

An Experimental and Qualitative Assessment of Smoke Control Systems

R J Paveley

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Dedication

To Rosie, Joshua and Lucy

No more long train trips to Brighton!

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Nomenclature

Nomenclature

A_f	Area of the fire (m ²)
A_i	Area of inlet (measured) (m ²)
A_v	Area of exhaust ventilator (measured) (m ²)
A_w	Area of opening into atrium from adjacent fire room (m ²)
c	Specific heat of air (kJ/kg- I K 1)
C_d	Coefficient of discharge for a vertical opening
C_e	Entrainment coefficient
C_j	Coefficient of discharge for an inlet
C_p	Wind pressure coefficient on the surface of a building
C_v	Coefficient of discharge for an exhaust ventilator
D	Depth of smoke beneath an extraction point (m)
D_b	Depth of a smoke layer under a balcony (m)
D_d	Depth of a downstand fascia (m)
D_f	Diameter of fire (m)
D_1	Design depth of a smoke layer in a reservoir (m)
D_w	Depth of a flowing smoke layer in a vertical opening (m)
D_{max}	Maximum depth of smoke in an atrium (m)
F	Froude Number
g	Acceleration due to gravity (ms ⁻²)
H	Height of a vertical opening (m)
h	Height of a vertical opening with no upstand (m)
K	A factor for flows from compartments
K_1	A factor for ceiling jets, 0.5 to 0.7)
M	Mass flow rate (kgs ⁻¹)
M_b	Mass flow rate under a balcony (kgs ⁻¹)
M_{CRIT}	Critical exhaust rate (kgs ⁻¹)
M_w	Mass flow rate through a vertical opening (w-plane) (kgs ⁻¹)
M_y	Mass flow rate through the y-plane (kgs ⁻¹)

M_z	Mass flow rate entering the smoke reservoir (z-plane) (kg s^{-1})
N	Number of exhaust points
P	Perimeter of the fire (m)
Q	Heat flux (kW)
Q_f	Heat release rate of a fire (kW)
Q_w	Convective heat flux passing through a vertical opening (or under a balcony) (kW)
Q_y	Convective heat flux passing through the y-plane (kW)
Q_z	Convective heat flux entering the smoke reservoir (z-plane) (kW)
q_f	Convective heat flux per unit fire area (kW m^{-2})
Ri	Richardson number
t	Time (seconds)
t_0	Time at ignition (seconds)
T	Absolute temperature of gases (K)
T_w	Absolute temperature of gases at a vertical opening (K)
T_B	Absolute temperature of gas layer under a balcony (K)
T_1	Absolute temperature of gas layer in a reservoir (K)
T_0	Absolute ambient temperature (K)
u	Velocity of gases (m s^{-1})
u_1	Velocity of gases (m s^{-1})
u_w	Wind velocity (m s^{-1})
V	Volumetric flow rate of gases ($\text{m}^3 \text{s}^{-1}$)
V_1	Volumetric flow rate of gases from a reservoir ($\text{m}^3 \text{s}^{-1}$)
W	Width of vertical opening (m)
W_B	Width of balcony (distance from vertical opening to front edge of balcony) (m)
x	Distance from centreline of plume (m)
y	Height from the base of a fire to the smoke layer above (m)
z	Height of rise of a thermal line plume from an opening or balcony edge

α	Fire growth coefficient
α'	An entrainment coefficient
β	Coefficient in critical exhaust rate equation (kgm-3)
Δ	Empirical height of virtual source below a balcony edge (m)
ΔP	Pressure difference (Pa)
ΔD_B	Additional smoke depth due to local deepening (m)
λ	An experimental factor in ceiling jets
θ	Temperature rise above ambient of gases (°C)
θ_β	Temperature rise above ambient of gases under a balcony (°C)
θ_1	Temperature rise above ambient of gases in a reservoir (°C)
θ_w	Temperature rise above ambient of gases in a vertical opening (°C)
κ_m	Profile correction factor for mass flow (approximately 1.3)
ρ	Density of gases (kgm-3)
ρ_0	Density of ambient air (kgm-3)

Part 1

Introductory Chapters

Chapter 1 Introduction

Chapter 2 Smoke Control

Chapter 3 Smoke Control Failure

Chapter 1 Introduction

1.1 Smoke Control and Fire Safety Engineering

Smoke control is the method of limiting the spread of smoke fires in buildings using physical barriers and air movement (using fans and the natural buoyancy of smoke).

Smoke control systems are usually provided for life safety, forming a major part of a fire safety engineering approach for buildings. Fire safety engineering is 'the use of engineering methodology to determine the precise fire safety requirements and the design of the system to provide the required level of safety'. (Malhotra 1996).

1.2 The Aims of the Thesis

1.2.1 General

Engineered smoke control systems, designed to maintain specified conditions have only been installed in buildings, in the last 30 years.

As systems to enhance life safety and property protection their benefit and potential for failure needs to be assessed. The limited experience of smoke control system performance in fires makes simple statistical analysis difficult. The reliability of these systems has not been assessed systematically.

The aim of this thesis is to identify the causes of variations in smoke control system performance and to identify the potential failure modes of smoke control systems in buildings, and to arrange these into a structured taxonomy.

The steps to achieve this are:

1. Define the aims of smoke control systems and define failure.
2. Identify basic smoke control system forms and their objectives.
3. Identify the possible causes of variations in system performance.
4. Identify the possible consequences of these variations
5. Define the range of acceptable deficiencies for particular systems.

1.2.2 Research Approach

The performance of a smoke control system would be judged on the system capabilities in relation to the developing fire environment, so the two main areas of concern become:

1. The chosen fire environment
2. The smoke control system performance

The potential for variations is identified and the combined effect is assessed.

1.2.3 Outline of the Thesis

In Chapters 1 to 3, the scope of the problem and areas for detailed research is identified. In Chapters 4 to 9 (Part 2), the potential for the variation in the fire environment is examined and one smoke flow model (smoke flow in atria) is examined experimentally.

In Part 3 (Chapters 10 to 12), the potential for the causes and range of variation of performance of smoke control installations during their lifetime is examined. An examination of the state of smoke control system performance is made with questionnaires and case studies, from several sources.

In Chapters 13 to 14 (Part 4) a basic failure mode taxonomy is presented and general conclusions regarding smoke control system performance are made.

This work does not develop a complete risk analysis of smoke control systems. It can only present a structured analysis of the potential failures of smoke control systems, with detailed analysis of certain aspects of smoke movement, in particular models for smoke flow in atria.

The main area of interest in this study is life-safety. Property protection and assistance to fire fighters is considered less rigorously.

Chapter 2 Smoke Control

2.1 The Objectives of Smoke Control Systems

2.1.1 Defining the Objectives

Most smoke control systems are installed as life-safety systems, but can also serve other objectives. They should be designed as part of an integrated fire safety engineering system. This can include other systems, such as means of escape, compartmentation, detection and suppression. Often, an engineered smoke control system is not required for life safety. Occasionally it is provided for other reasons. Marchant (1990) describes the objectives of smoke control as:

1. Minimise the exposure of the occupants of a building to the hazards of smoke
2. Minimise damage to property, by limiting the spread of smoke.
3. Minimise disruption to organisational activities, by limiting the spread of smoke.
4. Aid fire-fighters activities, by providing smoke free routes to reach the fire
5. To purge the smoke from buildings after a fire

In considering the objectives of smoke control, the nature of smoke needs to be understood. Smoke is a mass of hot gases, containing the products of combustion. This can include particles of soot and toxic gases such as hydrogen cyanide and carbon monoxide. As smoke flows through a building, it entrains ambient air and increases the smoke mass. Unless it has entrained large quantities of air, it is hazardous to occupants and damaging to certain equipment and finishes in a building.

2.1.2 Minimise the Exposure of Occupants to Smoke

As a life safety system, smoke control is usually intended to keep people away from smoke. It aims to keep people in separate zones from the smoke or maintain a clear layer of ambient air, below the smoke, through which people can move.

Occasionally smoke control systems can only reduce the hazard created by smoke, by dilution, mixing it with ambient air, so cooling it and reducing its toxicity.

In this thesis, it is assumed that smoke control systems aim to keep people away from smoke and that escape should not be made through it. This excludes situations where 'fogging' occurs. Fogging is very dilute smoke that is found on the edges of smoke masses. Systems that are designed to dilute smoke will be examined briefly.

It is beyond the scope of this work to examine the toxicity of smoke, although it should be noted that the specification of the materials needs to be carefully controlled, to avoid highly toxic products forming in a fire. These can be lethal or injurious in very small concentrations (Sumi and Tsuchiya 1971). For example hydrogen chloride (HCl) and hydrogen cyanide (HCN) are lethal at concentrations of approximately one tenth of that of carbon monoxide. HCl is produced with the combustion of synthetic materials such as PVC. HCN is usually produced with the combustion of cellulosic materials such as wood and natural fibres.

2.1.3 Minimise Damage to Property

Some finishes and materials in buildings are very sensitive to smoke. They can be easily damaged. By limiting the spread of smoke, the risk of damage is minimised. Certain areas in buildings are highly sensitive to smoke damage. This can include a variety of building uses: clean room environments, areas of electronic equipment, pharmacological laboratories, art galleries and so on. Circuit boards often need to be replaced following exposure to smoke, due to slow corrosion by combustion products.

A typical example of smoke effects on equipment is HCl, which is very corrosive and is often cited as the main cause of long term deterioration to electrical circuits after a fire. It is often produced in electrical fires, due PVC sheathing to cables burning.

2.1.4 Minimise The Disruption To Organisational Activities

Buildings contents may be easily replaceable, but the economic benefit of uninterrupted activities within a space needs to be considered when designing a smoke control system. If a fire occurs in building, the spread of smoke needs to be

limited to ensure that activities can continue in other areas. This can be provided by compartmentation, so that a fire in one compartment leaves activities in other compartments unaffected. A building may require a smoke control system to perform some of the functional requirements of compartmentation. For example a central computer processing room, for a bank, may require smoke control to prevent smoke entering the room and damaging circuit boards. The electronic equipment would be less expensive than lost processing capability.

The design requirements are similar to life safety protection. Areas that need to be kept free of smoke need to be identified. The spread of smoke needs to be limited.

2.1.5 Aid Fire-fighters Activities

Smoke can often delay fire-fighters from finding the seat of a fire and from efficiently marshalling their equipment within a building to fight the fire. Smoke control systems can reduce this problem, by providing smoke free areas.

2.1.6 Post Fire Smoke Purging

Once a fire is under control, it is necessary to remove smoke from a building to reduce the exposure of its contents to smoke, to allow clean up operations to commence and to allow the building to be used as soon as possible.

2.2 Smoke Control Methods

2.2.1 General

Most smoke control systems operate either by containment or removal. These involve a combination of active and passive measures. The terms active and passive are commonly used in fire safety engineering. They are applied as follows:

Passive An element that does not require electrical, mechanical or other means to perform a fire safety function. Examples include fire safety doors, fire rated walls, smoke seals, intumescent paints and fire protection cladding.

Active An element that does requires electrical, mechanical or other means to perform a fire safety function. Examples include smoke vents, fans, dampers, smoke curtains and sprinklers.

Passive and active methods of fire protection are used to create the whole fire protection system. Other aspects of a building's design will influence the choice. The degree of passive measures may reduced be if additional active systems are included. For example, a wall may be omitted, if a smoke control system can perform the same function as the wall, acting as a barrier to smoke.

In this thesis, most features of smoke control will be discussed in relation to life safety. The methods of smoke control are presented below in general form.

2.2.3 Methods of Smoke Removal

Smoke is removed (or released) from a building, either by natural ventilation or mechanical extraction. These are shown below, and in simplified form in Figure 2.1 and Figure 2.2.

The aim of these systems is to maintain a layer of clear ambient air below the smoke. This clear layer can allow occupiers to pass to safety, fire fighters to locate the fire, or

simply to prevent the smoke from passing into other adjoining spaces. The extraction system can also prevent excessive temperatures developing in the building.

The mass flow rate can be determined from various equations, that can include variables for the area of the fire, the convective heat output, the geometry of the compartment from which the smoke may have originated. These are described in detail in Chapter 5 'Smoke Flow in Atria'. A key relationship is that the mass of smoke is dependent on the height of rise of the plume, as shown in Equation 2.1 (Thomas, Hinkley, Theobald and Simms,1963):

$$m \propto y^{3/2} \qquad \text{kg/s} \qquad \text{Eq. 2.1}$$

By increasing the height of rise of the smoke reservoir, its mean temperature is decreased (the inverse of the mass flow rate). This cooler smoke is also further above the occupants, so that they will be subjected to less radiation hazards.

There is a minimum depth of smoke reservoir that will form, because a flowing layer (or ceiling jet) forms. Its temperature and mass flow rate determine the depth.

Smoke can be removed from the compartment in which the fire is located or it can be allowed to flow into an adjoining space, from which it is more convenient to remove. Screens and curtains are used to ensure that the spread of the smoke is limited.

This form of smoke control uses fans or vents, plus a system of other active and passive measures to direct the smoke to the vents or extraction points.

2.2.3.1 Natural Ventilation

This is shown in Figures 2.1 and 2.2. Vents are provided at high level to release the smoke from a smoke reservoir. If smoke is more than 20 °C above ambient, then it has sufficient buoyancy to drive it through vents. Inlets are provided for the throughflow of air, to replace the vented gases.

The buoyancy pressure of the gases determines the rate of venting of gases:

$$\Delta P = (\rho_o - \rho_{res}) g D_1 \quad \text{Pa} \quad \text{Eq. 2.2}$$

where:	ΔP	pressure generated by the hot smoke	Pa
	ρ_o	density of ambient air	kgm^{-3}
	ρ_{res}	density of smoke in reservoir	kgm^{-3}
	g	acceleration due to gravity	ms^{-2}
	D_1	depth of gases in the reservoir	m

The deeper and hotter smoke creates greater pressures in the smoke reservoir. As these increase, the area of vents can be reduced, as shown in Equation 2.3 Thomas et al (1963).

$$A_v C_v = \frac{M}{\rho_o} \left[\frac{T_c^2 + (A_v C_v / A_i C_i)^2 T_o T_c}{2 g D_1 \theta_c T_o} \right]^{1/2} \quad \text{m}^2 \quad \text{Eq. 2.3}$$

where:	A_v	-	Measured area of vent (m^2)
	C_v	-	Coefficient of discharge (usually between 0.5 and 0.7)
	A_i	-	Measured area of inlets (m^2)
	C_i	-	Entry coefficient for inlets (usually between 0.5 and 0.7)
	T_c	-	Absolute mean temperature of smoke layer (K)
	T_o	-	Absolute temperature of ambient air (K)
	M	-	Mass flow rate (kg/s)
	θ_1	-	Mean temperature rise of smoke layer above ambient ($^{\circ}\text{C}$)

The area of vents required is approximately proportional to the temperature of the gases, the mass flow rate and the inverse of the root of the depth of the smoke.

2.2.3.2 Mechanical Extraction

Extract is provided at high level to remove smoke from a reservoir. Inlets allow replacement air to flow into lower parts of the building. The temperature and mass of gasses arriving at the smoke reservoir determine the volume extract rate, as:

$$V_1 = \frac{MT_1}{\rho_o T_o} \quad \text{m}^3\text{s}^{-1} \quad \text{Eq. 2.4}$$

where: V_1 - volumetric extract rate m^3s^{-1}

The volume extract rate of a fan is constant with varying temperature (Klote and Milke 1992). Therefore, if temperatures are lower than anticipated, then with constant volume extract rate, the mass of smoke extracted will be less.

The required extract rate and the depth of the smoke determine the number of extract points. As shown in Equation 2.5, from BR 186:

$$M_{\max} = \beta(gD_1^5 T_o \theta / T^2)^{1/2} \quad \text{kgs}^{-1} \quad \text{Eq.2.5}$$

where: $M_{\max}$ - maximum mass flow through a vent
 β - a coefficient, 1.3 or 1.8

If smoke extraction is through too few points, then plugholing will occur, whereby ambient air is drawn up the smoke layer. The mass of smoke extracted is effectively less than in the plume for the height of rise. The smoke layer will descend and settle at a level where the effective removal rate is equal to mass flow rate of the plume.

2.2.3.3 Choice of System

Natural ventilation and powered extraction have the same function. Natural smoke ventilation cannot be used if wind pressures can adversely affect it. The buoyancy pressure developed by a deep, hot smoke layer is small compared to wind pressures.

For example, a 5 m deep smoke reservoir, with smoke at 200 °C, produces pressures up to 35 Pa. At wind velocities approaching 6 ms⁻¹, some roof vents could be subject to pressures exceeding 35 Pa. Some natural ventilators will be subject to adverse wind pressure if mounted at too steep an angle (at approximately 30° above the horizontal) or if subjected to downdraughting from adjacent higher structures.

Powered extraction systems have some disadvantages that make them a less attractive choice. They require emergency power supplies and spare fan capacity; they are complex, requiring attenuators, dampers, ducts, wiring, generators and control systems; and have higher capital costs than natural ventilators.

Natural smoke ventilation systems are simple and can be fail-safe. Vents in adjacent zones provide inlet air. Capital cost and maintenance costs are much lower.

2.2.4 Methods of Smoke Containment

The aim of these systems is to prevent smoke from entering other parts of a building, using passive or active measures. The mass flow rate is not an issue in this design, except with dispersion. The key design parameter is the pressure generated by the smoke. This is usually limited to 17 to 20 Pa for a standard sized room, but for a large compartment with a deep reservoir, it is nearly 87 Pa, for a reservoir 11 m deep, at 700° C above ambient (Klote and Milke 1992). This assumes a uniform temperature profile within the reservoir.

2.2.4.1 Dispersion

‘A space is separated from adjacent spaces by fire resistant construction and is large enough to allow all of the smoke produced by the design fire to collect in the upper part of the space’ (Marchant 1990), see Figure 2.3. The time at which the smoke descends below a safe level and the time for occupants to escape from the space need to be calculated. The filling time should be much greater than the escape time, otherwise additional measures are needed to ensure the safety of the occupants. These could include methods to reduce the fire size, improvements to reduce the

escape time for occupants or alternative (or additional) methods of smoke control. Usually it may be possible to add a minimal area of vents or number of fans to increase the time for hazardous conditions to develop.

2.2.4.2 Passive Containment

This method is best suited to buildings subdivided into many compartments, such as institutional buildings. The enclosing structure needs have a good construction to prevent significant smoke leakage into adjoining spaces. Smoke seals are often needed to prevent the passage of hot smoke around door cracks. Ceiling and wall junctions and penetrations through walls, by services, need to be sealed effectively. This is the most common form of smoke control, albeit not an engineered system, and can be achieved with traditional building forms and construction methods, if detailed and built correctly.

