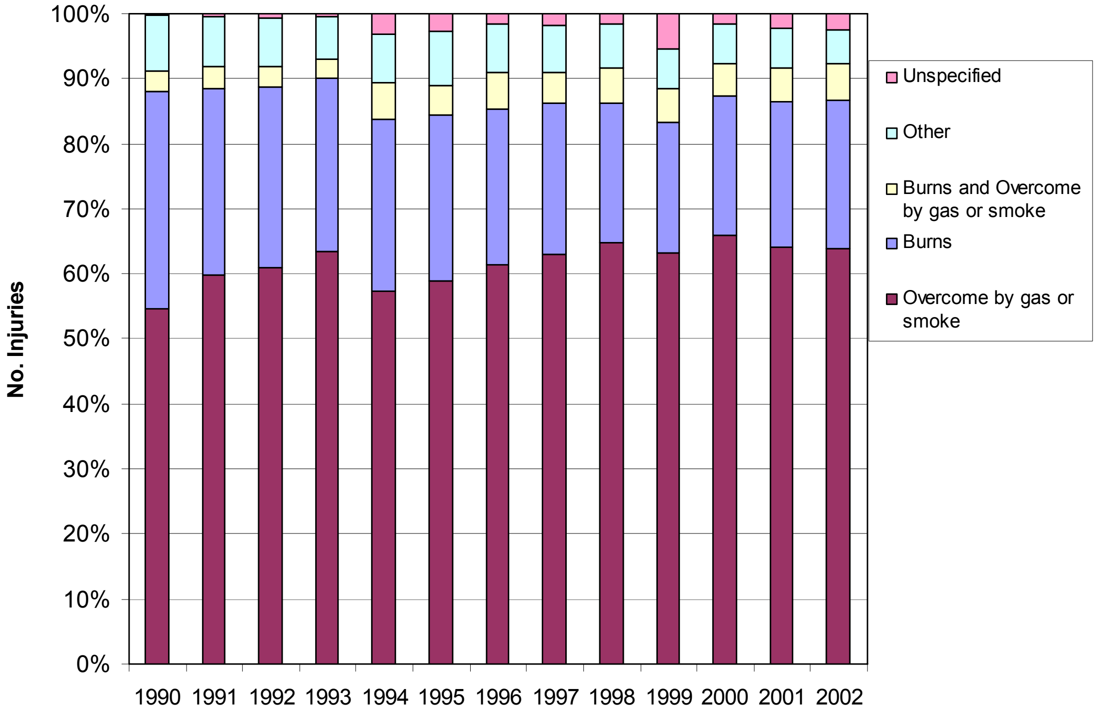


(b)

Figure 11: (a) Total and (b) percentages of fire-related fatalities that occurred in the UK over the period 1990 – 2000. Adapted from (National Statistics UK 2002; National Statistics UK 2004).



(a)



(b)

Figure 12: (a) Total and (b) percentage of fire-related injuries (not including shock only or precautionary checkups) that occurred in the UK over the period 1990 – 2000. Adapted from (National Statistics UK 2002; National Statistics UK 2004).

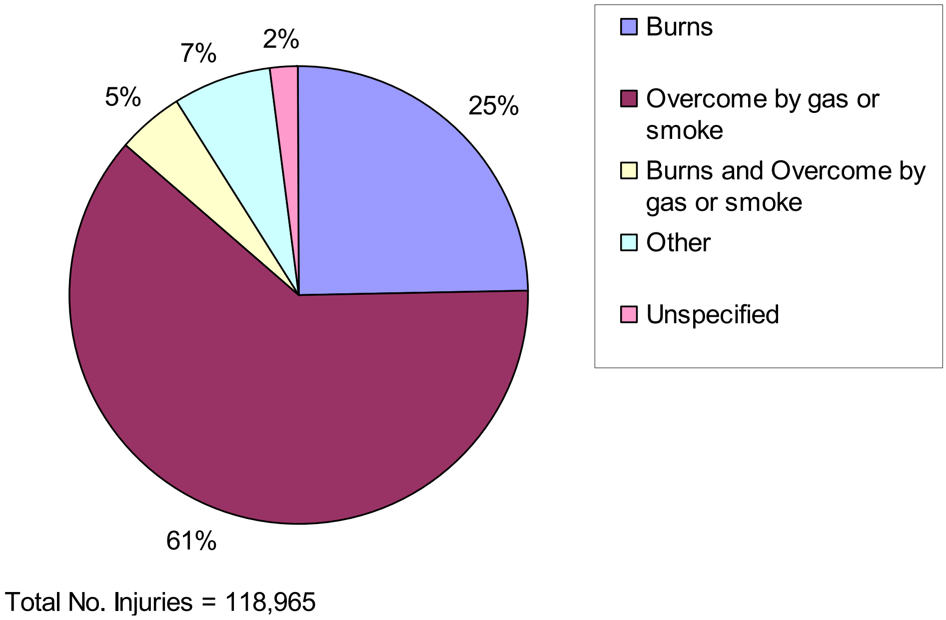


Figure 13: Overall proportions of the cause of injuries for all fire-related injuries (not including shock only or precautionary check-ups) that occurred in the UK in 1999 – 2000. Adapted from (National Statistics UK 2002; National Statistics, UK 2004).

Similarly, statistics from the US, over the period from 1979 to 1990, indicated that the major cause of death for fatalities that occurred in structure fires was smoke inhalation (71%, 36455 of 51233), whereas burns were attributed to approximately 24% of the fatalities, as shown in Figure 14 (Hall and Harwood 1995). From 1979 – 1990, the overall number of fatalities per year decreased (by approximately 25% overall from 5998 in 1979 to 4181 in 1990). However the proportion of fatalities attributed to smoke inhalation increased over this period, as shown in Figure 15.

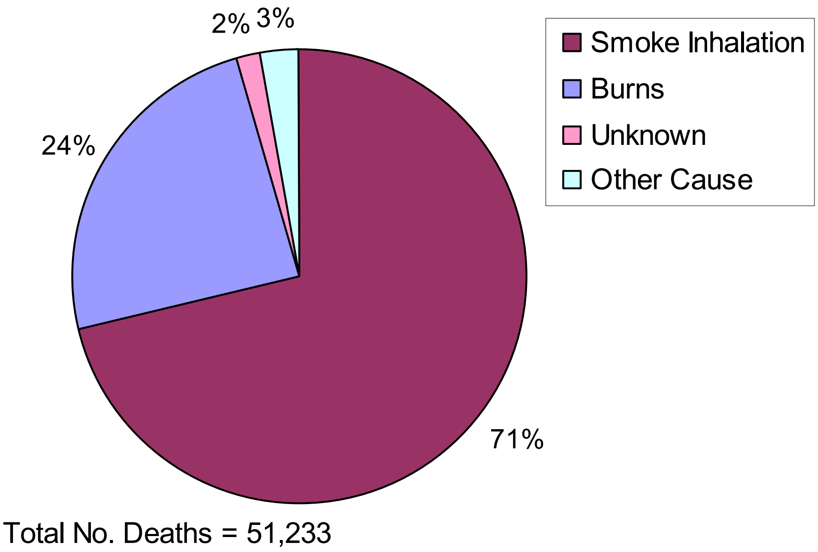
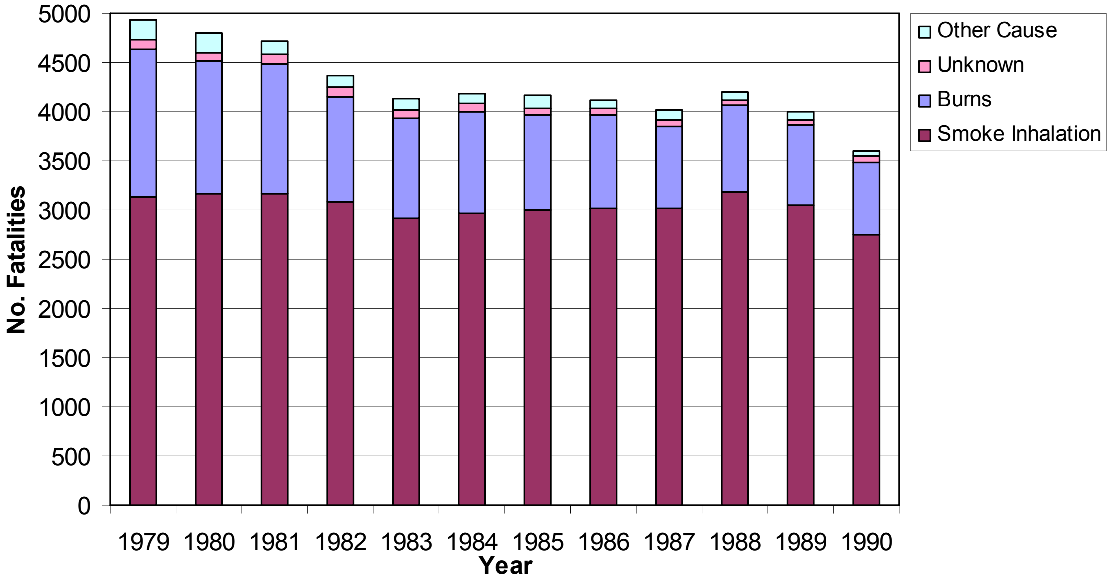
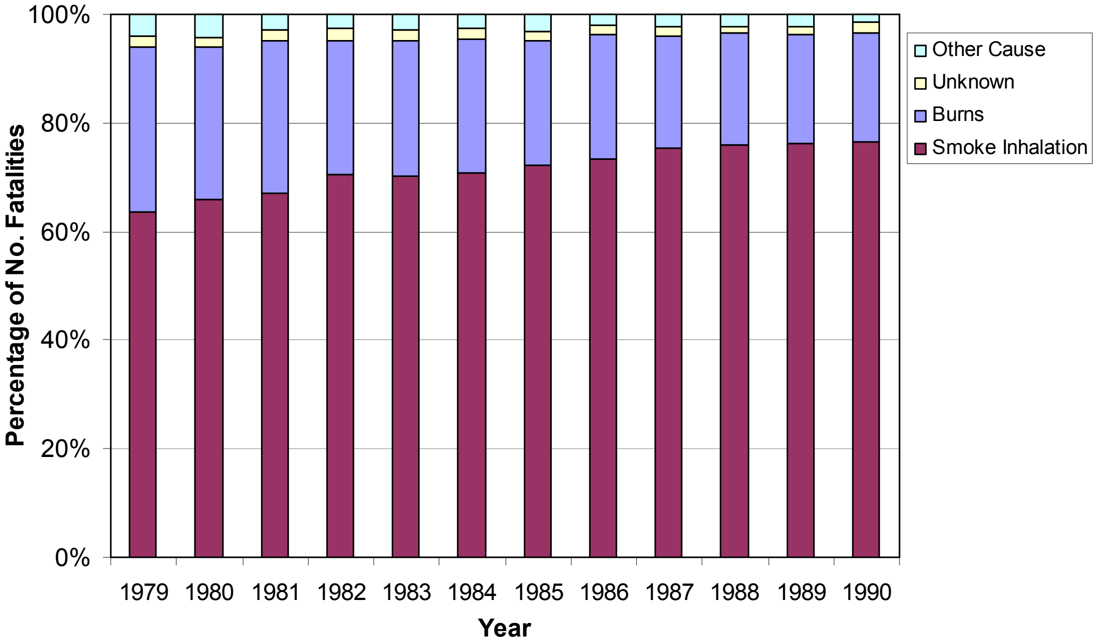


Figure 14: Distribution of causes of death for structure fires that occurred between 1979 and 1990 in the US. Adapted from (Hall and Harwood 1995).



(a)



(b)

Figure 15: (a) Total number and (b) percentages of the causes of fatalities that occurred in structure fires in the US (1979 – 1990). Adapted from (Hall and Harwood 1995).

Smith (1982) suggested that there are no reliable estimates of the cost of damage attributable to smoke damage, however typically smoke damage is more extensive than fire damage, especially when food or electronic equipment are involved.

6.2 Fire death statistics – residential dwellings

For the period from 1996 to 2000 in the London Boroughs, the most frequent number of deaths were recorded for residential dwellings (86% of the total number of fire deaths or 358 fatalities), as shown in Figure 16 (Holburn 2001). Similarly, for the period from 1994 to 1998 in the US, NFPA report statistics for children aged 6 – 19 show that 73% of all fatalities resulting in burns and smoke inhalation occurred in the home (Cunningham 1999).

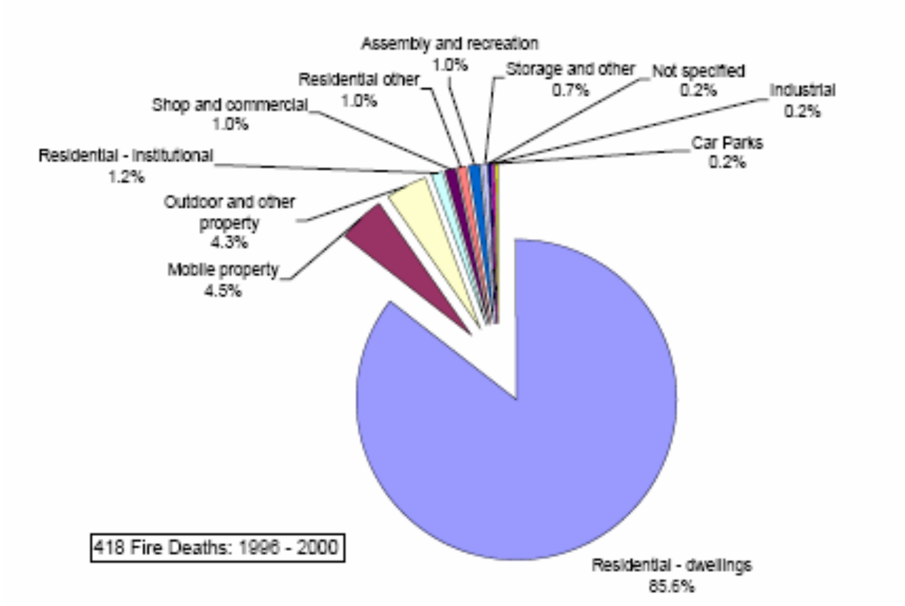


Figure 16: Proportions of the type of property in which fire deaths were recorded from 1996 to 2000 in the London Boroughs. Extracted from (Holburn 2001).

The most frequent cause of accidental death recorded for the London Boroughs (1996 – 2000) was being overcome by smoke inhalation (42% of the total accidental fire deaths occurring in dwellings or 117 fatalities), as shown in Figure 17 (Holburn 2001). Furthermore, 25% of the accidental deaths occurring in dwellings (69 fatalities) were due to both smoke inhalation and burns. For home fires NFPA statistics show that, in the US, “the ratio of smoke inhalation deaths to burn deaths is 2-to-1 if death certificates from 1999 are used, 3-to-1 if death certificates prior to 1999 are used, and 4-to-1 if NFIRS data are used” (Hall 2003a). In the UK, this ratio was approximately 3:2 for the period 1995 to 1999 (Hall 2003b). The differences in this ratio for the two countries is likely to be associated with the ratio of numbers of deaths in home fires where the fatality is located in the room of fire origin to the number where the fatality is located outside of the room of fire origin is nearly 2:3 in the US and 3:2 in the UK (Hall 2003b).

In Scotland (Scottish Executive 2004), in 2003, 61 fatalities (76% of the total fire-related deaths) occurred in residential fires. This was approximately eight deaths per 1000 residential fires, which was comparable to the other countries in the UK for the same year. The total number of fire-related injuries in Scotland in 2003 was 1880; of these 1625 (86%) occurred in residential fires.

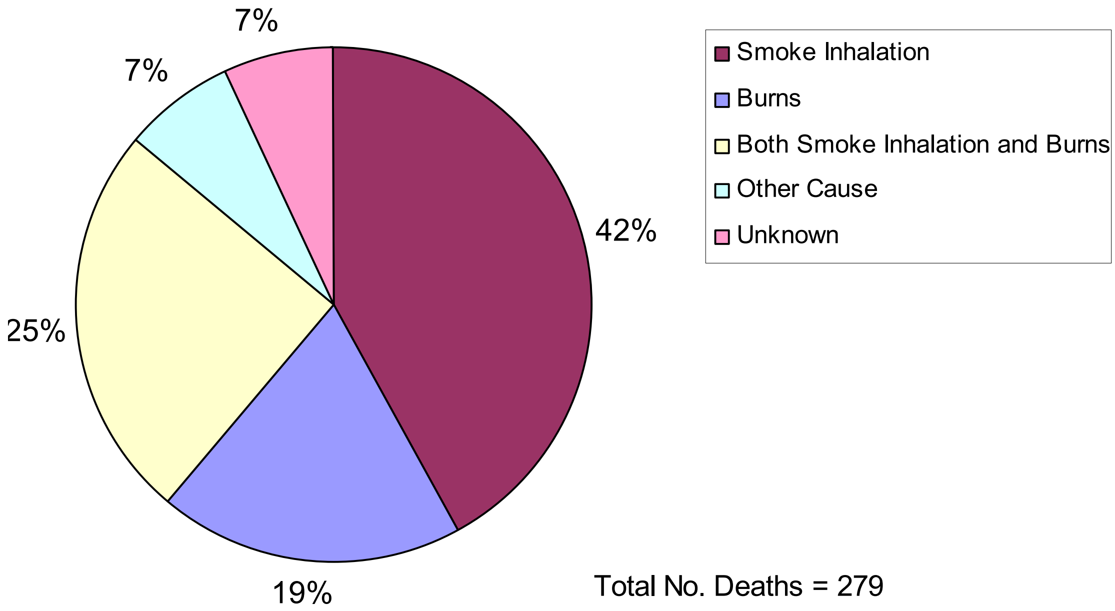


Figure 17: Proportions of the cause of accidental death in fires in dwellings in London from 1996 – 2000. Adapted from (Holburn 2001).

For all the countries considered, it is noted that the highest proportion of fire- and smoke-related casualties historically occur in private, single family dwellings. Single family dwellings also have the lowest level of fire precautions required in the New Zealand, Australian and English and Welsh building codes. Where these dwellings are on two or more levels, a single stairwell escape route from the upper floor(s) is in compliance with regulations. Fire doors may only be required in exceptional circumstances and there is no requirement at all for smoke control doors.

6.3 Case studies

Following are a selection of summarised examples of fires with smoke inhalation deaths and injuries remote from the fire room. This list is not intended to be comprehensive, but rather reflects fires with smoke inhalation that have been the subject of investigation and for which some detailed information has been made publicly available. A summary of theses case studies, in addition to other select cases, is included in Appendix A, Table 13.

6.3.1 Multi-storey apartment buildings

A fire started in the living room of an apartment on the third floor of an occupied three-storey building in Florida at 12:37 p.m. (Tremblay 2002). The building was equipped with a fire detection system and wet-pipe sprinklers. A smoke alarm in the apartment of origin alerted the occupants, who called the fire brigade. Firefighters arrived four minutes later to find smoke coming from the roof and the sprinkler system operating and controlling the fire. The fire was quickly extinguished. A 40-year-old man in the apartment next to the unit of origin suffered from smoke inhalation.

A fire started, at approximately 11 p.m. on Wednesday (12 November 2003), in the basement of a four-storey apartment building in West Rogers Park, Chicago (Rees 2003). Three people died before they could get out of the smoky building and 19 others were injured.

6.3.2 Multi-storey apartment buildings with offices on the ground floor

A fire started on an upholstered sofa in an office on the first floor of a 10-storey apartment building on East 50th Street, New York City on 11 January 1988 (Kirby 1988). The building had 120 units and had been constructed in the 1920s. Renovations had introduced decorative wood panelling into the office of fire origin that did not meet the current code. However since “the renovation did not exceed 20% of the cost of the building, the new code did not apply” (Kirby 1988). All exit and apartment entrance doors were metal fire doors, with a 17 mm gap at the bottom to promote air circulation. There was no sprinkler system, fire alarm system, emergency lighting or illuminated exit signs.

The cause of the fire was unknown. The office fire spread to involve the combustible wall linings in the office. Glass doors between the area of fire origin and the lobby had melted, where the open fire doors of two stairwells allowed smoke to pass into upper floors. One stairwell in the rear of the building was available for evacuation. Four fatalities (one from smoke inhalation inside an apartment and three from combinations of smoke inhalation and burns in a stairwell) and at least two injuries occurred (attributed to smoke inhalation). Five firefighters were also injured (Kirby 1988).

