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SMOKE CONTROL IN MULTI-STOREY BUILDINGS

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PREFACE

This report on a study carried out at BRANZ details research into the smoke control measures applicable to multi-storey buildings.

AUDIENCE

The report is intended primarily for Fire Engineers, Architects, Code Writers and Researchers.

SMOKE CONTROL IN MULTI-STOREY BUILDINGS

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KEYWORDS

Computer Programs Control, Fire Hazard, Fire Safety, Multi-storey building, Smoke, Smoke Detection Systems, Smoke Extraction, Smoke Proof Doors, Smoke Venting.

ABSTRACT

Multi-storey buildings typically have complex floor plans and unknown gaps between the compartments. The effectiveness of smoke control systems in these buildings relies on the accuracy with which the movement of smoke and air in buildings is predicted. Not only have smoke control systems failed in the past to control the spread of smoke, in many cases lack of understanding has also led to over designs and additional costs. Greater understanding of the movement of smoke and air within buildings and how it is affected by exterior weather and wind conditions will assist in the selection of economical and adequate smoke control systems. Factors affecting smoke movement in multi-storey buildings and the methods currently used to control smoke are discussed in this study report. The current research on smoke control in New Zealand and overseas is also reviewed. A comparison of regulatory codes from New Zealand with those of other countries has also been made, to assess adequacies and inadequacies related to control of smoke movement.

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1.0 INTRODUCTION

The working of smoke control systems for buildings with simple plans and non-complex connection between compartments is well understood. As a contrast, multi-storey buildings typically have complex floor plans with unknown gaps between compartments. This leads to complex requirements for smoke control in the buildings. This report will explain and discuss the various aspects of smoke movement in multi-storey buildings and the methods of control presently in use. A comparison of International Codes and their emphasis on smoke control has also been carried out.

Smoke may be simply defined as a cloud of well mixed gases and unburnt solid particles which are a product of combustion. Smoke generation is greatly influenced by the amount and type of fuel and the air available for combustion. In most building fires the cause of death is smoke rather than the fire itself. The delay in the escape of the occupants caused by loss of orientation and visibility combined with the inhalation of toxic fumes and lack of oxygen are often the causes of these deaths. Thus, the time available for escape is critical. The widely accepted time required for the evacuation of occupants from a building with two alternative means of escape is 2.5 minutes, and 1 minute in the case of a single means of escape (Wade, 1991; Bastings, 1988).

Smoke control system design and strategies generally aim to provide a tenable environment during evacuation. Smoke control systems in combination with sprinklers can in most cases be used effectively to lengthen the available time for escape. Investigative research work in this field is being carried out in the UK, Canada, USA, Japan, Australia and New Zealand.

Smoke control techniques are used to manage smoke movement in buildings and to direct smoke away from escape routes. Smoke control can involve passive and/or active means to modify and direct the passage of smoke to minimise its harmful effects on occupants and property, and in some cases to provide a tenable environment for fire fighters.

It is a common practice in multi-storey buildings for thermally activated sprinklers to be installed to control fires at an early stage and as a safeguard against the development of unmanageable fires. In such instances smoke generated before sprinkler activation becomes a major problem. Often sprinkler activation can be delayed, particularly in a smouldering fire where a large quantity of smoke is produced before sufficient heat is generated. In some smouldering fires, sprinklers have failed to activate and the fires have been extinguished by other means. Although sprinklers are essential in the fire safety of many buildings they cannot be considered as an alternative to, or in isolation from, adequate smoke control design of multi-storey buildings.

All building control documents recognize the difficulty of controlling smoke movement in high rise buildings. In most of the documents, height limits of buildings have been set based on the types of occupancies and the difficulties associated with the evacuation of occupants during emergencies. Buildings exceeding these height limits require increased or special fire and smoke control provisions. In setting these height restrictions, the degree of difficulty for fire fighters to get access to upper floors from outside the building, and the heights up to which adequate water pressure for fire fighting is available without delay have been taken into consideration.

Some building control documents, including the New Zealand Building Code (NZBC) (BIA, 1992) recommend smoke control and other life safety measures based on the occupancy load and type. The NZBC (BIA, 1992), as opposed to the prescriptive nature of NZS 1900 Chapter 5 (SANZ, 1988a) adopts a performance based approach. Table 1 shows the height limits set in the various control documents from various countries including those in NZS 1900 Chapter 5 (SANZ, 1988b) and the NZBC (BIA, 1992).

Table 1 **Comparison of Building Codes for the Heights of Multi-Storey Buildings Above Which Increased Fire Protection and Smoke Control Measures are Required**

Building Code Document	Building or Occupancy Type	Height	Remarks
Building Code of Australia, (BCA 1990)	All types except atriums	25 m	
	Atrium types	more than 3 storeys	
NZS 1900 Chapter 5, 1988 (SANZ, 1988a)	All types	24.4 m	
NZ 4238 (SANZ 1991)	Atrium type	lesser of 13 m or 4 floors	Automatic sprinklers mandatory for building exceeding 45.7 m.
National Building Code of Canada, (NRCC 1990)	Residential	18 m	
	Institutional	18 m	Including buildings with this occupancy type on floor level 3 and above.
	Business, Assembly or Industrial	36 m	Reduced to 18 m when occupancy loads are not in compliance or exceed other criteria or limits.
BS 5588 Pt.3 (BSI, 1983)	All types	18 m	
Draft BS 5588 Pt.7 (BSI, 1990)	Atrium types	18 m	Automatic sprinklers mandatory for buildings above 30 m height.
NZBC Fire Safety Annexe, Table B1/7 (BIA, 1992)	All types	Any height	When occupancy loads exceed 100 persons. Alternative fire engineering solutions applicable provided the same level of safety is maintained.

2.0 MOVEMENT OF SMOKE IN BUILDINGS

In taller or multi-storey buildings the movement of smoke is predominantly caused by fire effect, stack effect, wind effect, and air movement and ventilation systems.

These four main factors individually, or in any combination, can cause smoke to move from the fire compartment to other floors.

2.1 Fire Effect

In the early stages of a fire there is a rapid increase in the temperature in the fire compartment. Air just above the fire in the compartment expands, developing a pressure differential with adjacent spaces. This causes smoke to spread through horizontal and vertical openings to cooler parts and adjacent spaces. In a fully developed compartment fire with smoke temperatures of 1000 °C and the neutral axis at 1.0 m above the ground level, the increase in pressure at a door head 2.0 m above the floor is about 5 Pa (Butcher and Parnell, 1979). This small pressure differential is sufficient to transport smoke to adjacent spaces. All other factors remaining constant, in a steady state situation the effect of buoyancy diminishes due to heat loss and dilution as smoke moves further away from the fire, and as the temperature in the fire compartment stabilises. The effect of thermal expansion is therefore more pronounced in smaller buildings like residential dwellings rather than in high rise buildings where its influence is significant only in the very early stages of a fire. Thus some of the discussion of smoke movement carried out in this report may also be applicable to smaller buildings.

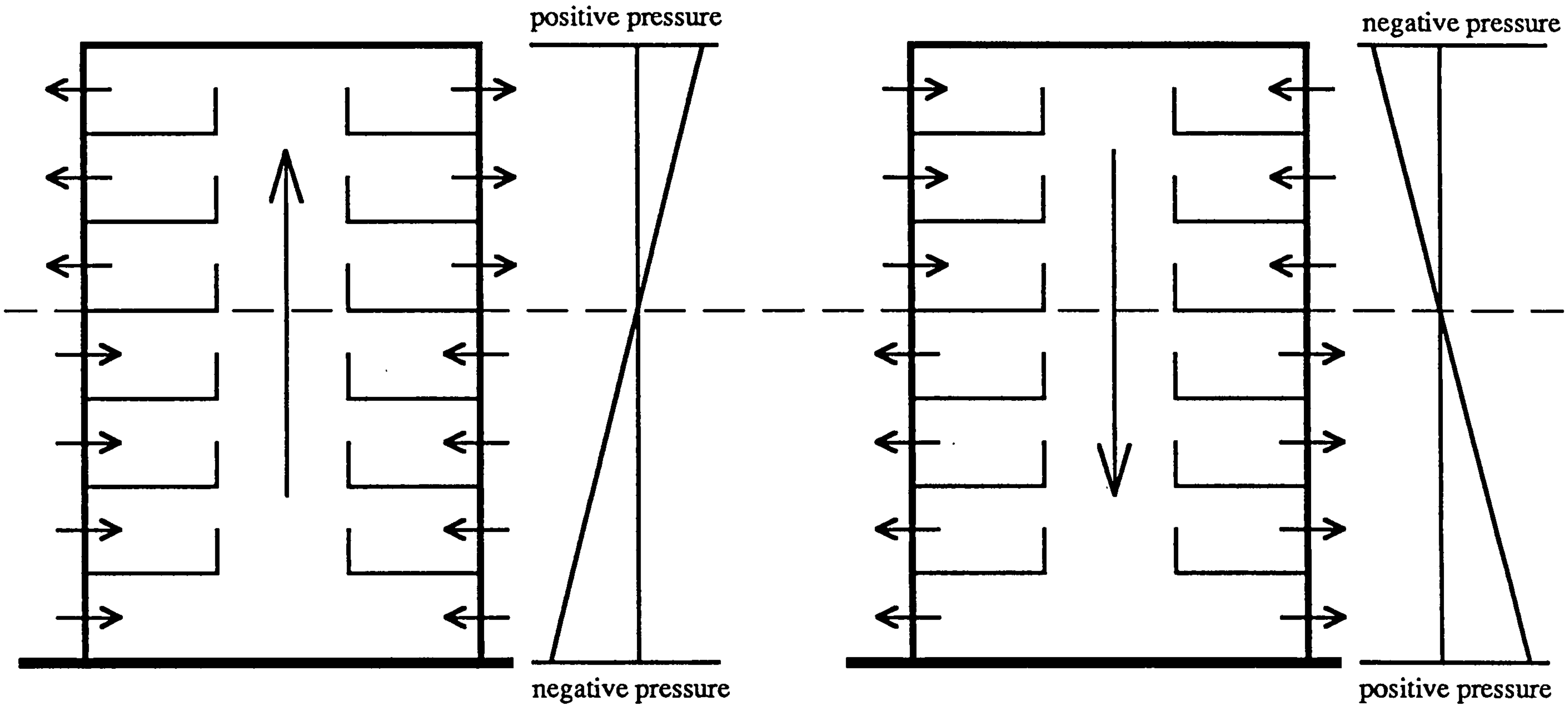
2.2 Stack Effect

Stack effect is caused by the difference in temperature between the interior and exterior of a building. Duing a fire, smoke and hot gases may spread to places very remote from the fire compartment due to this phenomenon. Normal stack effect exists when the exterior is cooler than the inside of a building. This causes dense cool air from the outside to flow into lower floors of the building and displace the lighter but warmer air in the building to the upper floors. This gives rise to a pressure differential between the interior and the exterior of the building as shown in Figure 1. At some height in the building a neutral plane exists where the pressure difference between the exterior and the interior of the building is zero. At this level there is no movement of air into or from the building. On floors above the neutral axis there is a horizontal and outward movement of air. The height of the neutral plane is generally affected by the air handling and ventilation systems and local floor temperatures in the building. Reverse stack effect exists when the interior of the building is cooler than the exterior.

If a fire occurs below the neutral plane of a building with normal stack effect, smoke travels up the building shafts and begins to migrate horizontally into adjacent floor areas once it rises past the neutral plane. Floors below the neutral plane remain relatively free from smoke. If the fire floor is above the neutral plane, smoke flows out of the building through vents or openings in the external walls or roof. Floors above the fire floor will remain smoke free if the vertical interfloor leakage is small. In buildings where reverse stack effect occurs, smoke movement to the floors above the neutral plane is still possible if the buoyancy pressure resulting from the fire is sufficiently high.

2.3 Wind Effect

The effect of wind on air movement within buildings is significant. Temperatures in fire compartments are often sufficient to shatter glass panels and windows at an early stage. Shattered windows on the leeward side of the fire floor help vent smoke and curtail smoke logging within the building. On the windward side, broken windows allow smoke on the fire floor to be pushed into adjacent spaces on the fire floor and other floors. Wind pressures on the exterior walls depend on the size and shape of the building and other buildings surrounding it. As defined in the Loadings Code NZS 4203 (SANZ, 1992) pressure p, on any point on the exterior surface of the building is given by the expression:



Normal Stack Effect

Reverse Stack Effect

Figure 1 Stack effect in buildings.

$$p = [C_{pe} - C_{pi}] \times q \qquad \text{Equation 1}$$

where :
C_{pe} = external pressure coefficient
C_{pi} = internal pressure coefficient
q = dynamic pressure of wind

In Equation 1 the values for C_{pe} are based on the distribution and area of openings on exterior walls. The values for C_{pi} depend on the structural geometry of the building.

2.4 Heating, Ventilation and Air Conditioning Systems

Heating, ventilation and air conditioning systems (or HVAC systems) are an integral part of modern high rise buildings. The overall pressure in a building is affected by variations in local air pressures between spaces, depending on whether there is outflow or inflow of air taking place. In well compartmented buildings the influence is localised; in open plan buildings, air movement in the building may be affected to a greater extent. In addition to this, HVAC ductwork interlinks compartments and often forms connections between compartments on different floors. This poses potential hazards when parts of the ductwork system fail during a fire because of fire, gases and smoke can spread to other parts of the building.