2.2.4.3 Active Containment with Pressure Differentials

Air will flow from area of high pressure to an area of low pressure. By creating a pressure differential between two spaces, airflow can be encouraged to flow in a known direction. If the air pressure in a space adjoining a fire compartment is increased, then air will flow into the fire compartment. If the pressure is great enough, then it will overcome the maximum pressures that could be expected in a fire compartment, preventing smoke from flowing into the protected zone. An alternative method is to depressurise the fire compartment, creating a similar pressure difference. The two common forms are stairwell pressurisation and zoned pressurisation.

STAIRWELL PRESSURISATION

The stairwells are pressurised, to keep them smoke free for escape and to allow access for fire-fighters, see Figure 2.4. All the spaces adjoining the stairwell are at negative pressure, relative to the stairwell. If the system is correctly designed, there will be no pressure differences from floor to floor, so that air will not flow between floors. This prevents smoke from being forced from the fire compartment into adjoining spaces.

In the UK, most pressurisation systems are designed to BS 5588 Part 4, Code of Practice for Smoke Control in Protected Escape Routes Using. This recommends that the system should maintain a 50 Pa pressure difference across closed doorways from the stairs and provide an airflow of 0.75 m/s through doorways when open. The system design can be adapted to provide 0.75 m/s across more than one open doorway. This pressure and velocity far exceed the velocities that would be expected from a fire across a doorway, during escape from a compartment of typical maximum height of 2.4 m. The maximum allowable pressure difference is 60 Pa, otherwise occupants may not be able to force open doors to the stairs.

BS 5588 Part 5, Code of Practice for Fire fighting Stairs and Lifts, has recommendations for the pressurisation of fire fighting shafts (stairwells), when natural ventilation is not possible. The system must be able to maintain a velocity of 2 m/s across an open door and through an open door at ground level. The higher velocity requirement is for a more severe fire, at a later stage in its growth.

There are two design conditions, one for closed doors in the stairwell and one for open doors. Maintaining the velocity or pressure difference would require two different volumes of air to be injected into the stairwell, when doors are open or closed. To avoid this, the system is designed to inject air at a constant pressure, and vents are fitted to the stairwell, to release excess pressures when doors are shut.

The airflow through an open door can pressurise the fire compartment. If this occurs, then there are no pressure differences to prevent smoke flowing into the stairwell. Smoke could also be forced into adjoining compartments. Vents are fitted to all accommodation adjoining the stairwell to provide a route for pressure relief.

ZONED PRESSURISATION

This technique is more common in the USA. The fire compartment depressurised with an extract system. Adjoining compartments are pressurised. A simplified version is shown in Figure 2.5, from Klote and Milke (1992). The buoyancy

pressures, and other pressure differences generated in a building due to the expansion of the gases, stack effects and wind effects are calculated to ensure and the system designed to achieve the appropriate pressure differential, between the fire zone and non-fire zone. Often this can be achieved by using the HVAC system. Complex controls are needed to ensure that the correct zones are pressurised and depressurised. Guidance is available in USA publications (cf. Klote and Milke 1992).

OTHER METHODS OF PRESSURISATION

Depressurisation is described in many publications, but is rarely used. Hansell and Morgan (1993) have investigated the possibility of depressurising atria to overcome the problems associated with leaky facades, in particular where the design require unsealed windows or doors to balconies on the atrium. Depressurisation raises the height of the neutral pressure plane (a plane where the pressure in the atrium is equal to that of outside), so that smoke is only able to flow into adjoining spaces.

2.2.5 Hybrid Smoke Control

Extraction can be used to provide a limited form of depressurisation. Hansell and Morgan (1994) have developed this concept. The basic principle is that smoke removal in tall atria can only keep the lower storeys clear of smoke. To keep upper storeys clear of smoke would require prohibitive extraction rates. However upper storeys need to be protected too. By extracting smoke, an atrium can become depressurised, raising the height of the neutral pressure plane. This limits the pressures that would develop above the neutral pressure plane, limiting the flow of smoke into adjoining spaces.

2.2.6 Dilution

Dilution reduces the hazard presented by smoke, rather than preventing exposure it. It generally uses smoke removal methods to lessen the concentration of smoke in a space. This method has limited success, due to the variations in toxicity of smoke.

2.3 Integrated Fire Safety Design

Smoke control systems need to be examined as a part of the total fire safety and property protection systems that can be installed in a building. An integrated fire safety engineering approach is needed to develop a design that achieves an acceptable level of life safety and property protection.

The concept of a total fire safety system has been a recent development, for which many countries are aiming to develop a systematic approach using performance based design systems (Magnusson, Frantzich and Harada 1995). This concept is being used increasingly for fire safety design, rather than a simple code based approach. A term used commonly is performance based design.

Integrated fire safety engineering is illustrated in the UK approach to performance based design. This is published in the Draft British Standard Code of Practice for the Application of Fire Safety Engineering Principles to Fire Safety in Buildings (1994). It contains six subsystems that need to be integrated into a total fire safety design:

SS1 Fire growth in compartment of origin

This includes calculations for heat release, smoke production, flame size, temperatures, time to flashover and area of fire.

SS2 Spread of smoke to other compartments

This includes calculations for the mass flow rate, temperature, toxicity and optical density of the smoke within and beyond the fire compartment.

SS3 Spread of fire (flames) to other compartments

This includes calculations for the spread of flames to other compartments, by fire severity, loss of structural stability and compartment temperatures and heat flux.

SS4 Times to detection and activation of fire alarms to other compartments

This includes times for the activation of alarms, smoke control systems, fire and smoke barriers, suppression systems and fire brigade notification.

SS5 Fire brigade communication and response

Methods are provided to evaluate the time for the arrival of the fire service, time to set-up and the time to attack and control the fire.

SS6 Calculation of evacuation times

Guidance is provided on the movement of people with respect to time, within a fire enclosure, between enclosure and to a place of safety.

These subsystems are integrated into a total fire safety system. Figure 2.6 (Draft British Standard Code of Practice for the Application of Fire Safety Engineering) shows the relationship of the different subsystems and component calculations. This design structure is analogous to a computer information bus, where data is passed around to all subsystems. The same basic data must be used for other subsystems.

This system reflects a deterministic design procedure. This is based on physical, chemical, and thermodynamic relationships derived from scientific theories and empirical methods (Deakin and Cooke 1993). Sensitivity analyses are needed to investigate the effect of uncertainties and simplifications in the data and calculation methods. These may indicate that some of the subsystems require higher standards. Deakin and Cooke (1993) suggest provisional factors of safety to be introduced into the design to overcome these uncertainties. A smoke control system would have a factor of safety of two to three.

A deterministic design provides a target performance for a smoke control system to achieve for example an extract rate. These performance values provide alternative allows alternative solutions to be developed for fire safety problems. For example, a smoke layer could be designed to be at a particular height. If that height is increased,

the height of rise is greater, resulting in a larger mass flow rate of smoke at lower temperatures. If the mass extraction rate of a smoke control system is increased, then the smoke layer is raised, and lower temperatures are found in the smoke reservoir. Therefore, the temperature rating of the enclosure to the reservoir can be lowered. The designer has a choice of a lower extract rate and higher temperature rating of the structure around the smoke reservoir, or a higher extract and lower temperature rating.

Often smoke control, is required to compensate for deficiencies in other fire safety or protection systems, usually the means of escape for occupants. For example in large complex buildings, the time for occupants to escape may exceed 'normal' parameters, therefore the potential flow of smoke onto escape routes needs to be controlled otherwise the possible smoke logging would create untenable conditions.

2.4 Performance of Smoke Control Systems

A variety of methods are available to control the flow of smoke in buildings. The characteristics of the smoke need to be calculated or assumed from codes, so that an appropriate smoke control system can be designed. A system needs to be designed to meet those conditions and deal with the smoke in an appropriate manner. As will be discussed in later Chapters, smoke control system performance can vary. There are two basic causes of that variability:

- The fire and smoke environment can vary from predictions.
- The systems controlling the smoke. Related systems (such as fire and occupant escape) can also vary, affecting the performance of the smoke control system.

These variations may reduce the effectiveness of the system. If the performance is outside an acceptable range, then the system has failed.

The failure of smoke control systems is defined in Chapter 3, where the methodologies to be used to analyse these variations in this study are explained.

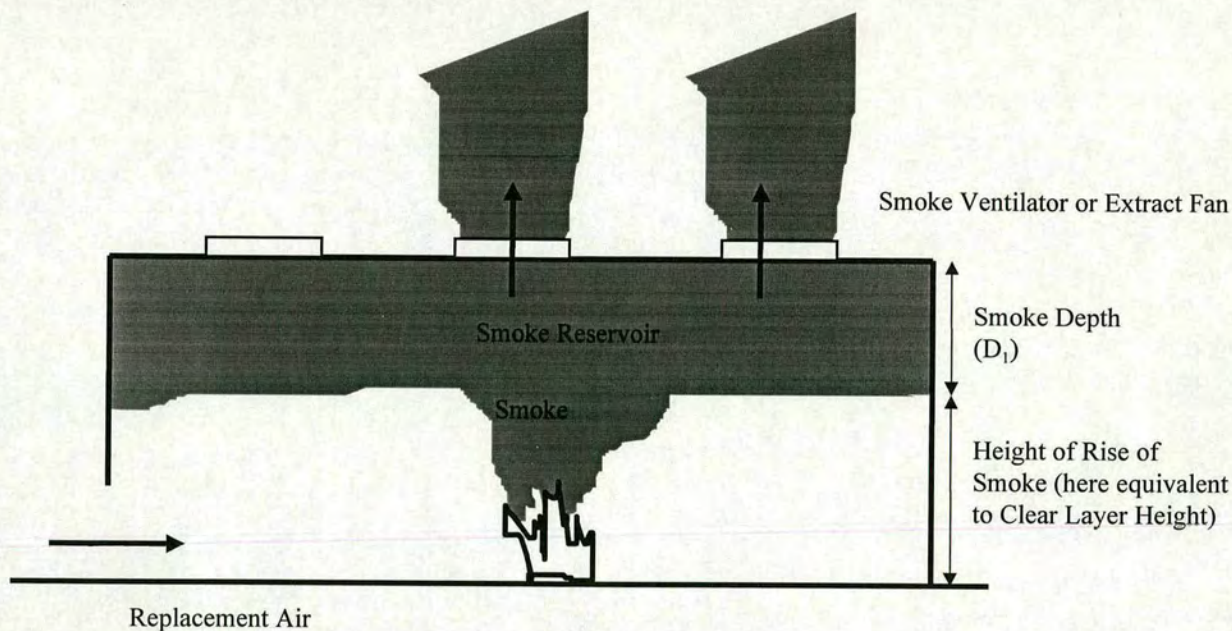
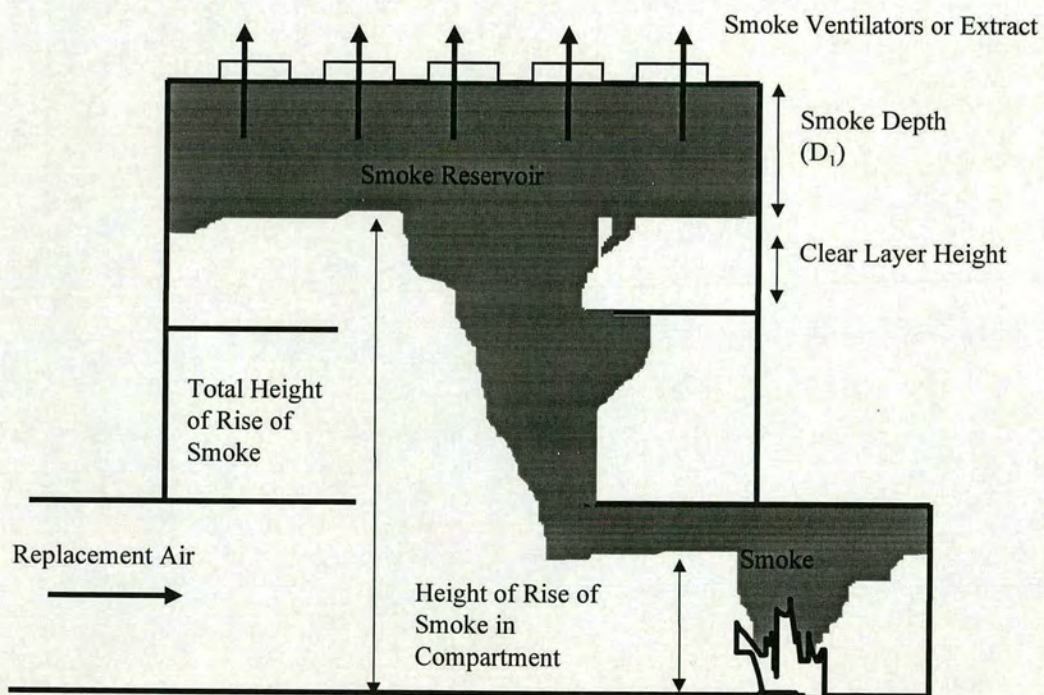