6.3.3 Multi-storey hotel complexes

At approximately 7 a.m. on 21 November, 1980, a fire started in the wall on the first floor, because of faulty wiring, at the MGM Grand, Las Vegas (Klote 1990b; Puit 2000a, 2000b). The hotel had 26 storeys. Approximately 5000 people were in the hotel when the fire started. Smoke spread throughout the building via a stairway, laundry chutes that did not seal and the HVAC system. No sprinklers were installed. Some people were exposed to smoke for hours before rescue. It was assumed that smoke inhibited visibility sufficiently to disorientate even hotel workers who should have been familiar with the layout, because the bodies of three security guards were found less than 4.5 m from an exit to the outside. Eighty-four people died, most from smoke inhalation. The majority of deaths occurred on floors far above the fire.

6.3.4 Hospitals and care facilities

A fire started in the bedding of one room at Greenwood Health Center, Hartford, Connecticut at 2:40 a.m. on 26 February 2003 (Wolf 2003). The nursing home cared for elderly and mentally challenged adults, and 148 coma and psychiatric patients. Possibly a nurse, trying to save one of the fireroom’s occupants, failed to close the door to the room where the fire started. At least one elderly patient, who was in a room separated from the area of the fire by smoke doors, was treated for smoke inhalation and later died. However, it was reported that most of the 16 patients who died as a result of the fire were in rooms with open doors.

Similarly, a fire started in a patient’s room on the second floor in the west wing of a five-storey, fire-resistive hospice, in Michigan, at approximately 6:30 a.m. on 15 December 1985 (Isner 1987). The physical and mental state of many of the hospice’s patients made self-escape from the fire impossible. Smoke filled the reception area, joining the north and west wings, and accumulated in areas of the floors above the fire. Firefighters extinguished the fire in approximately 15 minutes. The alarm was initiated by use of a manual pull station and all magnetic smoke doors were released and closed, except one in the wing of the fire. Six patients perished during the fire and two subsequently died from fire-related injuries over the following days. All the deceased were patients who had been located in the wing and on the floor of fire origin and were from rooms where doors were left fully or partially open, because the doors had not been properly latched. Smoke was reported as the primary cause of death or injury.

6.3.5 Office buildings

A fire started on the 29th floor of the 43-storey building of the LaSalle Bank corporate headquarters in Chicago on 6 December 2004 (Rees 2004). Office workers were escorted out of the building by firefighters. A witness described the smoke as “horribly thick” and the halls were “completely dark”. Thirty-seven people were treated for smoke inhalation.

A fire started on a Friday evening (15 October 2004), located in a storage room on the 12th floor of a 35-storey government office building in Cook County, IL (Coffee 2003; Fidler 2003). Smoke filled the two stairwells of the building. A witness on the 32nd floor smelt smoke as he headed to the stairwell. Fire had gutted a storage room and damaged much of the 12th floor. Firefighters found about a dozen people unconscious in a stairwell and on the 22nd floor. Six were dead from smoke inhalation. The victims in the stairwell had been searching for unlocked doors in the smoky stairwell. The un-pressurised stairwell was fitted with automatic door locks. The building had an alarm system, but no sprinklers above the first floor. A witness reported that when evacuating workers reached the 12th floor they were told by firefighters to go back up. However the doors were all locked from within the stairwell until the 27th floor.

A fire started in the basement in an multiple-occupancy building in Louyang, China on 25 December 2000 at approximately 21:35 (People's Daily – Luoyang 2000; People's Daily – Luoyang 2001; Hewitt 2000). The fire was not extinguished for more than three hours. Three hundred and nine people died from suffocation: more than 200 people at a Christmas party in a dance hall on the 4th floor and dozens of others were in stores and offices on other floors. The building was not fitted with a sprinkler system, fire exits had been blocked and prior safety reports had been falsified.

6.3.6 Passenger trains

A fire on an overnight train in Nancy, France, (on Wednesday 6 November 2002 at 2 a.m.) started in the compartment of a train attendant (Rees 2002). A sleeping car was filled with smoke. Twelve people died from smoke inhalation and panicked passengers smashed windows to jump to safety. The train had no smoke detectors and cigarette smoking was allowed in designated cars.

7. DOORSET DATA AND CHARACTERISTICS

The most important characteristic of a doorset that affects the leakage through a closed door is the leakage area, i.e. the gaps and clearances of the doorset. A summary of the range of gap geometries and types of seals or gaskets is presented, as well as suggested door sealing practices. It is noted that several manufacturers currently have door and seal combinations that have been tested to door leakage standards, including AS/NZS 1530.7, available on the New Zealand and Australian markets, even though this is not required by either of the building regulations.

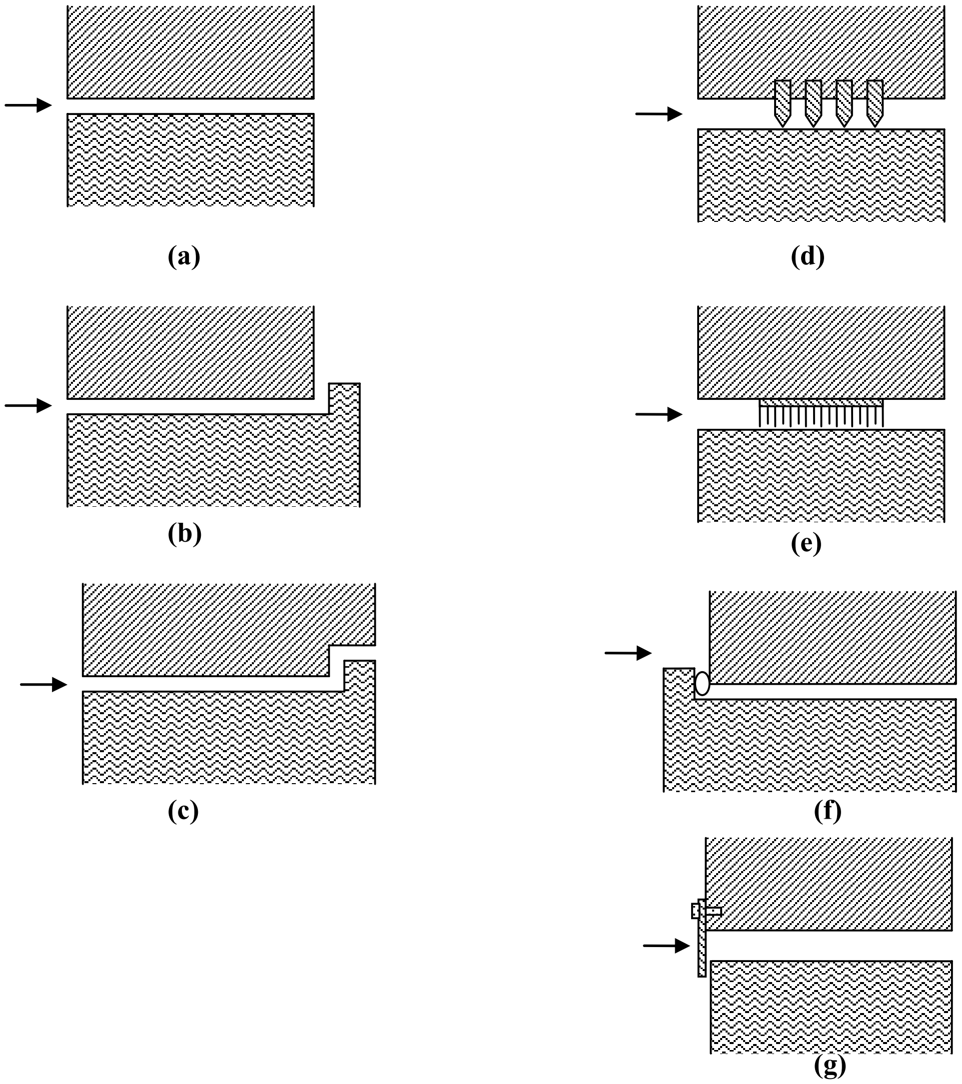
7.1 General characteristics

General cross-sectional shapes for leakage paths associated with doorsets may include (Gross 1990, 1991):

- straight-through, see Figure 18 (a)
- single-bend, see Figure 18 (b)
- double-bend, see Figure 18 (c)
- labyrinth – consisting of one or more blades that may be straight or angled between the leaf and frame (ifsa 2000), shown as a “wiping” seal in Figure 18 (d)

- fibres – consisting of many individual short or looped fibres, where there may be leakage paths between adjacent fibres, shown as a “wiping” seal in Figure 18 (e)
- baffle at the leading (“compression” seal) or trailing (“wiping” or “compression” seal, depending on the design) edge of the leaf, e.g. a gasket/seal between the leaf and frame or a flexible strip at the sill, see Figure 18 (f) and (g)
- or various combinations of these.

In general, there is an additional level of complexity when deformation of soft goods and wear sustained during operation is considered when estimating the shapes and tolerances of the gaps for leakage (ifsa 2000). Whether a seal is designed to be a wiping or compression seal depends on the location relative to the direction of operation of the leaf. It is noted that different sealing materials and methods may have a more appropriate orientation than another, and that sealing the head and jamb poses a different problem to sealing the threshold.



(a) **(d)**

(b) **(e)**

(c) **(f)**

(g)

Figure 18: Examples of general schematics for cross-sectional shapes associated with leakage paths through doorsets

General types of smoke seals or gaskets:

- Brush (bound short lengths of fibres – similar to a toothbrush):
    - typically made of Nylon
    - not widely used as smoke seals (Mann 2006)
    - do not require activation by temperature or smoke, therefore may be available for inhibiting cold smoke.
- Pile (woven fibres – similar to carpet):
    - sometimes erroneously referred to as "brush" (Mann 2006)
    - can provide a physical barrier to a large proportion of smoke (Pyatt 1990)
    - do not require activation by temperature or smoke, therefore may be available for inhibiting cold smoke.
- Interlocking pile:
    - individual fibres with a tri-lobal cross-section that, when under a pressure differential, induces an interlocking characteristic (Mann 2006)
    - work without activation by temperature or smoke, therefore available for inhibiting cold smoke
    - may inhibit hot swirling smoke (Pyatt 1990).
- Foam:
    - a wide range of types of "foam" are available: from (cheap, DIY) open-cell varieties to purpose designed closed-cell extrusions with integral surface skins and shape-specific profiles (Mann 2006)
    - work without activation by temperature or smoke, therefore may be available for inhibiting cold smoke.
- Rubber:
    - a wide range of materials considered as "rubber" are available (Mann 2006), therefore care must be applied when selecting appropriate material properties
    - depending on the material used, failure may start to occur at about 393 K (Welty 1998)
    - however, many types of rubber may not be affected by temperatures in excess of 473 K. For example, some grades of silicone rubber may tolerate short-term exposure of approximately 573 K (Mann 2006)
    - work without activation by temperature or smoke, therefore may be available for inhibiting cold smoke.

- Intumescent:
    - if exposed, may be vulnerable to physical abuse (Pyatt 1990), therefore would have a life expectancy dependent on maintenance as would any similar part of a door assembly
    - if enclosed (e.g. behind a metal capping over the edge of the leaf etc), to provide a physical barrier to direct impingement on the intumescent during operation, the intumescent would have a robust life expectancy
    - can begin to activate at temperatures about 373 K (Pyatt 1990), therefore is not intended to inhibit smoke before this temperature.
    - may be integral with another sealing system that will inhibit cold smoke to provide protection for a wider range of temperature than either seal individually.

Suggested general doorset sealing practices:

- Doorset configuration must be taken into account when choosing the most appropriate sealing technique. For example, a door assembly for a single leaf with a single direction of swing would require very different sealing practice in comparison to a double leaf assembly with bi-directional swing (ifsa 2000).

- Continuity of the seal around hardware positions must be maintained (Mann 2006).

- Permanent mounting of seals, to protect against easy removal or being torn off with wear (Welty 1998).

- Use of seals that are mounted on the surface of the stop or mortised into the frame or leaf, so clearances of the doorstop are not interfered with (Welty 1998). This is to ensure the operation of the door is not inhibited.

- Use of a combination of seals to effectively stop both cold and warm smoke (Welty 1998).

- Selection of sealing material appropriate to the required performance under expected normal-wear conditions and fire conditions, including temperature and chemical concentrations (Rose 1997).

- Sealing products that could detrimentally affect the rating of the doorset cannot be used (Rose 1997).

- Possibly the most controversial and important test procedure in ANSI A156.22, “Door Gasketing Systems”, is for measuring the closing force of a doorset (including latching) (Rose 1997). It is particularly important for anyone, regardless of age, size or ability, to be able to secure a smoke door.

- The general descriptions of “cheap” or “easy to replace” are only comparative descriptions. This must be considered in terms of the life of the doorset. For example, a cheaper quality product may require more frequent replacement, which may alter the actual financial savings that might be attached the subjective descriptions of “cheap” or “easily replaceable”. So “cheap and easy to replace” should not be the dominant criteria for choosing one smoke stopping method over another (Mann 2006).

- A survey of 7000 fire-check doors (which were intended to be kept closed) in British offices in 1970 indicated that 18% were either propped open or obstructed so that they would not close (Heselden and Baldwin 1976). This figure was 39% for institutional buildings.

- A balance between ease-of-opening and latching of door assemblies and the smoke leakage performance is important (Mann 2006).

8. EXPERIMENTS AND RESULTS

The majority of experimental investigations of smoke movement have focused on the general movement in buildings, and few have included detailed results of the effects and measurement of the smoke leakage of doorsets. A summary of the available literature on experiments and results associated with the leakage of smoke through doorsets is presented. This is followed by a summary of a selection of experimental investigations of the leakage of other assemblies. Depending on the details of the objective and method of the experiment(s) either leakage has been investigated in terms of air leakage or smoke leakage. Air leakage provides more general information on leakage for various temperatures and/or pressures, whereas smoke leakage is also dependent on the concentration and properties of the smoke on the fire-side of the door assembly. A summary of a selection of experimental investigations into pressurisation and ventilation techniques for exitways of multi-storey buildings is also presented. A summary of the suggestions for possible methods for measuring the air leakage of a doorset is presented, including the range of expected or estimated in-situ cross-door pressures, the pressure conditions required according to fire-resistance standards when testing a doorset, in-situ leakage testing of doorsets, and some alternative leakage measurement techniques.

8.1 Air leakage through doorsets

In 1967, H.L. Malhotra (Butcher 1974) concluded that investigations of the leakage through doorsets indicated that rebated doorsets could be used for smoke stopping if the gap between the door and the frame did not exceed 3 mm. However there is a wide range of values reported for air leakage rates through doorsets, even for doorsets of similar construction, as shown in Table 8 (Gross 1981b). In addition, it is to be noted that these experiments were carried out before the ISO 5925 series of reproducible standards, using full-sized door assemblies, were internationally adopted. Furthermore, current professional sealing systems are known to deliver far more effective performance than a rebated door edge, and a unsealed rebated door edge would not provide adequate smoke protection (Mann 2006).

Leakage rates have been shown to change with the local temperature of the smoke adjacent to any gap (Karlsson and Quintiere 2000; Zukoski 1978). The range of smoke temperatures over the height of a doorset may change according to the stage of fire development and location of the fire relative to the door. A measure of the change in the local conditions is indicated by the change in smoke layer height. For example, the proportion of the dimensionless lower layer height in the fire room changes with time, heat release rate and location of a leak, as shown in Figure 19 (Karlsson and Quintiere 2000), where y is dimensionless smoke layer height, $\dot{Q}^*$ is dimensionless heat release rate and τ is dimensionless time. The dimensionless smoke layer height, y, is calculated by:

$$y = \frac{z}{H}$$

Equation 6

where z is the height of the lower layer in the room, and H denotes the height of the room. The dimensionless heat release rate , $\dot{Q}^*$, is calculated by:

$$\dot{Q}^* = \frac{\dot{Q}}{\rho_a C_p T_a \sqrt{g} H^{5/2}}$$ Equation 7

where $\dot{Q}$ denotes the heat release rate, g denotes gravitational acceleration, ρ denotes density, T denotes temperature, C_p denotes specific heat at constant pressure and the subscript, a, denotes ambient conditions. The dimensionless time, τ, is calculated by:

$$\tau = t\frac{H^2}{S}\sqrt{\frac{g}{H}}$$ Equation 8

where t denotes time and S denotes the floor area of the room.

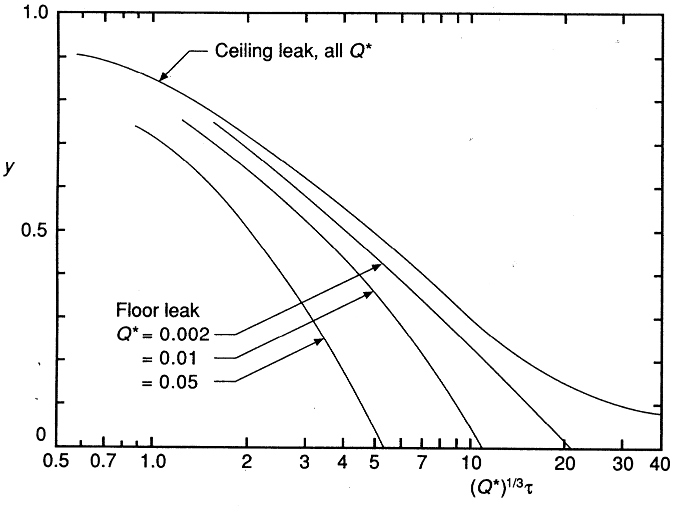


Figure 19: Dependence of dimensionless smoke layer height on time and heat release rate. Extracted from (Karlsson and Quintiere 2000).

Klote (1989, 1990b, 1990a) performed full-scale smoke control tests in a seven-storey building that was scheduled for demolition. Various combinations of closed, open and ajar (by 13 mm to simulate a door warped due to heat) stairwell doors were investigated. However the study focused the effect of smoke control on smoke movement within the building and the leakage characteristics of the stairwell doors were not reported. Comparison of the smoke obscuration results between the closed and open variations of the 2nd (fully closed and 13 mm ajar) and 7th (fully closed and fully open) floor stairway doors, for the unsprinklered case with no mechanical ventilation of the fire floor or pressurisation of the stairwell and closed basement door, showed little difference in the 3rd floor (approximately 0.05 /m, 30 minutes after ignition) results. However the smoke obscuration 30 minutes after ignition on the 7th floor increased from approximately 0.03 /m, for the closed door scenario, to 0.25 /m, for the open door scenario.

Kandola (1986) used experimental (wind tunnel facilities) and computer modelling techniques to investigate the effect of outside wind on smoke movement associated with cross-door pressures in a five-storey building. Results indicated that the pressure distribution over the building associated with the wind was important. In addition, it was suggested that generalisations of the pressure distribution, over the height and downwind distance of the building, may significantly affect the modelling results.

Examples of typical pressure differences across openings during fully-developed fires have been measured. The values ranged from 0.037 – 0.147 Pa for a burning rate of 4.55 kg/min at a temperature of 1140 K and an opening of 1.84 m^2 (a door) or 3.7 – 14.7 Pa for an opening of 0.18 m^2 (a small window) (Drysdale 1985; Fung 1973).

Table 8: Estimated and measured door leakage rates at a cross-door pressure of 25 Pa. Adapted from (Gross 1981b, 1981a).

Type	**Description**	**Leakage Rate per Unit of Gap Length (m3/h.m)**
Interior stair door	Gap width of 2.0 mm	38
	Gap width of 4.6 mm	92
Elevator door	Gap width of 4.8 mm	100
	Gap width of 6.8 mm	140
Installed office door		
single-leaf, with catch	Computed gap width of 1.9 mm	29
without catch	Computed gap width of 3.7 mm	55
double-leaf	Computed gap width of 3.2 mm	48
Installed elevator door	Computed gap width of 5.9 mm	88
Interior wood door	30 minutes fire rating, without seals, average rebated clearance 0.6 mm	8
acoustic door	60 minutes fire rating, double seals along four edges	0.5
Interior steel door	60 minutes fire rating, single seal all edges except bottom	16
Exterior steel door [a]	Weather-stripped on four edges and special bottom corner seal	0.2 – 0.8
Interior wood door	Threshold with 7 mm stop	> 15
	with sealing strips in door frame	5
	and threshold	0.3
	Hung as in use	> 40
	with 25 mm stop	> 40
	and smoke seal	20
	and threshold taped	1.3
Interior door	90 minutes fire rating, without seals	30
	Wired glass in aluminium frame, seals along four edges of door and frame	7
	Wired glass panels (2) in steel frame seal on all edges except bottom	24

[a] Measured at a cross-door pressure of 75 Pa.