3.0 METHODS OF SMOKE CONTROL

3.1 Passive Smoke Control

Passive smoke control systems such as smoke barriers, smoke reservoirs and natural ventilation form built-in features of the building that are functional at all times. They serve one or both of the following purposes during a fire:

- restricting the spread of smoke and fire by forming barriers or restricting ventilation.
- restricting the passage of smoke to areas away from escape routes.

The importance of passive systems lies in their ability to restrict the spread of smoke during the early stages of a fire (pre-flashover) when occupants are evacuating the building. Better smoke control performance can also be obtained in the later stages of the fire (post-flashover stages) from the use of fire resistant building elements.

Effective performance of passive smoke control systems is founded on their ability to maintain integrity for the required duration and intensity of the fire. Real fire temperatures may vary greatly from the standard time-temperature curves (ISO 834, 1975) used in testing the fire resisting performance of construction elements. However it may be expected of elements that satisfy the above standard test that integrity failure will not occur in the early stages of a fire in a firecell. Satisfactory fire resistance and effective design and location of these systems are important for their useful functioning. Their design and locations are based on fire and smoke control strategies for each individual building.

3.1.1 Smoke Barriers

As discussed in the preceding section, resistance and containment of hot gases is the primary consideration for the effectiveness of these systems. Floors, ceilings, walls and smoke stop doors are the usual forms of smoke barriers.

Imperforate floors, ceilings and walls form adequate smoke barriers. Smoke leakage problems arise when there are perforations or construction joints in these elements. Compliance with NZBC C3/AS1 6.6 (BIA, 1992) requires all gaps between penetrations and smoke separations to be impermeable to smoke, including all seismic gaps and service duct penetrations that may be provided in floors, ceiling and walls. Gap seals complying with AS 1530.4 (SA, 1990) or with BS 476 Part 24 (BSI, 1987), where the fire resisting performance of sealed gaps is tested as part of the ductwork, are accepted as suitable for building construction in New Zealand.

Smoke Control Doors: "Smoke stop door" has been used in NZS 1900 Chapter 5 (SANZ, 1988a) to define a fire door that prevents smoke leakage. NZS 4232 (SANZ, 1988b) requires the smoke leakage rates through such doors to be tested in accordance with ISO 5925/1 (1981) or BS 476 Part 31.1 (BSI, 1983b). These standard tests do not simulate situations where smoke stop doors may be used in conjunction with other smoke control methods like pressurisation of escape routes.

The requirements for smoke stop doors have been replaced in NZBC C3/AS1 (BIA, 1992) with smoke control doors. A smoke control door may not be a fire door. The term has been deliberately chosen to emphasize this difference. A smoke control door must be smoke sealed but need not meet the smoke leakage requirements of NZS 4232 (SANZ, 1988b). Smoke control doors are required by the NZBC (BIA, 1992) to be self-closing and where they form part of an exitway, to open in the direction of travel.

Studies carried out by Gross and Haberman (1989) show good agreement (to within 20 %) between theoretical and measured smoke flow rates through doorsets for a wide range of pressure differences. Although greater variations are expected when doors and frames contain sealing devices like flexible gaskets and fibre brushes, the theoretical method of Gross and Haberman (1989) may be used to predict smoke flow rates through ordinary smoke stop doors to pressurised compartments. A more detailed discussion on door opening and closure forces appears in the section "Pressurisation of the escape route" of this report.

3.1.2 Smoke Reservoirs

Uncontrolled horizontal smoke spread can cause loss of buoyancy due to cooling of the smoke layer. This may lead to increased downward mixing. There is also a tendency for cool smoke to stagnate, often rendering distant vents ineffective. In buildings with large undivided floor areas, smoke reservoirs restrict horizontal spread of smoke. They are structured underneath a roof or ceiling to form an inverted pool that stores smoke rising from the spaces within fire compartments, from which it can be extracted effectively [see Figure 2 (a)]. In multi-storey buildings, where there are large connecting spaces between floors, smoke reservoirs are required directly above these spaces to prevent smoke logging of the upper floors [see Figure 2 (b)].

Morgan (1979) and Morgan and Gardner (1990) have carried out investigative studies into the design and effective management of such reservoirs for atrium type buildings. Reservoirs are well suited in these buildings because of the large open spaces between floors. The design volume that the reservoir is required to retain at any one time is based on the mass flow rate of smoke entering the reservoir. The mass flow rates used in the study by Morgan and Gardner (1990) have been determined for a design fire with 5 MW heat output.

Limits for the size of smoke catchment areas, depths of smoke curtains and spacing of vents for the reservoirs are detailed in most building control documents. Spratt and Heseldon (1974) observed that if the rate of extraction was greater than a critical value at any point in the mechanical ventilation of shallow reservoirs, then air would be drawn up by entrainment. The authors concluded that maximum extraction of smoke (as opposed to air) is achieved by maintaining a deeper layer of hot smoke. In addition, deeper smoke curtains ensure that turbulence or downward mixing due to the extraction of smoke through vents may be contained within the depth of the reservoir and stop spillovers that may otherwise result.

Smoke, when it reaches the base of the reservoir, spreads horizontally. Its horizontal spread is curtailed and stagnation occurs due to the loss of buoyancy caused by cooling as it moves further away from the fire. Hence a design ventilation area in the form of a number of vents sparsely spaced in vast reservoirs cannot achieve the desired level of smoke extraction. Limiting the size of the catchment area of the reservoir ensures that vents remote from the source of smoke are not too far away to be effective.

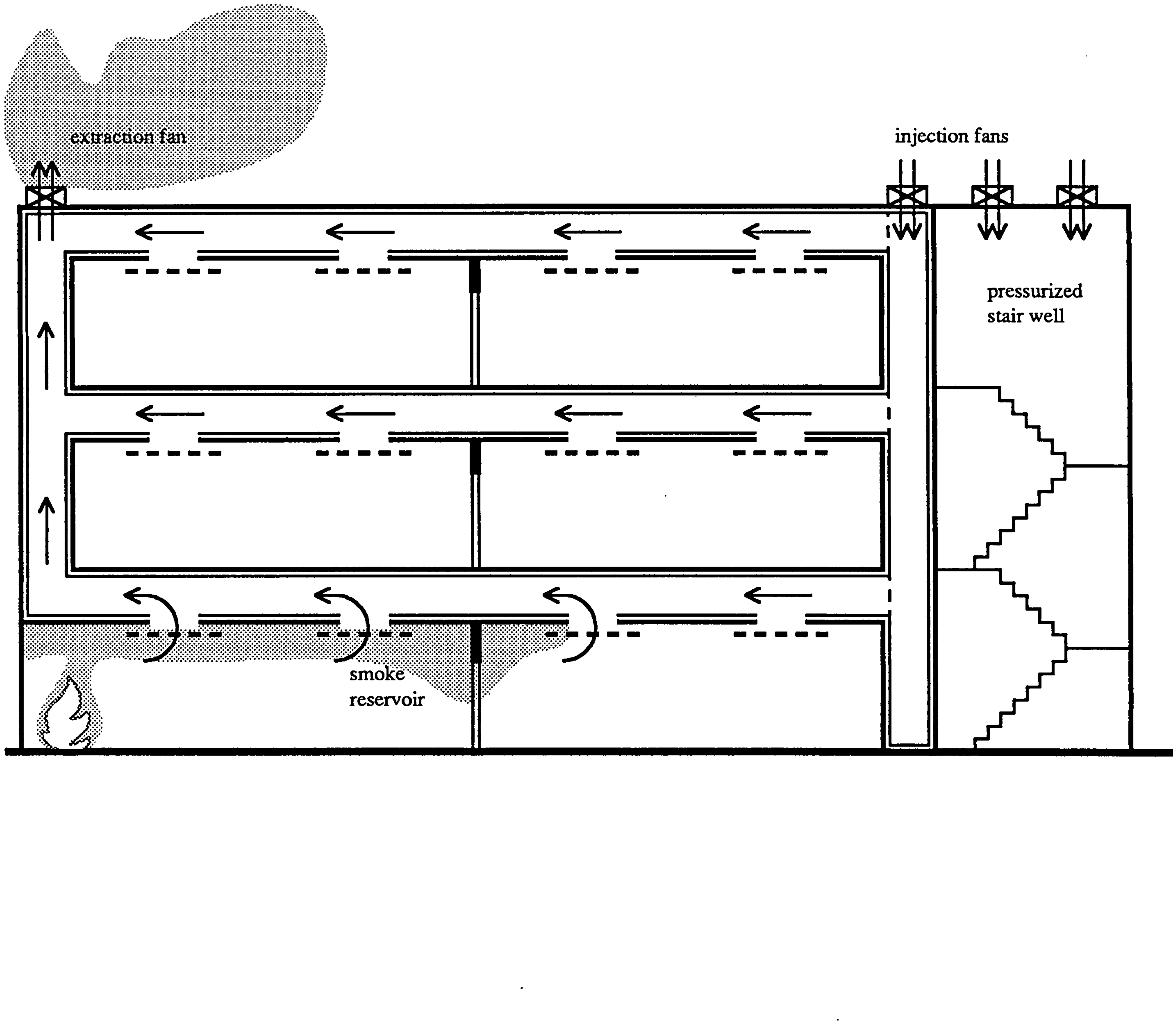


Figure 2 (a) Smoke reservoirs in a compartmented building

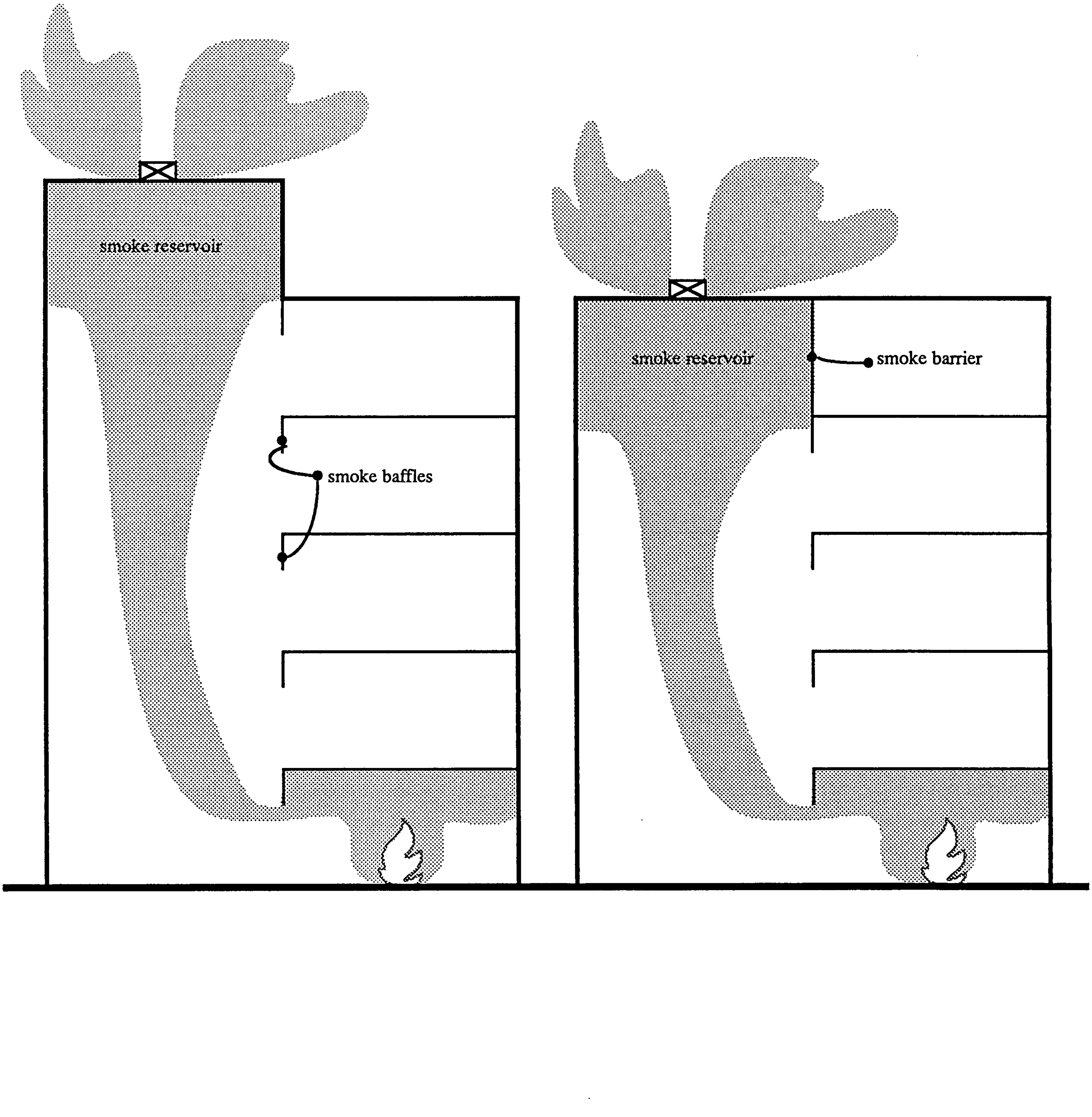


Figure 2 (b) Smoke reservoir in buildings with connecting spaces

An additional constraint on the design of reservoirs is the need to limit the base of the smoke layer to at least head height. The minimum acceptable height in NZBC (BIA, 1992) is 2.0 m above the floor.

Vent design and sizes are discussed in greater detail in the next section. Table 2 shows the recommendations of various building codes on the limits of depths and catchment areas for reservoirs. There is general agreement amongst them that deep and narrow smoke reservoirs are more effective than broad and/or shallow ones.