Figure 2.1 Single Storey Smoke Removal System



N.B. Smoke barriers to create zones not shown

Figure 2.2 Multi-Storey Smoke Removal System

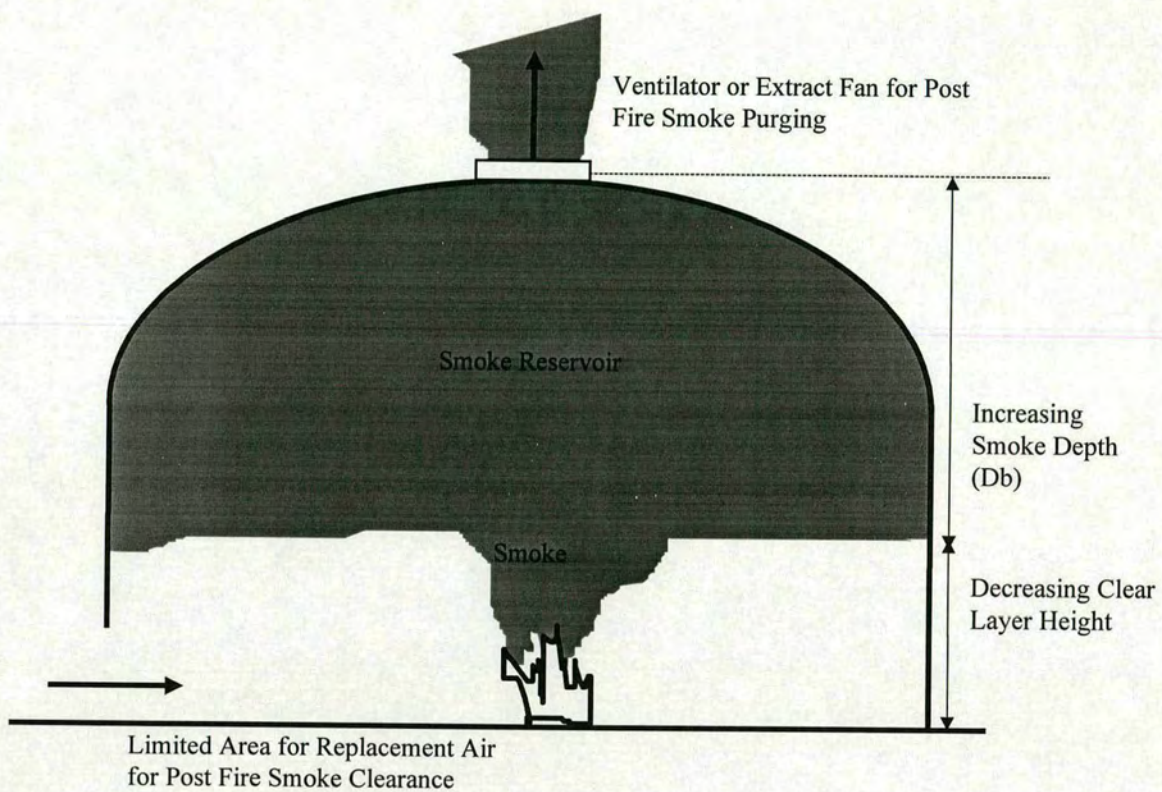


Figure 2.3 Smoke Dispersion

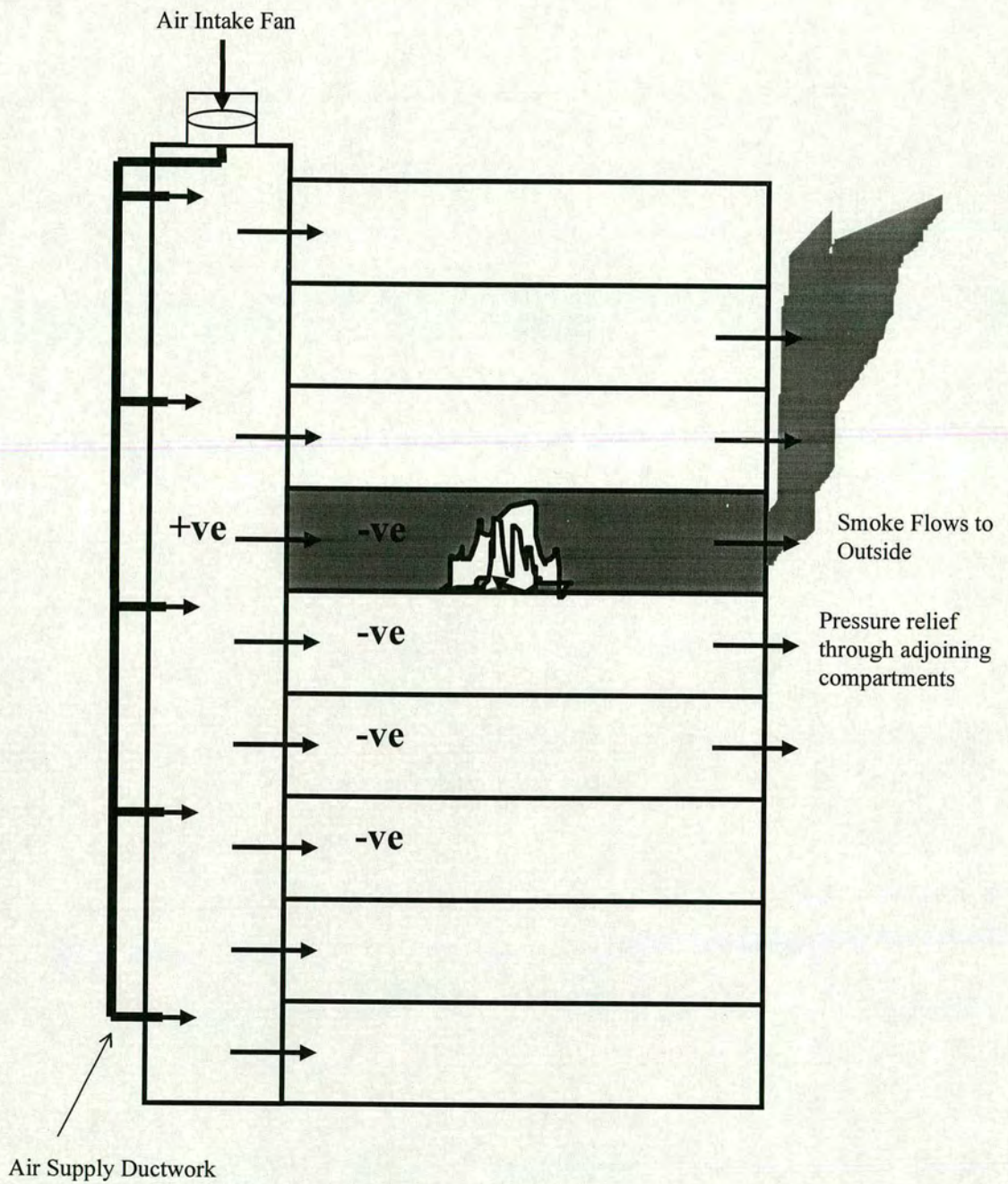
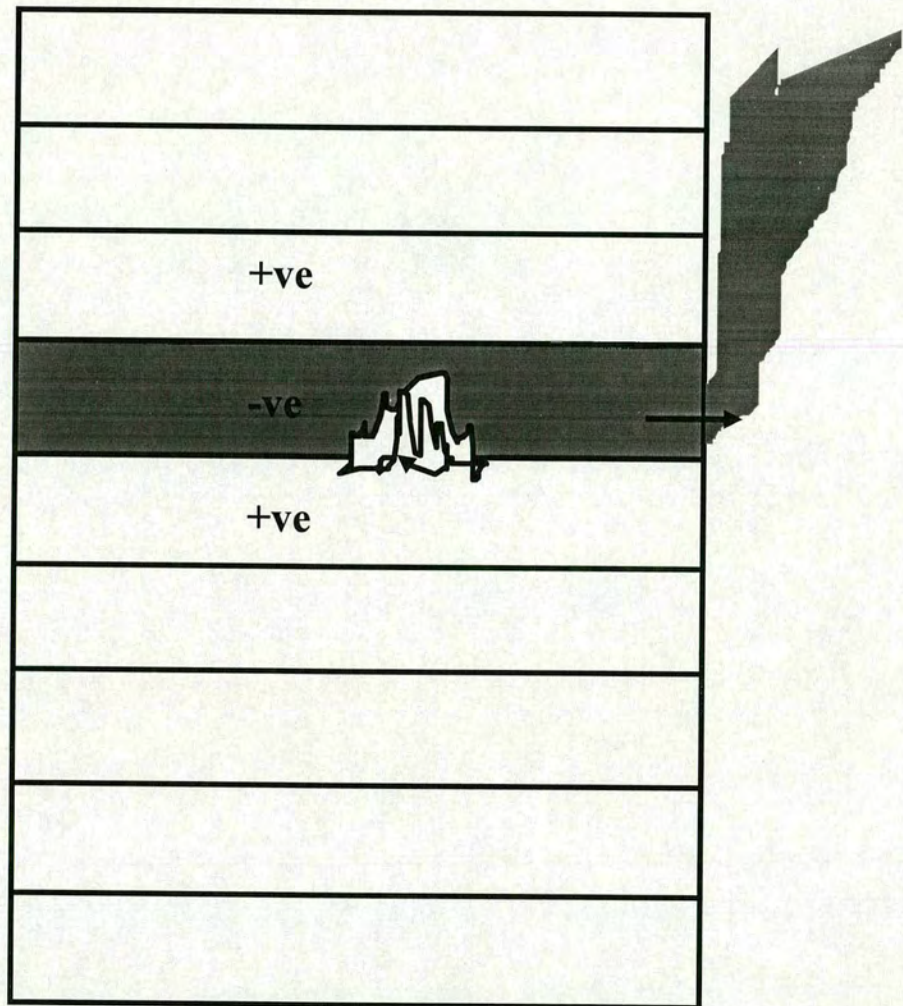


Figure 2.4 Stairwell Pressurisation System



NB All of the non-fire floors can have positive pressurisation.

Figure 2.5 A Simple Zoned Smoke Control Arrangement

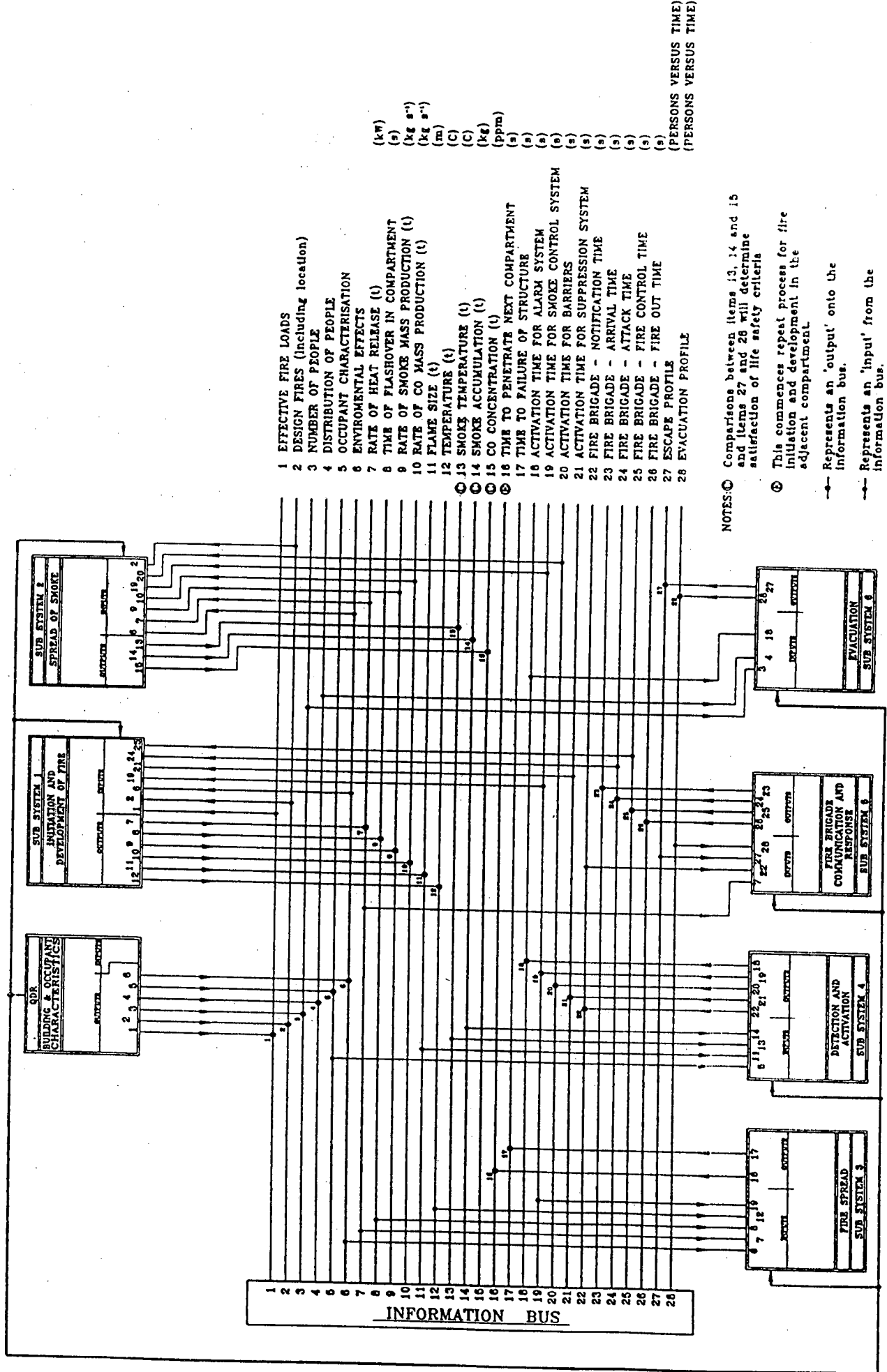


Figure 2.6 Integrated Fire Safety Engineering (Draft British Standard)

Chapter 3 Smoke Control System Failure

3.1 Probability of Success for Different Fire Safety Options

When a design is being developed, different options for fire safety and property protection need to be examined. The final choice should be made on the basis of:

1. The level of safety or protection obtained (the degree of hazard to occupants)
2. The cost of the systems
3. The reliability of the systems

Items 1 and 2 are always included within the design process. Different designs are evaluated on the basis of the levels of hazard to which occupants and property could be exposed. Within the design process, sensitivity analyses may be conducted to assess the effects of variations to the predicted conditions.

Some 'risk' based decisions or data may be included. For example when designing a smoke control system for a shopping complex, a 5 MW fire is often used for a sprinklered fire. This is based on statistical data. Only 10 % of sprinklered fires exceed this size (BR 186, 1990). Therefore, when using a 5 MW design size fire, there is an implicit decision that there is a 10 % probability that a larger fire size could occur, which could overwhelm the smoke control system. There are other design parameters, which would ensure that fire sizes above 5 MW could not automatically cause the smoke control system to be overwhelmed. Deakin and Cooke (1993) suggest that a safety factor of 2 to 3, should be used to deal with uncertainties in smoke control design, but without suggesting which aspects of design should have this applied to them.

Many design decisions are made through personal and collective experience. This can eliminate some unreliable aspects of a design, but reliability is not always considered systematically. Often a design solution or a part of the solution is chosen,

based on individual designers experiences and preferences (Aslksen and Belcher 1992 and MacPherson, Kelly, and Webb 1993). This can include reliability issues, but rarely a quantified risk assessment of the system (Magnusson, Frantzich and Harada 1995). In comparing a performance based fire safety system to a code based system, Beck (1993) describes the decision criterion for acceptance as:

'For an alternative design to be considered acceptable the expected risk-to-life value of a building conforming to the building regulations, and the fire-cost expectation for the alternative design shall be less than or equal to the value for the conforming building.'

It is important that as a life safety system, the risk to occupants of system failure, with fire safety techniques needs to be assessed. There needs to be a high probability of success for fire safety systems, if a fire were to occur in a building.

For property protection, the cost benefits of different fire protection systems need to be assessed. Any smoke control system needs to undergo a risk assessment to evaluate the benefit offered towards meeting the objectives of life safety and property protection and life safety. Similarly, its potential for reducing organisational loss and aiding fire fighting needs to be evaluated, although these objectives are likely to be met by the life safety and property protection objectives.

In order to evaluate the success or failure of a smoke control system, the criteria for failure needs to be defined and the failure modes identified.

3.2 Smoke Control System Failure

3.2.1 A Definition of Failure

There are no published definitions for smoke control system failure. Smith (1993) gives a general definition of failure as, 'non-conformance to some defined performance criterion'.

This can be adapted for a definition of failure of smoke control as:

For any fire scenario that could reasonably be expected to affect a building, a smoke control system can be deemed to have failed, if there is potential threat, that exceeds the design basis. The threat can be to:

1. Occupants
2. Property
3. Organisational activities
4. Fire-fighters activities

A system that could fail during a fire can be classed as a 'failure', even if never used. It can be 'failed' even if it has demonstrated a limited success.

An example is the Carlyle Condominium, Lakewood, Ohio (Taylor 1975). This 30-storey apartment block, had a stairwell and corridor pressurisation system. A fire destroyed 80 % of the interior of a 20th floor apartment. The fire and smoke were contained successfully. An investigation to ascertain what pressures achieved this, found that the system was poorly balanced. The 20th floor corridor had positive pressure close to design requirements, but on the 4th floor negative pressures were found. Thus a fire on the lower floors would have drawn smoke into the corridor and stairwell, up into top floor corridors.

3.2.2 Variations in Performance and Failure

Marchant (1993) defines the performance of smoke control systems according to the conditions imposed by the smoke regime. A system's performance is:

- deficient when it is below that required by the smoke quantities and characteristics.
- efficient, if well suited to a 'plausibly pessimistic' fire size and the resultant smoke flow.
- super-efficient if it exceeds that required by the smoke quantities and characteristics.

These variations in performance can be caused by many factors; natural variations to the fire and smoke regime; inappropriate design criteria; or inappropriate models. Variations can also occur due to the smoke control systems' performance.

Performance will also vary during the life of a fire. A system will have transient efficiency for a short period, when its performance is well suited to the particular fire and smoke regime; transient super-efficiency, when its performance exceeds that required by the fire; and transient deficiency, when below that required by the fire.

Super-efficiency is not just a matter of uneconomical performance. It can also create adverse conditions during a fire. For example excessive pressure differences across a door, could make it difficult or impossible to open. Another example is an extract system that depressurises a space excessively, so that the glass enclosure shatters.

Success cannot be based purely on an optimal performance value. For any system, there is a range of acceptable variation in performance. This concept is well understood in safety system design in other engineering disciplines. Wassell (1982) states that no product can be perfect, so there is an acceptable level of failure for a product or system. Gruhn (1991) reports that USA federal regulations for the management of highly hazardous chemicals state that there is an acceptable level of performance for safety systems. It will be acceptable to have a deficient system, if its

performance still meets safety requirements. The criteria for the acceptability of a deficient system depend on the risk posed to safety. The deficiency is acceptable if the additional risk to safety or property is not excessive or does not exceed a target value. No value will be stated here. This is outside the scope of this work. A great difficulty of risk assessment is the definition or quantification of an acceptable level of risk (Thomson 1987).

The acceptable deficiency or super efficiency of a smoke control system, for the purpose of this work, is defined as the performance of a system that lies within a range of values, so that it will meet its objectives and there is no significant threat to:

1. Occupants
2. Property
3. Organisational activities
4. Fire-fighters activities

It should be noted that 'significant' is a subjective term and is difficult to quantify here.

An example of an acceptably deficient system is a shopping mall in the UK (Marchant 1993), where a life-safety smoke extraction system had been installed. The fans could only achieve a maximum of 75 % of the design extract rate. No improvement could be made. The system was re-evaluated on the basis of the timed trial evacuations of occupants. The time to escape was quicker than expected. The occupants would not be subject to the smoke hazards in escape routes, caused by the deficient system.

3.2.3 The Cause of Performance Variation and Failure

The performance (and reliability) of any system is judged by the loads imposed upon it and its capacity to deal with those loads (Wassell, 1982). The performance of a smoke control system during a fire, is subject to two variables:

1. the fire environment
2. the smoke control installation and associated fire engineering systems

This is demonstrated in Figure 3.1, showing a simple example of the range of acceptable performance for an extract system. The performance of an efficiently designed system will match that of the smoke regime, the line of efficiency, E.

At E, the volume extract rate of the smoke control system will match mass flow rate of the smoke produced. The limit of acceptable deficiency, line D, will be defined by the quantity of excess smoke that can be tolerated. Quantities exceeding this will cause one or more of the objectives not being met, for example smoke could descend to below a certain height, making escape hazardous for occupants. The limit of acceptable super efficiency relates to the performance of the smoke control system, in relation to other building systems, rather than to the fire size. This is shown as an absolute value, line S. An example is the pressure difference across a door, which should not exceed 60 Pa (BS 5588 Part 4). If it exceeds this value (super-efficient performance), it could be impossible for some people to open.

The causes and effects of performance variations needs to be understood, to develop a rational analysis of smoke control failure modes.

3.2.4 Manifestation of Failure of Smoke Control Systems

The basic forms in which smoke control system failures are manifested are as follows:

3.2.4.1 Smoke Removal Systems

If a smoke removal system fails, smoke can occupy hazardous locations. These are:

1. Smoke forms a layer at a level below acceptable limits
2. Smoke flows into adjoining compartments
3. Smoke drawn down the perimeter of compartment, below reservoir
4. Smoke collects at low level, without rising

The smoke may be more hazardous, beyond acceptable levels, even though the smoke may be at the design height. The smoke may have excessive:

1. Temperatures
2. Toxicity
3. Obscuration (i.e. very poor visibility)

The smoke removal system can adversely affect other activities in the building:

1. Incoming air velocity can hinder escape, mix into the smoke layer and affect the fire or other aspects of fire safety.
2. Smoke removal systems can adversely affect the general performance of a building in its routine activities, due to excessive vibration, noise or air movement during testing.

3.2.4.2 Smoke Containment Systems

When a smoke containment system fails, smoke will occupy hazardous locations. There are two ways that smoke can form a hazard to occupants or property.

1. Space smoke logs too rapidly (dispersal method of containment)
2. Smoke enters protected areas

The smoke characteristics can also increase the hazard presented to the occupants, beyond acceptable levels, for dispersal systems (but are unlikely to affect a pressurisation system). The smoke may have excessive:

1. Temperatures
2. Toxicity
3. Obscuration (i.e. very poor visibility)

Smoke containment systems can also adversely affect other activities in a building:

1. Air velocities can hinder escape or prevent doors from being opened. A more remote possibility is that it could affect the fire or other aspects of fire safety
2. It can adversely affect the general performance of a building in its routine activities, such as through excessive vibration or noise during testing.

3.3 Risk Analysis of Smoke Control Systems

3.3.1 General

Smoke control systems can be analysed to determine their effectiveness as life-safety or property protection systems. This could help designers to assess the benefits of installing a smoke control system of a certain standard and capacity into a building, in comparison to other alternative systems.

System safety analysis is fraught with difficulties. The definitions and methods of analysis are the subject of much dispute (Clemens 1993). Many different methods of analysing system safety are available. There are continual developments in the subject. Clemens (1993) describes the 'inexorable march' to find the ideal analytic method.

This thesis aims to identify the causes of variations in smoke control performance that can lead to failure. It does not aim to provide a quantified risk analysis, rather a rational for analysing the risk of smoke control system failure.

3.3.2 Published Data on Failure Modes and Reliability of Smoke Control

There are many design guides providing detailed information on the requirements of smoke control systems. These aim to ensure that smoke control systems are effectively designed. There have been limited systematic studies of the failure modes of smoke control systems and a few case studies have been published.

Marchant (1993) developed an approach to classifying failure modes, according to when they are caused in the life cycle process. A range of typical examples of smoke control failures is provided, including component and system failures.

Campbell and Longahitano (1984) have also presented some examples of failure modes (including component and system failures). Both Marchant (1993) and Campbell and Longahitano (1984) outline some of the reasons for smoke control failures occurring.

There is little quantitative data on the reliability of smoke control systems. Campbell and Longahitano (1984) note that numerical goals are not well established for any life safety or property protection system and the data for analysis is not available.

There have been simple reliability studies, calculated from the reliability of the individual components (Milke and Klote 1992). This assumes that the system as a whole will operate effectively, with other systems. Unfortunately, the components may operate efficiently, but the system fails to achieve its objectives. This also assumes that a component failure, causes the whole system to fail. Most systems have spare capacity, including built-in redundancy, therefore failure may only occur after a series of component failures.

3.3.3 Reliability of Fire Safety Systems

Studies of other fire safety systems are more common. Some studies have concentrated on particular safety systems such, such as smoke detectors. The effect of the variability of the smoke detector installation and the fire growth and smoke flow have been modelled probabilistically to determine the performance parameters for alarm malfunctions and false detection (Smith 1994).