Klote and Tamura reported leakage areas for various sections of buildings (with doors opened and closed) from buildings used in experimental investigations associated with smoke control in multistorey buildings, similar to those values presented in Table 9 (Klote and Tamura 1986; Tamura 1975; Tamura and Klote 1987). Klote (1995) discussed the general state of smoke control research, including stairwell pressurisation systems. Klote summarised the debate of stairwell pressurisation as either airflow should be used to prevent smoke from entering stairwells on the fire floor, or keeping doors closed is preferable to using airflow, which may supply additional oxygen to the fire. Experimental results using airflow to stop smoke from flowing through a stairwell doorway resulted in supplying enough air to the fire to increase the burning rate by a factor of 10. Instead, it was suggested that stairwell doors are normally closed, except for short times when people are entering or exiting the stairwell. In addition, if a person on the fire floor opened a stairwell door, a small amount of smoke may enter the stairwell during an interval of a few seconds. Therefore it was considered that this should not result in untenable conditions. It was suggested that people would not use the door to the floor of the fire, because they would not be able to go near it and if a door to a stairwell were broken, then that stairwell should not be used for evacuation. The use of airflow for smoke control was cautioned. However it is noted that other experimental observations have indicated conditions using a positive pressure ventilation system may reverse flame spread and reduced the temperature within the burn room and therefore the potential for flashover. He (1999) performed full scale experiments to investigate the effect of active smoke management systems on fire growth and smoke movement. On activation, the ventilation system supplied 100% fresh air to all levels other than the floor of fire origin, the exhaust system was applied to the floor of fire origin only, and the stairway was pressurised separately. Based on the experimental results, it was suggested that active smoke control, such as stair pressurization systems and ventilation/exhaust, may hinder or prevent flashover by cooling and providing unfavourable air movement within the burn room.

Cooper (Cooper 1980), Berhining (Berhinig 1981), Ahonen and Loikkanen (Ahonen and Loikkanen 1984), and Young and England (England and Young 1999; Young and England 1999) investigated the leakage of doorsets during standard fire-resistance tests.

Cooper (1980) and Berhinig (1981) performed experimental investigations of a proposed method for high temperature leakage testing of a doorset as a part of ISO 5925. The objective of the proposed test method was to test and evaluate the smoke controlling performance of doorsets in high temperature conditions at one pressure level. The overall concept of the method was to attach a doorset to a furnace (in accordance with ISO 3008 or ASTM E152 and UL 10B which UBC 7-2/1 is based on) and then an enclosure to the unexposed side of the doorset. The enclosure had two vents, one at the top and bottom of the enclosure, as shown in Figure 20. These vents were used to release hot gases from the enclosure, so the unexposed face of the door would not be subjected to an unrealistic environment. These vents were opened (for 4 minutes) and closed (for 1 – 2 minutes) at intervals during the test to allow hot gases to escape and to measure the leakage of the doorset, respectively. A hot-wire anemometer and thermocouples that were located in a short duct at mid-height on the enclosure were used to measure the flow out of the enclosure. This outflow was a combination of the leakage of the doorset, leakage of the apparatus and any heating effects of the gases within the enclosure. The range of expected outflows of the apparatus was from 20 to 750 m^3/h. The locations within the enclosure where measurements of pressure (from manometers) and temperature were taken are shown in Figure 21. A zero (± 1 Pa) cross-door pressure was maintained at the door sill and 10 ± 5 Pa at the top of the door throughout each test. The cross-door pressure difference increased linearly with height. Cooper took additional measurements of the temperature and horizontal deflections of the unexposed side of the doorset. However, the deflection measurement method and results were not included in the report.

One to 1½ minutes after closing the top vent, a stratified layer of smoke was observed to flow out of the duct (Cooper 1980). The visual velocity of the smoke emitted a smoke layer was sometimes inordinately faster than the velocity recorded by the anemometer (which recorded only the average velocity through the middle of the duct). In addition, the temperature across the height of the outflow duct varied significantly during each closed-vent interval, as shown in Figure 22.

The maximum temperature recorded inside the enclosure at the top vent was 366 K and on the unexposed surface of the door was 672 K, which both occurred towards the end of the test and the end of closed vent intervals (Cooper 1980). Examples of the temperature distribution within the enclosure over the height of the doorset at various times during a test are shown in Figure 23.

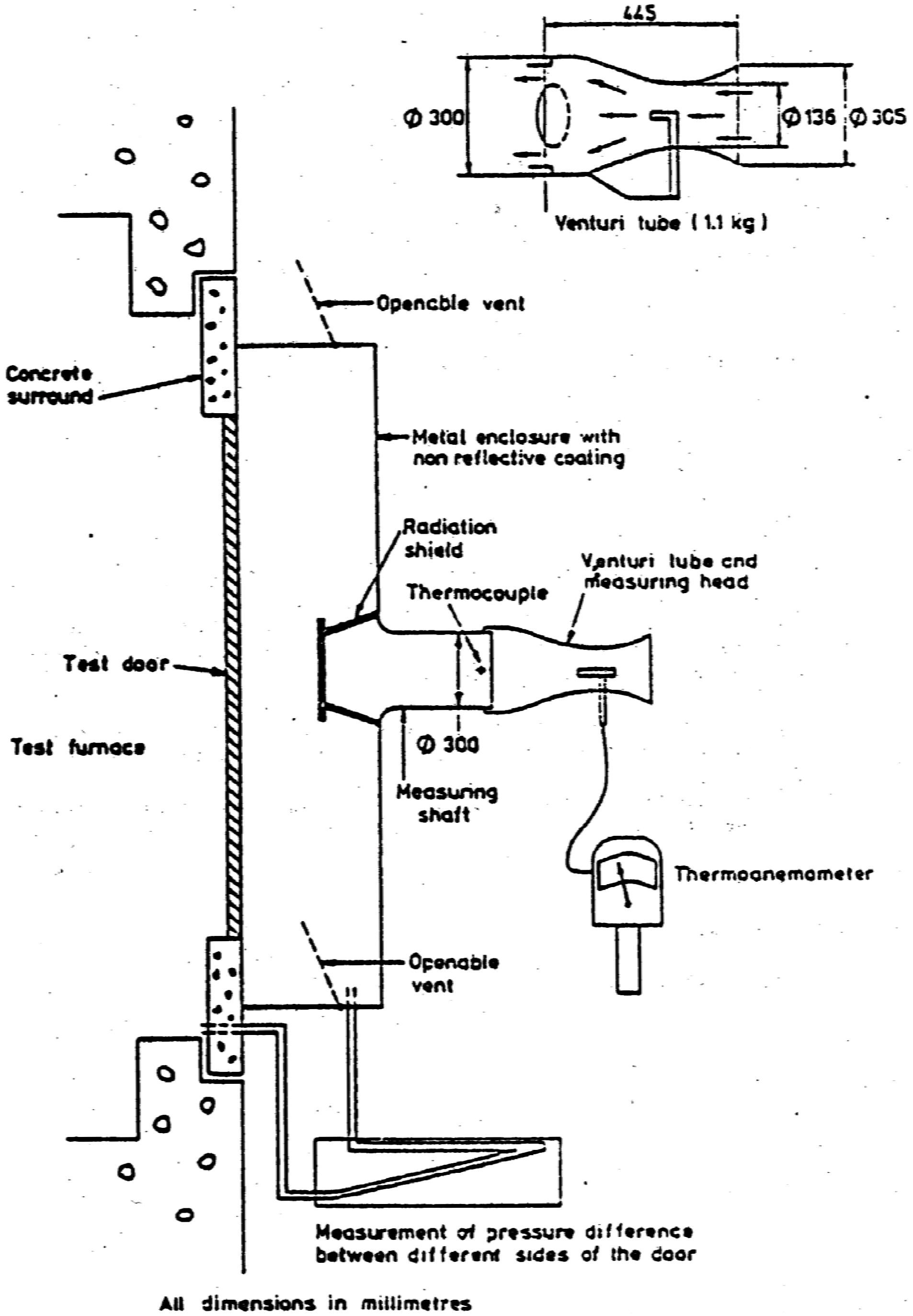


Figure 20: Schematic of high temperature air leakage test method. Extracted from (Cooper 1980).

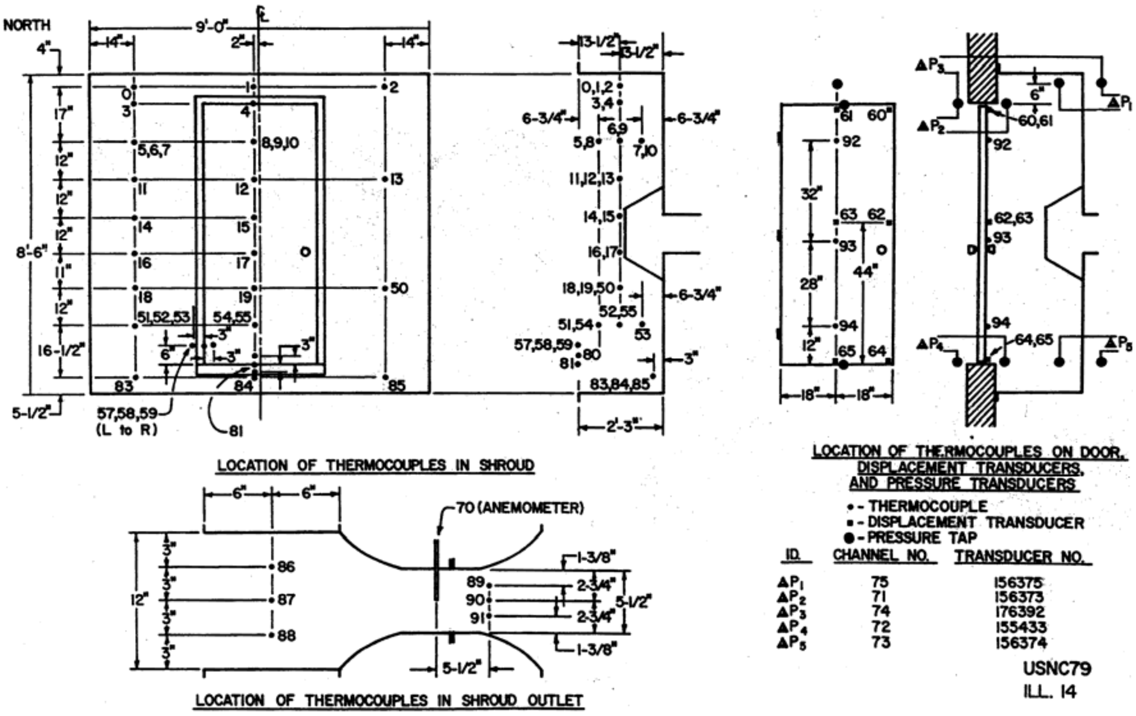


Figure 21: Location of instrumentation for temperature, pressure and velocity measurements within the enclosure. Extracted from (Berhinig 1981).

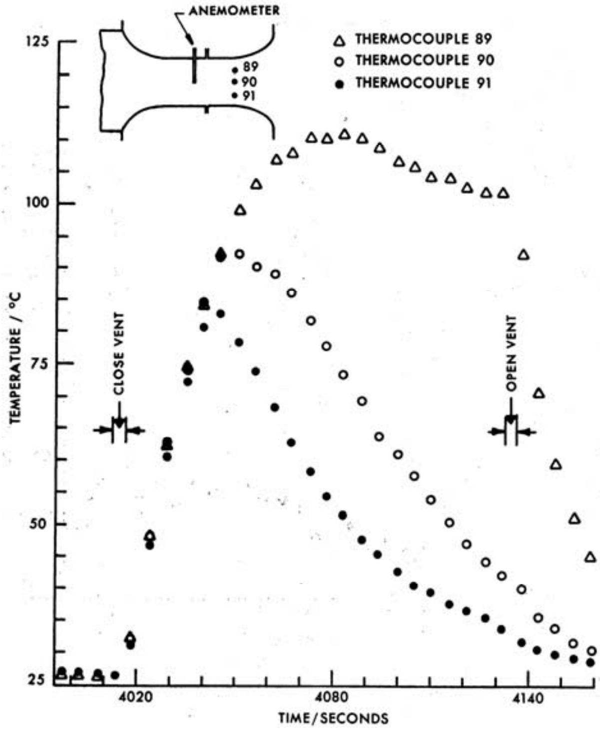


Figure 22: Venturi throat thermocouple measurements over the 4020 – 4140 s closed vent interval. Extracted from (Cooper 1980).

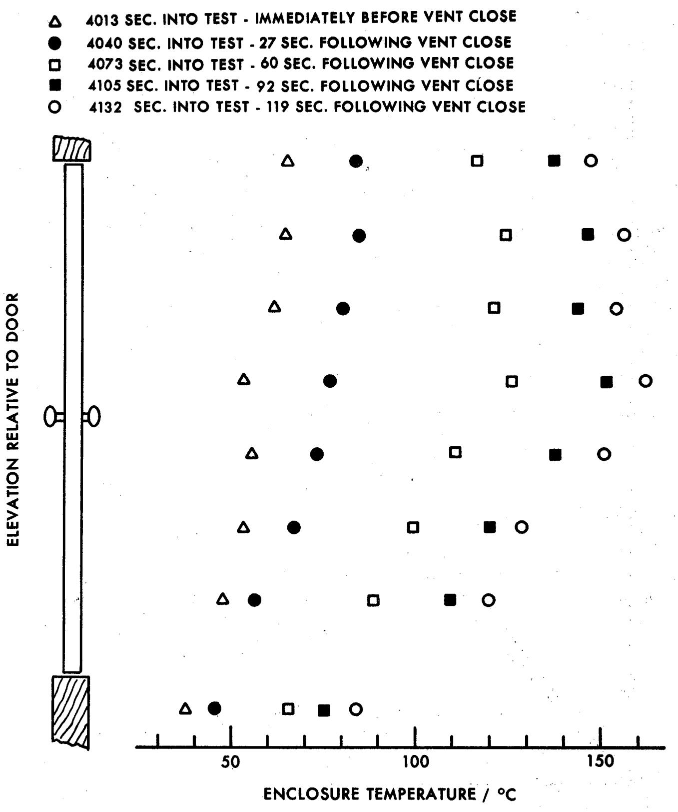
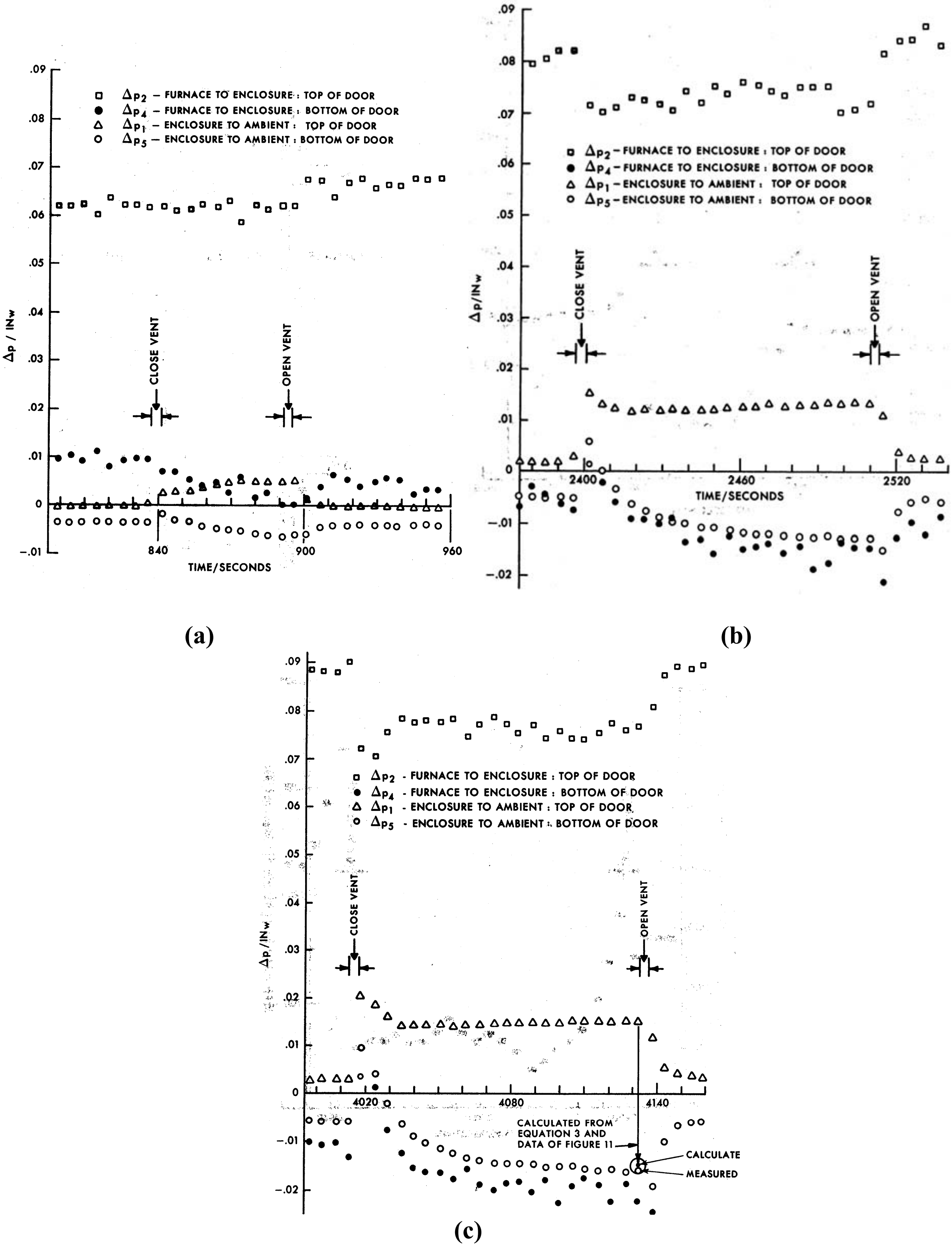


Figure 23: Enclosure temperature as a function of elevation at the 4020 – 4140 s closed vent interval.

Examples of the pressure differences recorded during the test for various closed-vent intervals are shown in Figure 24. A quasi-steady enclosure-to-ambient pressure difference was obtained after approximately 1 to 1½ minutes after the top and bottom vents were closed (Cooper 1980). The pressure differences between ambient conditions and the top and bottom of the door within the enclosure are approximately of equal value, but opposite sign. That is, a neutral plane was set up at approximately the mid-height of the door (near to the location of the outflow duct) between the inside and outside of the enclosure. If the location of the neutral plane is at the location of the duct, the flow through the duct may be significantly affected. Potentially, over the area of the duct, the flow through the duct may be reversed for the portion below the neutral plane. Examples of the outflow velocity measured by the anemometer set up, that correspond to the intervals shown in Figure 24, are shown in Figure 25. The measured outflow velocities indicate variability of the measurement even after the 1 to 1½ minute period after the closure of the vents, which may be an indication that the outflow velocity steady-state lags the steady-state of the ambient-to-enclosure pressure difference, or the outflow velocity measurement may be affected by a portion of the duct flow being reversed.