3.1.3 Natural Ventilation

Smoke extraction by natural ventilation may be used independently or in combination with mechanical extraction. Mechanical methods may be required when wind conditions are not favourable for natural ventilation. Mechanical extraction of smoke is discussed in more detail under active smoke control systems later in this section.

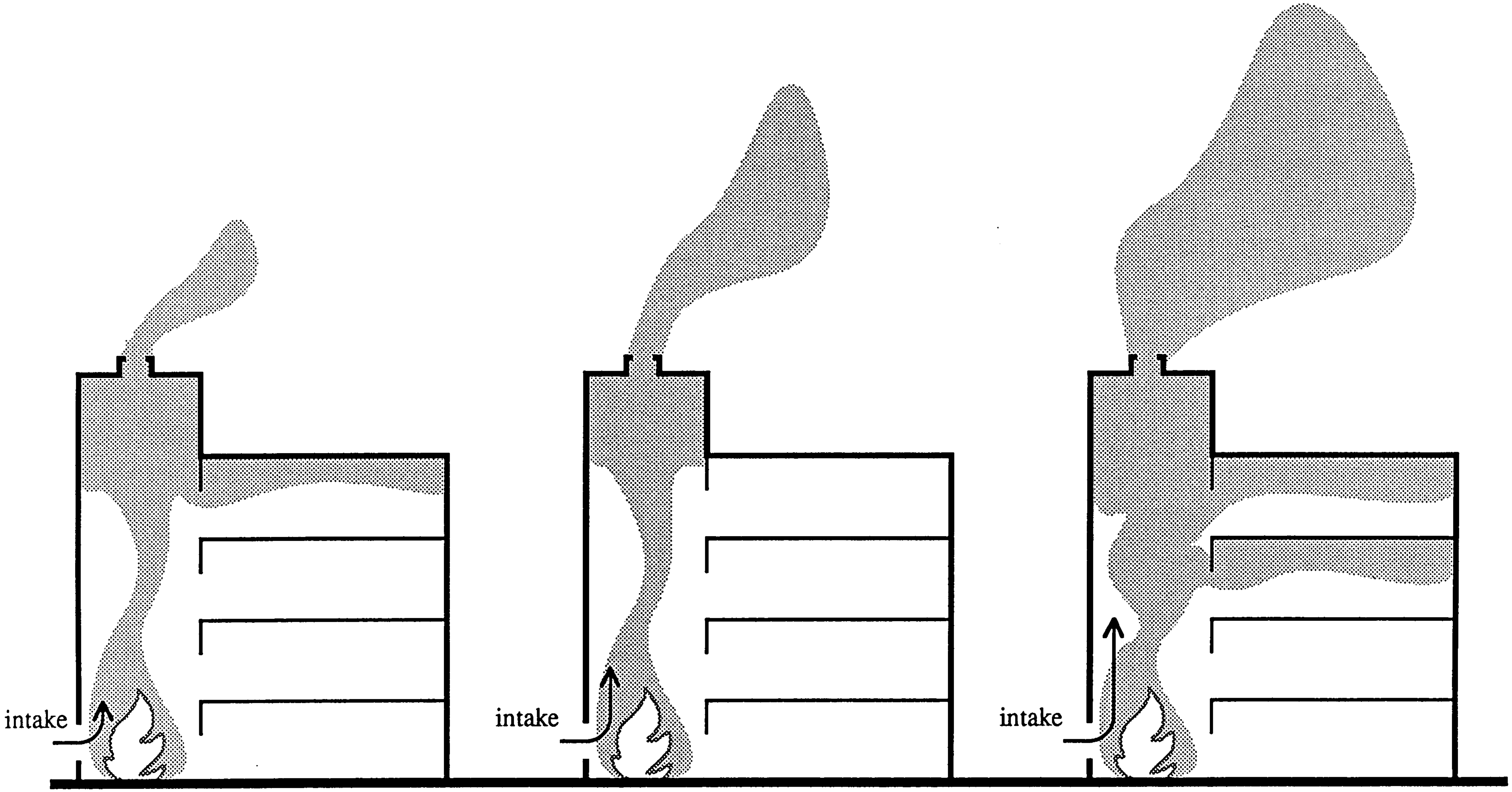
Vent Design and Sizing: Natural ventilation in buildings occurs due to a pressure differential between the inside and outside of a building. Design and sizing of vents is based on the calculated pressure differentials developed as a result of buoyancy (fire) and wind effects, which are the major reasons for smoke movement through vents.

Vent design aims to achieve a balance between the rates of extraction through the vents and the rate of smoke production by the fire plume in the compartment (Hinkley, 1988). The important consideration in this regard is that the extraction rates need to be approximately equal to smoke inflow rates. Greater extraction rates lead to turbulence in the smoke mass caused by the suction of cooler "make up" air into the reservoir. The buoyancy of smoke is reduced by the mixing of cooler air and as a result downward mixing occurs. On the other hand greater inflow rates cause the smoke layer interface to be lowered leading to smoke logging of floors immediately below the reservoir (see Figure 3).

To prevent disturbance to the smoke layer/air interface, restriction of the rate of inflow of "make up" air must be allowed for at the design phase. Morgan's (1979) "make up" air velocity values for natural ventilation of between 1 and 1.5 m/s are comparable with results

Table 2 **Comparison of Reservoir Dimensions and Catchment Areas Recommended in the Various Building Codes**

Building Code	Reservoir Dimensions	Max. Catchment Area (sq.m)
Building Code of Australia, (BCA, 1990)	Minimum curtain depth ranging from 0.5 m for reservoirs with mechancial extraction to 1 m for ceilings with vents only. Maximum distance between curtains is 40 m.	1500
DZ 4226, (SANZ, 1984)	Minimum average depth of curtains is 1.5 m.	1000
Uniform Building Code, (ICBO, 1991)	Minimum depth of curtain = 1.8 m Maximum depth extending from ceiling to 2.45 m above ground.	
Morgan and Gardner, 1990	Least depth of curtains for 5MW fire is 0.5 m. Minimum depth of reservoir based on possible mass flow rate of smoke in the building.	1000 for natural extraction 1300 for mechanical extraction.
NFPA 204M, 1988	Minimum depth of curtains = H/5, where H = height of shaft or compartment. Maximum depth of curtains extends from ceiling to 3.05 m from ground. Maximum distance between curtains = 8H Minimum distance between curtains = 2H unless curtain depth is greater than 40% of floor height.	
BIA Draft NZBC, (NFPA, 1991) Acceptable solution C3 Paragraph 9.2.6	Generally smoke reservoirs constructed with the ceiling 2 m higher than the ceiling level of the rest of the firecell.	



Extraction < Production
Spillover

Extraction = Production
Balance design

Extraction > Production
Downward mixing

Figure 3 Smoke extraction design

obtained from the fire plume deflection studies carried out by Mudan and Croce (1988). The value of 1 m/s is recommended in NFPA 92B (NFPA 1991b) based on the Mudan and Croce (1988) study. Morgan (1979) recommends that alternative means be used if the "make up" air velocity is expected to exceed 3 m/s. Special openings must be provided in the perimeter of the building if the doors and windows that are expected to be open during a fire below the smoke layer interface do not provide the required inlet area. The requirement generally is for the "make up" air inlet area to be at least equal to the total extract vent area. In addition to restricting air flow rates, downward mixing resulting from the turbulence caused by extraction may also be reduced considerably by adequate distribution of a greater number of small vents to meet design vent area requirements.

Different methods have been used in NFPA 204M (NFPA 1991c) and UK FRS Paper No. 7 (Thomas et al. 1963) to estimate the vent area required for the extraction of smoke from the reservoirs or compartments. In NFPA 204M (NFPA 1991c), heat output of the fire is used as the basis for vent area estimations. In Thomas et al (1963), vent area estimates are dependent on the mass rate of production of hot gases. Nonetheless, similar results are obtained using either method. Both the above approaches are based on the assumption that the fire size for which venting is required can be predicted at the beginning of the exercise. Estimations are then made based on whether the fire is a small or large one. The NFPA 204M (NFPA 1991c) definition of a small fire is one which is not expected to grow beyond a predictable maximum size. A large fire is one that grows indefinitely until there is intervention by fire fighters.

Smoke Plumes: The rate of smoke production is directly related to the smoke plume configuration. NFPA 92B (NFPA 1991b) addresses three types of smoke plumes:

- Axisymmetric Plumes for smoke from fires in the atrium space, distant from any walls;

- Balcony Spill Plumes for smoke spilling into a large space from fires under balcony spaces;

- Window Plumes for smoke flow through doors and windows into large open spaces.

A sample smoke extraction calculation based on axisymmetric and balcony spill plumes has been provided in Section 6.3.

Vent and Inlet Locations: Extraction rates are affected by pressures developed just outside the vents by wind or air movement on the exterior of the building. Roof vents, therefore, need to be located where the net wind pressure produces a suction effect. For this reason horizontally discharging outlets are not suitable for natural smoke ventilation.

"Make up" air inlets must be located no higher than the lower edge of the smoke reservoir. Any possibility of these air inlets being covered over at a later date or during refurbishing must be considered at the design stage and arrangements made to prevent this from occurring.

3.2 Active Smoke Control

Active smoke control measures consist of pressurisation of shafts and escape routes, mechanical smoke extraction and ventilation systems. Pressurisation systems may be designed to function at all times as part of the ventilation, system or to become operational in the early stages of the fire by activation through thermal, smoke or optical detectors.

3.2.1 Pressurisation Method of Smoke Control

In New Zealand, although this method of smoke control has been used in buildings in the past, it has not gained the support of designers until recently. Overseas, however, this method of active smoke control has been extensively researched and widely applied in buildings. With the greater emphasis on life safety in the NZBC (BIA, 1992) it is expected that there will be renewed interest in the pressurisation method

Pressurisation creates a pressure gradient across barriers of compartments that form part of the escape route or vertical shafts, with the aim of keeping these areas smoke-free. This is achieved simply by maintaining sufficiently high over-pressures in these areas to ensure that air movement is always outwards through gaps or when doors or windows are opened. This restricts the entry of smoke. The amount of pressure required in the compartment is determined by the most unfavourable combination of wind, stack and buoyancy pressures that has to be overcome to stop smoke entry into the compartment.

The principle of building pressurisation is to maintain higher pressures on all floors above the fire floor with respect to the exterior. This is achieved by keeping all floors adequately air-tight. In air-tight buildings, air for pressurisation supplied through the HVAC system and venting to the outside from the fire floor, through smoke shafts or exterior wall openings, ensures that air flow inside the building is always towards the fire floor. Tamura and McGuire (1973), in their study show that pressurisation of the whole building may be achieved with modifications to, and effective monitoring of, the level of air tightness, air distribution systems, smoke shafts and damper functions. Because of potential failure in each of the above elements, a high level of maintenance and periodic testing is needed.

There are three main forms of escape route pressurisation:

- Pressurisation of the stairwell area only;
- Pressurisation of the stairwell and connected lobbies; and
- Pressurisation of the elevator shaft and connected lobbies.

Pressurisation of the stairwell area only: The leakage and venting of air from pressurised compartments plays a vital role in the successful operation of any pressurisation scheme. Leakage occurs through spaces and gaps around doors and windows in the compartment. Tests conducted on pressurised stairwells in the UK (Butcher and Parnell, 1979) showed that 5 Pa excess pressure in the compartment prevented ingress of smoke through gaps. It was also shown that this excess pressure was adequate to keep the stairwell smoke-free when the doors were opened. Any smoke entering the stairwell was cleared in a short time after the door was closed. The test results also showed that the maximum pressure difference experienced across openings was around 12.5 Pa. This occurred when doors opened to the exterior of the building were exposed to wind speeds of up to 32 km/h. Based on these results, pressure differentials ranging from 25 to 50 Pa were recommended as being satisfactory for the pressurisation of compartments.

Pressurisation of the stairwell is sometimes carried out in two stages. In such systems a lower level of pressure is maintained at all times, then, the pressure is raised automatically to the design hazard level in an emergency. This ensures a level of protection against entry of smoke into the stairwell during the early stages of a fire. A lower level pressure differential of between 8 and 15 Pa was recommended by Butcher and Parnell (1979) as satisfactory for this purpose.

Contamination of air by the short circuiting of exhaust smoke from smoke exhaust vents on the exterior of the building, or smoke from a fire nearby, is the primary factor that determines the quality of air passing through the supply air fans. This problem is overcome by the suitable location of inlets and adequate separation from smoke exhaust vents.

Air for pressurisation may be supplied at one or more points in the stairwell. There is a greater potential for the loss of pressurisation by short circuiting in the case of a single injection system if a few doors close to the point of injection are open. Tests conducted on this system by Tamura (1989) and others revealed that the high pressure difference across doors near the single injection point made opening them difficult. Full scale tests in stairwells with single injection points at the top or the bottom of the stairwell by Achakji and Tamura (1988) indicated the following :

- Open-tread stairs offered less resistance to airflow than closed-tread stairs and hence pressure drops were less.
- The increase in the number of occupants in the stairwell increased the resistance to airflow, leading to a drop in pressure.
- There was a greater pressure drop in stairwells in buildings with lesser floor height for the same cross-section of stairwell and stair slope. This was attributed to the greater landing areas in the stairwells in buildings with lesser floor heights, which offer greater resistance to airflow.