Other analysis has been conducted examining the statistical data on the failure of life-safety systems. Burnett and Kwok (1993) have examined the reliability of essential electricity supply systems and generators in buildings in Hong Kong. They quantified the failure rates of these systems and highlighted the need for improved maintenance and identified common causes of system failure, such as battery failure. Unexpected failures also occurred, such as those due to controls logic causing systems to shut down at inappropriate times.

Boyd and Locurto (1985) used of fault tree analysis to examine the reliability and mean time between system failures of power supplies for fire protection systems.

The data for the fault trees was provided by standard component reliability data, such as from American Military Handbooks.

A range of analysis methods is available to examine the reliability of smoke control systems. An important facet of any study is that it should be systematic. The system should not be examined in isolation of other systems (Beard 1985).

3.3.4 Sprinkler System Reliability

Unlike smoke control systems, statistical records from many countries exist for over 100 years experience, for sprinkler system installation and operation (Dowling, Robinson, and Crouch, 1993). This can provide statistical data to calculate design fire sizes for different forms of building occupancies (see Chapter 4). This can also be related to deterministic models and case studies of sprinkler operation to develop reliability analyses of sprinkler operation, in different forms of occupancy, compartment geometry and sprinkler systems.

Detailed examinations of modes of failure have been conducted to account for anomalies in sprinkler performance. The range of response times for identical ceiling jet characteristics (temperature and velocity) have been examined in detail. Researchers have investigated the variation in performance of sprinkler heads due to natural variations in the materials. The effects of these variations on the conditions that exist within a compartment, with a growing fire have been examined. For example Williams (1989) has examined the effect of sprinkler skipping in fires, a process where the sprinkler closest to a fire plume does not operate first, as normally occurs. This can result in fires growing beyond the size predicted by simple compartment fire growth models. It demonstrates that variations in the environment and variations in the sprinkler manufacturing process, have a combined effect on the system performance.

Some of these theories are still only tentative, there is still much disagreement regarding the interpretation of the statistical and experimental data.

Some problems with the studies exist. For example the statistical data for the fire area is based on fire officers' post fire investigations. These often approximate estimates of the damage caused by fires (Hansell and Morgan 1986).

3.3.5 Methods for Assessing Smoke Control System Reliability

3.3.5.1 Quantitative Risk Assessment

Quantitative methods measure risk in terms of probability and severity. The ideal result of examining the safety of smoke control systems would be to develop a suitable range of probabilities of success and failure for different types of smoke control, in different locations. This would identify the optimal system performance for life safety and would aid cost benefit analysis for property protection.

This can be quantified with detailed methods such as fault tree and event tree analyses. These are reviewed in the Safe Systems Society Handbook (1993).

Event Tree Analysis (ETA) is a 'bottom up' approach to failure. It explores all events and their consequences, to result in a total risk assessment. It is a time consuming method, but can reveal concealed risks.

Fault Tree Analysis (FTA) is a 'top down' rather than a 'bottom up' approach. It requires all undesirable events to be identified, and all causes and effects to be known. Concealed risks are not revealed. This is the most common method of quantitative analysis.

Unfortunately, both methods require reliable data to assess the probability of the events occurring. Both also rely on key assumptions and judgements, particularly FTA. In attempting either analysis, the failure modes would need to be identified; for FTA, to develop the events that could lead up to system failure; and for ETA, to identify events that have caused failure.

Little data exists for the performance of smoke control systems. There are few published examples of smoke control system performance in real fires (see Chapter 12). Component performance can be assessed using guidance from common reliability data, such as contained in UK Defence Standards, US Military Standards and manufacturers information. This reliability data can vary according to source and little data is available for most components. Manufacturers have difficulty making predictions about performance, Mecker and Hamada (1995) and Wong (1995). Mecker et al and Wong found that not all data is suitable for specialist situations. This may apply to smoke control components (see Chapter 10).

It is difficult to calculate reliability from basic data on components, methods and data can differ, resulting in large variations in values. In a study of a particular type of circuit board (Wong, 1995) calculated a failure rate of 0.005 to 37 times per year, using the same method, but with data from different, well known sources.

These component reliability data sources do not contain information on reliability relating to system design and installation errors (see Chapter 10). There is no published data for the reliability of smoke control systems as a whole. The performance of a smoke control system needs to be examined as part of an integrated fire safety engineering system. It cannot be examined in isolation.

As will be discussed in Chapter 10, human error is a major cause of any system failure. This can contribute to deficiencies in a system at all stages of a system's life. A risk analysis that ignores human factors, ignores a large potential of error that could occur within a system's lifetime. Smith states (1993):

'Regulatory bodies, such as the UK Health and Safety Executive are taking a greater interest in this area and questions are frequently asked about the role of human error in hazard assessments which are a necessary part of the submissions required from operators of major installations'.

3.3.5.2 Qualitative Risk Assessment

This approach must be used when there is insufficient reliability data or system design information to conduct a qualitative risk assessment. It is an easier method, but can be as effective as quantitative methods, which are subject to the errors contained in the data and subjective inputs (Safe Systems Society, 1993).

An overview of the major areas of risk for system designs is provided. Qualitative analyses need to be conducted carefully and 'objectively'. The analyst must make judgements regarding the severity and risk of an event. This can include judgements based on the ease of engineering and previous operational experience. Organisations approach a system design and installation differently, so that the result of a risk assessment is best used for comparison purposes. A 'standardised' approach to qualitative analysis is questionable (Gruhn 1991), due to the complexity and variety of systems.

Common methods of quantitative risk assessment are (System Safety Handbook 1993):

3.3.5.2.1 Failure modes and effects analysis (FMEA)

The purpose of FMEA is to determine the results or effects of sub-element failures on a system operation and to classify its severity according to its severity.

The system is identified (element by element), modes of failure identified and the effects upon the system determined. The effects can be classified according to severity. The thoroughness of the analysis is determined by the degree to which failure modes and effects are identified.

FMEA can review hardware thoroughly and is good for complex systems, such as an integrated fire safety system, but human factors may be missed in the analysis.

3.3.5.2.2 Failure modes, effects and criticality analysis (FMECA)

This is similar to FMEA, but incorporates criticality analysis, in which the failure modes identified by FMEA are ranked according to their severity and probability.

The thoroughness of FMECA depends on the analysts' ability to identify the failure processes and effects. An example of the classification of failure mode probabilities and the severity is shown in Table 3.1 (next page).

FMECA for smoke control requires the following steps (adapted from the System Safety Handbook 1993) need to be performed:

1. Identify the major sub-systems and their components.
2. Identify related fire engineering systems and their relationship to the smoke control system.
3. Determine the consequences of interest.
4. Determine the location and scale of all potential fires and smoke characteristics.
5. Determine the potential failure modes.
6. Specify effects (impact) of failures.
7. Establish the criticality of each failure mode.

This could be performed for all smoke control system designs. Most studies could follow a standard format. The detail required could be limited according to the complexity of the system. Human error factors can be included in the analysis. This provides the basis for a 'pilot' format.

Frequency of Occurrence		
Level	Description	Individual Items
5	Frequent	Likely to Occur Frequently
4	Probable	Will occur several times in the life of an item
3	Occasional	Likely to occur sometime in the life of an item
2	Remote	Unlikely but possible to occur in the life of an item
1	Improbable	So unlikely that occurrence may not be experienced

		Potential Consequences	
Level	Description	Injury	Production/Equipment Loss
5	Catastrophic	Death	>£1.5 million
4	Severe	Serious Injury	£1.5 million to £500 000
3	Serious	Medical Treatment	£500 000 to £100 000
2	Minor	First Aid	£100 000 to £2 500
1	Negligible	No injury	£2 500

Table 3.1 The Classification of Failure Mode Probabilities and Severity
(adapted from Gruhn 1991)

3.4 Summary

3.4.1 Smoke Control Systems for Life Safety and Property Protection

The development of an effective design requires:

- The designer to be aware of failure modes so that failures can be actively avoided.
- Assessment of the potential risk of failure of the system, to identify the true benefits of its installation for life safety, property protection or some other objective.

The manifestations of smoke control failure are identified in Section 3.2.

If a risk assessment is to be conducted, then:

- The cause of system variations and the effects of variations in system performance need to be identified. These can either be due to a varying fire environment or varying hardware performance.
- It would be difficult to quantify the reliability of a smoke control system, but some limited data could be developed. Quantification methods would need to examine the variation in fire and smoke characteristics and smoke control installation performance.

This thesis identifies the factors that may cause a smoke control system's performance to vary. A method of classifying the failure modes of smoke control systems is developed. Identifying the generic forms of failure modes would allow systematic risk assessments of smoke control systems. This framework would allow risk assessment to be tailored to different smoke control designs, extending beyond simple component analysis that is currently used.

The rest of this thesis can be divided into three sections:

1. Variations in the fire and smoke environment
2. Variations in the performance of smoke control and other fire safety systems
3. The resulting failure modes and effects.

3.4.2 Variations in the Fire and Smoke Environment

This is examined in Chapters 4 to 9. Chapter 4 outlines the range in fire and smoke environments that could be expected and deviations from predictions that could occur. Chapters 5 to 9 examine one aspect of smoke; smoke flow in atria and malls. The possible variations from predicted mass flow rates and temperatures are examined experimentally.

3.4.3 Variations in the Performance of Smoke Control and Other Fire Safety Systems

This is examined in Chapters 10 to 13. Chapter 10 outlines the life-cycle events that can cause a system performance to vary from its most efficient. Chapter 11 reviews a pilot questionnaire conducted to examine professional experience with control systems in the UK. Chapter 12 reviews case studies derived from the questionnaire and from published sources.

3.4.4 Failure Modes and Effects.

The conclusions from Chapter 4 to 13 are examined in Chapters 14 to 15. Chapter 14 presents a taxonomy of failure, and Chapter 15 presents overall conclusions.

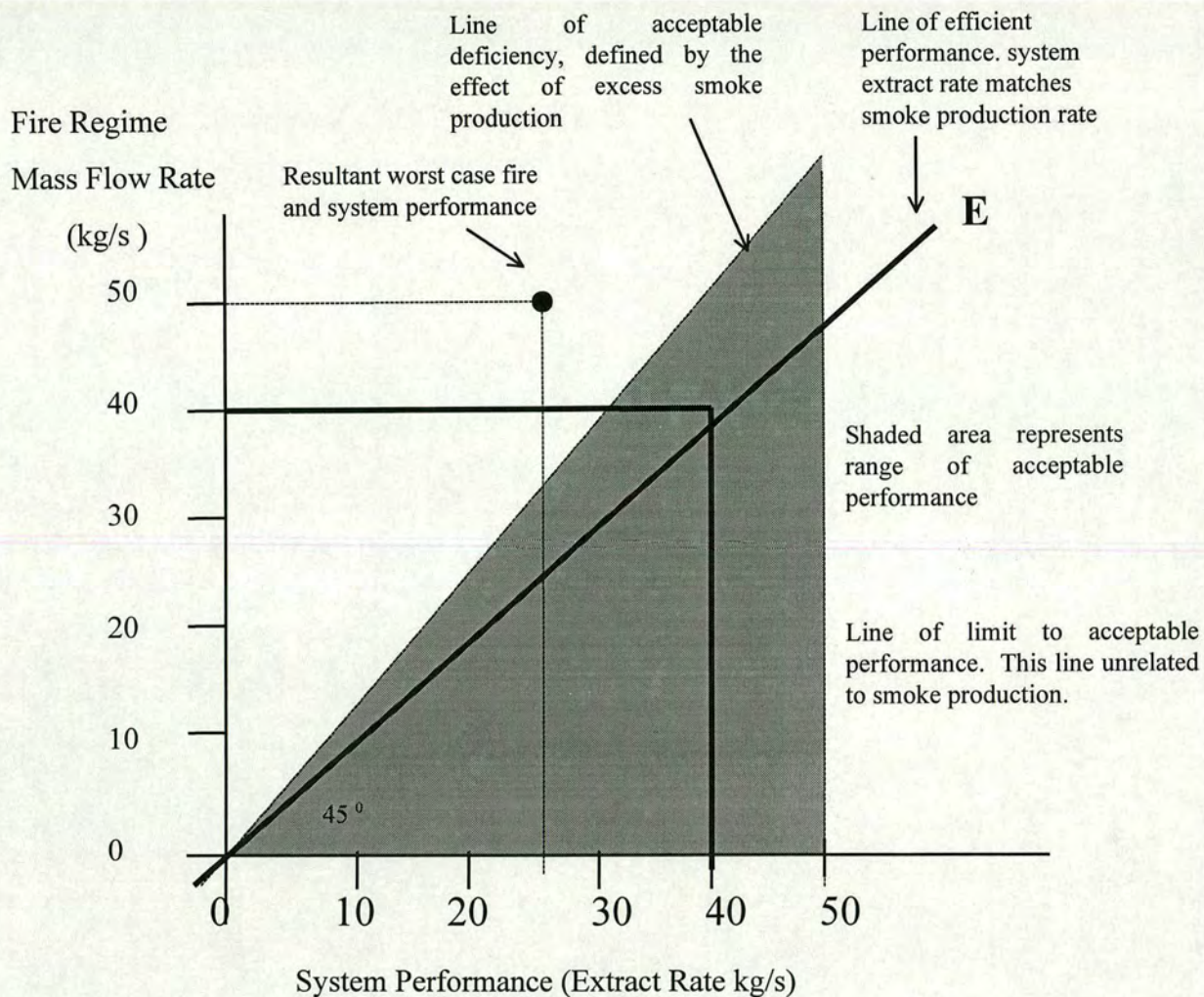


**Figure 3.1 Performance of a Smoke Control System:
Extract Rate versus Smoke Production**

Part 2

Smoke Modelling Chapters

Chapter 4 Fire and Smoke Environment

Chapter 5 Smoke Flow in Atria

Chapter 6 An Experimental Study of Smoke Flow in Atria

Chapter 7 Experimental Results

Chapter 8 Visual Observations from Experiments

Chapter 9 Discussion of the Results

Chapter 4 Fire and Smoke Environment

4.1 Scope of the Chapter

This chapter outlines the causes that cause fire and smoke environments to differ from predictions. It also examines the range of variations that could be expected and whether these would be significant enough to cause system failure. It provides a broad overview of fire and smoke models, before leading into the detailed analysis of smoke flow in atria in Chapters 5 to 9.

A very large number of potential fire scenarios exist for any building. Smoke control system designers must quantify the worst conditions (mass flux, temperature, toxicity and so on), that could reasonably be expected to develop with a fire, in all locations.

It is possible that a fire could occur and the smoke control system be overwhelmed. This could be due to the natural variations in the fire and smoke environment or due to the limitations of the model used to quantify the smoke.

The study shows the influence of variations with the fire environment on potential smoke quantities and characteristics, by examining the models, design information and data available for engineers. Other research has highlighted problems for modelling in general. A detailed examination will be conducted experimentally to evaluate one particular model.

4.2 Fire and Smoke Models

4.2.1 General

Various methods of modelling the fire and smoke environment exist. Engineers can use a mixture of statistical, probabilistic and deterministic methods to model smoke flow and its variability. The level of detail required can vary according to the complexity and vulnerability of the building and its contents. Simple algorithmic models are preferred for the majority of situations.

Investigations have revealed many limitations to these models (Beard 1992, Friedman 1992 and Cox 1993) and generally conclude that they are not exact representations of the fire and smoke, but are tools for qualitative assessments, with quantitative estimates.

For all models there is a level of uncertainty, which can occur with the theory, numerical solutions, processing errors and data input errors (Beard, 1994).

In a review of uncertainty with fire models Magnusson, Frantzich and Harada (1995) state that there are five categories for the factors that affect the reliability of model predictions. These are:

1. Uncertainty due to improper definition and conceptualisation of the problem.
2. Uncertainty due to improper formulation of the conceptual model.
3. Uncertainty involved in the formulation of the computational model.
4. Uncertainty within the estimation of parameter values.
5. Calculation and documentation errors in the production of results.

Beard (1994) developed a similar range of categories, but also included computer software and hardware faults. Items 1, 2, and 5 are design issues and are due to human factors. These are discussed in Chapter 10, as factors affecting smoke control hardware design. Item 4 can also be due to human factors.

Items 3 and 4, the uncertainty involved in the formulation of the computational model and within the estimation of parameter values, could be described as the inherent uncertainty of a model. These create the variation that could be observed between a correctly applied model's predictions and the conditions that could develop in a real fire.

These uncertainties can be split into two categories (Magnusson, Frantzich and Harada 1995):

1. Variability: such as wind direction, temperature and fire growth.
2. Knowledge uncertainty: model uncertainty, acceptable radiation doses to people.

These uncertainties are present in all types models. A design represents the state of understanding of the problem, at a particular period of time. As knowledge develops, so uncertainty can be reduced.

Only deterministic models will be examined here. Other methods of modelling the parameters for a smoke control system can include probabilistic, prescriptive (regulation based models) and physical models.

4.2.2 Deterministic Models

Deterministic models quantify fire growth, fire spread and smoke movement as a single possible development. These form the basis for this thesis, in studying the affect of variability smoke control model predictions from the conditions that could develop in a fire.

There main categories of deterministic models are:

1. Zone models
2. Field models

4.2.3 Zone Models

In zone models the space is divided into a small set of control volumes, with conditions (generally) uniform throughout each. The heat and mass transfer between zones is then calculated, using the appropriate equations (Mitler 1990). Usually the environment within a building is simplified to a one-dimensional model. A fire compartment is typically divided into two layers, a lower ambient layer and an upper hot smoke layer. The hot layer is usually modelled with a simple plume equation (the hot layer having the same temperature and mass flow rate as the plume).

Zone models are developed from basic physical laws and experimental data, and can range in complexity from simple algorithms to detailed computer models such as Hazard, containing many complex sub-routines (Mitler 1990). Most zone models describe idealised steady-state conditions. Programs, such as Hazard are able to incorporate transient conditions, but can only deal with simple room geometries.

These models have limitations with their application. A zone model needs to be carefully selected, so that the important phenomena are not ignored. Most zone models cannot account for the effect of obstructions, compartment lengths, inclined ceilings or growing fires. If, for example, the detailed effect of fire growth or interaction with other systems, such as sprinklers needs to be known, then most zone models will not be suitable, a model for sprinkler interaction is needed. Therefore a designer using zone models must, with the aid of design guidance, decide how smoke might behave in a fire and the relevant parameters that need to be quantified. The detail required depends on the smoke control system objectives and criticality.

Zone models can only provide broad values to quantify the fire and smoke, used within their limits, they can provide a good method of modelling, for most fire engineering problems. They can start to be very inaccurate with more complex problems and cannot predict when there will be a fundamental change in the conditions in a fire (Cox 1993).