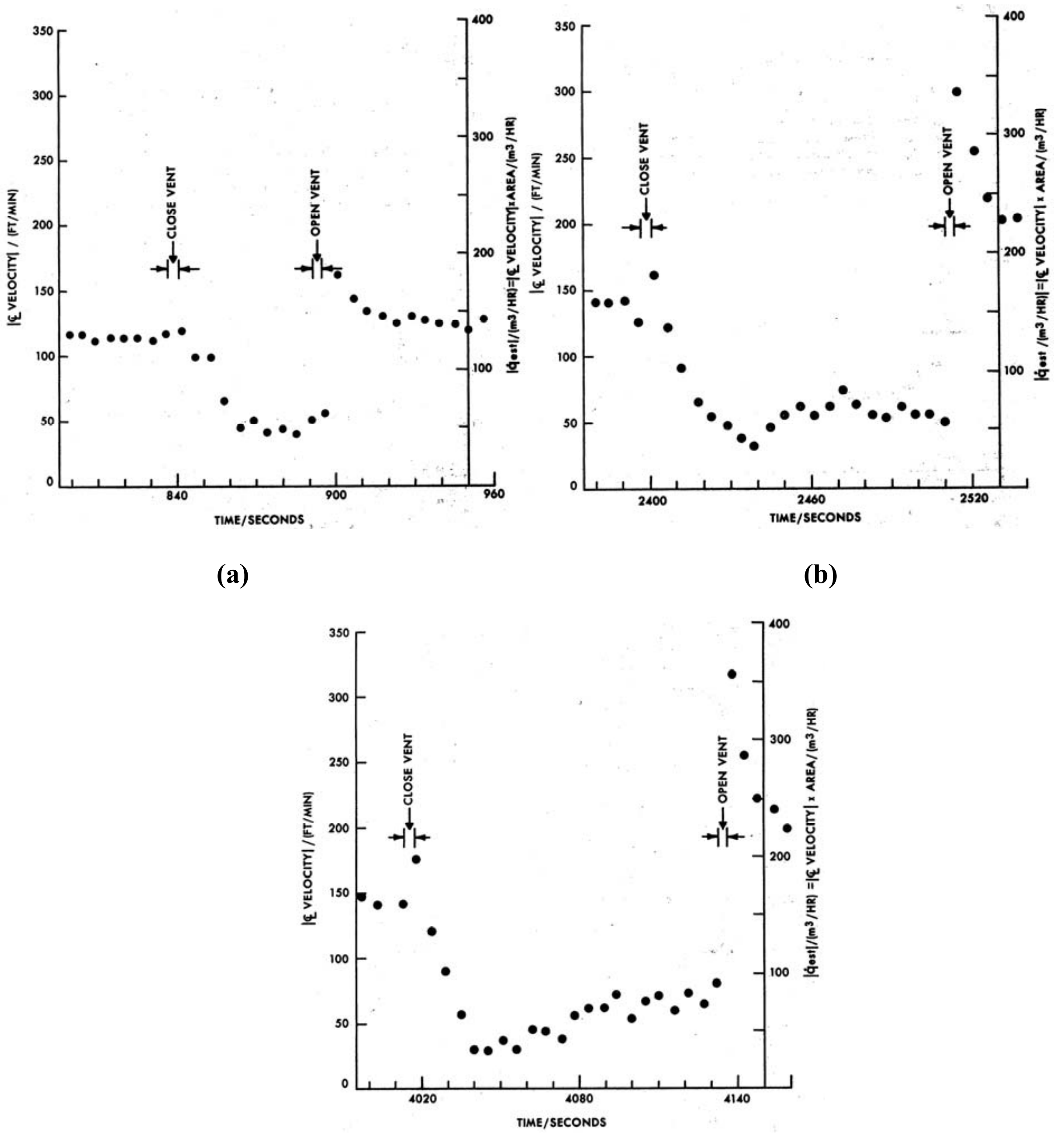


(a)

(b)

(c)

Figure 24: Pressure differences over the (a) 840 – 900 s closed vent interval, (b) 2400 – 2520 s closed vent interval, and (c) 4020 – 4140 s closed vent interval. Extracted from (Cooper 1980).



(a)

(b)

(c)

Figure 25: Outflow velocity over the (a) 840 – 900 s closed vent interval, (b) 2400 – 2520 s closed vent interval, and (c) 4020 – 4140 s closed vent interval. Extracted from (Cooper 1980).

Problems listed by Cooper for this method included (Cooper 1980):

- The cross-door pressure difference achievable with this method may only produce conservative results when compared to applications in low buildings. The cross-door pressure difference for an assembly in a high-rise building could be several times greater than that achieved with this method.

- Two coupled, time-dependent variables affecting the outflow measurement: leakage through the doorset (the required measured variable) and enclosure gas expansion, due to heat transfer from the doorset.

- Time taken to reach quasi-steady-state conditions within the enclosure (after the closure of the vents), which depended on the surface temperature of the door and the door leakage characteristics. Two minutes was not generally sufficient, using NBS/UL test methods.

- A highly non-uniform velocity distribution across the outflow port, where a single point was measured to estimate the net outflow.

- The pressure distribution over the height of the doorset may be very different for the open and closed vent positions.

Cooper therefore concluded that this test method would not yield reliable estimates for the desired leakage characteristics under a simulated condition of building smoke and fire exposure.

Ahonen and Loikkanen (1984) performed a series of tests based on the standard fire-resistance test (ISO 3008 1976), using a hood to collect and measure gases escaping through the doorset. In this case the tracer gas used to measure the leakage rate was carbon dioxide, which was produced by the burners of the test furnace. A test door was specifically chosen for testing, based on the ease of estimation of leakage rates for a modelling approach. Reasonable agreement was found between the experimental and theoretical results. This method is discussed in more detail in Section 8.4.

England and Young performed fire tests on a solid core door with an attached corridor (England and Young 1999; Young and England 1999). Temperature, pressure and visibility measurements were taken at locations within the corridor. The only smoke was produced by the burning of the door being tested and the furnace fuel. It was identified that the door leakage results were highly dependent on the furnace pressure. The objective of the investigation was to "establish design data for predicting smoke spread associated with leakage through a closed fire or smoke door in a fully developed fire" (England and Young 1999). England and Young recommended more refinement of the apparatus and test procedures.

Rakic (2000) conducted full-scale testing to quantify the smoke leakage characteristics of typical unit entry doors during a simulated sprinkler controlled fire in a hotel apartment or office building. The focus of this experimental investigation was to determine the leakage of doors claiming to be 'tight fitting', where the term 'tight fitting' is not defined by a standard and is therefore venerable to subjective interpretations. Initially, solid core doorsets (meeting the requirements of AS2688) were tested for leakage in ambient (see Table 9) and medium (see Table 10) temperatures, with perimeter (Lorient Batwing) and sill (Lorient RP8) seals fitted or with no seals fitted. Rakic noted that, after the medium temperature tests, the door leaves that had been manufactured using standard, one part water based PVA adhesives were observed to have undergone major delamination, with the facing almost completely separated from the core. In addition, the solid core door leaves complying with AS2688 in both steel and timber frames deflected significantly, therefore it is important to ensure that door seals that can accommodate this amount of deflection are installed. The results indicated excessive smoke leakage into adjoining corridors would be expected for a typical 'tight fitting' unit entry door, without any smoke gaskets or seals, and where no additional mechanical smoke control systems were employed.

Table 9: Leakage of a doorset with and without seals at ambient temperatures. Adapted from (Rakic 2000).

Cross-door Pressure Difference (Pa)	Total Leakage of a AS2688 Solid Core Door with No Seals (m3/h)	Total Leakage of a AS2688 Solid Core Door with Perimeter and Threshold Seals (m3/h)
12.5	144.82	7.07
25	213.74	10.97
50	> 340	15.74
75	> 340	22.64

Table 10: Leakage of a doorset with and without seals at medium temperatures, where the leakage rates are at 473 K (and have not been adjusted to STP). Adapted from (Rakic 2000).

Cross-door Pressure Difference (Pa)	Total Leakage of a AS 2688 Solid Core Door with No Seals (m^3/h)	Total Leakage of a AS 2688 Solid Core Door with Perimeter and Threshold Seals (m^3/h)
12.5	172.20	5.10
25	214.84	8.31
50	254.28	12.43
75	307.69	16.52

Stroup and Madrzykowski (1991) investigated the effect of a post-flashover fire in a room on the conditions in a corridor and a second (target) room adjoining the corridor, as shown in Figure 26. Tests were performed with three variations of door on the target room: a simulated standard door (of 13 mm thick calcium silicate board with a 6 mm top-, 6 mm side- and 22 mm under-cut), a simulated reduced-leakage door (with a 22 mm undercut only), and a commercial accordion fire door. The target room was also tested with and without pressurisation for the standard door. One test was performed with each variation (four tests in total). Gas temperature, wall surface temperatures and concentrations of oxygen, carbon dioxide and carbon monoxide were measured at locations in the fire room, corridor and target room. Pre-test measurements of air leakage rate at a cross-door pressure of 37 Pa for the simulated standard door was 0.24 m^3/s and for the reduced-leakage door 0.12 m^3/s. The accordion door bowed outward when pressure tested. Six to 11 wood cribs were used to simulate post-flashover conditions in the fire room. The heat release rates for each test are shown in Figure 27. Test results for the simulated standard door without pressurisation of the target room showed the oxygen concentration fell below 10% about 5 minutes after ignition of the wood cribs and the temperature of the target room started to significantly increase at about 50 s after ignition and reached a maximum temperature of approximately 383 K at about 400 s after ignition (as shown in Figure 28). For the same door, with pressurisation of the target room, no change of the target room conditions was recorded until 500 s after ignition of the wood cribs and temperatures remained at ambient until the pressurisation system was shut down (as shown in Figure 29). For the accordion doorset, the oxygen concentration of the target room started to slightly decrease at approximately 440 s after ignition (and was still above 20% by the end of the test at 500 s after ignition) and the temperature increased from 299 to 307 K between 275 and 500 s after ignition (as shown in Figure 31). For the reduced-leakage door, the oxygen concentration of the target room started to decrease about 250 s after ignition and the temperature profile of the target room was similar to the accordion door test result, with a maximum temperature of 314 K at the end of the test (as shown in Figure 30).

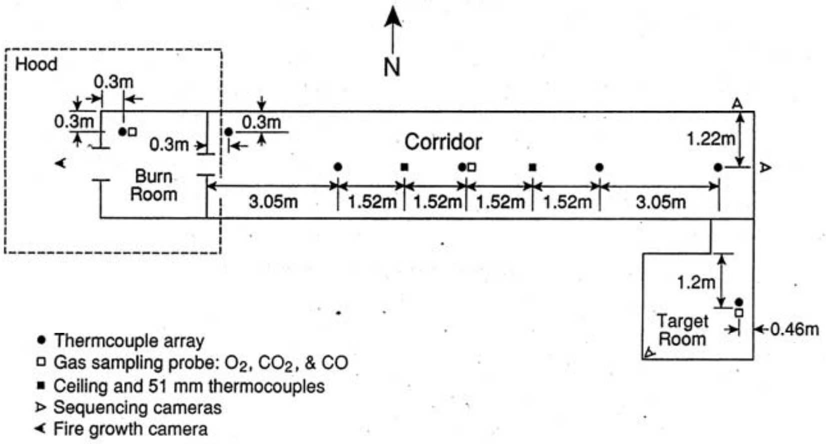


Figure 26: Location of instrumentation in the fire room, adjacent corridor and target room. Extracted from (Stroup and Madrzykowski 1991).

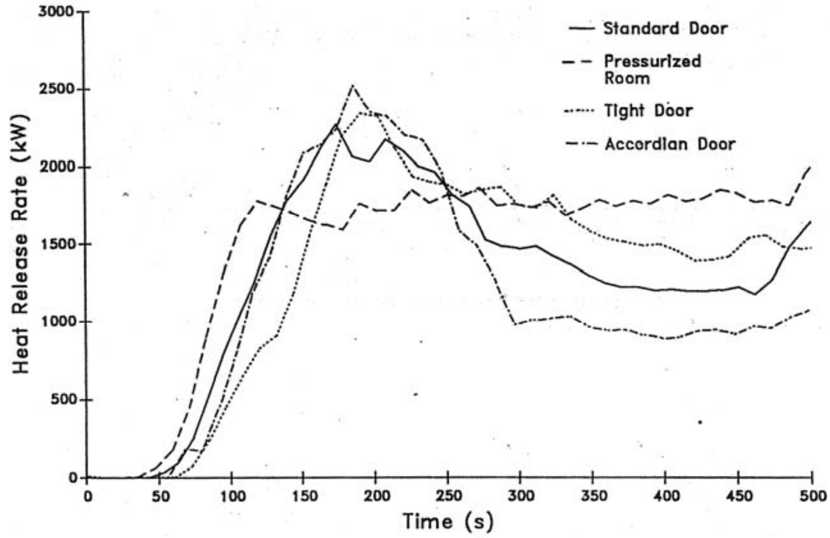
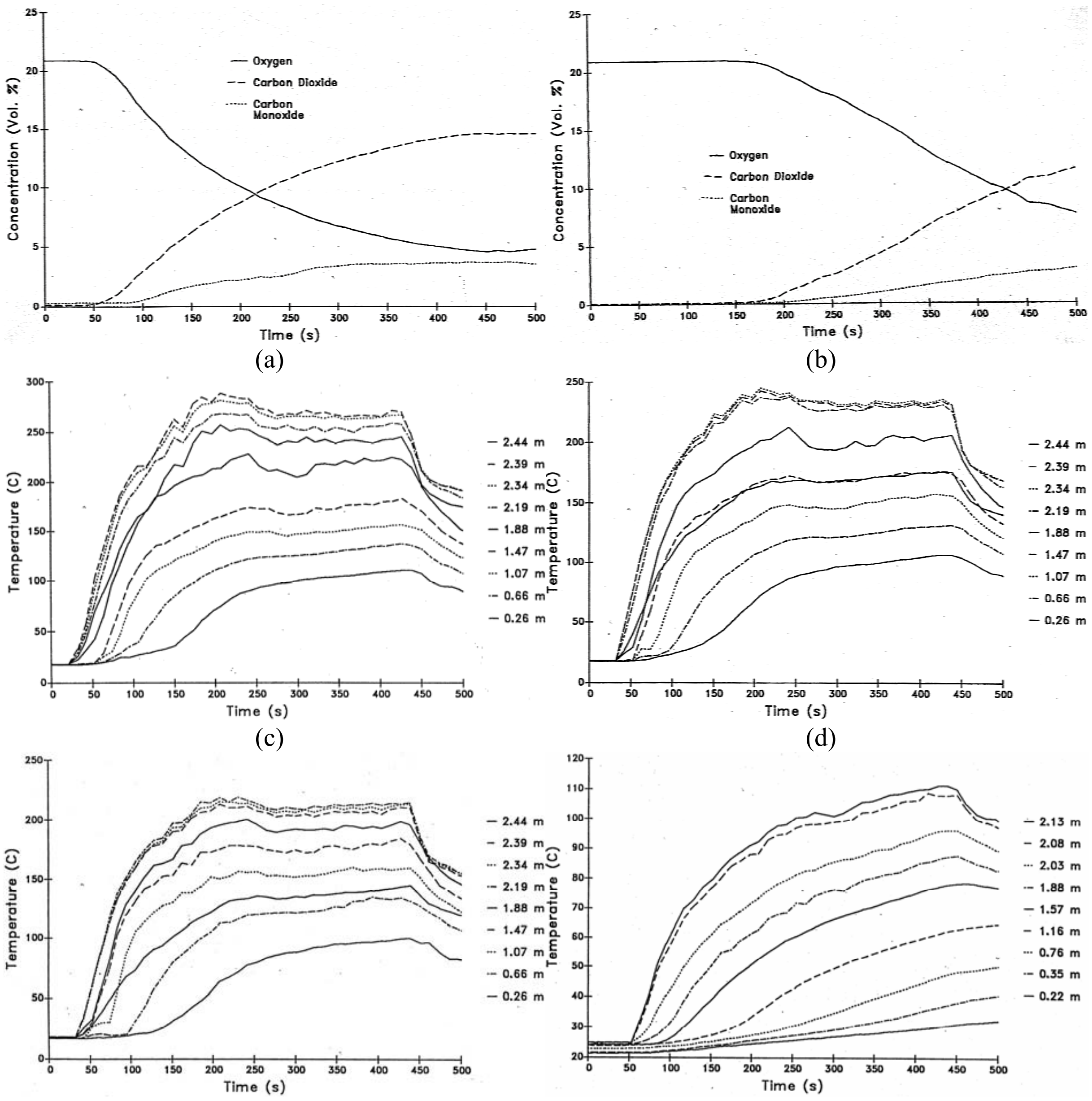


Figure 27: Heat release rates for all tests. Extracted from (Stroup and Madrzykowski 1991).

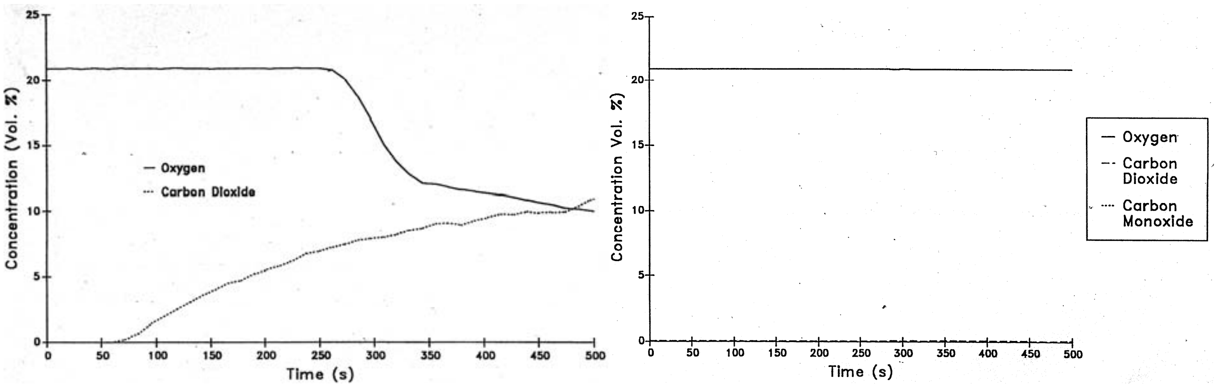


(a) (b)

(c) (d)

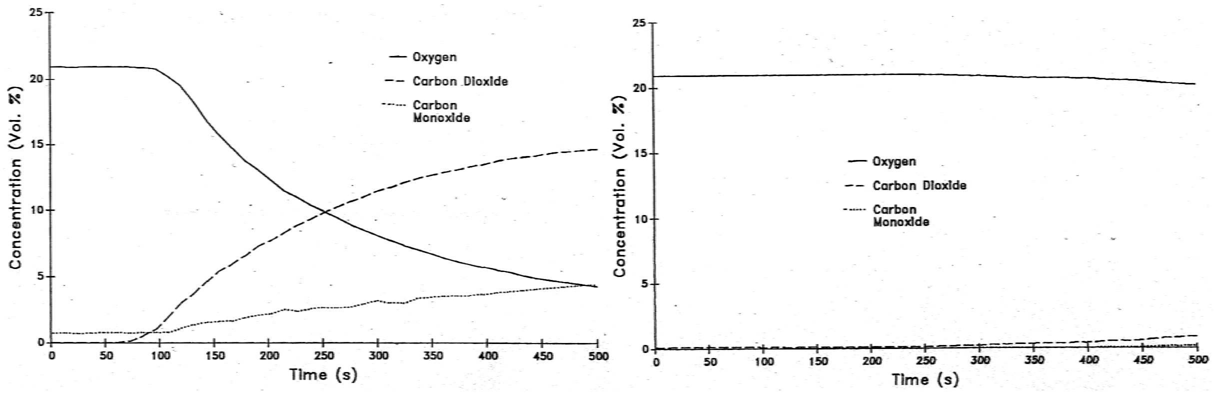
(e) (f)

Figure 28: Gas concentrations in the (a) corridor and (b) target room, and temperatures (c) 3.05 m, (d) 6.10 m and (e) 9.15 m from the burn room, and (f) in the target room, for the standard door test without pressurisation of the target room. Extracted from (Stroup and Madrzykowski 1991).