The presence of such asymmetries in stairwells will lead to significant pressure drops as the stairwells get deeper. In such instances multiple injection could be more practicable. To reduce the difficulty of opening doors near injection points multiple injection may also prove more suitable in multi-storey buildings housing the sick, the disabled and other people requiring care.

The above studies show that the efficiency of pressurisation using air injection fans may be improved by ascertaining the pressure drop characteristics of stairwells. On the other hand, controls for the performance of stairwell pressurisation, as set in AS 1668 Part 1 Cl. 6.4 (SAA, 1979), ensure that minimum air pressures and air flows across doors may be maintained for all types of stairwell configuration.

Difficulty in opening doors resulting from pressurisation may cause problems to occupants at normal times and cause delays in an emergency. Most building control documents have acknowledged the practical implications of door opening forces. Klote's (1983) method for the calculation of the required force (based on the assumption that the force is applied at the door knob) is useful in this regard. The minimum force needed to open the door is given as the sum of the force required to overcome the pressure difference and the force required to overcome the door closer, as follows :

$$F = F_d + F_p \qquad \text{Equation 2}$$

$$= F_d + \frac{w \times A \times \Delta P}{2 \times [w - d]} \qquad \text{Equation 3}$$

$$\Delta P = \frac{2 \times [F - F_d] \times [w - d]}{[w \times A]} \qquad \text{Equation 4}$$

or

$$\Delta P_{max} = \frac{2 \times [F_{max} - F_d] \times [w \times d]}{[w \times A]} \qquad \text{Equation 5}$$

where,

F = Force required to open the door
F_d = Door closure force
F_p = Force required to overcome pressure differential
w = Width of the door
A = Area of the door
d = Distance of the door knob from the nearer vertical edge
ΔP = Pressure differential

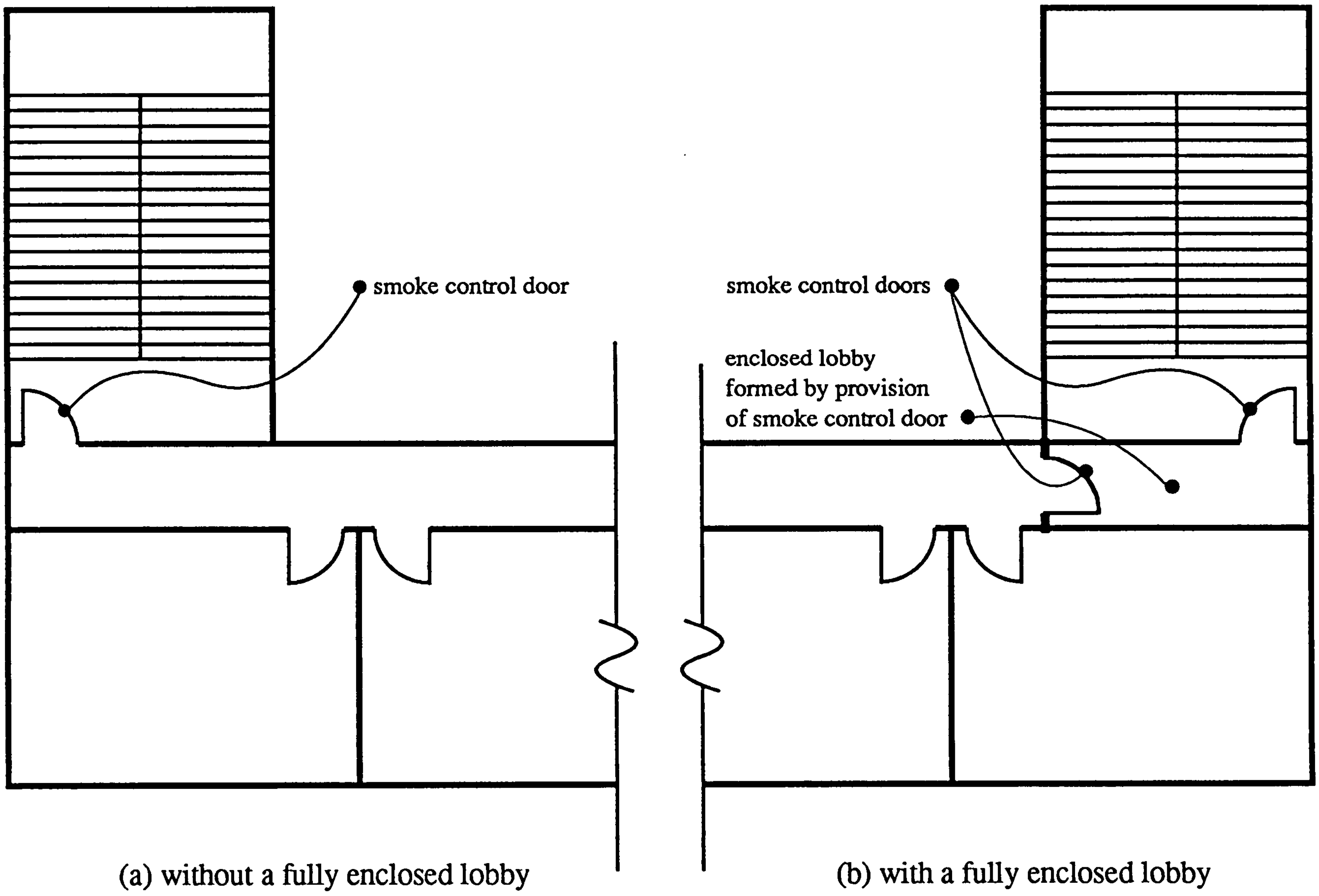
Although there is a general agreement between most building control documents on the maximum permissible pressure, the maximum door opening forces vary greatly. Based on Equation 2 and Table 3 it appears that the UBC (ICBO, 1991) and NFPA 101 (NFPA 1991a) allow for a greater door closure force. This may bring about quicker closing, and therefore reduce the entry of smoke which results from the loss of pressure while the door is open. The larger door opening forces may cause discomfort, making it more likely that the occupants will wedge doors open during normal operation, thus defeating the purpose for which the doors were provided. In buildings housing children, the disabled, the elderly or the sick, the larger force (133 N) required to open these doors may cause discomfort to the occupants and delays in evacuation. Table 3 below shows the forces and pressure differentials recommended in various building control documents.

Table 3 Comparison of the maximum door closing forces and maximum air pressure differences across doors for the pressurisation of stairwells

Building Control Documents	Maximum door opening force (N)	Pressure (Pa)
AS 1668 Part 1, (SAA, 1979)	110	50 (max.)
National Building Code of Canada, (NRCC 1990)	90	50 (max.)
Uniform Building Code, (ICBO 1991)	133	12.5 (min.)
NFPA 101, (NFPA, 1991a)	133	45
BS 5588 Part 3 and Butcher and Parnell, 1979		60
NZS 4232, (SANZ, 1988b)	110	50
NZBC, C3/AS1 (BIA, 1992) Paragraph 9.5.6	110	50

Pressurisation of the Escape Route (Stairwell and Connected Lobbies or Vestibules): The inclusion of vestibules or enclosed lobbies, even without pressurisation forms good smoke barriers. These areas are often provided with smoke reservoirs by raising their ceiling level adequately above the doors. This requires smoke from the floor area to pass through an additional compartment to reach the stairwell. Smoke entry into the stairwell may be further delayed by pressurising the vestibules. If the pressure in the enclosed lobby is maintained at a level higher than the floor area, but less than in the stairwell, an effective pressure gradient opposing the entry of smoke is established between the floor and the stairwell (see Figure 4). Tamura's (1989) study of a 17-storey building shows good evidence of the added protection achieved by the provision of vestibules connected to staircases. In the event of a fire, pressurised vestibules also provide a staging area for the fire service.

Pressurisation of the Escape Route (Elevator Shafts and Lobbies): Pressurisation of elevator shafts and spaces connected to them prevents transport of smoke through these areas to remote compartments. The introduction of new and better fire resistant construction materials has led to research into the possible use of elevators as a safe means of egress in buildings like hospitals and rest homes, with occupants whose evacuation via staircases may



(a) without a fully enclosed lobby

(b) with a fully enclosed lobby

Figure 4 Stairwell construction

be difficult and cause delays. The pressurisation of elevator shafts and elevator lobbies may be compared with the pressurisation of stairwells and connected lobbies. Indirect pressurisation of elevator lobbies can be achieved through pressurisation of the elevator shaft or vice versa.

Experiments conducted by Klote and Tamura (1987a) on pressurising the elevator shaft and elevator lobbies in an 11-storey building generally show good agreement with results from computer simulation and analysis. However tests simulating a common occurrence on the ground floors, where the doors to the elevator, lobby and to the exterior are all open simultaneously, resulted in large pressure drop in the lobbies and elevator shaft at all floor levels. Some success was achieved in overcoming this effect with pressurisation of the shaft with feedback control. Static pressure sensors which detected the pressure difference between the elevator lobbies and the rest of the building returned signals that regulated the rate of air supply in the elevator shaft thereby maintaining a reasonable level of pressurisation. Klote and Tamura (1987a) also noted the need for the sensors to be adequately protected from heat if they were to operate effectively.

Extending their elevator shaft and lobbies study, Klote and Tamura (1987b) investigated the piston effect of the elevator in the shaft on elevator smoke control. Elevators in motion cause suction below or above them, depending on their movement up or down. This led to entry of smoke into the shaft due to suction. In practice the loss of pressurisation due to the piston effect was overcome by maintaining a mass flow rate of pressurisation air above or equal to the critical pressurisation value determined theoretically.

3.3 Mechanical Smoke Extraction

Mechanical extraction of smoke is often used to supplement or replace natural ventilation in the following situations where:

- there is insufficient vent space to meet natural ventilation demands;
- adverse wind conditions may be expected outside vent openings; and
- the layout of a building does not permit effective smoke removal by natural ventilation.

The design of mechanical extract systems is generally similar to that for natural ventilation. Mechanical extract fans are required to work at temperatures around 100 °C above ambient (Hinkley, 1988). Hinkley noted that there was a drop in extraction rate of the fans with increase in the working temperature. Such shortfalls may be overcome by using, in the design phase, the extraction characteristics of the fan at the anticipated working temperature. The fan is required to produce this extraction characteristic for the full duration of the fire. Pyle (1975) recommends that the number and size of fans be determined based on a maximum velocity of 2.6 m/s for air and smoke drawn through them. This appears to have been recommended on the basis of his experience in preventing turbulence and downward mixing in smoke reservoirs.

3.4 Smoke Detection Devices

The advantage of smoke detection devices is that they detect fires earlier than heat detectors. Their early warning capabilities are especially useful in smouldering and electrical fires which often fail to activate fire alarms or sprinklers early enough to prevent considerable fire damage. Sampling for smoke entering the building, as a result of short circuiting of smoke from exhaust vents through intakes, may be carried out by locating smoke detection devices near intakes or inside intake ducts. Smoke detection devices may be either single station or multiple station. The single station type has been recommended by NZS 4514 (SANZ, 1989) for residential buildings as a low cost entry into smoke detection. Such units may be powered by means of batteries. Multiple station types are generally used in larger buildings where the detection of smoke by any one of the points in a multiple station type arrangement is required to set off the alarms in the rest of the devices. This system is usually designed to also activate the building services into fire mode in an emergency.

Ventilation systems that regulate air and smoke movement in the building have the potential to move smoke away from detection devices. Hence, using smoke detectors alone for fire detection is inadequate. Most designers and building services engineers use smoke detectors in conjunction with other automatic fire alarm systems that comply with NZS 4512 (SANZ, 1984a) as part of the fire and smoke detection scheme in high rise buildings.

Smoke detectors are usually activated by optical or ionisation mechanisms or by a combination type detector with sensors of both types. Alarm activation by optical or photoelectric smoke detector is achieved when airborne particulate matter of smoke obstruct the beam path or cause scattering of light beams. This type of detector is made up of a light source and a photosensitive device, placed some distance apart. Ionisation detectors activation occurs when smoke particles interfere with the current flow through the air gap between two charged electrodes housed within the detector.

Ionisation detectors are known to respond slightly earlier in flaming type fires, whereas photoelectric detectors respond more rapidly than the ionisation type in smouldering fires. Thus detectors may be selected on the basis of the type of fire that may be expected in a particular building, or part of a building.

A comparison of smoke detector requirements in some of the international codes is shown in Table 4. Generally, smoke detectors are required wherever fire detection is deemed compulsory and only as part of the fire alarm system. There is a general emphasis in these codes for intake air to be sampled by smoke detectors. Some codes do not require smoke detectors to be provided if the building is sprinklered. NZS 1900 Chapter 5 (SANZ, 1988a) does not appear to cover the early detection of smouldering fires. This is implied by the omission of the requirements for smoke detectors.