Zone models can disagree on relatively simple matters. Figure 4.1 (Cox 1993), shows the various mass flow rates out of compartments from a standard room, calculated from five fire plume expressions available in First (a computer program produced by the National Institute of Standards and Technology). Users of this program can choose which of these plume models to use. Each one may have its particular merits, but a wide range of outcomes are possible from this choice.

Cox (1993) states that Zone models are “good for preliminary assessment of a problem”. They may be all that is needed for many smoke control problems. However, zone models may be invalid in complicated building spaces, which have geometries that are very different from those for which they were developed.

4.2.4 Field Models

'Field model' is the generic term used in fire engineering for computational fluid dynamics. Field models do not assume a small number of zones, but a variation in the field variables (temperature, gas concentration and so on) throughout the space of concern. (Beard 1990). A compartment is divided into thousands of small cells. Each cell has uniform conditions.

There are many partial differential equations for each cell, to describe the principles of local conservation of mass, energy and species. These require a large amount of computing power to solve the equations. Field models are also able to model transient conditions. Therefore the user is not limited to steady state conditions.

Field modelling is 'in principle exact' (Kumar 1983). 'However to incorporate complicated phenomena like turbulence, field models must use' empirical values (Kumar 1983). These empirical assumptions are needed to eliminate the 'near infinite' sets of partial differential equations required to simulate turbulent processes'. Empirical values of some complex physical processes are also used to reduce the computing power and time required for some CFD simulations.

Designers do not need to determine what the main features of the flow are with field models. For example, (Cox 1993) states that:

'Assumptions are not needed for plume entrainment that creates difficulties for the zone approach. Whether the plume is deflected by a jet of incoming air through a door and as a consequence entrains more air or perhaps rises only part way to the

ceiling before it loses its buoyancy should be determined by the solution of the equations subject to the particular boundary conditions and not by prior assumption'

Despite the 'robust' claims of some authors regarding field models (and CFD), there are doubts about the accuracy of the results. As with zone models, errors can occur with field models CFD due to the assumptions needed to complete the modelling process and variations in the methods used to solve differential equations.

A major source of error are the assumptions used for turbulence, a key feature of field models, and is 'the chief outstanding difficulty of our subject' (a comment 80 years old, but still relevant, quoted by Bradshaw, 1994). Bradshaw shows how 'it is becoming more and more probable that really reliable turbulence models are likely to be long in development'. Computational methods using large-eddy simulations eliminating the need for cruder turbulence assumptions are being developed (Hunt 1995). In a study of wind flow around a building, the results were more accurate, in comparison to wind tunnel studies, than CFD models with turbulence assumptions, but required excessive computer power and time (Hunt 1995).

Other assumptions exist, such as the heat transfer at compartment boundaries, which is mainly dependent on turbulence (Cox, 1993).

Another problem with field models are the combustion parameters. The requirements for modelling the changes in chemical species, necessary for combustion processes, have not been fully resolved, but simplified models, giving good results in comparison to experiments, have been developed (Pedersen and Magnussen 1992). Most field (CFD) models in fire engineering often describe a fire as either as steady-state uniform heat source or a growing uniform heat source (growth defined by a simple algorithm). The heat source is determined 'a priori'.

CFD models provide a more detailed model of the fire environment, but also have limitations and can be as inaccurate as zone models.

Although CFD has uncertain accuracy for large and complex geometries, it can reveal complex details and unexpected phenomena. This qualitative ability was demonstrated with the Kings Cross Fire modelling (Cox, Chitty and Kumar, 1989).

Even as a qualitative tool, care should be taken in comparing two scenarios. Any small differences in results could be due to modelling errors, rather than those which would exist in reality. These errors may even hide major differences, leading to less suitable control methods being chosen. Unexpected results need to be subject to interpretative analysis, to decide if 'plausible' (Cox 1993).

4.2.5 Validation of Models

'Validation' is a term used to describe the process by which a model is tested against experimental results or analytical solutions. It is most commonly used by CFD code developers, but can be applied to models in general.

A model is often said to be validated when it has been tested against a set of experimental data and is shown to give a known accuracy. The thoroughness and the extent to which the tests are conducted vary. Some 'validations' are exhaustive, others superficial.

Beard (1992) examined the limitations of computers for fire modelling, concluding:

To say that a model has been 'validated' implies that it has been 'proven correct'. However the concept of 'proving' a model to be 'correct' is directly contrary to scientific method. It is logically impossible for a scientific theory in general and a model in particular to be 'proven correct'. The most that can be done is to compare the prediction with experiment and observe the differences. There is no number of 'good comparisons' which may have to taken to have proved a model 'true': comparison with theory and experiment needs to go on continually.

Sensitivity analysis is sometimes used to demonstrate the credibility of a model. In this analysis the input parameters of a model are changed by varying amounts, and the resultant characteristics of the fire environment are checked to ensure that they follow known trends. It can be used as a method of checking that a model follows known phenomenological trends reasonably well.

Sensitivity analyses cannot validate a model. It can be used as part on an initial validating process, for example indicating the parameters that would need varying for full-scale validation experiments. It is best at examining the effect of uncertainties in the design (Mehta 1991).

The major problem of any validation exercise is obtaining a good range of experimental data. Few full-scale tests are conducted and only a small proportion of these with the complex geometry and arrangement of spaces that exist in real buildings. The few experiments that are carried out do not always have enough data to 'validate' a model. For zone models this is less of a problem, because fewer points of measurement are needed.

CFD validation is more difficult, because 'most experiments for benchmarking are for zone models, so measurements are less demanding' (Galea, Mawhinney, et al,1994), so few 'rigorous experiments are carried out' to meet the requirements of CFD validation. For example some full-scale experimental data by Steckler (1982) is often used as a basic 'test case' for CFD models of compartment fires.

Full-scale tests with major instrumentation in buildings with complex geometry, are not common, due to their expense. When full-scale tests have been conducted, they tend to be for commissioning not 'validation' of models. Some recent tests are providing better data, such as the NRCC pressurisation experiments (Tamura 1988), and vent and sprinkler interaction tests conducted in Ghent, Belgium (Hinkley, Hansell, Marshall and Harrison, 1992). These were major experiments used to generate data for zone models, but also provide 'validation' data.

Note that comparing models to experimental results can introduce an extra layer of uncertainty, with the processing of data, measurement, physical modelling and experimental conditions, so a model can never be 'validated' (Beard 1992). A model can only be shown to be reasonably accurate for a particular range of conditions, so error cannot be clearly defined.

Beard (1992) has summarised that there is no clear assessment of the accuracy of models. Some preliminary investigations to evaluate the differences between experiment and theory includes work by (Mawhinney, Galea, Hoffman and Patel, 1994) this shows a maximum disagreement of 44 % for temperature, and 25 % for velocities for a simple fire in a simple compartment. It is difficult to use such figures to evaluate uncertainty. These are for simple geometries, the differences for more complex geometries and different fires are uncertain.

In summary, there are no clear estimates on how much a model's predictions may vary from reality.

4.2.6 Validation and Quantification Variability in Deterministic Models

Uncertainty analysis is essential for developing credibility of any design and for defining a safe margin to account for uncertainties. Sensitivity analysis forms a part of this. There are two approaches to uncertainty analysis in CFD (Mehta 1991):

- experimental
- computational

These approaches can be used to understand the effect of variability on a fire safety engineering designs. Magnusson, Frantzich and Harada (1995) have investigated the effect of uncertainty on fire engineering designs. They modelled the fire growth and the development of hazardous conditions in a building and the time for occupants to escape from that building (modelling the time to detection, time to respond to alarms and time to travel to safety). Probability functions were applied to the modelled

values. using various probability techniques, including simple probability analysis and random Monte Carlo simulation. For more complex scenarios, event tree analysis and event tree with Monte Carlo simulations were conducted. It was a pilot study to find the best analytical method, but some general conclusions were made:

1. the relative importance of uncertainty varies from one scenario to another.
2. random (stochastic) variations dominated over knowledge uncertainty, implying that the potential for safer design by improved knowledge may be limited.
3. probabilistic risk assessment should be made to examine the potential for success of a deterministic design. This could be with an automatic computer package.

This thesis will examine the uncertainty of design models using experimental methods.

4.3 Requirements for Designers

4.3.1 The Design Stages

The basic stages in modelling for smoke control system design are:

1. The Ambient Environment
2. Fire Size and Ventilation
3. Mass Flow Rate and Other Smoke Characteristics

These form the key parameters for smoke control design. Time based variations can be introduced into the models, or the design can be steady state.

At each stage, the affects of engineering options need to be assessed, to determine their effectiveness in relation to the smoke control system performance and the integrated fire safety system performance. For example installing a sprinkler system in a building will reduce the design fire size and reduce the temperature of the products of combustion.



Not all of these parameters are needed for every system design, but additional parameters may be needed when the system design requires the addition, because they will be major parts of the system, according to design needs. For example toxicity is modelled, when occupants are likely to be exposed to smoke. These parameters are discussed in the next sections.

4.3.2 The Ambient Environment

4.3.2.1 Inside the Building

This is required in situations where stratification could occur, such as in atria; or where air movement, due to the stack effect could have a significant effect on airflow. It is rarely modelled in detail for fire safety design, because a simple internal temperature measurement is usually all that is required.

4.3.2.2.1 Air Movement due to Ventilation and Air Conditioning Systems

These can transport smoke around a building, rapidly creating hazardous conditions well away from a fire. The basic approach to preventing this is turn the systems off upon detection of a fire and provide dampers where necessary (see Chapter 12). This normally does not require modelling.

4.3.2.2 The External Ambient Environment

Smoke flow can be greatly influenced by the ambient environment. The main influences are:

TEMPERATURE

This is needed to calculate the buoyancy pressures that may drive smoke through a vent or air movement due to the stack effect. Usually the degree of accuracy needed for this is limited and only approximate calculations are required, using extreme summertime or wintertime temperatures.

WIND ENVIRONMENT

The influence of the wind on smoke control performance is critical. As shown in Chapter 2, wind pressures can prevent smoke from flowing through vents. Marchant (1984) has examined many typical building configurations in wind tunnels, to show where the wind may create positive pressures. Other researchers have examined the affect of the wind, on air movement inside a building (e.g. Kandola, 1978).

It would be extremely difficult to develop a comprehensive set of 'wind' factors for all situations. Often wind tunnel studies are required for complex buildings to find whether areas of positive pressure may form on a roof or on walls.

AIR LEAKAGE

The rate of the air leakage through the external building fabric can have a significant effect on air movements within buildings. This can effect the pressurisation differences that can be achieved and entrainment into plumes and smoke reservoirs.

The ambient environment can greatly affect smoke flow and with the exception of understanding wind effects, does not need complex modelling for successful smoke control design.

4.3.3 Fire Size and Ventilation

4.3.3.1 General

Fire size is a dominant factor in the production of smoke in a fire. It is determined by many factors, such as the ignition sources, fire load distribution, fire location (central, wall, corner, voids, height and so on), ventilation regime, radiation, heat transfer, wind environment, wind, sprinklers, window breakage and time to flashover. Each of these can involve a major area of study. To derive a fire size from these parameters would involve modelling techniques far exceeding the requirements of a smoke control system design. As shown in the previous section, many of the complex methods of modelling fire sizes would be subject to large stochastic variations.

Estimating the fire size is a complex problem, from which an simple relationship needs to be found: heat output varying with time, or more usually a simple steady state heat output.

Many sources exist for designers to derive a design fire size, such as steady-state, doubling-time, t-squared, field models, experimental data and 'hybrid' mixtures of these. The choice of fire 'type' depends on the complexity, occupation, and activities of the building and the form of fire suppression used. These can be deceptively simplistic values to use or derive. Inexperienced designers could be tempted to use fire regimes, without considering the complexity of the problem and the limitations of the fire size model. If it is not carefully derived great inaccuracies could result in a smoke control design.

A limited examination of fire sizes is made here, looking at steady state fire sizes and simple fire growth models.

4.3.3.2 Steady-State Fires

Many smoke control designs are based on steady state fires, based on statistical data of fires in buildings, for example fire sizes in sprinklered retail premises (Morgan and Chandler, 1981); hotel bedrooms (Hansell and Morgan, 1984/5), and offices (Morgan and Hansell, 1984/5).

Some fire sizes have their origins as a committee decision, for use in prescriptive codes. For example a steady-state, 5 MW, 12 m perimeter fire is used for smoke control in sprinklered retail premises. It was decided to use a 12 m perimeter as the design fire size by a panel of experts drafting a Home Office publication 'Fire Prevention Guide 1, Fire Precautions in Town Centre Redevelopment (1972)' a guide for designing shopping malls. The convective heat output was derived from assumptions regarding the peak heat output, used previously by Thomas, Hinkley, Theobald, and Simms, in a major work on smoke venting, Fire Research Technical

Paper No.7 (1963). This was later confirmed by a ‘worst case’ full-scale experimental fire, representing a store fire (Law 1995b). This found a heat peak output of 0.5 MW/m². Law (1995b) shows that the ‘standard’ peak burning rate values, for large stores, might be an over-estimate, but adds that until other evidence is provided, smoke control designers may not wish to risk using smaller fire sizes.

Morgan and Chandler (1981) examined retail fire statistics to show that only 7 % of retail fires exceed 10 m² (approximately equivalent to a 12 m perimeter). This was used to confirm that a 5 MW, 12 m perimeter fire is a suitable design basis for retail smoke control systems. There is some disagreement about the analysis of these statistics (Law 1995). Morgan and Chandler (1981) used the assumption that convective heat output is 0.5 MW/m². However, Law states that this is a high heat output value for any arrangement of cellulosic fire loads, in arrangements commonly found in shops. This can be exceeded in high rack warehouses.

Further fire tests are being conducted to provide an estimate of the expected fire sizes that could be expected in different classes of buildings, but no data has been developed to ‘challenge’ the use of the 5 MW fire for retail shops that have sprinklers installed - yet.

4.3.3.3 Fire Growth

Various models for fire growth exist. The most commonly used is the ‘t²’ fire:

$$Q = \alpha t^2$$

Equation 4.1

where:

Q

-

heat release rate

kW

t

-

time

s

α

-

growth rate coefficient

Heskestad (1972) originally proposed this, as theoretical basis for modelling fire growth the principle, in the following form:

$$Q_c = \alpha_c t^p \quad \text{Equation 4.2}$$

where: p - a power, nominally 2, for radially spreading fires in low fuel piles.
 C - convective values

Delichatsios (1976) developed this:

$$Q = \alpha (t-t_0)^2 \quad \text{Equation 4.3}$$

where: t_0 - virtual time origin, the time when a fire starts to spread from its point of origin and radial flame spread is established. This is strongly dependant on the ignition process.

A series of experiments using wood crib fires confirmed that $Q \propto t^2$ because the dominant feature of fire growth was found to be radial fire spread. Radial spread, from the point of origin is linear, and the area of fire grows as r^2 , therefore, as Q is proportional to area, r^2 is proportional to t^2 .

A set of fire experiments (Nelson, 1987) has determined values for α . It has allowed potential fire sizes to be classified, by building use and contents type as; slow, medium, fast and ultra-fast fire growth (defined by α).

More complex room geometries and fuel load arrangements have been examined experimentally and α has been shown to increase with time during the course of a fire, due to fire growth having a vertical component and compartment conditions affecting the growth rate. The result of this work is being developed into revised design information (Davidson 1996).

Other deterministic models have been developed for fire growth, some producing more reliable fire growth predictions than the t-squared model, but the latter remains the most commonly used, due to its simplicity in predicting fire.

A great difficulty in using any fire growth model is deciding when the fire starts to spread from the point of origin. Many sophisticated stochastic based models exist to model this and the later stages of a fire. This reflects the uncertainties and variability associated with fire growth.

4.3.3.4 Fire Size and Smoke Control Design

It can be seen in this limited example that smoke control designs are based on uncertain fire sizes, with uncertain growth patterns. Most are designed to a steady state condition, using a worst case fire size, so that a smoke control system capacity is designed for the largest fire size that could reasonable be expected to occur.

Fire sizes are not intended to be based on ‘doomsday’ criteria though, where an extreme set of events has occurred, to cause a very large fire size. Most fire sizes are intended to be plausibly pessimistic (Morgan 1994). In certain respects, if a design fire size has been chosen correctly, it is unlikely that a fire will occur that will exceed that size. The potential for error increases as the building form, loads and activities become more remote from those considered for the original with the design fire.

A design fire size based on a compartment being sprinklered would be exceeded if the sprinklers failed. There would be no effective control to the fire size.

4.3.4 Mass Flow Rate and Smoke Characteristics

As shown earlier, many models are available for smoke control design, but few have been rigorously compared to experimental data, so the degree of accuracy of the quantitative output is uncertain for all of them. Many have common sources of error, for example CFD and Zone models both treat fire growth as input data (Beard 1992). In quantifying smoke movement errors are hard to predict.

One example will be examined in detail in this thesis. This will be the spill plumes models for calculating the size of smoke extract or ventilation systems in shopping malls and atria. These could be subject to significant variation too. The experiments may not be able to show the degree of variation that can occur between predicted and actual smoke volumes in atria or malls, but they should be able to indicate where knowledge based variations may occur and the affect of stochastic variations.

4.4 Conclusion

This chapter has shown the source of the variations that may occur with smoke flow modelling. These variations could occur due to:

Variability:	such as wind direction, temperature and fire growth.
Knowledge uncertainty:	such as model uncertainty, or uncertain targets, such as acceptable radiation doses to people.

It has demonstrated that quantifying the variations is difficult, but computational and experimental methods exist to analysis the uncertainty.