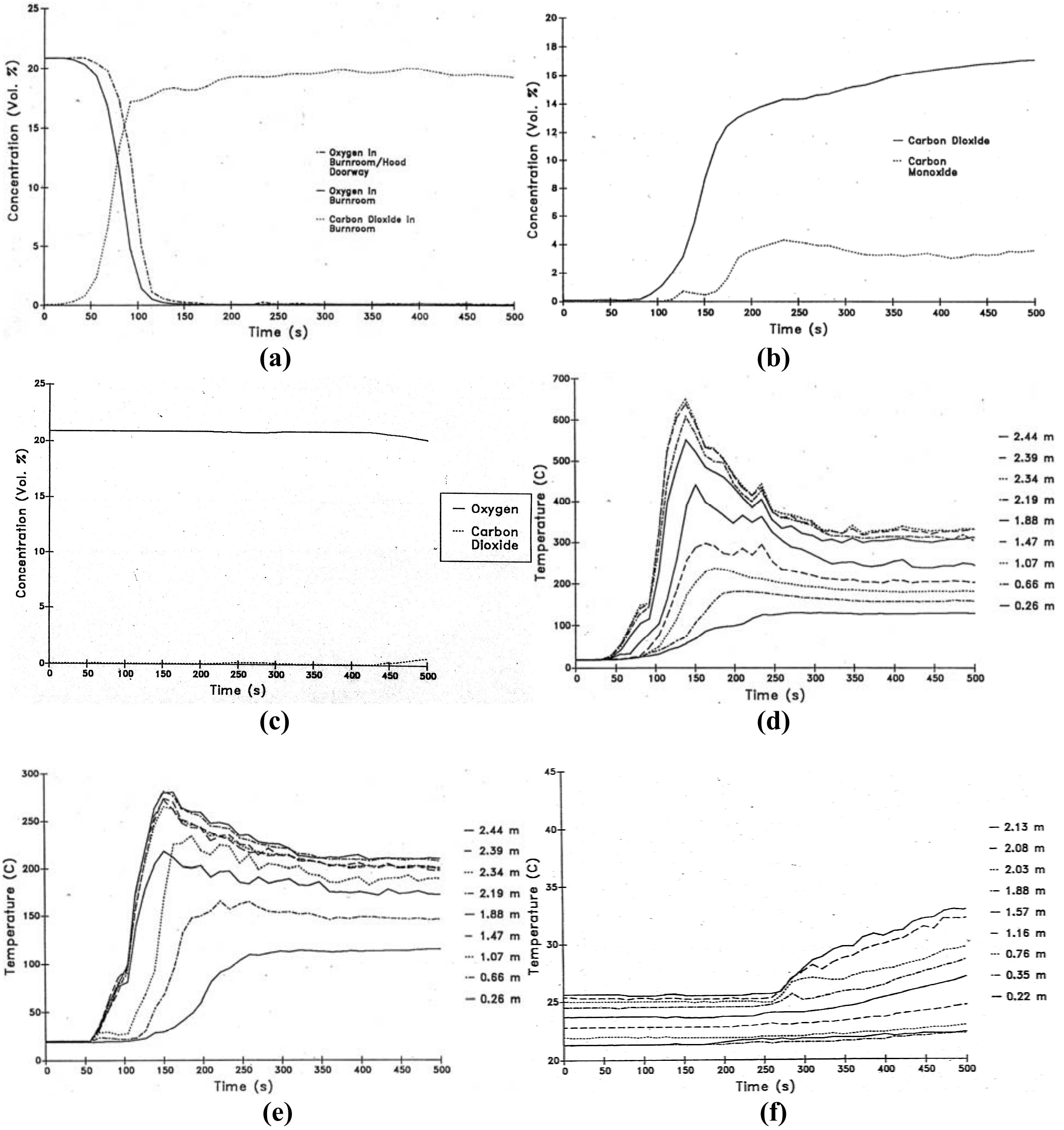
(a) (b)

Figure 29: Gas concentrations in the (a) corridor and (b) target room, for the standard door test with pressurisation of the target room. Extracted from (Stroup and Madrzykowski 1991).



(a) (b)

Figure 30: Gas concentrations in the (a) corridor and (b) target room, for the reduced-leakage door test without pressurisation of the target room. Extracted from (Stroup and Madrzykowski 1991).



(a) (b)

(c) (d)

(e) (f)

Figure 31: Gas concentrations in the (a) fire room, (b) corridor and (c) target room, and corridor temperatures (d) outside the burn room door and (e) adjacent to the target room door, and (f) temperature in the target room, for the accordion door test without pressurisation of the target room. Extracted from (Stroup and Madrzykowski 1991).

Sugawa, Kawagoe, Ozaki, Sato and Hasegawa (1985) performed tests using a set up that included three doors to investigate the leakage of smoke for a simulated high-rise apartment. One door separated the fire room from an entrance hall and the other two doors (in parallel) separated the entrance hall from the corridor. Two fire sources were tested: a simulated fire source and a full-size fire source. The simulated fire source consisted of 1 hour smouldering (using three cushions to produce an optical smoke density of approximately 4.7 /m in the fire room) and 10 minutes flaming (using alcohol to produce a heat release rate of about 100 kW). The full-size fire source consisted of a sofa, two loungers, a wooden side table, a wooden magazine rack, a 36 cm TV set with wooden frame, 4 × 4.5 m carpet, wall and ceiling paper, and a bookshelf (0.9 × 1.2 m) with 150 kg books. An average wind velocity of 3 m/s was assumed (based on average weather conditions for Tokyo) for estimation of the pressure difference between the fire room and the central corridor (5 Pa).

Three doors were tested: a wooden partition door (between the fire room and entrance hall), and two class A fire doors with airtight material (in parallel, one opening in and one opening out, between the entrance hall and corridor). Preliminary testing of the leakage characteristics of the doors gave an air volume rate of $Q = 0.22\,\Delta P$ m^3/h (pressure used in mmAq), where the positive pressure between the inside and outside is $5 < \Delta P < 200$ Pa. The temperature was measured. The gas was sampled from about 10 cm below the ceiling and analysed for CO, CO_2 and O_2 concentrations for the fire room, entrance hall and corridor. Smoke movement and concentration was measured using extinction beams. Smoke detectors (I.S.D. and L.S.D) were modified to give analogue outputs. Heat detectors were used to measure the rate of heat rise and fixed temperature. Measurements were recorded every 2 minutes.

Preliminary testing (using a blower) of the leakage characteristics of the test apparatus gave an air volume leakage rate of $Q = 37.4\,\Delta P^{0.46}$ m^3/h (pressure used in mmAq), where the positive pressure between the inside and outside is $5 < \Delta P < 67$ Pa. However this leakage rate characteristic included a sliding door, two observation windows as well as the three doors separating the fire room and the corridor. The data used to produce this relationship is shown in Figure 32, however the error associated with the measurements was not included. Furthermore, the measurement associated with flaming conditions in the fire room was included with the data for the leakage characteristics of the test apparatus (see Figure 32), for comparison.

Smoke and gas concentrations in the burn room were observed to vary only a little, whether the door between the fire room and the entrance hall was open or closed, as presented in Table 11. With this door open, little difference was measured between the conditions within the burn room and the entrance hall (an optical smoke density of approximately 4 – 5 /m). With this door closed, during the smouldering phase, the smoke concentration at 1.2 m above the floor in the entrance hall was less than 3% of the smoke concentration measured in the burn room just above the floor, and below the ceiling was less than 25%. The concentrations of CO and CO_2 were almost 20% of those in the fire room. A marked increase in smoke, CO and CO_2 concentrations was observed in the entrance hall associated with the transition from smouldering to flaming (at approximately 60 minutes after smouldering ignition as presented in Table 11). When the doors between the entrance hall and corridor were closed, negligible smoke leakage was measurable in the corridor for the duration of the test (even during flaming conditions in the fire room when the pressure difference between the fire room and corridor was approximately 49 Pa, see Table 11). When the doors between the entrance hall and corridor were open, the smoke, carbon dioxide and carbon monoxide were observed to be a little less in the corridor than measured in the entrance hall, although measurements were of the same magnitude (1/3 to 1/2 of that in the fire room). A closed entrance door, was associated with an optical smoke density of about 0.3 – 0.5 /m approximately 10 minutes before flaming conditions in the fire room. Smoke penetrated the corridor at least 4 m either side of the doorway. Based on these results, Sugawa et al suggested that it is necessary to fit an auto door closer and to make sure of an ‘airtight’ seal.

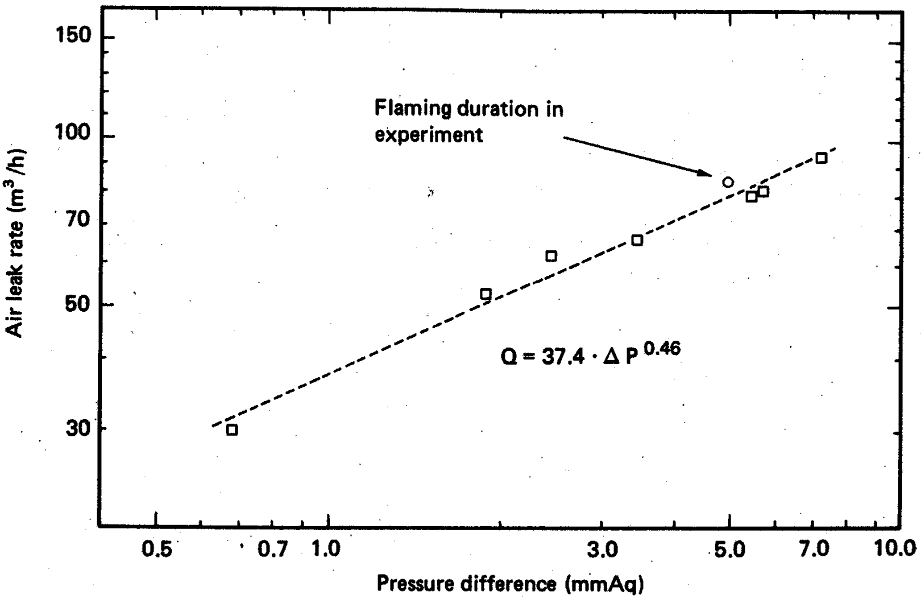


Figure 32: Air leakage rate versus cross-door pressure difference (between fire room and corridor). Showing experimental data and average trend for ambient temperature tests and one experimental result for the flaming condition. Extracted from (Sugawa et al 1985).

The pressure difference measured between the fire room and the corridor during smouldering conditions was negligible, and during the flaming condition were approximately 49 Pa. The air exchange rates measured, using a tracer gas, were 1.1 /h for the smouldering condition and 1.8 /h for the flaming condition. The equivalent leakage rates were 53 and 87 m^3/h for the smouldering condition and flaming condition, respectively. Concentration measurements were summarised as average values over the smouldering or flaming type of burning, with the maximum values sometimes presented (Table 11). No difference in smoke, carbon dioxide or carbon monoxide was observed between doors opening inwards or outwards.

Chiltern International Fire Ltd investigated the performance of smoke seals fitted to the edges of fire-resisting doorsets (PIF 190 1998). Of particular interest was the durability of smoke seals (in normal service use) and the subsequent impact on the ability of smoke seals to restrict smoke spread. The standard test procedures for fire door smoke seals were also reviewed in conjunction with the consideration of the effect of the installation of smoke seals on the fire-resistance performance of fire doors.

Results of surveys and durability testing indicated the difficulties of installation and maintenance of edge mounted smoke seals in the field. Stop-mounted smoke seals were found to be much more durable. It was suggested that this may have been because they were not subjected to the same frictional shear forces as edge-mounted seals. “Single leaf doors with a high quality of build construction where the faces of the doorstops were in close contact over their entirety with the surface of the door leaf” (PIF 190 1998) were shown to meet leakage criteria required by (English and Welsh) statutory guidance without the need to install smoke seals within the doorset. It was suggested that the current test standard overlooked the contribution of the doorstop to the smoke sealing performance of doorsets. However it is noted that such results might be obtained from a perfectly fitting test assembly, whereas the reproduction of these conditions in the field are highly unlikely (Mann 2006). Furthermore, although Approved Document B, England and Wales, specifies ambient temperature leakage values taken over head-and-jambs only, by definition, ambient temperature smoke can not be buoyant and smoke at the sill level would be expected. The threshold is often overlooked as a leakage path, yet even a 3 mm gap at the bottom of the door may leak smoke at such a rate that the contribution of the perimeter barrier, whether a deep stop or a professional sealing system, may be entirely negated (Mann 2006).

Table 11: Optical density and gas concentrations measured in each of three connected rooms with open or closed doors, during smouldering and flaming conditions in the fire room. Adapted from (Sugawa et al 1985).

Time	**Fire Room**		**Door 1**	**Entrance Hall**		**Door 2 / 3**	**Corridor**	
	Optical Density **(m^{-1})**	**Gas Conc.** **(%)**		**Optical Density** **(m^{-1})**	**Gas Conc.** **(%)**		**Optical Density** **(m^{-1})**	**Gas Conc.** **(%)**
Up to 60 min from ignition	4 ~ 5	CO = 0.2 CO_2 = 1.0 O_2 = 20.3	open	4 ~ 5	Not measured	closed	0	CO = 0.0048 CO_2 = 0.048 O_2 = 20.81
After 60 min from ignition	2 ~ 2.4	CO = 0.2 CO_2 = 2.0 O_2 = 18.5		2 ~ 2.4	Not measured		0	CO = 0.0056 CO_2 = 0.069 O_2 = 20.78
Up to 60 min from ignition	4 ~ 5	CO = 0.2 CO_2 = 1.0 O_2 = 20.3	closed	~ 0.1 (max. 0.7 ~ 1.2)	CO = 0.037 ~ 0.047 CO_2 = 0.20 O_2 = 20.7 ~ 20.8	closed	0	CO = 0.0048 CO_2 = 0.48 O_2 = 20.81
After 60 min from ignition	2 ~ 2.4	CO = 0.2 CO_2 = 2.0 O_2 = 18.5		0.7 ~ 1.2	CO = 0.063 ~0.064 CO_2 = 0.7 ~ 0.9 O_2 = 20.03		0	CO = 0.0056 CO_2 = 0.069 O_2 = 20.78
Up to 60 min from ignition	4 ~ 5	CO = 0.2 CO_2 = 1.0 O_2 = 20.3	closed	~ 0.1 (max. 0.7 ~ 1.2)	CO = 0.037 ~ 0.047 CO_2 = 0.20 O_2 = 20.7	open	0.1 ~ 0.2	CO = 0.011 ~ 0.013 CO_2 = 0.053 ~ 0.060 O_2 = 20.9
After 60 min from ignition	2 ~ 2.4	CO = 0.2 CO_2 = 2.0 O_2 = 18.5		0.7 ~ 1.2	CO = 0.063 ~ 0.064 CO_2 = 0.7 ~ 0.9 O_2 = 20.03		0.7 ~ 0.8	CO = 0.023 CO_2 = 0.11 ~ 0.12 O_2 = 20.83

It is noted that the test results of specific products are not intended to provide a typical indication of the wide range of similar types of products. For instance, a number of commercially available edge-mounted seals have successfully completed more than a million opening and closing sequences under test on full-sized door assemblies (Mann 2006). The primary intent is to highlight the important features of smoke control door assemblies that have been tested. For example, susceptibility to wear during operation must be balanced with other parameters, such as the ability to maintain a seal in locations of minor imperfections of fit or any subsequent movement of the alignment between the leaf and frame. Therefore, when analysing experimental results, it is important to consider whether one or more attributes are being tested before determining the most appropriate design for a specified situation.

8.1.1 Other experimental investigations of air leakage

The available literature of experimental methods investigating the air leakage of assemblies, other than doorsets, was also reviewed to determine relevance and possible novel approaches that could be applied to doorsets. A summary of the more relevant information is presented.

Liu, Alevantis et al (Alevantis et al 2003; Liu, Alevantis and Offermann 2001) investigated the air leakage from smoking areas to adjacent non-smoking areas of 23 smoking areas in 21 buildings. The smoking rooms and the adjacent rooms were monitored for nicotine and fluorescent particulate matter. In addition, a tracer gas, sulphur hexafluoride (SF6), was released in smoking areas to measure the leakage into adjacent areas. No smoke doors were considered in this investigation.

Sheppard and Attaniemi (1997) investigated smoke leakage through fire doors for US marine applications. A smoke leakage test protocol and the identification of acceptance criteria were developed to complement the standard International Maritime Organisation for 1 hour fire tests for class A divisions. (Currently the full report is not available.)

8.2 Experimental investigations of general smoke movement in exitways, compartments and buildings

The available literature of experimental methods investigating general smoke movement within buildings was also reviewed to determine relevance and possible novel approaches that could be applied to doorsets. A summary of the more relevant information is presented.

Hasemi, Mizukami, Yamada and Jin (2002) performed smoke movement experiments using a 1:25 scale model of a building. The Froude number was used for similarity, and the movement of smoke was visualised. The results showed the distribution of smoke in different fire scenarios, and of particular interest were the zones that were unaffected or inundated by smoke. However doorsets (open or closed) were not included in this investigation, as they were culturally unnecessary.

Klote (1989, 1990b, 1990a) performed full-scale smoke control tests in a seven-storey building that was scheduled for demolition. The study focused on smoke movement with and without mechanical ventilation of the fire floor and the effect of stair pressurisation on zoned smoke control. Sprinklered and unsprinklered wood fires and smoke bombs were used as the smoke source. The window of the fire room was left open to simulate the ventilation of a broken window. For some experiments, the stairway door to the fire floor was left ajar to simulate the leakage of a deformed door. Various combinations of open and closed basement (which opened to the outside) and 7th floor stairway doors were investigated. Temperatures of the fire floor (which was the 2nd floor) were measured. Smoke obscuration and oxygen, carbon dioxide and carbon monoxide concentrations on the fire floor, 3rd and 7th floor, and within the stairwell at the levels of the 3rd and 7th floors were measured. Experimental results showed that the smoke movement was very different for the chemical smoke from smoke bombs compared to hot smoke from the flaming fires used. Klote recommended that, “with very few exceptions, smoke bombs should not be used for acceptance tests” (Klote 1990b). For fires occurring below the neutral plane in multi-storey buildings, modelling and experimental results showed incapacitation from CO exposure for occupants trapped above the neutral plane could occur within 30 minutes to 2 hours, depending on the CO concentration and gas temperatures in the building shafts, outside temperature and the leakage of the building.

He and Beck (1997) conducted a series of full-scale fire experiments in a four-storey building that was fitted-out to represent a residential building. The experimental results were designed for comparison to model results for smoke spread using CFAST and a specially developed network model, called CESARE-SMOKE. Door leakage was not considered. All doors between the burn room and the areas of interest in the building were fully open. The burn room was situated on the first level, separated from the corridor by one room. Temperatures were measured in doorways and in the stairway joining the floors. Smoke obscuration was measured in the stairway and the corridor on the top (fourth floor). Concentrations of carbon dioxide, carbon monoxide and oxygen and air velocities were measured at the doorway between the corridor and the room adjacent to the burn room. Pressure differences between the stairway and the lift shaft (that was open to the surrounds) were measured at the second, third and fourth levels. For the experiments where the stairway doors were closed on the second and third floors, the smoke optical density in the stairway was consistently less on the third level compare to the second level. This coincided with a decrease in temperature with increase in height of the stairway. It was suggested that the temperature decrease was caused by dilution of the smoke by fresh air that had leaked through the gaps in the walls. In addition, it was suggested that the decrease in smoke optical density may have been caused by the deposition of smoke particles onto surfaces of the building. The results of the modelling using CFAST estimates consistently higher average temperatures and species concentrations of the upper layer compared to the experimental results. It was suggested that unmeasured heat losses to the building during the test may have been the cause of low temperatures remote from the burn room. It was also acknowledged that using measurements taken at a single point or with a single array of thermocouples to represent the average zone parameters used in the modelling would have limited accuracy, especially when representing the condition of enclosures with large aspect ratios. The output of the model in CFAST was used along with experimental measurements as input for the CESARE-SMOKE network model. Therefore errors accumulated, however a qualitative comparison of the experimental and model results showed general agreement and the concept of the network model output was demonstrated.