Table 4 Comparision of Building Codes for Requirements for Smoke Detectors in Multi-Storey Buildings

Control Document	Occupancy Type	Requirements
National Building Code of Canada, (NRCC 1990)	Whenever fire alarms are required in all buildings with more than 3 storeys or where the occupancy is greater than 300 persons.	In every public corridor and stair shaft.
(cl 9.10.17.3)	In buildings that are not sprinklered but where fire alarm systems are required.	In storage rooms, elevator shafts, janitor closets or any room where hazardous material is intended to be used or stored.
Uniform Building Code, 1991 (ICBO, 1991) sec. 1210 (a)	All sleeping accommodations including dwelling units.	Installed to approved manufacturer's instructions. To be located on upper floors with sleeping rooms, on the ceiling close to the stairway.
sec. 1807 (a) & (d)	In sprinklered buildings with accommodation occupancies on floors 22.8 m above the lowest level of fire department access.	In every room housing an elevator, electrical, mechanical telecommunication type equipment. In critical locations inside air conditioning ductwork.
sec 1715	In atrium type buildings	The ceiling around the perimeter of the atrium at 9.15 m centres and not more than 4.6 m from the atrium opening or spaced according to the listing.
Building Code of Australia, (BCA, 1990) Part E1.7 Specification E1.7	All health care or lodging type occupancies (with more than 20 beds) and parts of buildings with such occupancies.	Surface mounted. Outside air handling systems. Located at natural collection points of hot smoke. To be situated not more than 1.5 m from smoke stop or fire doors. Photo electric type to be used if installed within ducts or locations where dust particles are expected.
G3.8.4.2	In atrium type buildings.	To be located inside all intakes of pressurization and air handling systems.
DZ 4226 (SANZ, 1984) (cl 7.3.3.2)	Commercial buildings of 2 storeys or more. Sleeping accommodation sharing means of escape with other types of occupancy and, institutional and custody type buildings of any height. Spaces used for storage of 4 storeys and over.	Mutiple station type
New Zealand Standard 1900, Chapter 5 (SANZ, 1988a)	—	—
NZBC Fire Safety Annexe Table B1 (BIA, 1992)	Any type of building based on the occupancy type and load.	Smoke detectors to activate smoke extraction. Smoke detectors to be located in accordance with NZS 4512. Additional smoke detectors beneath each intermediate floor 200-500 mm from smoke baffles.

4.0 COMPUTER MODELLING OF SMOKE MOVEMENT AND CONTROL

Computer simulation and analysis of smoke movement and control in multi-storey buildings have been useful in research to understand the dynamics of air and smoke movement. Such models have been used successfully in residential type buildings with less complicated floor plans and leakage paths between compartments (Bukowski et al. 1989). Most of the computer programs for multi-storey buildings are still in their developmental stage and extensive use of complex models will depend on how well they test with a large number of fire scenarios. Said (1988), in his review of the computer programs that existed at that time discussed the success achieved by various research organisations in incorporating the factors affecting smoke movement in multi-storey buildings, and how the non-linearities that arose as a result had been solved or overcome.

Most of the current computer programs used in research can be classified into two categories: steady state and transient type analytical models. Some of the computer programs used for analysing smoke control systems and smoke movement in multi-storey buildings are discussed briefly below.

The Wakamatsu (1968) or BRI model for the steady state analysis of airflows and pressures with smoke concentration uses time as the only variant. It is recognized as a simple start into the area of computer simulation of smoke movement. The model can also be used to determine evacuation times. In a more advanced version of his 1968 model, Wakamatsu (1971) noted large differences between predicted air flow and air flows from real fire tests. This was attributed to unknown leakage paths in the buildings tested. Further developmental work towards an unsteady state and transient model was documented in Wakamatsu (1973).

The Computer Program for the Analysis of Smoke Control Systems by Klote and Fothergill (1983), often known as the NBS model, is an extension of Klote's (1981) program previously developed for the analysis of pressurised stairwells and elevator shafts. This program was developed to study fire effects and not the behaviour of fire, and is based on the stack, wind and mechanical ventilation effects. Nevertheless, it is useful in the study of smoke movement. Steady state airflows and pressures of all the compartments in the building are calculated. Friction losses in vertical shafts are taken into consideration in this program. In its extended form the program may be used to analyse stairwells with vestibules, elevators with elevator lobbies, pressurised corridors and zoned smoke control or fully pressurised buildings where smoke is exhausted directly from the fire floors. Based on the successful use of the earlier version in analysing pressurised stairwells, Klote (1985) recommends that the NBS model is the best one for commercial use by designers until further programs are developed. The program's output includes pressure differences across all of the building shafts and the flows and pressures throughout the building. Said (1988) noted that in situations where wind pressures play a significant role, the program was unable to produce an effective simulation.

The Irving (1979) model has the capability of carrying out steady state, pseudo-steady state and transient analyses. This model takes into account the approximated effects of thermal expansion. The accuracy of the outputs of this program have been tested against a real hospital fire situation (Irving, 1981). The prediction of smoke movement was in general agreement with observations of actual smoke staining that resulted from the fire.

The IRC model was originally developed by Sander and Tamura (cited in Said, 1988). Further advancements and modification have been carried out since (Said, 1988). Steady state analyses of buildings with open floor plans may be carried out using this program. Like the NBS model, friction losses in vertical shafts are also accounted for. Verification work for this model was carried out by Said and MacDonald (1991). Physical experiments for this exercise were carried out on the 10-storey experimental fire tower (Achakji, 1987) of the National Research Council of Canada. Deviations in pressure drops across doors in the computer output were reduced when the leakage area was increased by 25%. This improvement of results led Said and MacDonald (1991) to believe that there were unknown leakage areas in the building. In general, there was good agreement between their computer outputs and experimental results.

Computational fluid dynamics models such as JASMINE (BRE, 1987) developed by the Fire Research Station at Borehamwood, England are also available commercially. Fluid dynamics equations are used in JASMINE to describe three-dimensional heat and mass transfers within enclosed spaces to enable the prediction of smoke movement. Smoke movement in enclosed spaces such as, hospital wards, road tunnels and aircraft cabins have been examined using JASMINE.

5.0 ACCEPTANCE TESTING OF SMOKE CONTROL SYSTEMS

Acceptance tests in New Zealand are conducted to meet performance criteria for the smoke control systems established by agreement between the owner and the territorial authority (NZBC, Appendix D (BIA, 1992)).

Acceptance testing of smoke control systems must be carried out to assess the effectiveness of the systems and their ability to provide the protection they were intended to. Klote and Fothergill (1983) have classified the acceptance testing of smoke control systems into two phases:

- Testing of individual components to determine their functional performance to specification.
- Testing of the smoke control system for the whole or parts of the building to determine the effectiveness of components when working as a system.

This double phase in-situ testing ensures that successfully operating individual components can also effectively function as a system.

Testing of smoke control systems in a building is conducted using heated (hot) or unheated (cold) chemical smoke or tracer gases. The major problem with the use of chemical smoke or tracer gas is their obvious lack of buoyancy. The spread of cold tracer gas and chemical smoke from "smoke bombs" may be likened to smoke movement in a sprinklered fire where the buoyancy of smoke is reduced due to cooling by the water spray from sprinklers. Nonetheless, chemical smoke and tracer gases are useful in testing smoke feedback and locating leakage paths in a building. An outline of test methods is included in the following section.

Buoyancy is provided to chemical smoke by releasing it directly above trays of burning methylated spirit. The dimensions of the trays and the depth of the pool of methylated spirits is determined by the heat output required for the simulation. The heat output is estimated on the basis of the expected fire load in the compartment.

When tracer gas is used, continous or batch sampling may be carried out at various locations in the building using a gas chromatograph to determine the amounts present. Klote and Fothergill (1983) recommend the use of tracer gases such as Sulphur Hexafluoride (SF_6) to test air and smoke movement in buildings. SF_6 is inert and chemically stable. In smoke control testing, concentrations of up to 2 ppm are generally used. At this concentration, the gas may be considered non-toxic. It is not used industrially, this eliminates possible interference from other sources during a test. When SF_6 is used to simulate hot smoke movement care should be taken as it may disintegrate into toxic compounds at very high temperatures. The use of tracer gases for such testing requires the use of suitably trained professionals.

Klote (1987a) and others have raised concerns that smoke control systems which pass the chemical smoke tests may give all concerned a misleading sense of security that smoke control significantly improves tenability within fire compartments. Klote's (1987a) study also highlighted the lack of information relating smoke obscuration by chemical smoke to that of real smoke. White chemical smoke disperses any light in a building whereas black smoke from most fires will absorb light, leading to earlier obscuration. The results from tests with white smoke therefore will be different to what is expected in a real fire. Acceptance criteria for the time for obscuration demonstrated by these tests in any building must be set much higher than that required as a minimum for the total evacuation of occupants.

Guidelines for testing smoke control systems in New Zealand are set in the appropriate codes (NZS 4238, SANZ 1991) and are in general agreement with the two phase testing as discussed above. Case studies of the smoke tests carried out at the Pan Pacific Hotel in Auckland and the Melbourne Central atrium spaces are included in Sections 6.1 and 6.2. In both tests the fire generated using industrial methylated spirits could not have produced the design heat as required by the building control documents. On the basis of the fuel and tray arrangement used only, the heat generated would have been between 0.9 and 1.0 MW for the 6 m perimeter Pan Pacific fire and between 3.5 and 3.75 MW for the the 12 m perimeter Melbourne Central fire (estimations based on mean weighted calorific and burning rate values of industrial methlylated spirit (91 percent ethanol) taken as 26.2 MJ/kg. and 0.0152 kg/m^2/sec respectively).

Table 5 Arrangements required to generate design fire for smoke tests

Design Fire Size	Arrangements	
	Circular	Rectangular
1.5 MW		
Area required (m^2)	3.8	3.8
Perimeter required (m)	6.9	7.7
5.0 MW		
Area required (m^2)	12.6	12.6
Perimeter required (m)	12.6	14.2

5.1 Testing of Components

Testing of smoke detection devices is conducted using hot smoke and must be carried out with the usual ventilation systems working. The possibility of an air draught deflecting smoke away from detectors is tested by this means. If the smoke and fire safety scheme includes an emergency mode then the test must be extended to cover the observation of its operation.

Testing for short circuiting of exhaust smoke or smoke feedback through air intakes can be done using either cold smoke or tracer gases (SF_6). Klote's (1987a) tests for feedback involves release of cold smoke into the airstream of exhaust vents, with smoke detectors or air samplers placed near intakes or inside intake ducts at the downstream end. If smoke or tracer gas is detected in the intake air then that path is blocked and the test is repeated.

Tests (Klote, 1987b) on shaft pressurisation must be conducted to measure the pressurisation levels across compartments. It may be expected that pressurisation levels achieved could vary in practice from design values, and tests will ensure that adequate pressures are maintained under all operating conditions. The pressure gradient across each closed stairwell door is measured initially with all doors closed, then with one door open. The test is repeated until the total number of doors opened during the test meets the requirements set in the acceptance criteria.

For successful pressurisation, the lowest pressure levels observed must be greater than the minimum required. These tests also provide an opportunity to balance relief vents and air supply. In stairwells pressurised by multiple injection systems, balancing of injection velocities may be required to correct pressurisation levels (Klote and Fothergill, 1983).

6.0 CASE STUDIES AND SAMPLE SMOKE EXTRACTION CALCULATION

6.1. Pan Pacific Hotel Atrium and associated spaces

The 14-storey central atrium in the Pan Pacific Hotel in Auckland extends about 42 metres from the lobby level to the glass roof. The access to guestrooms is along balconies that flank the atrium (see Figures 5 and 6). Dispensation was sought for the construction of this atrium as neither the Auckland City Council Bylaws that existed at that time nor NZS 1900 Chapter 5 (SANZ, 1988a) covered the smoke control and life safety requirements in an atrium of this nature (which could not prevent the spread of fire or smoke). Dispensation was granted (Rankine & Hill Ltd., 1989, pers. comm.) on the basis that additional fire safety be provided to the area based on design by fire safety specialists, and that the effectiveness of the fire safety scheme be proven to the Council engineers by means of practical tests.

An acceptance test was carried out to demonstrate that the fire and smoke control provisions performed to the satisfaction of the Auckland City Council. The special smoke control provisions demonstrated included:

- Atrium smoke ventilation systems.
- Atrium smoke and fire detection systems.
- Atrium drencher system.
- Stairwell pressurization and smoke ventilation systems.
- Balcony air curtains.