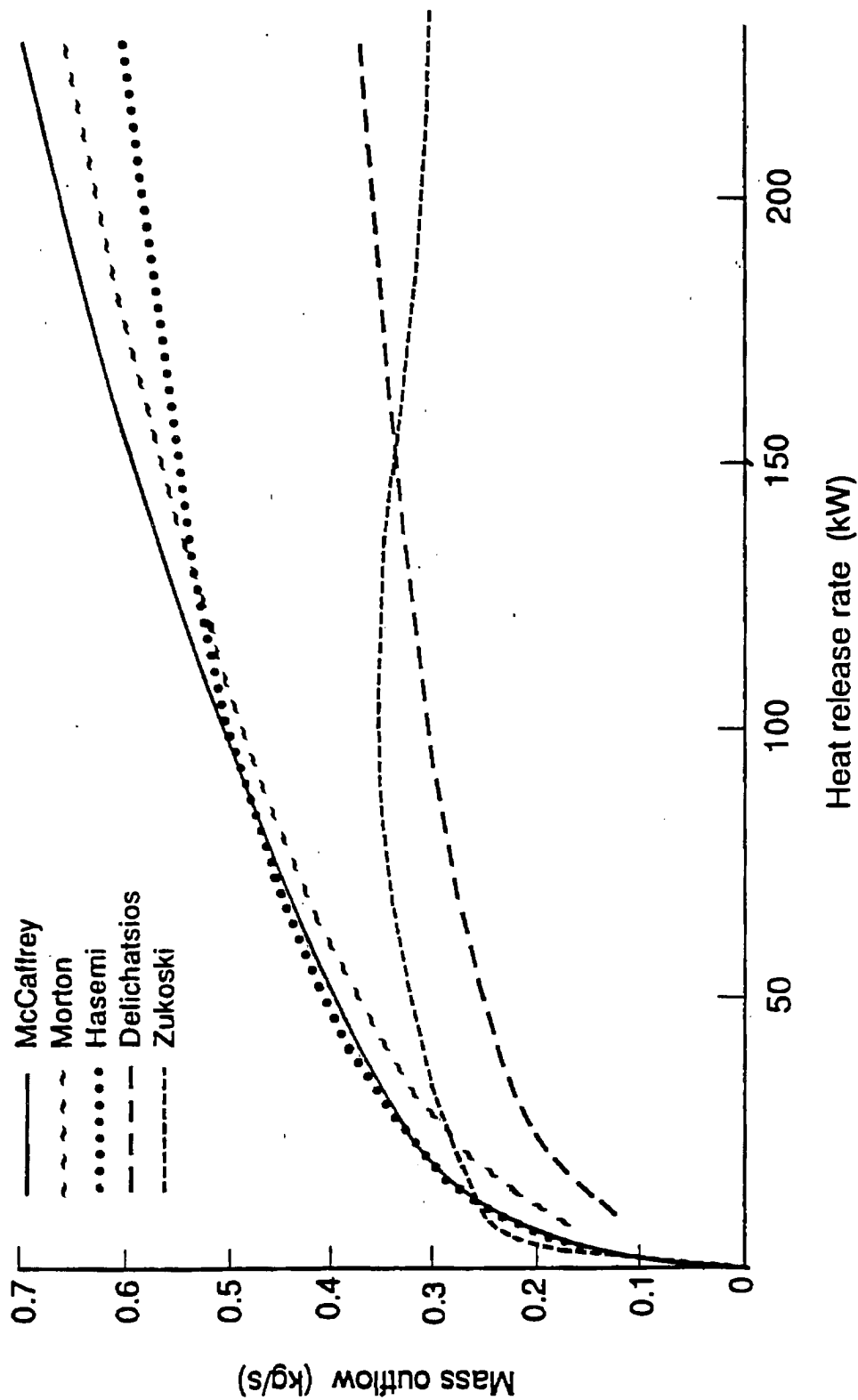


Figure 4.1 Variations in Mass Flow Rates from a Standard Room Using Five Fire Plume Expressions (Cox 1993)

Chapter 5: Smoke Flow in Atria

5.1 Introduction

In the Chapter 4, the limitations of zone models are discussed in general terms. In this chapter, zone models for flows out of compartments and spill plumes are analysed, and the currently accepted formulae identified. Areas requiring further research are identified and form the basis for the experimental work, described in Chapter 6. The implications of limitations for the application of these models is discussed in Chapter 8.

5.2 Spill Plumes in Shopping Malls and Atria

5.2.1 Sprinklered or Unsprinklered Pre-Flashover Fires

Spill plumes (also referred to as line plumes) are associated with fires in buildings, where smoke leaves one compartment and enters a larger void. They can occur in fires in a variety of building types and forms, particularly in shopping malls and atria. Interest is often centred on sprinklered or pre-flashover fires: Fuel Bed Controlled (FBC) fires. The basic structure of a spill plume from a FBC fire is shown in Figure 5.1. Smoke issues from a fire compartment, and rises up through a larger space, usually an atrium or mall. These features involve very complex flow structures. In order to develop a smoke flow model suitable for design purposes only the key parameters affecting smoke movement, such as height of rise of a plume, are used.

The design process is simplified by considering the time averaged values for smoke flow. The flow is turbulent, with large scale eddies creating fluctuating temperatures and mass flow rates, but the design of a smoke control system only requires time averaged values.

Usually, the fire source is assumed to be to be a steady-state fire. For unsprinklered fires, this is often a reasonable design assumption, as once the fire is fully developed, the heat release rate is reasonably constant. For sprinklered fires the peak heat output is the point of initial sprinkler activation. This is followed by a rapid reduction in heat output and fire area. Therefore the peak heat output is a transient phenomenon. Designing to this maximum value may be very conservative, overestimating the quantity of smoke.

The Fire Research Station has carried much research into spill plumes. A recent Fire Research Station Report, BRE Guide BR 258 “Design Approaches for Smoke Control in Atrium Buildings” (1993) presents the results of this research. This publication forms the basis for the discussion of smoke movement in atria in this thesis, although reference is made other models.

5.2.2 Post Flashover Fires

Although the flow of smoke from post flashover fires is not analysed in detail here, the limitations to the formulae are identified.

5.3 BRE Guide, BR 258

This provides guidance on smoke movement in atria for Fuel Bed Controlled fires. It is based on the results of research within the Fire Research Station, representing the current knowledge (1993) on smoke flow atria. It acknowledges that modifications to the guidance are needed, as research continues. It does not aim to be a conclusive design guide.

BR 258 provides guidance on fires in offices and to a lesser extent retail fires (more detailed information on retail fires and resultant smoke flow in shopping malls is found in BR186). The formulae are for smoke from sprinkler-controlled fires or fires

in an early period of growth, prior to flashover. The flow of smoke in atria in post flashover fire regimes is discussed only briefly.

For ease of calculation, the calculation of the mass flow rates of gases arriving at the reservoir, the z-plane, is split into three major components:

- the flow out of a compartment M_w at the w-plane
- the rotation region M_y at the y-plane
- the spill plume M_z at the z-plane

In the remainder of this section the contents of BR258 are examined, with little reference to other methods or published work, key issues and limitations that may be problematic during design and require further research are identified.

5.3.1 Formulae for Flow Out of a Compartment in BR258

The calculations for M_w (the mass flow rate out of the compartment, see Figure 5.1) presented in the main text of BR 258 (p.10) are shown over:

$$M_w = \frac{C_e P W h^{\frac{3}{2}}}{\left[W^{\frac{2}{3}} + \frac{1}{C_d} \left[\frac{C_e P}{2} \right]^{\frac{2}{3}} \right]^{\frac{3}{2}}} \quad \text{kg s}^{-1} \quad \text{Eq.5.1}$$

$$C_d = 0.65 \left[\frac{D_w + D_d}{D_w} \right]^{\frac{1}{3}} \quad \text{Eq.5.2}$$

$$D_w = \frac{1}{C_d} \left[\frac{M_w}{2W} \right]^{\frac{1}{3}} \quad \text{m} \quad \text{Eq.5.3}$$

These are empirically derived formulae. These take no account of the heat output of the fire (except the fire area).

In Appendix B of BR258, ‘A Users Guide to BRE Spill Plume Calculations’ (previously published under this title elsewhere), an alternative version of Equation 5.1 is presented:

$$M_w = \frac{2}{3} C_d^{3/2} (2g\theta_{cw}T_o)^{1/2} \frac{W\rho_o}{T_{cw}} d_w^{3/2} \kappa_M \quad \text{kgs}^{-1} \quad \text{Eq.5.4}$$

This is an earlier formula, which was based on Bernoulli's Theorem. Equation 5.1 was developed from this, but additional research has lead to some changes in format. The major difference between the two equations is that the smoke temperature and heat flux is not directly included in Equation 5.1.

Other differences are apparent, such as Equation 5.4 not having a factor for compartment height or a room geometry (C_e), but this is because the mass flow rates in these equations are defined by different variables.

In Equation 5.4, the user must know one of the mass flux dependent parameters, such as T_{cw} , to obtain a solution, which would require other calculations not present in the original document. Equation 5.1 a more approximate formula, for ease of design, developed empirically by Morgan and Hansell (Hansell (1993)).

5.3.2 Application of the Formulae for Flow Out of a Compartment in BR258

If values derived in Equation 5.1 (BR 258), for θ_{cw} , T_{cw} and C_d are used in Equation 5.4, a significantly different value for M_w is found. A comparison is shown in Table 5.1. For deeper downstands, Equation 5.1 appears to predict twice the mass flow rate. At lower values of D_d , the difference is less.

h (m)	4.0	4.4	4.7	5.0
Dd (m)	1.0	0.6	0.3	0.0
Mw eq.5.1. (kg/s)	22.0	24.5	26.2	32.2
Mw eq.5.4. (kg/s)	11.8	13.1	21.6	36.7

Q = 5 MW P = 12 m W = 16 m

h (m)	4.0	4.4	4.7	5.0
Dd (m)	1	0.6	0.3	0
Mw eq.5.1. (kg/s)	16.3	18.9	20.6	26.1
Mw eq.5.4. (kg/s)	7.2	8.0	13.2	21.5

Q=1MW P = 14 m W = 16 m

Table 5.1. Variations in M_w Using Eq.5.1. and 5.4.

In Equation 5.4, the value for C_d dominates the mass flow rate of the gases leaving the compartment. Although these equations have some different input, the values for M_w should not differ so greatly. Equation 5.4 uses a generally accepted format for flow from compartments. Equation 5.1 is intended to be a more approximate design calculation, but not with such a large margin of error.

C_d is defined in this thesis in Equation 5.2, but it is not certain the range of D_d that this applies. It is stated that for all values over 1.0 m for D_d , a nominal value of $D_d = 1.0$ should be used to calculate C_d . With no downstand, $C_d = 1.0$. This is shown in Table 5.2.

h (m)	4	4.4	4.7	4.9	4.95	5
D_d (m)	1	0.6	0.3	0.1	0.05	0
D_w (m)	0.78	0.84	0.88	0.90	0.90	1.09
Cd	0.86	0.78	0.72	0.67	0.67	1.00

Q = 5 MW, C_e = 0.337, P = 12 m, W = 16 m

h (m)	3	3.4	3.7	3.9	3.95	4
D_d (m)	1	0.6	0.3	0.1	0.05	0
D_w (m)	0.64	0.70	0.75	0.77	0.78	0.87
Cd	0.89	0.80	0.73	0.68	0.66	1.00

Q = 1 MW, C_e = 0.337, P = 14 m, W = 16 m

Table 5.2. Calculated Values of M_w and Cd for Typical Fire Sizes and Geometry

Table 5.2 shows Mw and Cd calculated from typical values of Q and varying downstand sizes. There appears to be an unrealistic jump in values of Cd. As Dd approaches 0 m, Cd tends to 0.65, with a small change in value for Dd from 0 to 50 mm. Therefore, Equation 5.2 may not accurately predict values for Cd at low values of Dd.

It is not clear whether these sets of calculations apply to adhered plumes without balconies. The diagrams accompanying the text, appear to indicate otherwise, as shown in Figure 5.2. The point of measurement for Dd, indicate that it is related to the height of rise of the plume beyond the opening, from the underside of the downstand to the underside of the balcony. Thus Equations 5.1, 5.2, and 5.3 may not be valid for the flow of gases out of a compartment. If no balcony is present, Cd may need to be redefined.

The co-efficient, C_e , is used to account for the extra entrainment, due to the geometry of the fire compartment. BR 258 research summarises the mass flow for an asymmetric plume as:

$$M = C_e P Y^{3/2} \quad \text{kgs}^{-1} \quad \text{Eq. 5.5.}$$

- $C_e = 0.188$ for large-space rooms such as auditoria, stadia, large open-plan offices, atrium floors, etc. where the ceiling is well above the fire.
- $C_e = 0.210$ for large space rooms, such as open-plan offices, where the ceiling is close to the fire.
- $C_e = 0.337$ for small-space rooms such as unit shops, cellular offices, hotel bedrooms, etc. with ventilation openings predominantly on one side of the fire (e.g. from an office window in one wall only). Most small rooms use this value.

BR 258 states that for most large-space rooms can be taken as having $C_e = 0.188$, as this produces little error, if the larger value should have been used. The choice, between $C_e = 0.21$ and 0.337 is defined as small-space rooms are ‘considered to be those in which the maximum room dimension is less than or equal to five times the diameter of the design fire size, and the incoming air can only enter from one direction’. This is stated to be an arbitrary demarcation and that further research is needed. This research would need to develop a greater range of values for C_e , in relation to room geometry and fire size, to provide a greater degree of accuracy in calculating M_w .

The co-efficient C_e is not a comprehensive factor for variations in compartment sizes, geometry and fire plume locations. It is known that other factors can influence the flow of gases within a compartment space. Some of these, such as the proximity of the plume to walls and corners can greatly reduce the mass flow rate in a plume, but these calculations reflect the worst case situations (assumed to be a large mass of

smoke). In small compartments, air entering the compartment, ‘pushes’ over the plume, creates a more turbulent environment, so increases entrainment into the plume. The co-efficient C_e accounts for this by having a higher value for small compartments.

Other factors may influence the mass flow rate, such as the compartment length and its thermal properties, but appear do not to be considered significant, as they are not included in BR 258.

5.3.3. The Rotation Entrainment

Once the gases have left the compartment, they enter a rotation region, in which gases passing under a balcony (if present), flowing horizontally, turn to rise into the atrium, starting to flow vertically. In this region a large amount of entrainment is purported to occur, doubling the mass flow rate according to Equation 5.6.

$$M_B = 2M_w \quad \text{kgs}^{-1} \quad \text{Eq. 5.6.}$$

This is an approximate relationship developed from earlier experimental work. A more detailed calculation of smoke at the y-plane appears in Appendix B of BR258;

$$M_y = \frac{2}{3} \rho_o W \alpha' \left[2g \frac{\theta_c}{T_o} \right]^{1/2} d_w^{3/2} + M_w \quad \text{kgs}^{-1} \quad \text{Eq. 5.7.}$$

The different mass flow rates predicted by these calculations are shown in Table 5.3.

h (m)	4.0	4.4	4.7	5.0
Dd (m)	1.0	0.6	0.3	0.0
Mw (kg/s) eq.5.1	22.0	24.5	26.2	32.2
My (kg/s) eq.5.6	44.0	49.0	52.5	64.6
My (kg/s) eq.5.7	66.0	71.0	74.4	85.7

Q = 5 MW Ce = 0.337 P = 12 m W = 16 m

h (m)	3.0	3.4	3.7	4.0
Dd (m)	1.0	0.6	0.3	0.0
Mw (kg/s) eq.5.1	16.3	18.9	20.6	21.8
My (kg/s) eq.5.6	32.6	39.6	41.2	52.2
My (kg/s) eq.5.7	35.3	39.4	42.2	49.6

Q = 1 MW Ce = 0.337 P = 14 m W = 16 m

Table 5.3. Variations in Calculated Mass Flow Rates at the Y-Plane

A large difference in mass flow rates can be derived from the two forms of equation, for the larger fire size, because heat flux is not a factor in Equation 5.1. The more complex formula, from Equation 5.7 would normally be expected to be the most accurate, but for the 5 MW size fire, 200 % entrainment into the plume is predicted. This is an extremely large entrainment rate in the rotation region (see Section 5.10).

It is not clear whether Equations 5.6. and 5.7 apply to adhered plumes, without any form of balcony to pass under. It appears that the ‘rotation region’ includes the turning of the gases to the underside of a balcony, the flow of gases under a balcony and the turning of the gases up into the atrium. An adhered plume only has one turning region, from the exit up into the atrium, so there are fewer ‘zones’ in which entrainment can occur, and possibly less intense turbulence (see Figure 5.3).

5.3.4. The Spill Plume

A spill plume can be adhered or free, as shown in Figure 5.1. Generally, an adhered plume forms when no balcony or similar form of obstruction is present. The spill plume is pushed back against the spill wall by the air being entrained into the plume. If a balcony or ledge is small, extending less than 2 m from the spill wall (BR258), there is insufficient free space behind the plume, to allow full entrainment to develop. The pressure of the entraining air, forces the plume is back against the spill wall.

Free plumes, which have air entrained from both sides, appear to have slightly different characteristics, described later in this chapter.

Calculations for the mass flow rate for the plume as it rises up into the atrium, are not present in the main text. However, there are graphs for typical mass flow rates from 1 MW and 6 MW fires, from rooms of typical geometry (4 m high from slab to slab). Further graphs can be found in BR 186 'Design Principles for Smoke Ventilation in Enclosed Shopping Centres' (Morgan and Gardner, 1990), although these have a different derivation and are developed from a different geometry.

In the Appendix of BR 258, there is a calculation method (see Appendix), developed from previous work, published in a BRE Current Paper CP48/75 (Morgan and Marshall 1975), which was based on research by Lee and Emmons (1961). This uses the concept that the smoke emerging at the w-plane and passing through the y-plane can be described by a characteristic non-dimensional number, which can be used in a series of calculations for the mass flow rate. A similar method for calculating adhered or free plumes is used.

Table 5.4 demonstrates the increase in mass flow rate for a typical height of rise (z) for an adhered plume. The point of measurement for z is shown in Figure 5.7.

h (m)	4.0	4.4	4.7	5.0
Dd (m)	1	0.6	0.3	0
Mz (kg/s);5.0 MW	120.3	127.1	130.8	141.5

h (m)	3	3.4	3.7	4
Dd (m)	1	0.6	0.3	0
Mz (kg/s);1.0 MW	70.4	73.7	75.9	81.9

Table 5.4 Flow at Z-Plane: Height of Rise of Gases; 9m
(e.g. a 4-storey atrium with smoke reservoir above)

5.3.5. Heat Loss Assumptions in the Calculations

In the calculations in Section 5.3, Q is the convective heat release rate. This is usually taken to be 60 to 80% of the heat release rate from a fire. Heat loss is an uncertain factor in smoke control (Hansell 1993) and more research is needed. The large range in differences for heat loss estimates, even without the influence of sprinklers, have a significant effect on plume buoyancy and other factors, such as time to flashover.

Sprinklers cool smoke, but no further reduction in Q is made in the equations, within the fire compartment for this. BR 258 recommends a further reduction to 55% to Q, for cooling by sprinklers in the atrium. It also states that other methods can be used to determine the affect of cooling inside and outside the compartment.

5.3.6. Limitations to Calculations Identified in Text of BR258

Within the text various limitations or assumptions to the calculations are identified:

1. It covers Fuel Bed Controlled fires only.
2. It has one ceiling smoke zone; a combined ceiling jet and hot layer, for which the maximum temperature must be below 350°C. It does not account for the effect of obstructions, compartment lengths, inclined ceilings or growing fires.
3. The air velocity of incoming air needs to be low.
4. The classification of rooms according to their dimension and fire size needs to be developed in more detail.
5. It does not account for the effect of sprinklers on the flow of gases from compartments, apart from reducing the value of the convective heat flux in the smoke. The effects of sprinkler cooling could be underestimated and smoke could lose its buoyancy, either smoke logging the fire compartment or the atrium. In examination of the properties of smoke from fires in large single storey buildings it can be assumed that the maximum gas temperature is close to the temperature at which the sprinkler heads operate.
6. Heat losses in the atrium are not known, and are not included in the calculations. Thus when temperature above ambient, θ , is less than 15°C it is likely that extra cooling will lower the temperature, so the gas will lose its buoyancy, and may stratify at a lower level in the atrium or create a deeper smoke layer than would be predicted normally.
7. The effects of air movement (due to external wind or ambient air movement) in atria are not fully understood. It has been shown that smoke is only a few degrees above ambient is unstable, so that even small air movements can destabilise the smoke layer. BR 258 recommends more research on the problem of the effect of air movement on cool smoke in reservoirs.