Bullock, Lennon and Enjily (2000) performed full-scale fire experiments utilising a simulated six-storey block of flats. The fire load was simulated by timber cribs set on the floor of the lounge area of a flat on the third level. The window of the room with fire was broken at 21 minutes 30 s after ignition to accelerate the time to flashover. The flat entrance was not opened until 59 minutes 12 s after ignition, when the fire brigade entered. In the lobby on the level of the fire unit, it was noted that visibility gradually reduced to 30 m over a period of 59 minutes after ignition and then rapidly dropped to approximately 6 m in a matter of seconds. The concentration of carbon dioxide was reported at alarm conditions (30 ppm) in the lobby at 28 minutes 30 s after ignition. However the carbon dioxide concentration at nominal respiratory height (1.58 m above floor level) in the area close to the stair access door was only measured as a few parts per million above the ambient level, until the fire brigade opened the flat entrance door. The dynamic positive pressure peaked (5.5 Pa) at the top of the entrance door during post-flashover conditions. Conclusions based on these results include that visibility, carbon monoxide and temperature measurements in the lobby indicated favourable conditions for means of escape.

Cooper, Harkleroad, Quintiere and Rinkinen (1981, 1982) performed full-scale tests when investigating the stratification layers that form in the fire room and an attached corridor. Connections between rooms and the corridor were via open doorways. The major objective of this study was the generation of data to populate a database for use in the verification of mathematical fire simulation models. The development of the hot stratified layers in the various spaces was measured using vertical arrays of thermocouples and photometers. The location of the interface between the stratified layers was reported as a function of time.

Hill (1999) performed field experiments to determine ventilation characteristics in suites in recently constructed mid- and high-rise residential buildings. Mechanical ventilation systems, such as central corridor air supply systems and central or individual suite exhaust systems, were found to be neither effective nor efficient. Hill investigated environmental driving forces, pressure and airflow capabilities of the suite exhaust systems, corridor air system supply airflow rates, air leakage characteristics of suite access doors, determination of suite and room air-exchange rates and inter-suite transfer air fractions. Tests were conducted in winter, as this was deemed the worst-case conditions. Experimental data consisted of only ‘snap-shots’ of the ventilation performance, as there was no long-term monitoring in place. Hill noted that the measured flows for both the corridor and exhaust systems were consistently less than the design capacities. In addition, the designed suite exhaust capacities were usually far greater than the designed suite corridor supply airflow. Furthermore, it was found that little consideration was given to ensure that there would be sufficient leakage between the corridor and suite for the transfer of air. In summary, there were large differences between design and actual measurements for both airflow and leakage. The ventilation was found to be mainly influenced by weather, suite location within the building and the treatment of both interior and corridor access doors. The ventilation within a suite was difficult to predict at any given moment. Most of the buildings investigated had varying design specifications for the ventilation systems.

Hill (2002) then investigated different fan venting strategies, specifically for the Canadian climate. Of particular interest was a smoke control strategy for during and after a fire, to clear and maintain access for attendance or evacuation, and cold weather performance. Based on extensive previous experience with positive pressure ventilation in low-rise residential and commercial structures, Hill suggested positive pressure ventilation of stairwells and corridors for high-rise apartment buildings. However the systems installed in low-rise structures were not originally designed to control and vent smoke in multi-unit residential buildings. The positive pressure ventilation system relied on a fan placed at an external door at the bottom of the stairwell to provide the airflow.

For a various venting arrangements (including vent location, size, variable leakage area between corridors and stairwells, open stairwell doors) the temperature, CO_2 concentrations and smoke movement were measured in the stairwell. It was noted that potential fire increase due to increased airflow caused by venting should be considered if a positive pressure ventilation system is to be used during a fire attack (Hill 2002).

Tamura and Shaw (Tamura 1975, 1990, 1994; Tamura and Shaw 1975, 1981) performed experiments investigating pressurised exitways for smoke control, including elevator, lobby and stairway pressurisation systems, with and without over-pressurisation feedback control or mechanical ventilation. Tamura (1975) investigated the effectiveness of pressurised stairways using two buildings (a conventional stairway in a 23-storey building and a scissor stairway in a 37-storey building). The stairway of the 23-storey building was ventilated from the bottom using a mobile fan. The stairway of the 37-storey building had an inbuilt ventilation system that introduced air into the stairway from the top. The stairways of both buildings were constructed from concrete blocks, with the same doorsets. The leakage of the stairway walls and doors were measured with all doors closed. The pressure in the stairway was measured for various combinations of open and closed stairway doors, and with and without the building air handling system operating. It was shown that the stairway pressure over the height of the building varied significantly with the location and number of open doors. Other tests were conducted in a 10-storey experimental fire tower with and without fire conditions (where the fire room was located on the second floor) (Tamura 1990, 1994). Leakage areas in the walls of the fire tower were set to be representative of a typical office building. The leakage areas of the closed stair and lobby doors were reported as 0.023 m^2 each, and 1.95 m^2 each when open. Several combinations of opened and closed stairway and lobby doors were tested for various pressurisation and exhaust systems. Temperatures and carbon dioxide concentrations were measured at 10 and six locations on each floor, respectively. Static pressure differences across various walls at 18 locations throughout the building were recorded. A smoke contamination of 1% was used as the criteria for the tenable limit in the vicinity of the fire. For all scenarios investigated with over-pressurisation relief (via exit door relief, via barometric damper relief and via static pressure feedback control), experimental results showed that with the doorway to the fire room open the stairway was contaminated with smoke unless the fire room was vented to the outside and no additional doors were open (Tamura 1990). For all scenarios investigated without over-pressurisation relief, the order of increasing protection of the stairway from smoke contamination was lobby pressurisation (of 25 Pa by an air supply rate of 0.165 m^3/s into each lobby), lobby and stairway pressurisation (of 25 Pa by an air supply rate of 0.165 m^3/s into each lobby and 8.7 m^3/s into the stairway) and then lobby pressurisation with mechanical exhaust of the fire floor (of 25 Pa by an air supply rate of 0.165 m^3/s into each lobby and with an exhaust rate of 4.53 m^3/s from the second floor) (Tamura 1994).

Tamura, Shaw and Tsuji (Tamura and Shaw 1978; Tamura and Tsuji 1985) also investigated mechanical ventilation systems for smoke control in high-rise buildings. The ventilation system investigated consisted of a vertical shaft with dampers protecting the openings onto each floor and an extraction fan at the top of the shaft. Measured values and results from simplified calculations were found to be in good agreement for the investigation of the mechanical ventilation system of an actual 34-storey office building (Tamura and Tsuji 1985).

Moureh and Flick (2005) numerically (using Fluent, a commercial CFD package) and experimentally (using an isothermal-scaled model) investigated the characteristics of the airflow throughout a slot-ventilated compartment. The characteristic velocity within the enclosure was measured as a function of the inlet flow arrangement and location. The focus of the study was to determine the effect of the enclosure on the airflow and the stabilisation of the wall jet characteristics, and subsequently on the efficiency of the room ventilation.

8.3 Previous BRANZ experiments

Ambient temperature smoke door leakage testing had been performed in the late 1980s and early 1990s. However this testing was ceased due to a medium temperature test being considered more useful and the non-inclusion of leakage criteria for smoke doors in the NZBC. Therefore, there is currently little demand for ambient temperature smoke door leakage testing in New Zealand.

8.4 Suggested doorset leakage measurement methods

The leakage measurement methods for air leakage through doorsets discussed in this section are alternatives or additional to those presented in the standards (Section 3).

During the development of the proposed ISO three-part series of test methods for the measurement of the leakage of doorsets under ambient (that eventually became (ISO/DIS 5925/1 1981; ISO/TR 5925/2 1997)), medium and high temperatures, various methods of measurement were proposed.

During the development period of the high temperature leakage test (the proposed ISO/DP 5925 Part 3) throughout the 1970s, Oksanen developed test methods for measurement of doorset leakage during fully developed fire exposure with near-zero cross-door pressure differences in Finland (Cooper 1980, 1981). Based on in-depth experimental analysis of the proposed high-temperature test method as part of the ISO three-part series by Cooper (1980), Berhinig (1981) and Westhoff and Ueberall, Cooper (Cooper 1980, 1981) reported that the test method was generally unreliable and recommended an alternate test concept that would not use a near-zero cross-door pressure difference. This is discussed below. However, this alternate test concept has not currently been implemented.

Cooper (1980, 1981) suggested some short-comings of proposals for the ISO high-temperature air leakage test presented in the late 1970s. These included:

- the leakage of the furnace contributed an unknown component to the air leakage of the entire system
- the gas expansion due to heat transfer from the hot door surface was unknown
- the time, of 1 minute, to approach quasi-steady-state conditions within the enclosure was suggested to be insufficient, since the 2 minutes required by NBS/UL tests was observed to be not generally sufficient
- a one-point measurement for estimating the net outflow was suggested to lead to significant errors.

Experimental studies on an improved high temperature leakage test method were also carried out in the Netherlands, by J. Dekker and L. Haffmans (Cooper 1980, 1981). It was suggested that a ventilated enclosure box would improve the reliability of the test. However, the suggested test method did not take into account of cross-door pressure differences.

Another test method was developed in Finland by Ahonen and Loikkanen (1984), that did not use a enclosed box for the ambient temperature side of the test doorset. Instead a collection hood was placed at the top of the door and the flow into the collection hood of a tracer gas (carbon dioxide), of known (and assumed uniformly mixed) concentration within furnace, was measured (Cooper 1980, 1981). Some potential uncontrolled or uncontrollable variables associated with this test method were raised by Loikkanen, including the non-uniform concentration of carbon dioxide within the furnace and that unknown amounts of carbon dioxide may be introduced into the system by burning surfaces (especially near leakage gaps).

During this developmental period, suggestions for a rating or classification system, which could be used as a means of reference between facility design guides, standards, codes, etc, were also raised (Cooper 1980, 1981).

Cooper (1980, 1981) suggested an example of a method for measuring air leakage of a doorset at a controlled cross-door pressure difference at high temperatures, using the basis of a standard fire exposure test. This approach used an enclosure that surrounded the ‘ambient’ room facing side of the door, as shown in Figure 33. This enclosure was to be instrumented for temperature and pressure measurements, with openings for measured flow in and flow out. Any extraneous leakage of the enclosure was to be sealed. The enclosure was to be maintained at ambient temperature, to simulate the radiant heat exchange between the hot door surface and the ambient walls of a room adjacent to the fire room. The airflow of ambient air within the enclosure was to be maintained at a low to zero velocity, to simulate natural convection heat transfer at the hot door surface. The enclosure box would be operated at such a pressure, relative to the ambient pressure of the furnace, to maintain a positive or negative cross-door pressure difference.

This test procedure was not intended to be used to determine the criteria of ISO 3008 nor measure mechanical damage of the doorset. A separate test was recommended to determine these (Cooper 1980, 1981).

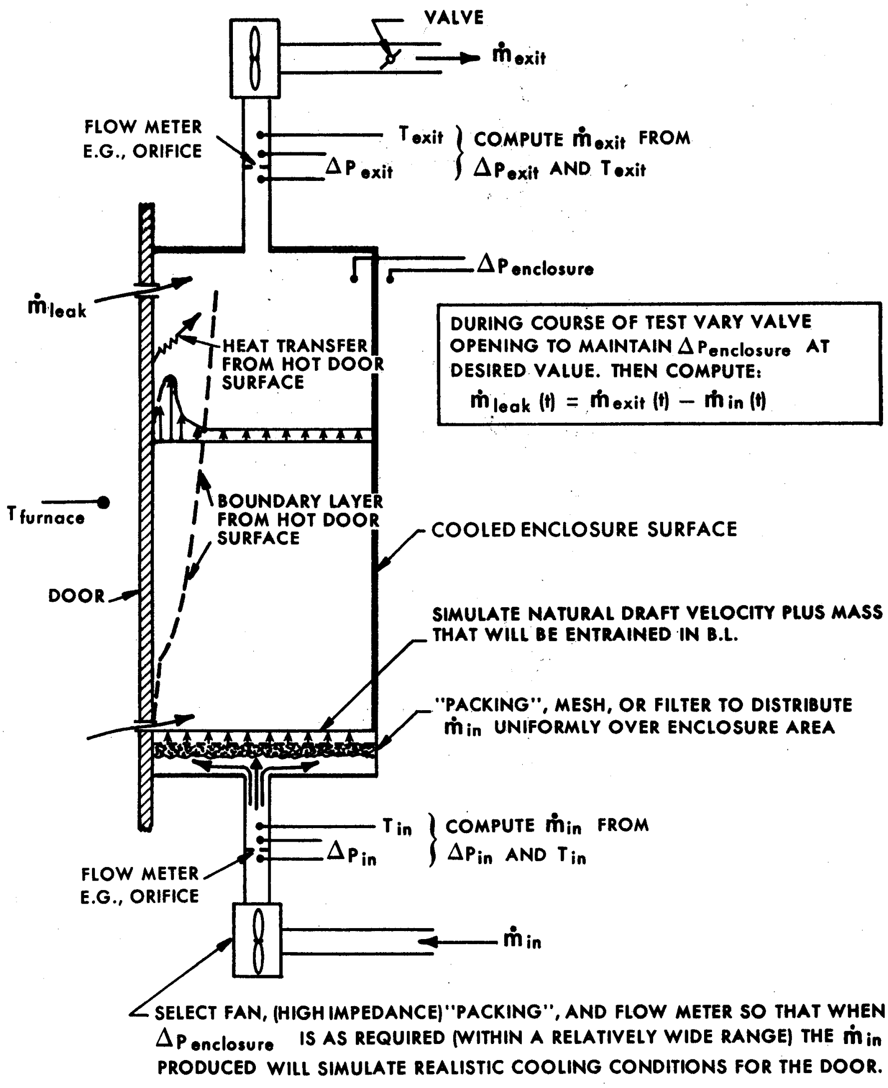


Figure 33: A proposed test concept for measuring air leakage of doorsets during standard fire tests. Extracted from (Cooper 1980, 1981).

Furthermore, Cooper (1984, 1985) recommended the need for leakage characteristics of partition assemblies during fire exposure. It was assumed that buoyancy forces would dominate the dynamics of smoke migration within one or all spaces of a smoke compartment of fire involvement. After the smoke had leaked from this compartment to an adjacent smoke compartment, the primary mechanisms of smoke migration were assumed to be different. It was also suggested that "… the ability to carry out the indicated type of analysis of hazard development at any level of sophistication is totally dependent on a quantitative description of the leakage characteristics of door assemblies" (Cooper 1984, 1985).

Cross-door pressure differential was suggested as the key to the evaluation of a doorset design: a combination of relatively uniform (e.g. stack effect, steady wind loadings and/or ventilation systems induced ~ 10 – 100 Pa or greater) and variable (e.g. fire induced ~ 5 – 10 Pa) distributions of cross-door pressure. In addition, it was suggested that increasing cross-door pressure differences may affect the fire endurance rating of a doorset, compared to an ASTM E152 or ISO 3008 standard test, where the test sample may be subject to a cross-door pressure of a modest ± 10 Pa. Cooper recommended that the cross-door pressure differential be taken into account during standard fire endurance tests.

When designing compartments of safe refuge (e.g. pressurised stairwells), Cooper suggested knowledge of the leakage characteristics of doorsets for consideration was important. Furthermore, Cooper also suggested that if "… if facility designs are to be responsive to more flexible fire safety performance criteria, it is evident that approaches for solving the inherently coupled problems of compartment-to-compartment smoke spread are required" (Cooper 1984, 1985). Suggested required measurements (Cooper 1984, 1985) included:

- Rate of leakage under ambient temperature conditions, as a function of cross-door pressure differential.
- Fire-resistance time, where one side of an interior doorset is exposed to an ambient environment and where the assembly is subjected to a cross-door specified pressure differential (e.g. ± 100 Pa).
- Rate of leakage as a function of time under conditions where one side is exposed to a fully developed fire simulation and the other side is exposed to an ambient environment, with a specified cross-door pressure differential (e.g. + 100 Pa). And measurement of the cross-door pressure required to produce zero leakage conditions, which would be potentially a slightly negative value.

In addition, Cooper suggested that since the cross-door pressure leakage test would likely require destructive tests, it would be more cost-effective to incorporate this with the current fire endurance test. Cooper also proposed that the summary of the test results might include the cross-door pressure differential used for the test, as well as the test exposure (e.g. maximum leakage during the first 30 minutes, second 30 minutes, etc, up to the fire endurance rating of the assembly).

Rakic (2000) suggested that the following were important variables in characterising door leakage:

- clearances and gaps around the edge of the leaf
- pressure difference across the doorset
- gas temperature, which affects density and may also cause distortion of the doorset, and
- gas species concentrations, for fire safety engineering calculations.

Testing of air leakage of doorsets was carried out at the Fire Research Station at Borehamwood, Hertfordshire, UK (Smith 1982) by fixing the doorset into a wall of a fire compartment. A reproducible wood fire was used to gradually increase the temperature and pressure within the compartment to approximately 673 K and 5 – 6 Pa at the top of the door.

Wilson (1961) suggested that for complex openings, such as cracks around doors, airflow relationships must be determined by testing. As an example, Wilson used the relationship between volume flow rate and pressure difference shown in Eq. 10, below, and found an equivalent orifice area of 4.9×10^{-3} m^2 for a 'tight fitting' door (0.9 × 2 m).

8.4.1 Range of cross-door pressure differences

Positive or negative cross-door pressure on the order of several tens of Pascals can occur when a compartment fire is exposed to the outside environment through an open or broken window (Klote and Fothergill 1983). Steady wind velocities would add or subtract additional pressure, proportional to the square of the wind velocity (Klote and Fothergill 1983). In addition, fire-generated cross-door pressure differentials have been measured to vary from top to bottom of a doorway on the order of ± 5 – 10 Pa (Cooper 1980, 1981).

The maximum cross-door pressure difference allowed, in accordance with C4.7 of (AS/NZS 1668.1 2002), is such that (in combination with any self-closing mechanism) the force to open the door does not exceed 110 N at the door handle. This maximum limit is applicable to all smoke control systems irrespective of whether or not the area is pressurised.

8.4.1.1 Pressure conditions during fire testing of doorsets

In accordance with AS 1530.4, the furnace pressure is assumed to vary only slightly as a function of the furnace temperature, and fluctuations of pressure associated with turbulence etc are disregarded (AS 1530.4 1997). A linear pressure gradient of 8.5 Pa per meter of height, based on the nominal mean value relative to the pressure outside the furnace at the same height, is assumed to exist over the height of the furnace. The mean value of the furnace control pressure is monitored and controlled continuously. Five minutes from the commencement of the test the furnace pressure is required to be within ± 5 Pa. After 10 minutes from the commencement of the test the furnace pressure must have achieved, and be maintained for each subsequent 10 minute period, ± 3 Pa. For doorsets, the furnace is to be operated such that a neutral plane is established at a height of 500 mm above the notional floor level.

ISO 3008 requires that a means is "… provided for increasing and maintaining the pressure conditions within the furnace chamber to a positive value in relation to the pressure in the laboratory…" (ISO 3008 1976). The static furnace pressure is to be measured at a minimum of three locations along a vertical axis on one side of, and close to, the doorset: in line with the top and bottom of the leaf, and one at one-third of the height from the sill level, as shown in Figure 34. The furnace pressure is to be controlled, so that a positive pressure is maintained over the upper two-thirds of the doorset.

According to the British Standard, BS 476: Section 22, the furnace pressure is to be controlled as specified in BS 476: Section 20 (BS 476/22 1987). In general, after the first 5 minutes of the heating period and for the remainder of the test duration, a positive pressure relative to the laboratory is to be established within the furnace (BS 476/20 1990). This pressure is to be controlled, so that a linear pressure gradient of 8.5 Pa per meter of height is applied to the doorset (similar to (AS 1530.4 1997)), with a neutral pressure axis at 1 m above the notional floor level. The pressure condition is to be maintained to within ± 2 Pa. At no time is the pressure at the top of the doorset to exceed 20 Pa.

The British standard for the fire-resistance test for doorsets (BS/EN 1634/1 2000) refers to BS/EN 1363/1 for the furnace conditions. BS/EN 1363/1 specifies the general furnace pressure conditions required for all fire testing. Between 5 and 10 minutes from furnace ignition, the furnace pressure is to be maintained to within ± 5 Pa of the pressure specified for the specific element under test. For the remainder of the duration of the test, the furnace pressure is to be ± 3 Pa of the specified pressure. The neutral pressure plane is to be located 500 mm above the notional floor level. The maximum pressure allowable is 20 Pa at the top of the specimen. The location of the neutral plane may be adjusted to achieve this maximum pressure (BS/EN 1363/1 1999).