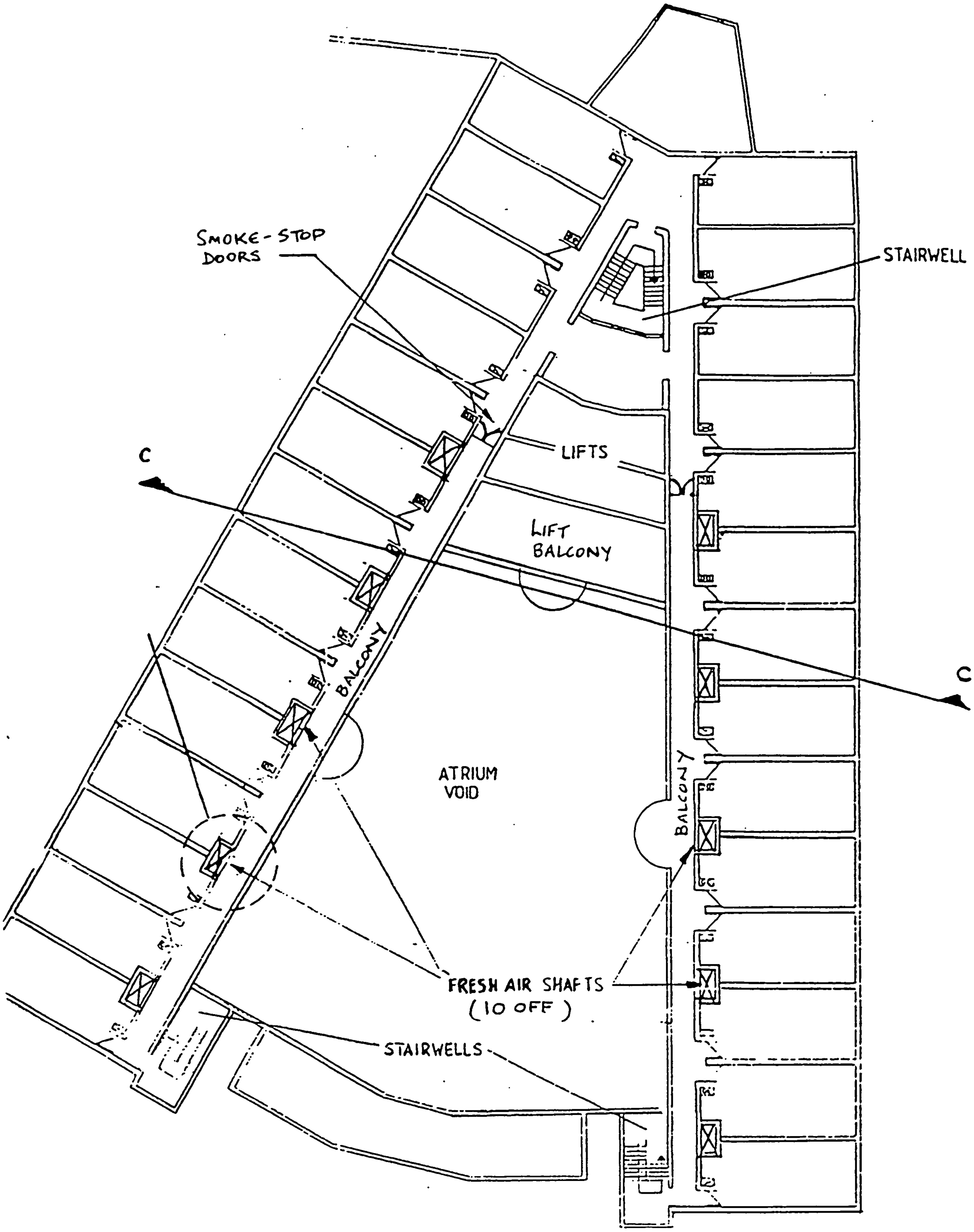
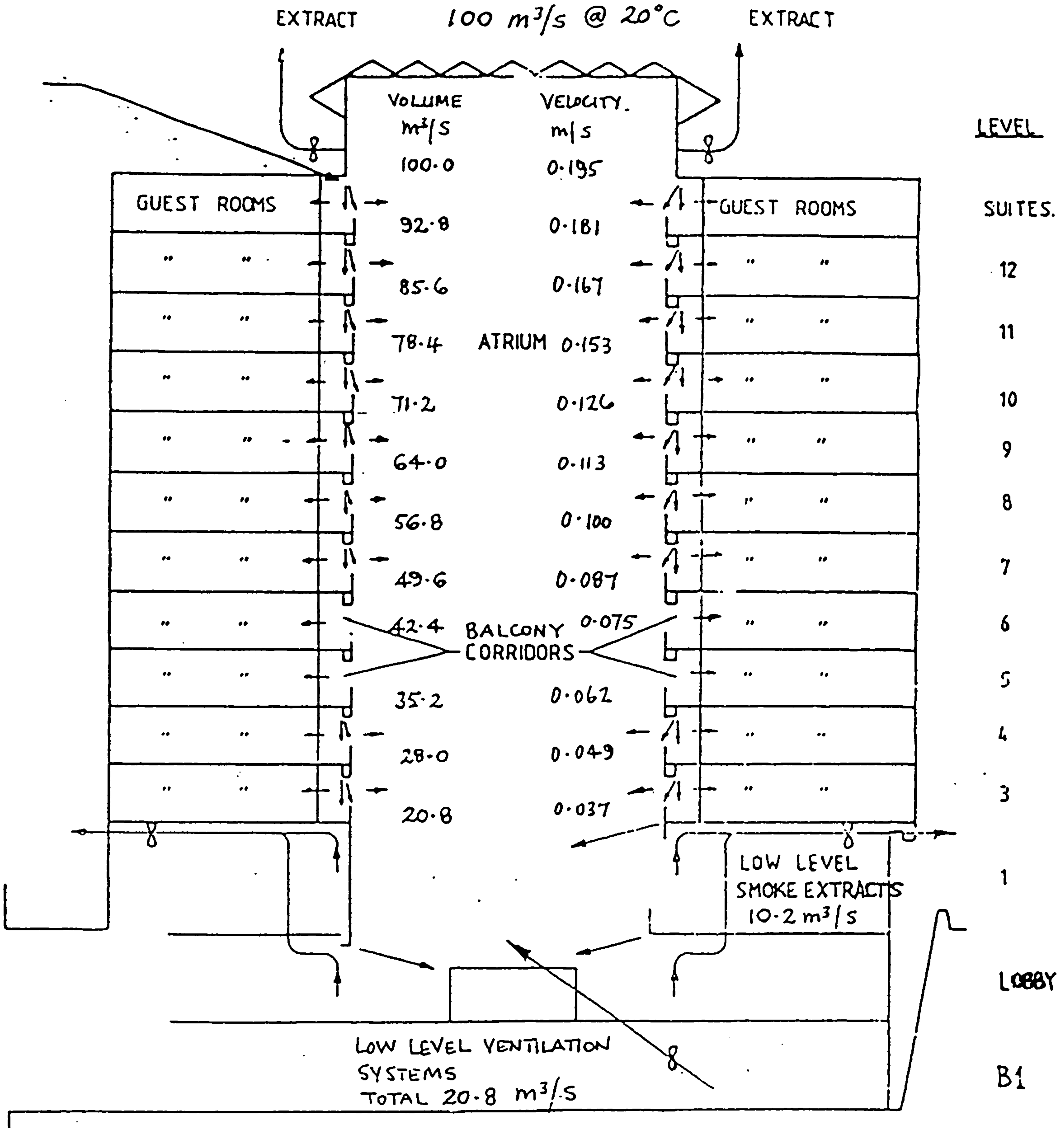


Figure 5 Typical floor plan of the Pan Pacific Hotel



(DRAWING NOT TO SCALE)

Figure 6 Section C - C through the atrium of the Pan Pacific Hotel

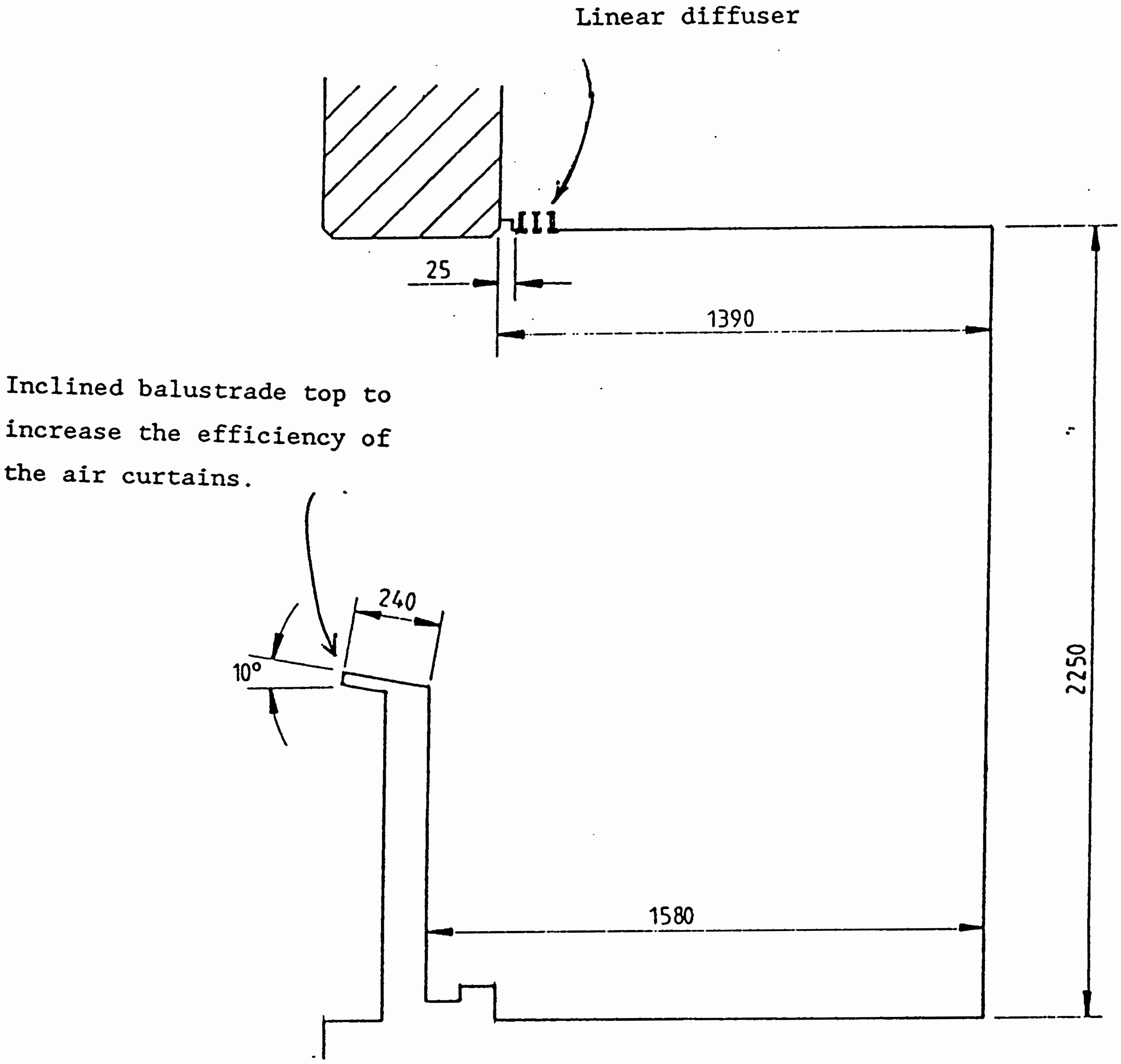


Figure 7 Typical section through the balcony showing location of linear diffuser in relation to balustrade

Preliminary and trial smoke testing of components was carried out before acceptance testing. These tests ensured that the components functioned as designed and manufactured. Fire and smoke detectors in the atrium and the bedrooms were tested manually and with cold smoke to see if they activated related systems and set the fire safety systems of the building into emergency mode. Smoke was extracted at the atrium roof level by 10 exhaust fans.

The use of the "make up" air facility as part of the smoke control scheme is an interesting feature in this building. A large portion of the "make up" air is supplied through linear diffusers located along the edge of the balcony which protrudes into the atrium space (see Figure 7). The aim was to produce an air curtain between the ceiling and the balustrade to prevent the migration of smoke from the atrium into the balcony area. A cold smoke test was carried out before full scale testing to ensure that this system worked as expected. Fine tuning of the diffusers at this stage resulted in further restriction to smoke spill.

Active smoke curtains were provided along the periphery of the lobby area on the lowest floor (see Figure 6) for the smoke separation of this area from the atrium shaft. Smoke detectors in the lobby area activated lowering of these curtains.

6.1.1 Acceptance Criteria For Full Scale Test Results

In the event of a fire in the guestrooms or balconies on any of the floors, it was required that the escape routes remain usable by other occupants on the same floor and at the same time required illuminated exit signs at the other end to be visible for at least five minutes.

No spillage of smoke into the atrium shaft was to occur as a result of a fire in the surrounding lobby space. Fire and smoke was required to be detected and controlled by the automatic devices in this area.

It was also required to demonstrate that a fire in the atrium shaft would be detected automatically and that the atrium smoke extraction and air supply systems could prevent the migration of smoke into the balconies and guestrooms for at least five minutes from the time of the initiation of the alarm.

6.1.2 Acceptance Test

A cold smoke test was carried out in the guestroom opposite the staircase with the room door held open. An observer on the balcony near the door of the next bedroom noted the duration for which the exit sign at the other end was visible. Sufficient visibility was reported for the five-minute period.

A hot smoke test with one tray of methylated spirit set alight to produce approximately 0.25 MW of heat was conducted in the lobby area. Although the smoke detectors activated the lowering of the automatic smoke curtains, not all of the smoke was contained within the lobby. A draught through the open lobby doors moved the smoke into the atrium shaft. A fault in the installation of the extract system was detected and as a result the installation of additional equipment was required.

A further hot smoke test was conducted in the atrium space. In the first instance a design fire of 1.5 MW (NZS 4238, SANZ 1991; Bastings, 1988; Morgan and Hansell, 1987) was generated using six trays of burning methylated spirits with a total perimeter of approximately 6 metres. A large generator was used to supply chemical smoke through the fire. This quantity of smoke set the linear diffusers into a faulty mode very early in the test. It was then decided that the generation of a large quantity of smoke did not occur during the early stages of the fire and that a realistic fire development needed to be simulated. Thus with some adjustments to the air supply and the projection angles of the linear diffusers the test was repeated again with a smaller fire (using a single tray producing approximately 0.25MW) and smaller smoke generators. The larger generator was only used at the time when it was considered appropriate for the fire growth to have reached a suitable stage. There was a delay in the response of the linear smoke detectors, as smoke production in this manner was slower than anticipated. Although this allowed the atrium to be filled with smoke, visibility was not greatly reduced. When sufficient smoke had been generated the detectors activated the extraction system automatically. The generation of smoke by the larger generator reduced visibility in the atrium space greatly but the smoke was rapidly removed by the extract fans at the atrium roof. The exit sign visibility criteria was met on all floors at all times of the test.