5.3.7. Summary of Design Issues in BR 258 to be Examined

It can be concluded that certain issues within BR 258 need resolving:

1. The values for M_w from different calculation methods are significantly different.
2. The values for C_e are not detailed enough. Just 3 values cover a wide range of possible geometry, for which the definitions are uncertain and based on assumptions.
3. The methods to calculate C_d for small downstands require clarification, especially when no balcony is present.
4. When no balcony is present, the entrainment rate in the rotation region may not be as high as when a balcony is present.
5. Line plumes need to be examined to find when they become fully developed and demonstrating Gaussian distribution.
6. The methods for calculating heat loss from the smoke are ambiguous. A clearer set of values is required to express the relationship between the heat released by the fire and the heat flux in the plume, ceiling jet and line plume. The effect of sprinklers on smoke flow and heat flux is not clear.

This list represents a summary of the issues that a designer examining BR 258 may encounter. Information and methods exists outside BR 258, to overcome some these problems. However, some issues require further investigation. Some are the objectives of current Fire Research Station work, and are discussed only briefly in the next section.

5.4. Theories for Smoke Flow in Atria

5.4.1. Introduction

BR 258 was published as a results of research within the Fire Research Station and other related work. It combines two major sets of theories, that for flows out of compartments and line plume theory. Alternative models for flow out of compartments exist, some significantly different from those in BR 258.

Only steady state theory is examined here, the effects of fire growth are not be considered, unless particular limitations with steady state models are identified.

5.4.2. Atrium and Mall Smoke Flow, Identifying the Problem

With the development of shopping malls in the 1960's, there was concern about smoke hazards in these buildings, calculation methods were needed to provide engineered smoke control systems. This lead to large-scale tests and reduced-scale model tests, being conducted by the Fire Research Station, to examine smoke flow in malls. Full scale tests such as in a disused railway tunnel in Glasgow (Heselden and Hinkley 1970). These demonstrated the extent of the problem of smoke production in large enclosed spaces such as shopping malls, particularly that relatively small fires can create large volumes of smoke, in relatively large building spaces and that inefficiently designed vent systems are of little use.

Further studies by Heselden et al (1972), found that there were main regions of entrainment into the smoke occurred in:

- flames and hot gases
- the passage of hot gases into the mall from the compartment
- flows along the mall and at the entry of the gases into the vent shaft.

Heselden et al (1972) found that with no balcony at the exit of a fire compartment, when no fascia (downstand) was present, the average temperature drop was approximately 15%; when a fascia board was present, it was about 45%. Also unexpected entrainment occurred along the mall (under a ceiling), possibly due to the flow being disturbed. The entrainment at the vent shaft was due to plug holing. Tentative theories on the smoke flow were produced from these results.

Developments in the understanding of the behaviour of buoyant fluids (smoke and hot gases), as a discipline of fluid mechanics, were already in progress, for plumes and for flows under ceilings and from compartments. Morgan, Marshall, Hansell and others at the Fire Research Station, used this, and the work on smoke flow in malls, as the basis of an 1/10 scale experimental research programme, to develop calculations for shopping mall and later atria smoke control systems.

Larger scale tests have rarely been conducted. Hansell (1993) conducted a number of detailed tests at the Fire Research Station. A few other full-scale tests have been conducted, but more to demonstrate the effectiveness of smoke venting and extraction, and as a commissioning method. These include tests at Brussels Airport (Morgan et al 1994) and Ghent in 1988. These demonstrated that the overall outcome of the calculations appeared to be correct, but not the detail within. Nor is it known how many variations to the theory cancelled each other out, and whether these would hold with a different set of conditions.

5.5. General Models for Flow Out of Compartments

5.5.1 Introduction

Research into compartment fires and smoke flows has been conducted, at varying levels of detail. Many formulae have been developed. Those that quantify the flow of gases from a compartment are of primary interest in this work. More detailed formulae for parts of the flow within compartments are examined.

Models exist for different ventilation regimes. Fuel Bed Controlled (FBC) regimes are the primary interest here, although aspects of Ventilation Controlled (VC) and Fully Involved Large Openings (FILO) regimes are discussed later in the chapter.

5.5.2. Flow of Gases from Fuel Bed Controlled Fires

In general, the formulae for the flow of smoke out of a compartment are in a form derived from basic theory of fluid flow and the gas laws, refined by empirical data.

The flow of gases from a compartment with a Fuel Bed Controlled fire, is determined mainly by the fire size, plume, ceiling jet and the restriction to the flow from the compartment. This restriction is usually expressed as C_d , although it could be incorporated into a constant such as 'k', in Equation 5.12.

The formulae presented in this section (5.5.2) have been developed to show the net flow from a compartment. They represent the product of all of the smoke movement and entrainment inside and up to the exit of the compartment. Any factors that have little significant effect on the mass flow rate are ignored.

Thomas et al (1963) examined the flow of hot gases through roof vents, for industrial buildings. For smaller fires (Fuel Bed Controlled regimes) Equation 5.10 was

developed to calculate the flow through a vertical opening, under a screen for a horizontal roof vent. This equation is based on Bernoulli's Theorem.

$$M_w = \frac{2}{3} \rho_0 C_d D_w^{3/2} (2g\theta_c T_0)^{1/2} / (T_0 + \theta_c) \quad \text{kgs}^{-1} \quad \text{Eq. 5.10}$$

Prahl and Emmons (1975), Rockett (1976) and others have developed alternative theories for the flow into and out of compartments for Fuel Bed Controlled fires. Equation 5.11 shows a general form by Thomas (1992a) from the work by Prahl and Emmons:

$$M_w = \frac{2}{3} \rho_0 C_d (T_0 / T) \sqrt{2g\theta} / TD_w \quad \text{kgs}^{-1} \quad \text{Eq.5.11}$$

Thomas (1992a) used this, in conjunction with other work on flows out of compartments, and theories on line plumes to develop the following relationships, Equation 5.12 and 5.13:

$$M_w = KW(H\rho_0)^{-1} \left[\frac{gQ}{\rho_0 c_p T_0} \right]^{1/3} \quad \text{kgs}^{-1} \quad \text{Eq.5.12}$$

$$K = 0.155 \left(\theta / T_0 \right)^{1/3} \quad \text{kgs}^{-1} \quad \text{Eq.5.13}$$

This value for K is based on statistical analysis of the results. K is reasonably constant, within limited temperature ranges, but needs to be examined for application to flows over different geometries, at different temperatures. The relationship with line plumes is not fully developed by Thomas (1992). This equation is for all widths of fire compartment, being a two-dimensional theory.

developed to calculate the flow through a vertical opening, under a screen for a horizontal roof vent. This equation is based on Bernoulli's Theorem.

$$M_w = \frac{2}{3} C_d W D_w^{3/2} (2g\theta_c / T_0)^{1/2} \quad \text{kgs}^{-1} \quad \text{Eq. 5.10}$$

Prahl and Emmons (1975), Rockett (1976) and others have developed alternative theories for the flow into and out of compartments for Fuel Bed Controlled fires. Equation 5.11 shows a general form by Thomas (1992a) from the work by Prahl and Emmons:

$$M_w = \frac{2}{3} \rho_0 C_d (T_0 / T) \sqrt{2g\theta} / T D_w \quad \text{kgs}^{-1} \quad \text{Eq.5.11}$$

Thomas (1992a) used this, in conjunction with other work on flows out of compartments, and theories on line plumes to develop the following relationships, Equation 5.12 and 5.13:

$$M_w = KW(H\rho_0)^{-1} \left[\frac{gQ}{\rho_0 c_p T_0} \right]^{1/3} \quad \text{kgs}^{-1} \quad \text{Eq.5.12}$$

$$K = 0.155 \left(\theta / T_0 \right)^{1/3} \quad \text{kgs}^{-1} \quad \text{Eq.5.13}$$

This value for K is based on statistical analysis of the results. K is reasonably constant, within limited temperature ranges, but needs to be examined for application to flows over different geometries, at different temperatures. The relationship with line plumes is not fully developed by Thomas (1992). This equation is for all widths of fire compartment, being a two-dimensional theory.

Morgan (1986), states that Equation 5.11, is more suitable for flows from a narrow doorway. This paper presents the theoretical basis for Equation 5.4. It concluded that Equations 5.1 and 5.4 should be used for wide openings.

Morgan and Hansell (1987) presented a version of Equation 5.4 suitable for design purposes. This developed into Equation 5.1, as a result of experimental and theoretical work by the authors and others at the Fire Research Station.

Law (1989) reanalysed the data from Morgan et al. She notes that Morgan and Hansell (1987) did not consider certain compartment effects in analysis of their data. Law developed equation 5.14, as an empirical relationship for flows from narrow openings in compartments (such as doorways):

$$M_w = K (Qw^2)^{1/3}H$$

kgs⁻¹

Eq.5.14

K varies from 0.041 to 0.092 according to the location of the fire and the geometry of the compartment, as shown in Table 5.5.

Location	Flush With Floor	Raised 300 Mm
Centre of compartment	0.57	0.52
Middle of back wall of compartment	0.50	0.48
Back corner of the compartment	0.44	0.47

Table 5.5 The Effect on K of Varying the Fire Location and Height of Base of Flame (from Law (1989) Q = 63 h = 1.83 w = 0.74 b = 0.35

Work at the FRS by Morgan, Hansell, Marshall and others since the 1970's, has refined the calculations for Mw. Certain aspects of these calculations are discussed

in later sections. Equations 5.1 and 5.4 are the most recent versions. Equation 5.1 was developed from Equation 5.4, based on the results of a series of full-scale experiments. Certain approximations have been used to reduce the complexity of the calculation, for ease of use in engineering design. Some significant errors are introduced at the limits of these approximations. In particular $T\theta^{-1/2}$ has been reduced to 38.7, which is the true value when $\theta \cong 105^\circ \text{ C}$. At low temperatures the error can be up to 25% ($\theta \cong 50^\circ \text{ C}$). At the limiting maximum temperature the error is approximately 12.5% ($\theta \cong 250^\circ \text{ C}$).

Various formulae exist for flows from compartments, but applicable to different compartment geometries. Equations 5.1 and 5.4 are for wide compartments, other formulae shown are for narrow compartments. The formulae developed by Law (1986) could be developed for simpler mass flow calculations for wide compartments. Equations 5.1, 5.12 and 5.14 are engineering relationships, suitable for ease of design, as they do not contain interdependent variables. Some of the major variables for the flow from compartments are in agreement, but forms of presentation and 'Ce', 'Cd' and 'k' factors need resolving.

5.6 Coefficient of Discharge for Flow Out of a Compartment

The flow of smoke from a compartment is controlled by the geometry of its exit. Within a fire compartment, the potential exists for a certain quantity of smoke to be produced. A clear opening, when no downstand is present, produces limited restrictions to the flow. Obstructions create back pressures, reducing the quantity of smoke produced in the compartment. Cd defines the effect of this restriction in equations. When there are no restrictions to the flow $Cd = 1.0$, when restrictions occur, $Cd < 1.0$.

Thomas et al (1963) recognised that C_d can vary, from near 1.0 for certain velocity profiles normal to an orifice; to near 0, when the flow is tangential to an orifice and that conventionally the value is 0.6. They stated that values for C_d must be clarified for these flows. Hansell (1992) summarised the values of C_d (all empirical values) from previous research, see Table 5.6.

Author(s) of Research	Value	Comment
Steckler	0.75	Doorway
Prahl and Emmons ¹	0.77	No density gradient
Quintiere and DenBraven	0.75	Varies with width of doorway
Shaw	0.65	Very low θ (4 - 10 °C) through doorway
Brown and Solvason	0.6	Low θ (20 - 30 °C) through doorway
Heskestad	0.64	High θ , doorway
Nakaya	0.68	High θ , doorway, small density gradient
Hansell, Morgan, Marshall	0.6-1.0	Wide compartments, high θ , varies with D_d

Table 5.6 Values for C_d

In examining the engineering relationships for the flow of smoke out of compartments, Thomas (1992a) does not suggest a value for C_d and it does not appear in the formulae (shown here as Equation 5.12). It may be inferred that C_d has insignificant variations, and is included as a factor within ‘ k ’.

More complex formulae for C_d exist, expressing the more complex processes that restrict flows from compartments. Prahl and Emmons (1975) defined C_d for flows out of compartments as:

$$C_d = \frac{M_w}{0.943 \left(\frac{\rho}{\rho_a} \left(1 - \frac{\rho}{\rho_a} \right) \right)^{1/2} D_w^{3/2}} \quad \text{Eq.5.16}$$

This is essentially a rearrangement of Equation 5.11.

They used kerosene represent a hot layer and water as the ambient air, to model buoyant flows from a compartment with a fixed value for ρ/ρ_a (0.79). C_d for inflows and outflows were found to be 0.68. This was for a narrow compartment, with a downstand equivalent to $H/6$ (approximately 0.5 m at full scale). The relationship to ρ/ρ_a was calculated mathematically. This paper also develops a theoretical understanding of how C_d varies with temperature, is not tested experimentally.

Morgan (1986) developed a theoretical analysis of the horizontal flow of gases towards an opening. In the examination of flows from compartments $M_w \propto C_d^{2/3}$, (as is D_w , see Equation 5.4) as the coefficient of discharge is directly related to the depth of smoke. Here, it was assumed that $C_d = 0.6$, for deep downstands and that $C_d = 1.0$, where no downstand is present.

In Morgan's and Hansell's (1987) paper, presented design calculations for smoke control purposes. It had a different notation for C_d ; γ , although this was presented differently within the calculations, it is still based on the common values of 0.6 and 1.0 for C_d . It was recognised that further research was needed.

Hansell (1992) conducted an experimental study into the coefficient of discharge for the flow out of compartments. He argues that C_d is not just determined by the vena contracta at the compartment exit, but also by the static pressure generated in the

plume, which in turn is influenced by D_d . An approximate empirical relationship (full-scale only) is shown in Equation 5.17.

$$C_d = 0.55 + 0.2D_d \quad \text{Eq. 5.17}$$

This produces an approximate average for C_d of 0.65. C_d varies from 0.85 to 0.6, with downstands present ($D_d > 0$) and to 0.6 with no downstand ($D_d = 0$) present.

Hansell (1993) states that previous theories (including Morgan 1986) had assumed that flows from compartments entered a mass sink, where no further resistance to flow was offered, so that the vena contracta is the only major influence on C_d . Hansell states that this ignores the pressure created within the plume, either as it reaches its terminal velocity or as it meets an obstruction, usually a balcony. A plume usually reaches terminal velocity, when it has risen approximately 1.0 m. A major influence on C_d is the height from the bottom of a downstand to the underside of a balcony or to the point of terminal velocity. This is the point of measurement for D_d in Equation 5.2, for which D_d has a nominal maximum value of 1.0.

In Hansell's experiments, Equation 5.17 was not found to apply to flows where no downstand is present. It was assumed that in this case $C_d = 1.0$, as confirmed by Marshall and Harrison (1992). Their work also demonstrated that C_d is not affected by the height of rise, even if the underside of the smoke reservoir is brought down to the same level as the balcony. This does not mean that the flow of smoke above the top of a balcony or opening (if no balcony present) has no effect on the flow out of a compartment, as a spill still forms, but within the smoke reservoir. Hansell (1992) also found C_d to be greater than 1.0 in some experiments, caused by a particular geometry enhancing the flow, indicating that unforeseen mechanisms are occurring.

The range of values of D_d used were limited to 0.5 m, 1.0 m and 1.5 m, representing 17 %, 34 % and 50 % of the internal compartment height. There is no indication of a 'transition' depth in which C_d falls from 1.0 to the value determined by Equation 5.2.

Little other research into the values of C_d , for the flow of compartments has been conducted. The effect of small downstands on the flow of gases from compartments needs to be investigated to discover if their effect is significant.

5.7 Flow Within Compartments

Variations in geometry fire size and location can effect the production of smoke within a compartment and the resultant flow through the exit. The following sections outline some of these, with a more detailed look at the effect of varying the compartment length.

5.8 Plumes in Compartments

Rouse, Yih and Humphries (1952) developed the concept of a plume acting as if it came from a point source. Thomas et al (1963) defined the mass flow rate for smoke from fires as follows:

SMALL FIRES

$$M_y = 0.153 \rho_y (Q_{cg} / \rho_y c T_0)^{1/3} (h + r_g - d)^{5/3} \quad \text{kgs}^{-1} \quad \text{Eq.5.18}$$

where $r_g \simeq 1.5 A_f^{1/2}$ based on a 15° angle to plume. $A_f^{1/2}$ (see Figure 5.4) represents the distance of the point source below the fire (the 'virtual source').

Equation 5.18 is only valid at plume heights several times greater than $A_f^{1/2}$ where $\rho_c \simeq \rho_o$, so does not apply to large area fires (Thomas et al 1963, Hinkley 1986).

A large fire equation was developed for situations where $Af^{1/2} > (h-d)/2$ and $hf > (h - d)$ (Thomas et al 1963, Hinkley 1986). The last condition implying that with large fires, flames extend into the hot layer.

LARGE FIRES

$$M_y = 0.096 P (h-d)^{3/2} \rho_0 (g\rho/\rho_0) \quad \text{kgs}^{-1} \quad \text{Eq.5.19}$$

Equation 5.19 reduces to a simple engineering relationship (see Figure 5.4), from Hinkley (1986).

$$M_y = 0.188P (h-d)^{3/2} \quad \text{kgs}^{-1} \quad \text{Eq. 5.20}$$

‘h-d’ is often expressed as ‘y’, the height of rise of the plume.

Hinkley (1986) analysed experimental data from ‘large’ and ‘small’ fires, and found that Equation 5.20, is suitable for both fire ‘sizes’, down to fire diameters as small as 1/10 the height of rise. He states that there is little theoretical justification for this experimental result. At smaller diameters no empirical data is available to justify the use of Equation 5.20.

Hansell (1993) replaced the fixed value coefficient, 0.188, in Equation 5.20, with the variable coefficient, C_e , the values of which are described in Section 5.3.2. The development of the C_e factor is as follows:

$$C_e = 0.188C_\omega C_s C_j \quad \text{Eq.5.21}$$

where:

C_ω is an empirical tilt correction factor, developed by Zukoski et al (1981) and Quintiere (1984) to account for the aerodynamic disturbance of a plume in compartments. The smaller a compartment, the less space is available for entraining air to circulate around a plume. If incoming air is dominant from one direction, then this cause a plume to tilt. The smaller the compartment, the greater the tilt and the greater the entrainment.