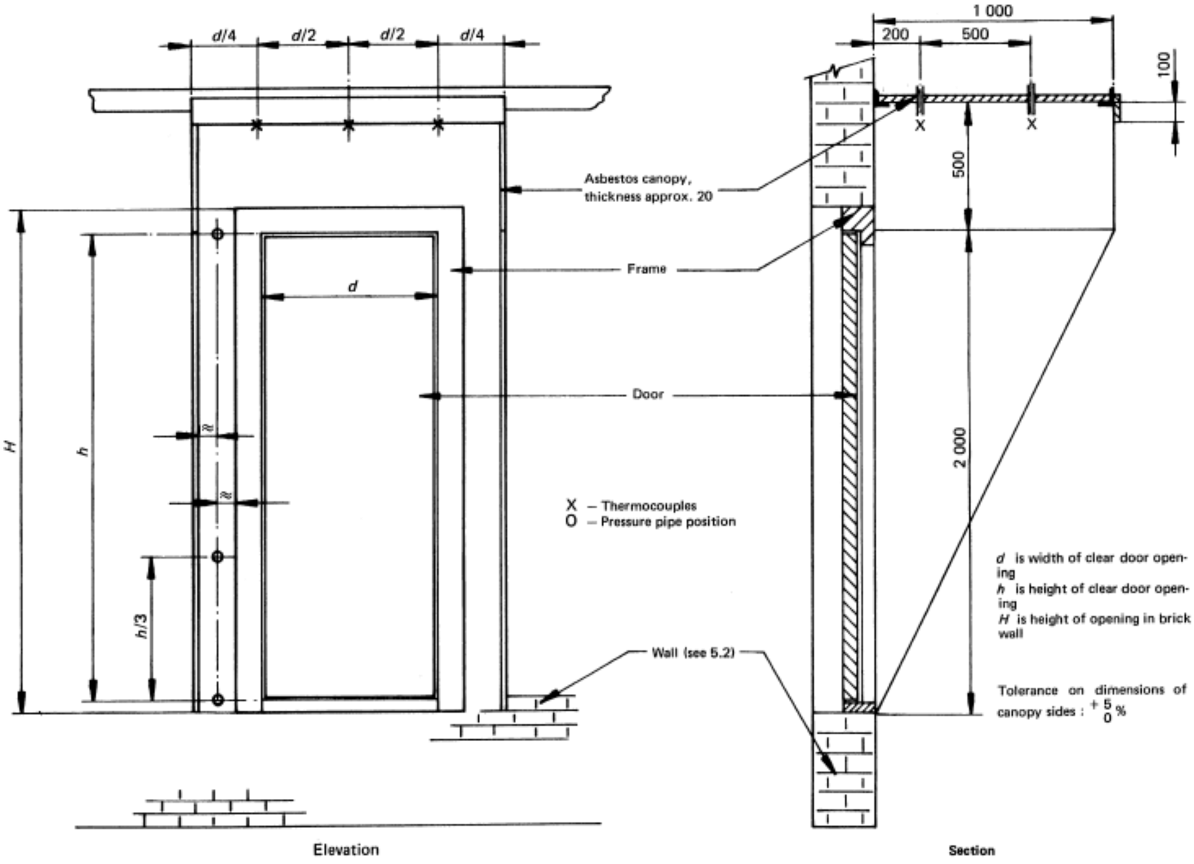


Figure 34: Schematic showing locations of thermocouples and pressure pipes for the ISO 3008 fire-resistance test for door and shutter assemblies. Extracted from (ISO 3008 1976).

ASTM E2074 notes that positive furnace pressure is required by some regulatory agencies, however it is only required that the furnace pressure measurement method and values are reported with the test results (ASTM E2074 2000a). Two pressure measurements are to be taken as close to the vertical centre line of the furnace as appropriate, separated by 1.8 m (or 0.9 m, if one is located 1 m from the sill). ASTM E125, the withdrawn standard for methods of fire testing doorsets (and replaced by ASTM E2074), required the furnace pressure to be maintained as close to atmospheric pressure as possible.

UBCS 7-2, Fire Test of Door Assemblies (UBCS 7-2/2 1997), does not discuss the pressure conditions required during the fire testing of doorsets.

8.4.2 In-situ leakage

Garden (1965) indicated potential leakage paths at the connection of the doorset to the building elements, as shown in Figure 35. This type of leakage may change the expected smoke-stopping integrity of the combined building components, such that the combined leakage is not the sum of the parts.

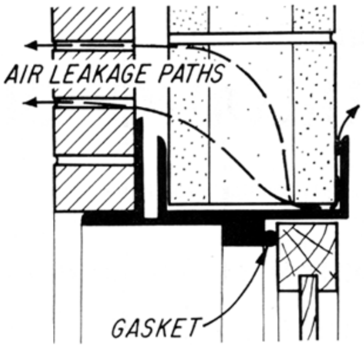


Figure 35: Cross-section schematic showing potential leakage paths between the doorset and adjacent building elements. Extracted from (Garden 1965).

8.4.3 Alternate measurement techniques

Alternatively, acoustic methods have been used for locating potential fire spread paths in old buildings in Stockholm (Johannesson, Ljunggren and Finney 1998). The acoustic measurement method, employed by Johannesson et al, involved analysing the transmission of sound between two selected rooms. The sound leakage was used as a measure of the cracks in the barrier between the two rooms. “Even a very small leakage will give a significant contribution to the transmission and is easily detected during the measurements” (Johannesson, Ljunggren and Finney 1998). Although this concept was primarily used simply to locate unknown cracks, possibly a test using this non-destructive concept (or utilising an ultrasonic source rather than a sonic source) would be an alternate leakage measurement system for characterising in-situ measurement testing of doorsets. Then the installed doorset response could be compared to the manufacturer’s specifications from laboratory testing as an additional check of clearances and contacts.

8.4.4 Summary of alternate test methods to current standards

A summary of proposed and suggested published alternative test methods to the current standards that have been discussed in this section is presented in Table 12.

Table 12: Summary of the alternate smoke door leakage test methods to the current standards

Brief Description	**Reference**	**Smoke Temp. (K)**	**Cross-door Pressures (Pa)**	**Description of Test Method**	**Published Comments on Problems**
ISO 5925 Oksanen – high temperature test development	(Cooper 1980, 1981) (Berhinig 1981)	Fully developed fire conditions	Near-zero	Use of an enclosure over the unexposed side of the box and a passive venturi throat to measure the flow out of the box	• Unknown leakage from furnace contributing to leakage of the system • Unknown gas expansion due to heat transfer • Time to reach quasi-steady-state was too short • One-point measurement suggested to have significant errors
ISO 5925 Dekker and Haffman – high temperature test development	(Cooper 1980, 1981)	Fully developed fire conditions	Furnace conditions on exposed side and ambient on unexposed side	Use of a ventilated box to remove the heated air	• Cross-door pressures were not possible • Measurement method for leakage was not specified
ISO 5925 Ahonen and Loikkanen – high temperature test development	(Cooper 1980, 1981)	Fully developed fire conditions	Furnace conditions on exposed side and ambient on unexposed side	Collection hood and CO_2 as a tracer gas	• Non-uniform concentration of CO_2 within furnace • Unknown amounts of CO_2 introduced by the burning specimen, esp. at the leakage gaps
ISO 5925 Cooper – high temperature test development	(Cooper 1980, 1981)	Fully developed fire conditions	Cross-door pressure could be controlled	Enclosure over the unexposed face of the door, enclosure box to be kept at ambient temperature with air extracted at top and make-up air introduced at the bottom of the enclosure, enclosure box could be pressurised	• Theoretical only – i.e. not currently implemented
Door attached to a corridor	(England and Young 1999; Young and England 1999)	Standard fire-resistance test time/temperature curve	Furnace conditions on exposed side and ambient corridor conditions on the unexposed side	Temperature, pressure and visibility were measured inside the attached corridor	• Leakage was not directly measured • More refinement of the apparatus and test procedures were recommended by the researchers

9. MODELLING AND RESULTS FOR LEAKAGE OF DOORSETS

A summary of the analytical and numerical modelling associated with leakage through doorsets is presented. In general, the amount of literature on the modelling of doorsets is limited.

9.1 Analytical and empirical models

Klote and Milke (1992) discussed analytical approaches for flow through cracks and gaps dominated by pressure differences. A general function for the flow through a crack or other opening is:

$$Q = f(\Delta P)$$

Equation 9

Where Q denotes the volumetric flow rate through the path, ΔP denotes the pressure difference across path, where:

$$\Delta P = P_i - P_o + \rho g(Z_i - Z_o)$$

Equation 10

Where subscripts i and o represent path inlet and path outlet conditions, P denotes pressure, Z denotes elevation, ρ denotes density of gas, and g denotes gravitational acceleration. f represents the general functional relation. The particular form of the function depends on the geometry of the opening and the Reynolds number:

$$\mathrm{Re} = \frac{D_h V}{\nu}$$

Equation 11

Where Re denotes the Reynolds number, D_h denotes the effective hydraulic diameter of the flow path, V denotes the average velocity in the flow path, and ν denotes kinematic viscosity.

For large Reynolds numbers (for Re > 2000 or 4000, depending on path geometry), the flow is dominated by dynamic forces. Using Bernoulli's equation (Fox and McDonald 1985):

$$P + \frac{1}{2}\rho V^2 + \rho g Z = const$$

Equation 12

Assuming steady, frictionless, incompressible flow, the flow can be written as (Fire Protection Handbook 1997; Klote and Milke 1992):

$$Q = KCA\sqrt{\frac{2\Delta P}{\rho}}$$

Equation 13

Where K denotes a flow coefficient (to account for frictional and dynamic losses), C denotes a dimensionless flow coefficient, and A denotes the flow area.

For low Reynolds numbers (for Re < 100 to 1000, depending on path geometry), the flow is dominated by viscous forces. Using the Navier-Stokes equations and assuming flow between two infinitely long flat plates, which has an exact solution (plane Poiseuille flow) (Klote and Milke 1992):

$$V = \frac{-a^2}{12\mu}\frac{dP}{dx}$$

Equation 14

Where a denotes the gap thickness perpendicular to the flow direction, x denotes the distance in the flow direction, and μ denotes absolute viscosity.

For flow between viscous and dynamic force dominated flows (100 to 1000 < Re <2000 to 4000, depending on flow path geometry) an empirically determined exponential relation has been used extensively (for low ΔP values) (Gross 1981b; Klote and Milke 1992):

$$Q = C_e \left(\Delta P\right)^n$$

Equation 15

Where C_e denotes a flow coefficient for the exponential flow equation ($m^3.s^{-1}.Pa^{-n}$), and n denotes the dimensionless flow exponent (0.5 to 1). For interior paths n is taken at 0.5 and for exterior walls n is taken at ~ 0.6 or 0.65.

Equation 10 was used by Klote and Fothergill (1983) for all smoke control analysis, as $n = ½$ of Eq. 12 was considered as sufficiently accurate. Klote and Bodart (1985) experimentally determined flow coefficients and exponents (for Eq. 12, above) for the leakage paths of a fire research tower using regression analysis. Comparison of results using the experimentally determined exponents with analysis using $n = 0.5$ was in good agreement.

Based on experimental data (Homma 1975; Hopkins and Hansford 1974; Ishira 1964), Gross and Haberman (1988) developed a general non-dimensional approach to approximate leakage through gaps of various geometries:

$$N_Q = \mathrm{Re}\left(\frac{a}{x}\right)$$

Equation 16

and

$$N_P = \frac{\Delta P D_h^2}{\rho v^2}\left(\frac{D_h}{x}\right)^2$$

Equation 17

where N denotes a dimensionless number, D_h denotes the hydraulic diameter, $D_h = 2a$, and subscripts Q and P refer to volumetric flow and pressure, respectively. Figure 36 shows the relationship between N_p and N_Q. Pressure losses at the entrance to the gap were accounted for using an analytical method, previously developed by Miller and Han (1971).

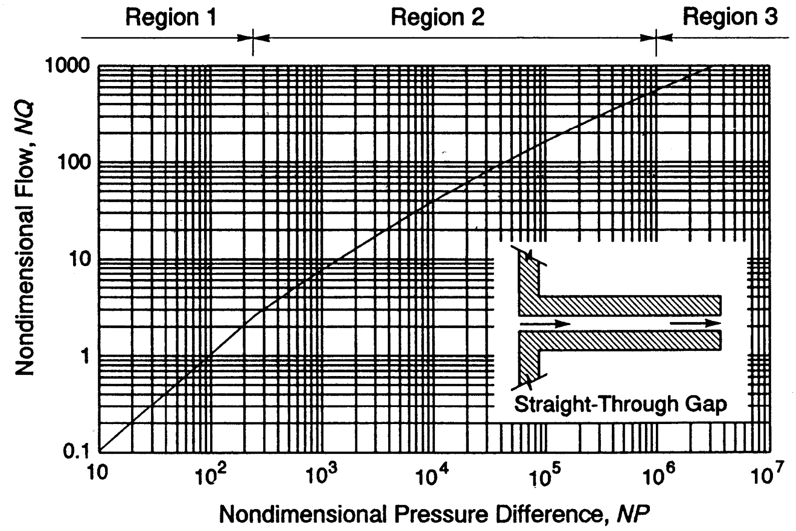


Figure 36: Relationship between flow and pressure difference for a straight-through gap. Extracted from (Klote and Milke 1992).

Region 1: viscous dominated, $N_P \leq 250$ (Gross and Haberman 1988):

$$N_Q = 0.01042 N_P$$

Equation 18

Region 2: transition region between viscous and kinetic dominated flows, $250 < N_P < 10^6$, (an approximation (± 6%), presented by Klote and Milke (1992), of the curve developed by Gross and Haberman (1988)):

$$N_Q = 0.016984 N_P^{\alpha}$$

Equation 19

where $\alpha = 1.01746 - 0.044181 \log_{10}(N_P)$.

Region 3: kinetic dominated, $N_P \geq 10^6$ (Gross and Haberman 1988):

$$N_Q = 0.555 N_P^{0.5}$$

Equation 20

Then the flow can be calculated by:

$$Q = \frac{\nu x L N_Q}{D_h}$$

Equation 21

Where ν denotes the kinematic viscosity, x denotes the depth of gap in the direction of flow, L denotes the length of gap, and D_h denotes the hydraulic diameter (D_h=2a).

The non-dimensional pressure, N_P, can be used to obtain flow factors, F_1 and F_2, for single- and double-bend slots, respectively, as shown in Figure 37 (Klote and Milke 1992). The flow factors are then used to account for frictional losses of the calculated flow due to the number of bends in the flow path, e.g. Q_{single_bend}=$F_1 Q$. A similar dimensionless analytical approach for straight-through, single-bend, double-bend, labyrinth and filament brush seals by Gross (1990, 1991).

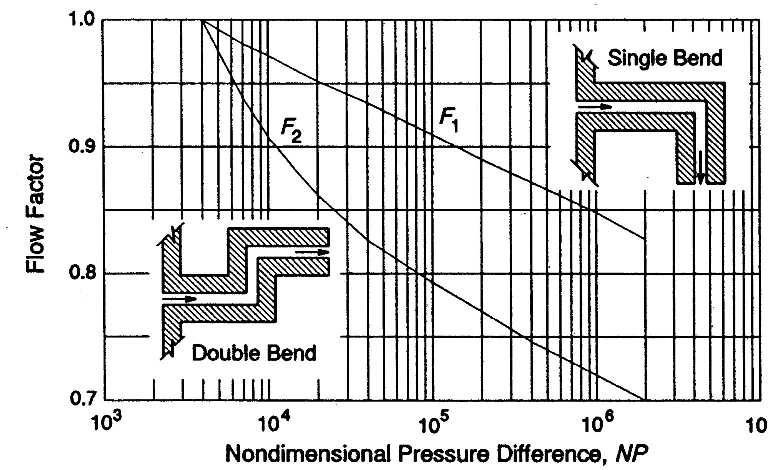


Figure 37: Flow factors for single- and double-bend slots. Extracted from (Klote and Milke 1992).

9.2 Numerical models

Increased use and acceptance of modelling approaches has been attributable to moves away from prescriptive codes towards performance-based codes in the US and other countries (Olenick and Carpenter 2003). That is, unique geometries under various fire conditions can be considered by engineering design and subsequently more diverse design solutions are being accepted.

A selection of available modelling packages that can be applied to smoke movement is discussed below, with specific interest in possible application of incorporating leakage characteristics of doorsets.

9.2.1 Zone modelling approach

A zone model predicts the effects of fire development inside a compartment, with possible flow through user-described doors, windows and vents that may be used to link several compartments (Olenick and Carpenter 2003). A zone model may comprise of a single room or a multiple compartment configuration. Each area is divided into a number of uniform zones, for which (mass and energy) conservation equations are solved. For example, a fire compartment may comprise of a hot upper smoke layer and a lower cool air layer. A general limitation of a zone model is that, depending on the heat release rate and the size of the fire compartment, the interface between the upper hot layer and the lower cold layer may not be perfectly defined and the temperature within the upper layer may not be uniform, with higher temperatures expected nearer to the fire and plume. In general, the zone modelling method has been tested for numerous fire scenarios (Sutula 2002) and has shown reasonable approximations of fire development in an enclosure (Olenick and Carpenter 2003). The zone modelling method is also better known within the fire protection community and is far less computationally intensive than field modelling approaches (Sutula 2002).

9.2.1.1 BRANZfire

BRANZFIRE is a multi-room zone model that can include such features as multiple fires and mechanical ventilation to provide predictions of ignition and flame spread on walls and ceilings, evolution of species, and time-dependent distribution of smoke, hot gases and heat (Wade 2004). Modelling of the leakage of doorsets can be attempted using vents of appropriate sizes and location. To allow for reduced buoyancy of smoke as it leaks around the door leaf to another enclosed space, the attached space can be modelled as a single-zone, thus assuming the smoke becomes well-mixed throughout the rest of the space. However, no validation studies for the case of door leakage to an adjacent space have been carried out for the BRANZFIRE model.

BRANZFIRE equations for modelling horizontal vents are based on CCFM.VENT (Cooper and Forney 1990). The vent flow is driven by the pressure differences between the spaces joined by the vent, i.e. effectively solving the Bernoulli equation. The effect of various geometries (such as door/seal/frame configurations) is not included in the vent flow calculations.

9.2.1.2 CFAST

Similarly, the Consolidated Model of Fire Growth and Smoke Transport (CFAST) is a zone model that predicts the environment in compartmented structures (Jones and Forney et al 2004; Peacock, Jones and Forney 2004). "The governing equation set of CFAST is formulated to allow the actual physical phenomena to be couched as source terms. The pressure is not assumed to be in the steady state, nor the lower layer temperature to be at ambient conditions." (Fu and Hadjisophocleous 2000) In CFAST, rooms are assumed to be perfectly sealed (Jones and Peacock et al 2004; Peacock et al 1993; Peacock, Jones and Forney 2004). Horizontal flow connections (vents) may be used to account for leakage between compartments or to the outdoors.

CFAST explicitly solves the Bernoulli equation to model the flow through a vent (Jones and Peacock et al 2004), resulting in an expression similar to Eq. 10. The use of vents to model leakage associated with a door does not account for differences in flow rate due to a single-bend or double-bend (or other complicated door/frame geometry) in the leakage flow path.

Jones, Peacock, Forney and Reneke (2004) reported that leakage could have a dramatic effect on the results predicted by a CFAST model. An example of this was presented for a single room with a single doorway and an upholstered chair. The model was run for leakage areas from 0 to 100% of the vent area with a second vent of appropriate size and located at floor level. The model results showed that temperatures and pressures change by more than a factor of two, as shown in Figure 38, and it was suggested that other variables can be expected to change with similar variation. Temperature was reported to change by about 20% for a 10% leakage area.