6.2 Melbourne Central Atrium and Associated Spaces

The 6-storey atrium building at Melbourne Central is a podium for the 56-storey tower building. The atrium building consists of a department store and a retail shopping mall.

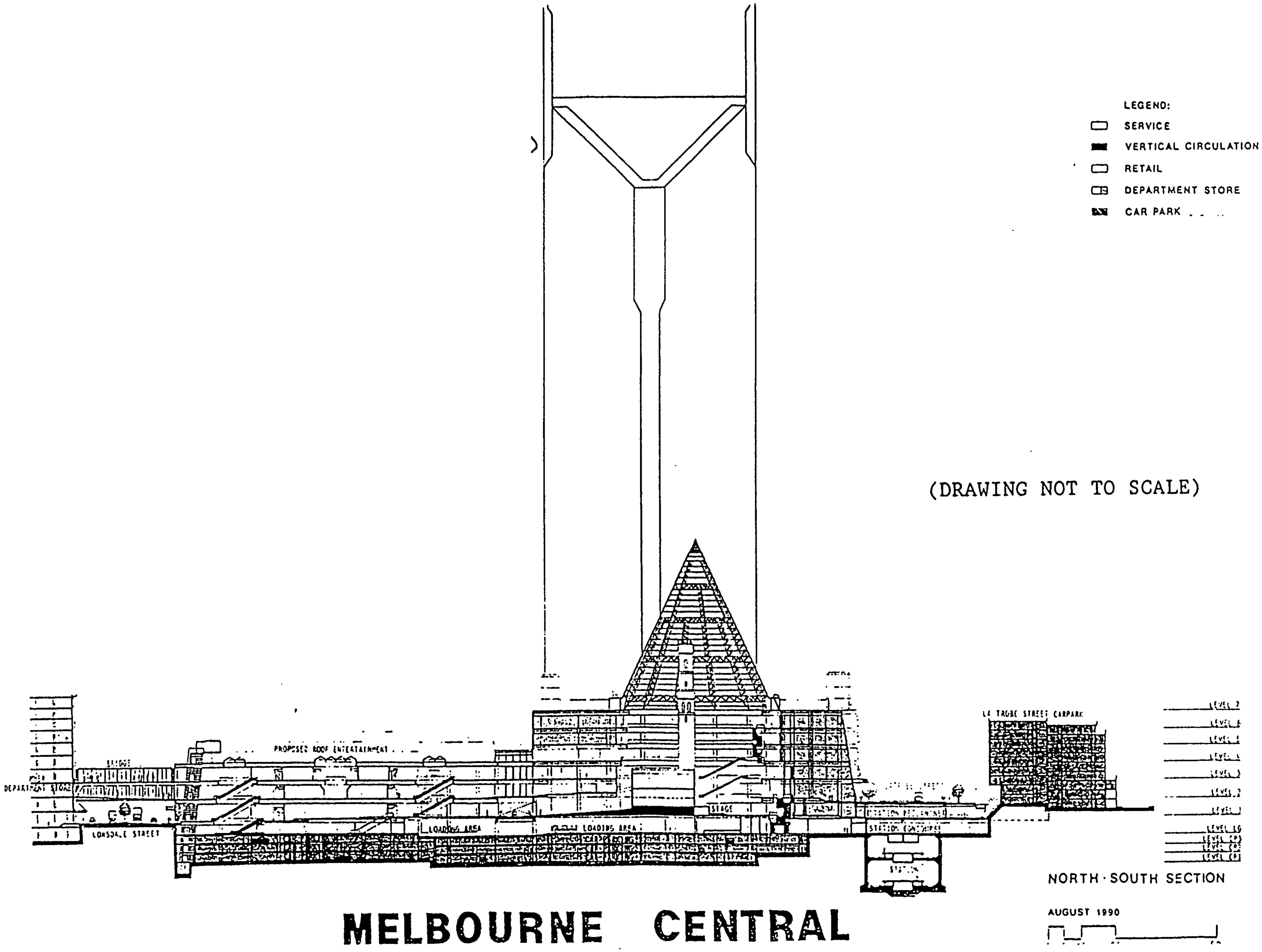


Figure 8 Elevation of the Melbourne Central Complex showing the atrium cone and the outline of the 56-storey office building in the background

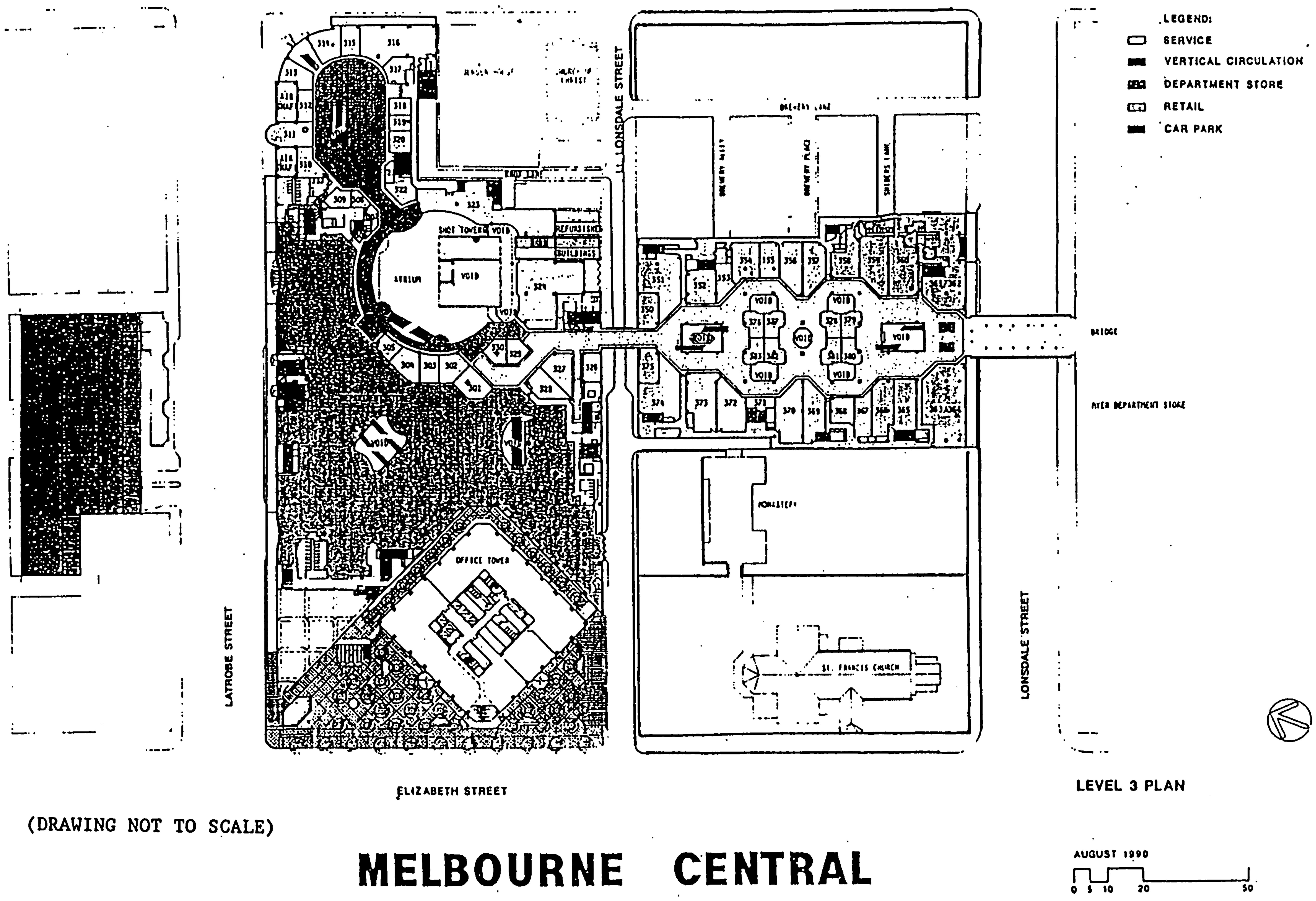


Figure 9 Typical floor plan of the Melbourne Central Complex

The main feature of this atrium building is that it houses an historic tower. To accommodate the tower, the atrium has been covered over with a cone type roof structure with transparent glass cladding (see Figure 8). The atrium space design was based on Level 4 being the base of the atrium and mechanical smoke extraction by exhaust fans being carried out at Level 10 (the base of the atrium cone). The active smoke control design for the atrium space was based on a 3m x 3m design fire with 5 MW steady state intensity.

During a fire it is expected that the smoke exhaust fans on Level 10 would be activated by the photo-electric smoke detectors on the detection of smoke in the atrium space. The total exhaust capacity of the fans was estimated at 190 000 l/s. Make up air to meet this exhaust demand was designed to be provided through air handling units at the various floors adjoining the atrium void and through doors opening to the outside at Levels 4A and 5.

Table 6 "Make up" air quantities made available to various floors through air handling units.

Level	Volume (litres/sec)
5	18600
6	47085
7	35860
8	44035
9	30405
Total (through air handling units)	175985
Natural Ventilation at levels 4A and 5 (through open doors)	14015
Total air supplied	190000

6.2.1 Acceptance Criteria for Full Scale Test Results

In the event of a fire in the atrium space it was required that the nearest exit signs remain visible from any point on the balconies for a period of at least 10 minutes from the first generation of smoke. It was also required that the smoke fill fans, balcony pressurisation fans and stair pressurisation fans be activated automatically by the smoke generated.

6.2.2 Acceptance Test

A hot smoke test was carried out in the atrium space using smoke bombs and methylated spirits. The methylated spirits was placed in rectangular trays, side by side, to provide the perimeter of approximately 12 m required for the generation of a 5 MW fire. Smoke bombs were placed around the perimeter and in a metal drum with a spout to release the smoke immediately above the flame. Smoke generation ceased around the eleventh minute of the test but the generation of heat from the burning methylated spirit was allowed to continue for at least another 5 minutes.

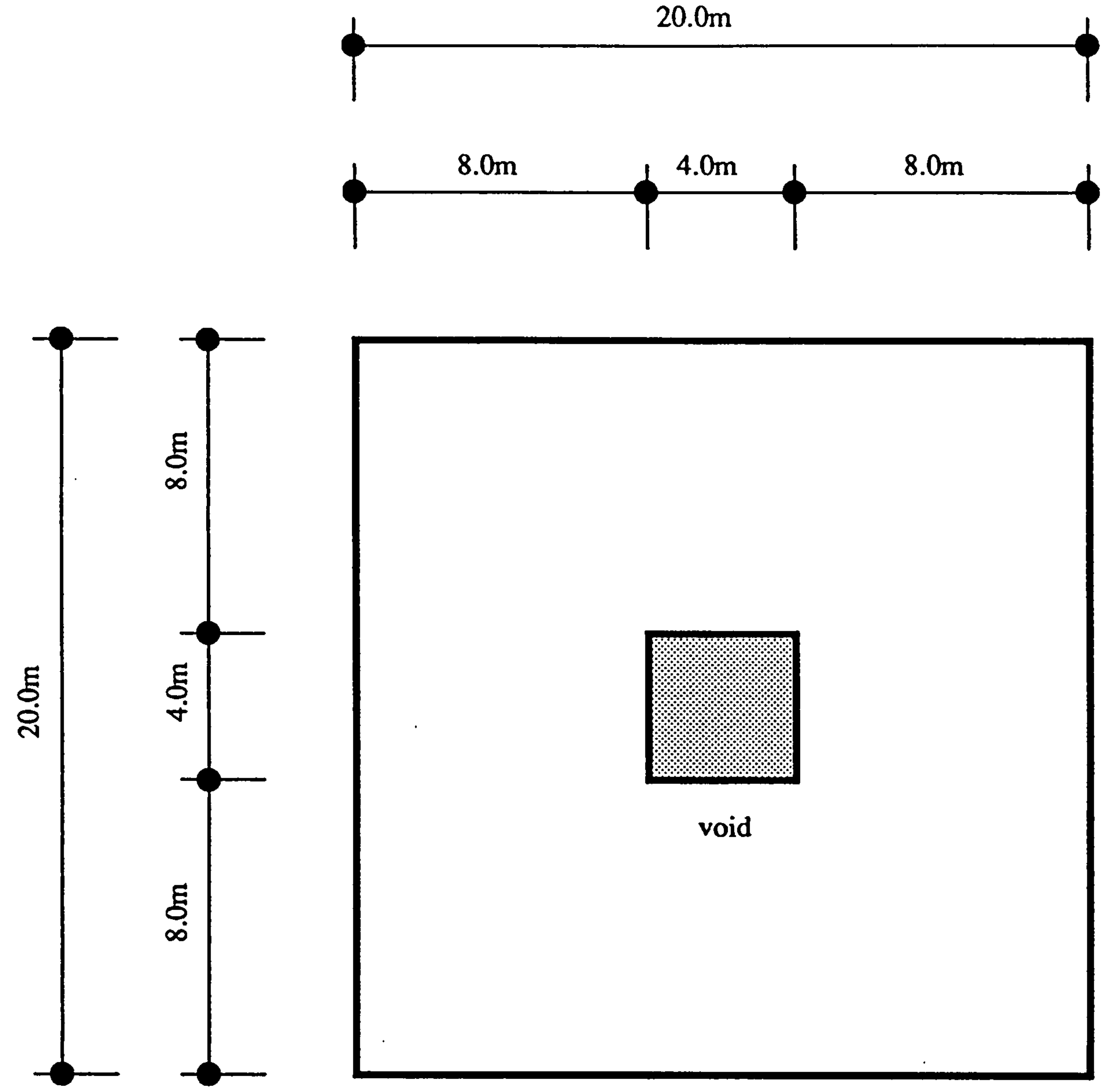
The smoke in the atrium space activated the mechanical smoke extractors within the first minute. Some smoke logging was observed 4 minutes into the test behind the tower in the cooler part of the cone space well above level ten where the extract fans were located. The smoke layer interface formed between levels seven and eight. There was little smoke spread into any of the balconies between levels five and nine. The exit signs on all these floors were adequately visible throughout the duration of the test.