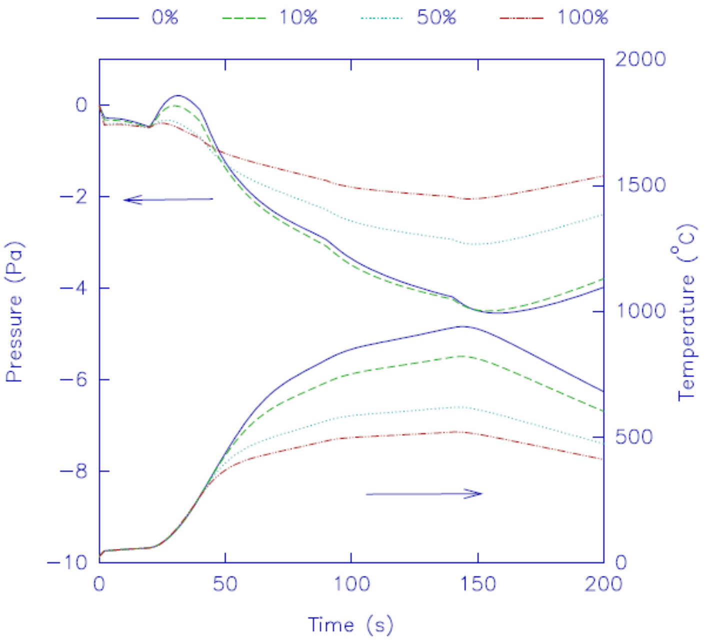


Figure 38: An example of CFAST model output for various leakage rates, modelled using a vent from a fire room. Extracted from (Jones and Peacock et al 2004).

9.2.2 Computational fluid dynamics approach

The field model approach to modelling fire development inside a compartment is based on the concept of dividing the area of interest into a large number of much smaller control volumes than used in a zone model approach. Field models can provide a more detailed solution than zone models, however more detailed input is required and the computations take longer to process (Olenick and Carpenter 2003). Although computational fluid dynamics (CFD) modelling, or field modelling, approaches are more computationally intensive than zone models, with ever-increasing computer processor speeds it has become possible for CFD models to be run on desktop personal computers without necessarily relying upon sophisticated computer workstations or supercomputers (Sutula 2002).

9.2.2.1 Fire dynamics simulator

Fire Dynamics Simulator (FDS) is a large eddy simulation based fire model, using the low Mach number approximation to the Navier-Stokes equation and mixture fraction based combustion (McGrattan 2005). FDS is one of the most widely used of the CFD codes, which were specifically written for the investigation of large-scale fire scenarios (Sutula 2002). FDS was produced at the National Institute of Standards and Technology (NIST) and has been made available to the public. Smokeview, which is also publicly available, is companion software to FDS that provides a graphical representation of the problem and FDS solution. The FDS Version 4.0 code allows the user to specify the soot yield as a mass fraction of the fuel (McGrattan 2005).

9.2.3 Other models specifically designed for smoke control

Models, other than zone and field types, have been developed specifically for investigating the effect of fire. A selection of the more predominant ones is summarised here.

Klote (1982) developed a computer program for the analysis of smoke control systems. A building was modelled using a network of nodes, each representing a space with an average pressure and temperature. Leakage through closed doors was included as an option in the model. Leakage through windows, partitions, floors, exterior walls and roofs was also included in the model. Flow through a leakage path was modelled as a function of the pressure difference across the leakage path. All flows and leakage paths were assumed to occur at mid-height of each level. The equations used are a simplified flow equation (similar to Eq. 10, above) and mass balances. Steady, frictionless and incompressible flow and ideal gas behaviour were assumed. Losses due to friction were incorporated into pressure calculations for flows in shafts. Some examples of model output for some initial building conditions were provided, however these results were not compared to experimental results.

Klote and Milke (1992) developed the Analysis of Smoke Control Systems (ASCOS) model, which used a network model approach for modelling steady airflow analysis of smoke control systems (Friedman, Olenick and Carpenter 2002). This program was designed as a tool to analyse smoke control systems that used pressure differences to limit smoke movement in a building during a fire event. Stack effect could be included in the analysis. The required input consisted of the outside and building temperatures, a description of the building flow network and flows produced by the ventilation or smoke control system. The output consisted of the steady state pressures and flows throughout the building. ASCOS has been superseded by another network model, CONTAM.

Tanaka (1983) and Jones (1985) developed numerical models for the movement of smoke and toxic gases in multi-compartment structures. Two zones in each compartment (corresponding to the stratified layers observed during fire spread) were used to model the composition of the gas in each compartment. This approach was a compromise between a network model (with no information on the internal structure of a compartment) and a CFD finite difference model (which would be more computationally intensive). Flow through open doorways was included, however no closed doors or the associated leakage were considered.

Similarly, some other models (Cooper 1983; Emmons 1979; Hagglund 1983; Zukoski and Kubota 1980) were developed that also utilised a two-zone approach for the modelling of smoke movement. However these models were developed primarily for the prediction of smoke in the smoke compartment of fire involvement (with strong buoyancy-driven stratification of the compartment atmosphere), and did not include flow or leakage from the fire room.

Other models (Edwards and Greuer 1982; Evers and Waterhouse 1978; Fu and Hadjisophocleous 2000; Jones and Quintiere 1984; Wakamatsu 1968) were developed for the prediction of smoke spread to rooms adjacent to the smoke compartment of fire involvement. Some (Edwards and Greuer 1982; Evers and Waterhouse 1978; Wakamatsu 1968) utilised an approach analogous to tracer-gas migration type flow. However these models also did not include leakage through doorsets.

10. SUMMARY AND CONCLUSIONS

Good smoke management, whether using the strategy of exhaust, ventilation, pressurisation or containment, depends on a combination of known and dependable elements – of which smoke doors are one element – to protect means of egress, area of refuge or similar areas. Smoke doors are of no value unless appropriate smoke stopping characteristics for the situation are selected, an ongoing maintenance schedule is practised and the operation of the door is unhindered (i.e. providing unblocked passage for evacuating occupants and firefighting measures and closes fully during a fire). Therefore characterisation of the air leakage of a door exposed to a range of conditions similar to those expected during its function as a smoke barrier is an integral part of the selection of appropriate fire safety measures.

New Zealand and Australian building code regulations require protection from smoke, but do not call up standards that specify test methods for measuring leakage of doorsets, nor are acceptability criteria defined. US building regulations and standards specify maximum values for the leakage criteria of doorsets as 54 m^3/h per unit area of opening (NFPA 105 1999) at a cross-door pressure of 25, 50 or 75 Pa at ambient and medium temperatures (UBCS 7-2/2 1997; IBC 2003; NFPA 5000 2003). The English and Welsh building regulations specify a maximum leakage rate of 3 m^3/h per metre of gap, when tested at a cross-door pressure of 25 Pa (ODPM, Build. Reg. 2000, Approved Doc. B 2004). Warrington Fire Research recommended a maximum leakage of 15 m^3/h per leaf under the conditions of AS/NZS 1530.7 (WFRA FSE 04.1 2003). The German standards for doorset leakage set a maximum leakage requirement of 20 m^3/h for single-leaf and 30 m^3/h for double-leaf doors at ambient and medium temperatures (DIN 18095/2 1991). In addition, the maximum leakage criteria for larger doors, shutter assemblies, folding and other types of doors is a maximum of 50 m^3/h for an assembly of clear opening 3 – 7 m wide and 3 – 4.5 m high, 40 m^3/h for an opening of 3 × 3 m. For other sizes of openings, the maximum leakage rate is to be calculated from the ratio of area opening compared to the 3 × 3 m case (DIN 18095/3 1999).

In general, the temperature conditions for testing leakage of doorsets are:

- Ambient temperature is chosen to represent the very early stages of fire development or when the doorset is sufficiently remote from the fire for gases and smoke to have cooled.
- Medium temperature is chosen to represent partially cooled gases and smoke from a fire, but high enough to "cause physical distress due to distortion or surface damage".
- High temperature is chosen to represent conditions similar to a fully developed fire.

Results from ambient temperature air leakage tests (ASTM E283-73 1980; ISO/DIS 5925/1 1981; ASTM E 783-81 1981; AS/NZS 1530.7 1998) would be useful for providing doorset leakage characteristics required in the analysis of pressurised and ventilated stairwell designs, early-time analysis of smoke leakage from fire compartments to the rest of a facility and general intra-facility smoke migration.

Difficulties of establishing performance criteria for doorsets include:

- Lack of a standard test that provides meaningful and useful data for assessment of performance in high temperature conditions for comparison with ambient temperature results.
- Lack of quantitative smoke door requirements in New Zealand and Australian building codes.

- Lack of smoke door ratings.
- Determining an acceptable leakage rate – a nominal leakage rate, a proportional reduction in the flow through the fully open door, or a rate dependent on the maximum smoke concentration allowed in the adjacent room and the time necessary to maintain tenable conditions.

As an aside, similar to smoke control doorsets, the New Zealand requirements for lift landing doorsets are qualitative and not quantitative.

A range of experiments investigating the movement of smoke within buildings have been conducted and reported in the literature. A limited number of these included doorset leakage, while the majority focused on active smoke control systems. There is currently insufficient data for use in fully characterising the leakage of doorsets under various temperature and cross-door pressure conditions for modelling purposes. Comparisons of results from experiments and analytical studies have shown the relationship between the leakage rate of the whole test apparatus and cross-door pressure (e.g. for an apparatus including three test doors, a sliding door and two observation windows, as shown in Figure 32 (Sugawa et al 1985)) was similar to analytical and empirical equations used to describe leakage (e.g. Eq. 10 and 12, above). Furthermore, the leakage rate associated with flaming conditions was shown to be slightly higher than the rate associated with the ambient conditions. However care must be applied, since the error associated with these measurements was not presented, therefore it is difficult to discern how significant the increase in leakage rate for the flaming conditions compared to the ambient conditions actually were. It may be useful to determine the empirical relationship between leakage rate and temperature for a range of cross-door pressures.

Doorset leakage could be incorporated into zone models using appropriately described ‘equivalent-area’ vents, subject to validation studies being conducted. The field modelling package, FDS, has not been applied specifically to leakage problems.

11. RECOMMENDATIONS FOR FUTURE WORK

Based on the literature summarised in this study report the following recommendations for future work are proposed.

Doorset leakage regulations:

- It is recommended that smoke doorsets should be tested to a recognised standard to determine the smoke leakage rate. Possibly AS/NZS 1530.7 should be called up by NZBC C/AS1 and an acceptance criteria defined.

Characterisation of doorsets:

- In order to achieve a better understanding of the leakage rates of doorsets, it is recommended that a series of ambient and high temperature experiments be performed at a range of cross-door pressures. The objectives of this series of experiments would include:
    - Determination of the high temperature leakage of current doorsets for various cross-door pressures.
    - Determination of the relationship between ambient measurements and high temperature measurements.
    - Determination of the acceptability during fire conditions, in terms of the tenability of the space to be protected, of doorsets with known leakage characteristics.

Proposed experimental methods for achieving these objectives:

- High temperature testing of doorset leakage based on the principles of the ambient testing of AS/NZS 1530.7 is proposed for testing single-leaf doorsets while exposed to a pilot furnace. That is, the pressure is controlled on the unexposed face of the doorset to maintain the appropriate average cross-door pressure during the duration of a test. The leakage of the doorset is to be determined from the flow required to maintain the appropriate pressure on the unexposed side of the doorset, in conjunction with the characterised leakage of the apparatus and expansion of the gases in the apparatus volume due to heating.

- Measurement of the smoke filling an adjacent corridor to a burn room via a door with known leakage characteristics, as determined by ambient testing, in accordance with AS/NZS 1530.7, and the proposed high temperature test. The smoke would be provided by the item ignited in the burn room. This method of testing would aid in the determination of the appropriateness of the other methods of determining characteristic doorset leakage rates and acceptable leakage limits.

Modelling of doorset leakage:

- Determine the level of detail of the leakage characteristics and environmental conditions required to balance accuracy and computational expense to provide sufficient information for the reliable assessment of a design.

- Validate the incorporation of doorset leakage characteristics into models.

- Characterise various doorsets, to provide modelling parameters for fire engineering design purposes.

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APPENDIX A: Summary of Case Studies of Building Fires where Smoke Inhalation was Identified as a Major Cause of Death or Injury

A summary of some of the available information for a selection of case studies of building fires (where multiple fatalities and/or injuries that were predominately attributed to smoke inhalation) is presented in Table 13.

Table 13: A Summary of case studies where smoke inhalation was a major cause of death or injury

Year	Building Type	Location	No. Storeys	No. Fatalities /Injuries (firefighters)	Fatality Information	Fire Origin	Fire Spread	Building Information	Fire Safety Precautions	References
1967	Dormitory	Cornell University, USA	3	9/60	7 found attempting to escape; 2 found in their room with door open	Started in basement	Doors held open on fire floor	48 rooms	No alarm system	(Gaudet 1967)
1972	Apartments with elderly residents	Baptist Towers	11	10/-	9 on floor of fire origin (2 from burns), 1 on 10th floor	Started in 7th floor apartment	Fire burned through apartment door and spread to corridor			(Willey 1973; Wu 2001)
1980 21 Nov	Multi-storey Hotel	MGM Grand, Las Vegas	26	84/-	Most from smoke inhalation, the majority occurred on floors far above fire floor	Fire started in wall of a restaurant on the first floor, faulty wiring blamed	Smoke spread throughout the building via a stairway, laundry chutes that did not seal and the HAVAC system	~5000 people in hotel when fire started	No sprinklers	(Klote 1990b; Puit 2000a, 2000b)
1985 15 Dec	Hospice	Michigan	5	8/-	All suffered from smoke inhalation, and were in rooms with open or partially closed doors	In a patient's room on the second floor	All magnetic smoke doors were release and close, except for in the wing of the fire; Patients' doors were not latched properly	The physical and mental state of many patients made self-escape impossible	Manual pull station	(Isner 1987)

Table 13: Continued: A summary of case studies where smoke inhalation was a major cause of death or injury

Year	**Building Type**	**Location**	**No. Storeys**	**No. Fatalities /Injuries (firefighters)**	**Fatality Information**	**Fire Origin**	**Fire Spread**	**Building Information**	**Fire Safety Precautions**	**References**
1987 22 Mar	Apartments	Schomberg Plaza, Harlem, NY, USA	35	7/-	Deaths occurred on the 33rd and 34th floors	A lit cigarette (or similar) ignited trash in a chute between the 27th and 29th floors	Fire spread through trash chute to apartments on the 23rd, 33rd and 34th floors and the public corridor on the 29th floor; Fire also spread through a window from 34th to 35th floor		Sprinkler system installed in chute, but was not operational	(Schaenman 1987)
1988 11 Jan	Apartments with ground floor offices	New York City, NY, USA	10	4/2 (0/5)	1 in 9th floor apartment, 3 in stairwell	Ignition cause unknown; Started in a professional office on ground floor	Smoke filled stairwells through open fire doors on the fire floor	120 units; Constructed in 1920's ; Renovations – decorative wood panelling in office	All exit and apartment doors were metal fire doors with 17 mm gap at bottom; No sprinkler system, fire alarm system, emergency lighting or illuminated exit signs	(Isner 1988; Kirby 1988)
1989 30 Jun	Commercial	Atlanta, Georgia, USA	10	5/23 (0/6)	1 was electrician at scene of ignition, 4 from smoke inhalation	Fire started in an electric closet on the 6th floor			No sprinklers	(Grimwood 2003)

Table 13: Continued: A summary of case studies where smoke inhalation was a major cause of death or injury

Year	Building Type	Location	No. Storeys	No. Fatalities /Injuries (firefighters)	Fatality Information	Fire Origin	Fire Spread	Building Information	Fire Safety Precautions	References
1989 24 Dec	Apartments with elderly residents	John Sevier Center, Johnson City, TN, USA	11	16/50 (0/15)	1 in unit on fire floor, 1 in elevator lobby on 6th floor, 14 in units on higher floors	Fire started in a loveseat in an apartment on 1st floor		Originally a hotel, then converted into residence; Number of prior false alarms; Sub-freezing temperatures – residents did not want to leave	No sprinklers; Official were updating building; Fire-resistant doors installed on all apartment entrance ways, but many closers had been removed	(Carpenter 1989)
1992 5 Dec	Row house	Chester, Pennsylvania, USA	2	8/-	Smoke inhalation, all were children from one family	Bed in 1st floor bedroom, smoke materials suspected		Balloon frame wall construction; Combustible interior finish	One inoperable smoke alarm – batteries removed	(Chubb 1992)
1993 28 Feb	Low-rise Apartments	Ludinton, MI, USA	2	9/-	Smoke inhalation on 2nd floor in apartments	On or near a wall-mounted light fixture in 2nd floor corridor	Leakage of smoke into apartments through vents in corridor		No fire systems installed	(Kirby 1993)
1995 6 Jan	Apartment	North York, Ontario, Canada	29	6/-	On floors above the fire, in exit stairways	Smoking materials ignited a couch in a 5th floor apartment	Apartment of fire origin entrance door was left open; Fire spread to an exitway corridor; Residents that stayed in their apartments with the door closed were all unharmed		Loud speakers – but not audible; No sprinkler system; No fire safety training	(NFPA 2002; Richardson 2002; Yung and Lougheed 2001)

Table 13: Continued: A summary of case studies where smoke inhalation was a major cause of death or injury

Year	Building Type	Location	No. Storeys	No. Fatalities /Injuries (firefighters)	Fatality Information	Fire Origin	Fire Spread	Building Information	Fire Safety Precautions	References
1996 21 Nov	Commercial	Hong Kong	16	39/80	22 were found in a single office on the 15th floor	Fire started from welding in an elevator shaft in the basement	Fire spread through the elevator shaft to the top 3 floors	21 year old building	No sprinkler ; No automatic fire alarm	(Grimwood 2003)
1998 23 Dec	Apartments	Upper West Side of Manhattan, NY, USA	51	4/-	Smoke inhalation in the stairway between the 27th and 29th floors	Fire started on the 19th floor	Hallway and stairway acted as a smokestack		No sprinkler systems; only a fire hose and standpipe in the stairwell	(Kirby 1988)
2000 Apr	Apartments	Detroit, MI, USA	12	4/multiple	3 from smoke inhalation – 2 in an apartment on the fire floor, 1 in the stairwell, 1 had limited mobility and sustained burns found in the stairwell	Apartment on 8th floor	Poorly equipped emergency services; Faulty hydrant		-	(Claxton and Hurt 2000)
2000 25 Dec	Multi-Occupancy Building	Louyang, China	4	309/-	Suffocation	Started in basement by welding crew doing maintenance		Building contained offices and a dance hall	No sprinkler system; Fire exits had been blocked; Safety reports had been falsified	(People's Daily - Luoyang 2000; People's Daily - Luoyang 2001; Hewitt 2000)
2002 6 Nov	Passenger Train	Nancy, France	1	12/-	Smoke inhalation	Started in the compartment of a train attendant	Panicked passengers smashed windows and jumped to safety	A sleeping car was filled with smoke	No smoke detectors; Cigarette smoking was allowed in designated cars	(Rees 2002)

Table 13: Continued: A summary of case studies where smoke inhalation was a major cause of death or injury

Year	Building Type	Location	No. Storeys	No. Fatalities /Injuries (firefighters)	Fatality Information	Fire Origin	Fire Spread	Building Information	Fire Safety Precautions	References
2002	Residential Apartments	Florida	3	-/1	Smoke inhalation of a man in the unit adjacent to origin of fire	Heat from a pinched, overloaded electrical cord ignited combustibles in an apartment	Fire quickly detected and controlled by sprinkler system	48 units	Fire detection system; Wet-pipe sprinkler system	(Tremblay 2002)
2003 26 Feb	Nursing Home	Greenwood Health Center, Hartford, Connecticut	-	16/-	Most were in rooms with open doors	Fire started in bedding of one room	Door of fire room left open	Elderly and mentally challenged adults, and 148 coma and psychiatric patients		(Wolf 2003)
2003 12 Nov	Residential Apartments	West Rogers Park, Chicago	4	3/19	Smoke inhalation generally blamed	Started in basement				(Rees 2003)
2004 15 Oct	Office Building	Cook County, IL	35	6/6	12 found unconscious in stairwell and on 22nd floor – 6 dead – all smoke inhalation	Started in a storage room on 12th floor		Stairwell doors locked on inside until 27nd floor	Unpressurised stairwell with automatically locking doors; Fire alarm system; No sprinklers above first floor	(Coffee 2003; Fidler 2003)
2004 6 Dec	Office Building	LaSalle Bank, Chicago	43	-/37	Smoke inhalation	Started on 29th floor				(Rees 2004)