6.3 Sample Smoke Extraction Calculations

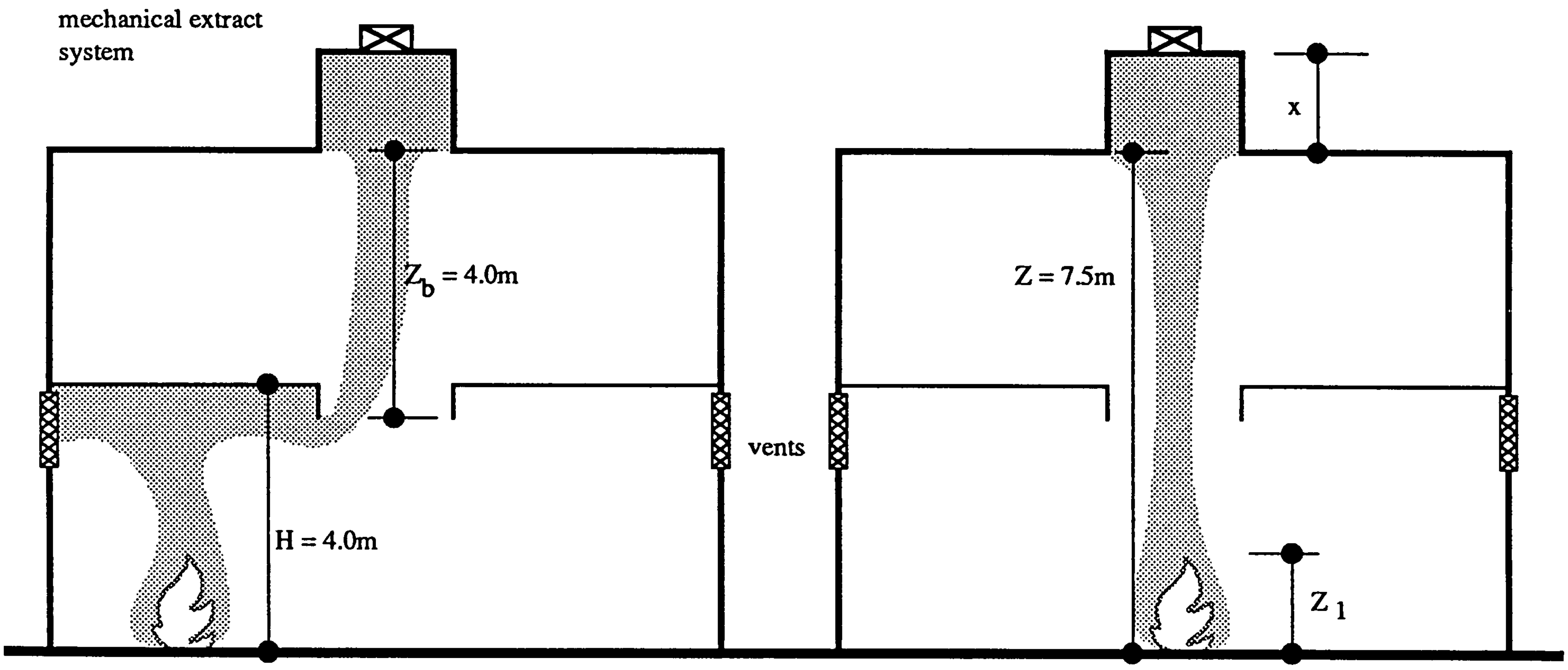
Smoke extraction rate and "make up" air supply estimations are required for the building shown in Fig 7.6. Intake air is to be supplied at the ground floor level. A design heat release rate of 1.5 MW is assumed for the fire in the building.

The NFPA 92B method is used in this example

m_p = Mass flow rate in the plume [kg / s]
Q = Heat release rate [kW]
Q_c = Convective portion of heat release rate [use $Q_c = 0.7 \times Q$]
z_b = Height above the balcony to the base of the smoke layer
z = Height of the base of the smoke layer from floor
z_l = Height of luminous flame
V = Volumetric flow rate [m^3 / s]
r_{sm} = Density of smoke [$= 0.73$ kg / m^3 at 200°C]
W = Width of plume as it spills under the balcony [m]
H = Ceiling height above the fire surface [m]
x = Depth of smoke reservoir



Plan



(a) Fire in the balcony area
(balcony flow plane)

(b) Fire in the void area
(axisymmetric plane)

Figure 10 Plan and elevation of sample building used for smoke extraction calculations.

Mass flow rates for an axisymmetric plume of a fire in the atrium space and a balcony plume flow for a fire under the balcony are first estimated.

Axisymmetric Plume

$$z_1 = 0.166\, Q_c^{2/5} \qquad \text{Equation 6}$$

$$= 0.166 \times 1050^{2/5}$$

$$= 2.68 \text{ m.} \qquad [z = 7.5 \quad \therefore z > z_1]$$

for $z \geq z_1$

$$m_p = [0.071 \times Q_c^{1/3} \times z^{5/3}] + [0.0018 \times Q_c] \qquad \text{Equation 7}$$

$$= [0.071 \times 1050^{1/3} \times 7.5^{5/3}] + [0.0018 \times 1050]$$

$$= 22.60 \text{ kg/s}$$

Balcony Flow Plume

$$m_p = 0.41\, [Q\, W^2]^{1/3} \times [z_b + 0.3\, H]$$

$$\times \{1 + (0.063 \times [z_b + 0.6 \times H] \div W)\}^{2/3} \qquad \text{Equation 8}$$

$$= 0.41 \times [1500 \times 4.0^2]^{1/3} \times [4.0 + 0.3 \times 4.0]$$

$$\times \{1 + (0.0063 \times [0.4 + 0.6 \times 4.0] \div 4.0)\}^{2/3}$$

$$= 63.6 \text{ kg/s}$$

In this example, the balcony plume shows a more critical mass flow rate . Hence, volumetric smoke extraction rate will be estimated for this case. The volumetric flow rate estimates are based on the density of smoke. The density of smoke reduces with temperature. Thus, overestimation of smoke temperature at extraction points could, in practice, lead to an overdesign situation. Estimates based on NFPA 92B (NFPA, 1991b) and NZBC AS1/C3 (BIA, 1992) are shown in this example to emphasize this point.

1. NFPA Method

$$\Delta T = Q_c \div [m \times c]$$ Equation 9

$$= 1050 \div [63.6 \times 1]$$

$$= 16.5 \text{ K}$$

$$T = T_a + \Delta T$$

$$= 306.5 \text{ K} \approx 307 \text{ K or } 35^\circ \text{ C}$$

ρ_{sm} = 1.152 [based on dry air pressure at 1 atmosphere at corresponding temperature]

The volumetric flow rate,

$$V = m_p \div \rho_{sm}$$ Equation 10

$$V_{35} = 63.6 \div 1.152$$

$$= 55.21 \text{ m}^3/\text{s}$$

2. NZBC AS1/C3 (BIA, 1992)

The density of smoke to be estimated for a recommended maximum smoke temperature of 200 ° C. This gives,

$$\rho_{sm} = 0.73$$

$$V_{200} = 63.6 \div 0.73$$

$$= 87.12 \text{ m}^3/s$$

where,

ΔT = Temperature rise [K]
m = Mass exhaust rate [kg/s] = mass production rate m_p [for a balanced design]
c = Specific heat of smoke at smoke layer temperature [kJ/kg - K]
T_a = Ambient temperature [say 17 ° C or 290 K]
T = Temperature of smoke at the extraction point
$\rho_{\sigma\mu}$ = Density of smoke at corresponding temperature
V = Volumetric flow rate
ϑ = Design upward air velocity

The extract volume estimated at 200 °C is approximately 58 % greater than the volume derived on the basis of calculations for actual smoke temperatures.

The cross-sectional area associated with the void area is 4 x 4 = 16 m^2. This gives $\vartheta = 55.21 \div 16 = 3.45\ \mathrm{m/s}$. This gives an upward air velocity which is acceptable given that an average upward velocity of 3.5 m/s in the void area is the allowable upper limit for design purposes [NZBC AS1/C3 (BIA,1992)].

Assuming that the vent area required for this flow rate is unavailable at roof level, an alternative would be to use two or more extract fans at this level to extract smoke at the rate of 56 m^3/s.

"Make up" air supply: Make up air supply must equal extraction rate. Although not stated in NZBC AS1/C3 (BIA, 1991), the maximum velocity of the fresh air supply should ideally not exceed 1 m/s in order to avoid turbulence around the fire plume. Therefore, the vent area required for natural ventilation (A_V), estimated for the ambient temperature of 17 ° C, is

$$A_v = 63.6\ \mathrm{kg/s} \div [\ 1\mathrm{m/s} \times 1.22\ \mathrm{kg}\ /\ \mathrm{m}^3\ ]$$

$$= 52.13\ \mathrm{m}^3\ /\ \mathrm{s}$$

The area available from vents above the entrance $= 2 \times 1.5 \times 10.0 = 30.0\ \mathrm{m}^2$.

30 m^3 intake through these vents is insufficient. An alternative would be to provide additional intake air of up to 23 m^3/s through an emergency mechanical air supply system.

This system may be part of the HVAC system that can supply the required volume during an emergency. This supply must be activated automatically by detection devices and should be operational only after an exhaust flow has been established. This will ensure that the pressurisation of the fire area does not occur.

7.0 SUMMARY AND CONCLUSIONS

7.1 Summary

- Smoke control system design and strategies are generally aimed at increasing occupant safety by improving tenability during occupant evacuation within a compartment in the event of a fire.

- Although sprinklers are essential in the fire safety of many buildings, they cannot be considered in isolation from adequate smoke control design.

- The four main factors, individually or in any combination, causing movement of smoke from the fire compartment to adjacent spaces are fire effect, stack effect, wind effect and air movement and ventilation systems.

- Passive smoke control systems such as smoke barriers, smoke reservoirs and natural ventilation restrict the spread of smoke by restricting ventilation and/or by directing smoke away from escape routes.

- Active smoke control systems consist of pressurisation of shafts and escape routes, mechanical smoke extraction, and ventilation systems. The basic aim of pressurisation is to create a pressure gradient across compartments so that air always flows out of the area to be protected, e.g., exitways. A study of the building codes of New Zealand and other countries shows that the required pressure differences range from 12.5 Pa to 60 Pa.

- Smoke detection devices detect fires earlier than heat detectors. It has been the practice in most countries, including New Zealand, to provide smoke detectors wherever fire detection has been deemed compulsory and only as a part of an alarm system.

- Computer simulation and analysis of smoke movement and control in multi-storey buildings have been useful in research in understanding the dynamics of air and smoke movement. Assessment of hazards and optimisation of smoke control systems in high rise buildings are two areas where computer simulations will be used in the future. Most computer programs for multi-storey buildings are still in their developmental stage.

- Acceptance tests of smoke control systems in New Zealand are conducted to meet performance standards established by agreement between the owner, the local authority and in some cases the Fire Service. Acceptance testing of smoke control systems must be carried out to assess the effectiveness of the systems and their ability to provide the protection they are supposed to. Smoke testing with white chemical smoke is used extensively for this purpose. Acceptance testing of smoke control systems may be classified into two phases:

    * Testing of individual components to determine their functional performance to specification.

    * Testing of the smoke control system for the whole or parts of the building to determine the effectiveness of the components working as a system.

7.2 Conclusions

- Smoke control cannot be considered in isolation; adequate escape routes and simple evacuation schemes must be given equal emphasis to ensure the safety of building occupants.

- A combination of smoke control systems alone cannot provide the adequate safety to occupants in multi-storey buildings unless they are designed to take full advantage of the unique design of the building, air movement and the weather conditions affecting it. Smoke management studies of the combined effectiveness of the various smoke control components in a building will improve the efficiency with which smoke may be directed away safely. Such studies will enable the cost effectiveness of any proposed scheme to be measured. Any scheme proposed must be simple and practical.

- It must be recognized that visibility reduces more rapidly with black smoke in real fires than during smoke tests with white smoke. It is therefore important that the criteria set for acceptance testing reflect this. Limits for the minimum duration for any such tests should be set in the relevant New Zealand codes.

- Pressurisation of escape routes is a safe and viable means of active smoke control. The encouragement of the use of such means of control should be reflected by the inclusion of more specific controls and trade-offs in building control documents.

- There has been rapid advance in the computer programs developed by researchers for modelling smoke movement. Non-linearities that arise as a result of asymmetries in buildings have been in most cases very closely approximated. The computer simulations have in many cases been compared to actual smoke movement during real fires with encouraging results. Future research work in New Zealand should include using these models to predict more accurately the movement of smoke and the working of smoke control systems. The results of such studies showing the effectiveness of the computer models in predicting smoke movement will encourage various smoke control options to be verified for their efficiency and cost effectiveness at the very early stages in the design of buildings, which is desirable.

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