C_s is an empirical correction factor for the proximity of a plume to a wall. If close enough, the plume can be pushed up against a wall, so less air is entrained, even less air in a corner. Zukoski (1981) developed values for C_s .

C_j is a factor representing additional entrainment into a ceiling jet. This can range from 20 - 40 % to the mass flow rate, but is limited to small rooms, such as small offices and hotel bedrooms. The upper (worst case) value of entrainment has been used to develop a coefficient of 1.4, for small rooms. For large rooms this additional entrainment is considered to be irrelevant. This factor does not account for the variable of compartment length. The potential effects of ceiling jets and compartment length are discussed in Section 5.9.

The values of the coefficients assumed by Hansell (1993) in C_e are:

C_ω -	Very large spaces (high ceilings)	e.g. exhibition halls	$C_\omega = 1.1$
	Very large space rooms	e.g. open plan offices	$C_\omega = 1.28$
	Smaller rooms with a single opening	e.g. hotel bedroom	$C_\omega = 1.49$
C_s -	Fire away from walls		$C_s = 1.0$
	Fire next to a wall		$C_s = 0.75$
	Fire in a corner		$C_s = 0.5$
C_j -	Small room	e.g. hotel room	$C_j = 1.4$
	Larger rooms	e.g open plan office	$C_j = 1.0$

These are combined in Equation 5.21 to derive C_e as shown in Table 5.7.

Space Volume	C_w	C_s	C_j	C_e
Very Large	1.00	1.00	1.00	0.188
Very Large, Low Ceiling	1.10	1.00	1.10	0.210
Smaller	1.28	1.00	1.40	0.337

Table 5.7 Derivation of Values for C_e

These represent the worst case values for the production of smoke in a compartment, for all possible fires. The value of C_s is taken to be 1.0, in all cases, as this gives the highest mass flow rate. In situations where the temperature rise is critical, the value of C_e causes this to be underestimated. If a smoke control system is to be designed, with critical temperatures and smoke layer height, then it is possible that a range of values for C_e need to be used. These would provide a sensitivity analysis of the range of temperatures and mass flow rates of smoke that could leave a compartment.

The value of C_e 0.337 was found to be in agreement, by +/- 15 %, with reduced scale experiments (Hansell 1993), with simple compartment geometry. A range of values of C_e was not examined. As stated in BR258, further investigation of these values is needed (see Section 5.3.2). Each of the values, C_w , C_s and C_j represent a large simplification of the complexities of fire and smoke dynamics in compartments. It is possible that significant errors could be introduced to the final value of M_w . It should be noted that only Equations 5.1 (Hansell and Morgan) and 5.14 (Law; 1989) consider the details of internal compartment geometry, beyond the height and width, as significant.

The coefficient, C_j represents the effects of ceiling jets on the entrainment in a compartment. These are discussed in the next section.

5.9 Ceiling Jets

In the Glasgow tunnel experiments (Heselden et al 1972), unexpectedly high entrainment was found in the ceiling jet and hot layer.

Ceiling jets have been studied in much detail, to understand fire and smoke dynamics for compartment fires, and smoke flow and its relation to detector and sprinkler activation. There has been much research in America, to develop complex models for smoke spread and detection in compartmented buildings, such as apartment blocks and hotels. The full detail of these is beyond the scope of this work, but some general concepts can be used to understand how the mass flow from compartments may vary due to the influence of the ceiling jet.

C_j is a factor representing additional entrainment into a ceiling jet. Additional entrainment of 20 - 40 % for small rooms, such as small offices and hotel bedrooms, has been derived by Jaluria (1988). This value is due to wall effects, see Figure 5.5.

C_j includes a significant amount of wall entrainment. Jaluria (1988), shows that as the height of rise increases, the wall entrainment is less significant. In the discussion of entrainment within a compartment, he considers that only the wall flow and the plume are significant factors determining the mass flow rate in a room. The effect of the wall jets varies, depending on whether it is buoyant enough to rise and mix with the hot layer, and what proportion is much less buoyant and descends to mix with the cooler lower layer. This unpredictable factor produces a range of 25 to 67 % additional entrainment within a compartment, due to wall entrainment, for a small compartment. Hansell interprets Jaluria's figures as 20 to 40 %. If an error, C_j could

have a worst case value of approximately 1.7, rather than 1.4 in stated by Hansell (1993). C_e could have a large resultant value of 4.1 for small compartments. Using this worst case value could lead to over estimates of mass flow rates. Jaluria’s work demonstrates that C_j can vary for compartment area and height relative to plume size. More research is needed to determine how a variable C_j factor can be developed to account for these relative compartment sizes.

The effect of wall plumes is considered irrelevant for larger compartments, as it is insignificant compared to the mass flow of the plume. This factor does not evaluate variations to the additional entrainment that may occur due to varying the length of the ceiling jet or hot layer. The role of ceiling jets needs to be examined to determine if significant additional entrainment occurs due to increased compartment length.

The basic entrainment process is caused by turbulent mixing. Work by Ellison and Turner (1959) found that the rate of mixing (hence entrainment rate) between layers is determined by the degree of stratification between the layers and the turbulence. Strongly stratified layers have little mixing between layers. The greater the temperature difference, the greater the degree of stratification, so less mixing occurs. Increased turbulence reduces the degree of stratification, so mixing increases. The strength of stratification is represented by the non-dimensional number: Richardson’s number, Ri . Thomas et al (1963) version is shown below, Equation 5.22.

$$Ri = g d_b \theta_c / T_c u_1^2$$

Equation 5.22

where:

g	-	acceleration due to gravity	ms^{-2}
d_b	-	depth of smoke	m
θ_c	-	maximum temperature rise of the smoke	$^{\circ}C$
T_c	-	absolute temperature rise of the smoke	K
u_1	-	maximum velocity of the ceiling jet	ms^{-1}

This is the basic formula for Ri , suitable for the needs of a zone model.

The mixing between layers (and resultant entrainment), is negligible when Ri is greater than approximately 0.8. As Ri approaches zero, the entrainment rate is assumed to be constant, equal to that of a wall plume (0.07 - 0.085) (Alpert 1971).

Two generalisations can be made:

- as ceiling jet velocity decreases, Ri increases, so entrainment is negligible, such as in a smoke reservoir. Conversely higher velocity ceiling jets would be expected to have a high degree of entrainment. An early assessment of this is by Thomas et al (1963), who reports that experiments on smoke reservoirs conducted by General Motors, found considerable mixing for large flat ceilings with much radial flow. These reservoirs had unusually high velocities, so had low Ri values, confirming the conditions for mixing.
- as the ceiling jet temperature decreases, Ri decreases, so entrainment increases, when $Ri < 0.8$. Entrainment decreases as Ri approaches 0.8.

More detailed analyses of ceiling jets, experimentally and theoretically, have found that entrainment usually causes rapid velocity and temperature reduction, and a stable jet forms, which has little mixing with the layer below. Research by Alpert (1972 and 1974) provides a good summary of the stages of a plume meeting a ceiling, and the developing ceiling jet, refer to Figure 5.6.

Alpert (1971, 1974) developed an empirical model of ceiling jet, using basic theoretical principles. The following conclusions were developed for ceiling jets, when the fire plume does not reach the ceiling:

- the ceiling jet is not ordinarily affected by friction or heat transfer out to distances up to 2 to 5 times the height of rise of the fire plume.

- heat transfer rates to the ceiling at 1 to 2 times the height of rise of the plume are an order of magnitude less than at the edge of the turning zone.
- ceiling jets increase in thickness, from $1/20^{\text{th}}$ of the height of rise, at the edge of the turning zone, to $1/10^{\text{th}}$ the height of rise, at 1 to 2 times the height of rise from the plume.

The turning zone (also known as the stagnation region or impingement zone), lies approximately within the boundaries of the plume, prior to reaching ceiling level. The stagnation zone has a radius equal to approximately 20 % of the plume height. The ceiling jet zone is the flow outside the turning zone. In summary, a ceiling jet reaches a fully developed condition at a radius of one to two times the height of rise and remains stable, with little additional entrainment, for radii up to five times the height, when the effects of friction and heat loss begin to dominate. Alpert's research examined unconfined ceiling jets, to avoid wall jet effects. If applied to a jet in a long compartment, and no wall effects were to occur, the radii would be extended, because the length of the jet front would be constant (the width of the compartment).

Heskestad and Delichatsios (1978) developed an empirical formula (following research by Alpert and from data by Thomas 1955) for unobstructed jets (i.e. no compartment walls) outside the turning zone. This is shown in Equation 5.23 below:

$$u_1 / \theta_1^{1/2} = k(r/H)^{-0.63} \quad \text{Eq.5.23}$$

where:

u_1 = maximum velocity in the ceiling jet.

ΔT_1 = maximum temperature difference in the ceiling jet

k = a factor of varying value, 0.5 to 0.7; further research is needed to find how k varies with different compartment geometry.

At large jet radii, where heat losses start to dominate, the formula may be invalid.

This formula can be rearranged as shown in Equation 5.24:

$$u_1 = k \theta_1^{1/2} r^{-0.63} H^{0.63} \quad \text{Eq.5.24}$$

So that, the velocity is related to the temperature difference, radial distance from the plume and height of compartment as follows:

$$u_1 \propto \theta^{0.5}$$

$$u_1 \propto r^{-0.63}$$

As the ceiling jet flows along the ceiling, the temperature can either remain constant or fall, so the velocity remains constant or falls too, though at a slower rate. With increasing radial distance, velocity falls, though at a slower rate.

Many researchers have examined other factors influencing ceiling jets. These are:

- The surrounding walls confine compartment ceiling jets. The flow remains radial close to the plume turning zone, but beyond this area it is channelled by the walls, to form a parallel flow. The jet changes at a slower rate than with unconfined flow radial flow (Evans 1988). Formula have been developed, but have a complexity that is beyond the requirements for a design for the flow out of a compartment.
- If the ceiling jet is obstructed, then warm gases will accumulate in the upper levels of a compartment. The hot layer can completely submerge the ceiling jet. The temperatures in the ceiling jet are then greater, as air is entrained from the hot layer, rather than the cooler ambient air (Evans 1988). Formula have been developed to model this situation, but are beyond the scope of this work.
- Van de Leur, Kleijn, and Hoogendoorn (1989) conducted a CFD study to investigate the parameters that effect the stratification of smoke flow, down corridor ceilings of different lengths. They attempted to find what would cause the

loss of stratification, beyond the 'crude switch from fully stratified to mixed conditions presented by the $Ri (= 0.8)$ criterion'. They found that, in common with other assumptions and theories, strong external disturbances are needed to cause the break up of stratification (hence large scale entrainment). Heat loss in long corridors, due to radiation and conductive losses caused reductions in temperature, resulting in reduced velocities and the smoke layer thickened, but the mass flow rate was not significantly different than to shorter corridors.

- McCaffrey and Quintiere (1975) found complex layers of positive and negative velocities from a compartment. When no downstand is present, a simple ceiling jet forms. With downstands present, layers of recirculation form. As the downstand depth increases, so the number and complexity of recirculation layers increases. This could be an additional factor influencing the value of C_d , for equations for flows out of compartments. Reducing the opening width also increased the three-dimensional complexity of the flow. These complex flows occur in full and reduced scale models.
- The angle of slope of a ceiling, greater than 0.5° and the buoyancy force can overcome frictional drag in a ceiling, resulting in faster velocities, thus entrainment increases (Chan, Zukowski and Kubota, 1993). Entrainment is only negligible under ceilings with slopes less than a couple of degrees ($\cong 5^\circ$).
- The effect of beams, and other obstructions on ceiling jets has been the subject recent research, in relation to models of early fire growth smoke detection. Koslowski and Motevalli (1994) have shown that the main effect is a decrease in temperature and increase in velocity. This applies to beams either across or parallel to the flow. There is no additional entrainment. These beams are equivalent to shallow downstands and there may be some similar effects that can be observed.
- Ambient air movement and complex flow patterns can locally decrease Ri values, so that localised high entrainment can occur. This was, in part, the cause of the

unexpectedly high entrainment in the hot layer and ceiling jet, in the Glasgow tunnel fire experiments.

For large compartments, heat loss is a dominant factor upon the potential flow from a compartment. The prediction for heat transfer from ceiling jets is limited (Atkinson and Drysdale 1992, Woodburn 1995), as more research is needed on methods of estimating heat transfer coefficient values. Atkinson and Drysdale demonstrated that a ceiling could be treated as having a single heat transfer coefficient across the whole of a ceiling, as outside the plume turning zone it is almost constant. Inside the plume impingement area, it is significantly higher, but accounts for a small part of heat transfer for the whole of a ceiling jet. This is in accord with Thomas's assumption (1955), that the heat loss from a hot layer is proportional to L^2 . For small compartments, this assumption does not hold, as plume impingement heat transfer is relatively large, in comparison to the ceiling temperature losses away from the plume.

In summary, there is limited variation to the mass flow rate, in ceiling jets, once the flow is fully developed, with radii at approximately 2 to 3 times the height of the plume. Additional entrainment may occur with large, extended compartments, with lengths over five times greater than the height. Eventually, as the length increases, cooling and friction effects are sufficient to cause a ceiling jet to detach from a ceiling, and mix with the incoming ambient air. This effect is commonly seen in tunnel flows, where loss of smoke layer stratification is a major research concern (cf. Woodburn 1995).

There is no empirical data examining the influence of the flow from compartments of varying length. For shorter compartments, a slight increase in mass flow rate could be expected, as length increases. For very long compartments, as length increases, greater cooling and mixing could occur. Experimental work is needed to find the

effects of varying compartment lengths on the mass flow rate from these compartments.

5.10. Rotation Area

The coefficient of entrainment for the gases rotating around the horizontal edge is the subject of disagreement. According to Morgan, Marshall and others at the Fire Research Station, their experiments (cf. BR 258) demonstrate that an approximate doubling of the mass flow rate occurs as the gases leaving a compartment, flow around the void edge. This is assumed to be due to large scale eddies flowing past the spill edge, entraining large quantities of ambient air.

Thomas (1987) and Law (1995), reanalysing Morgan et al's data, believe that the large amount of entrainment found in research by Morgan and others at the Fire Research Station (Eq.2 of BR258) does not occur in the rotation region.

The mass flow rate at the y-plane is shown in Equation 5.7, below:

$$M_y = \frac{2}{3} \rho_o W \alpha' \left[2g \frac{\theta_c}{T_o} \right]^{1/2} d_w^{3/2} + M_w \quad \text{kgs}^{-1} \quad \text{Eq. 5.7}$$

Morgan et al found that $\alpha' = 1.1$. Thomas analysed the theoretical basis of Morgan's design calculation and reviewed the experimental data. He states that the high value for α' , results from different assumptions about flow profiles, when developing the theory on flows from compartments and plumes. The compartment flow is assumed to be uniform, through its depth and the plume flow Gaussian, across the width. Thomas (1992b) states that the theory that couples these two flow regimes together, ignores the difference in profile forms, creating an error in matching the maximum and mean temperatures.

The profile forms can be described as follows:

Ceiling Flow:	$\theta = \theta_c$	C	Eq. 5.25
	$u = u_c$	m/s	Eq. 5.26
Flow in Plumes:	$\theta = \theta_c \exp - (x^2/(\lambda^2 b^2))$	C	Eq. 5.27
	$u = u_c \exp - (x^2/b^2)$	m/s	Eq. 5.28

- where:
- c - centre line peak values
 - x - distance from the centreline of the plume
 - b - characteristic width of a plume at a certain height
 - λ - is an experimental factor

Thomas (1992b) states that combining the different plume profiles, in developing the formulae for the calculations for flow creates ‘a fictitious entrainment, to explain the measured axial temperature being less than the theoretical’. This error is the source of the imaginary 100 % entrainment in the rotation region.

It should be noted that in developing a theory for the flows out of a compartment, Morgan (1986) uses a non-uniform profile, so some aspects of Thomas’s criticisms may not hold.

Thomas (1992b) speculates that this error contributes to the high entrainment rate. However, Hansell (1993) has measured the mass flow from a compartment, in a full scale experiment, finding entrainment of 20 % to 150 %, as the smoke flowed through the w-plane and under the balcony. This entrainment occurred as the smoke flowed around the downstand, and up against the underside of the balcony. Hansell (1992) did not measure the flow in the y-plane. When no downstand was present, and the

ceiling jet could flow straight out of the compartment, a reduction in mass flow rate was found.

Thomas (1992b) recommends that field model (CFD) simulations of the flow around the spill edge be carried out, to investigate entrainment at the spill edge. Some recent unpublished CFD simulations of smoke flow in atria found no evidence of large rates of entrainment in the rotation region (Miles, Kumar and Cox 1995).

This rotation region around the spill edge needs further investigation experimentally.

5.11. Spill Plumes

5.11.1. General

Yokoi (1960) examines the flow of hot gases out of a compartment, and resultant wall plumes characteristics, for different balcony sizes. These are for Ventilation Controlled fire regimes and used narrow window openings. The conditions used were not similar to the geometries commonly found in atria.

Lee and Emmons (1961) examined the flow of hot gases in line plumes theoretically and experimentally. The results are developed to form a series of non-dimensional relationships for line plumes. They define the flow of gases in a plume, as if originating from a simple imaginary line source, of finite width. A Gaussian profile (as characterised by Eq.5.27 and 5.28) for the smoke velocity and temperature was found for the whole height of the plume. Gaussian profiles were assumed for the line plume and imaginary portion, below the z-plane.

5.11.2 Source Froude Number

A line plume can be characterised by its Source Froude Number (F):

$$F = \left(\frac{2}{\pi} \right)^{1/4} \left(\frac{\alpha \gamma_1}{\lambda \Delta \gamma_0} \right)^{1/2} \frac{u_o}{(gb_o)^{1/2}} \quad \text{Eq. 5.29}$$

where: α = entrainment constant, 0.16 for free plumes

$$\Delta \gamma_0 = \gamma \Delta \rho$$

$$\gamma_1 = g \rho_1$$

λ = an empirical value

If: $F > 1$, an impelled source; a jet

$F < 1$, a restrained source; a buoyant plume

$F = 1$, an ideal source

Morgan and Marshall (1975) state that 'in practice, for a mall $F < 1$ ', as this a buoyant plume, with zero initial velocity.

Morgan and Marshall (1975) used this concept and other formulae from Lee and Emmons (1961) to develop a calculation method for plumes in malls. In developing the calculation method, Morgan and Marshall used the same values for α (0.16 for a free plume) and λ (0.9) as found by Lee and Emmons in their experiment. The method by Morgan and Marshall is developed for BR258, although it has been adapted to be used for adhered plumes too, where $\alpha = 0.077$.

5.11.3 The Effective Height of Rise

In CP48/75, 'Smoke Hazards in Covered Multi-Level Shopping Malls: an Experimentally Based Theory for Smoke Production', Morgan and Marshall (1975) introduced the concept of 'effective height of rise'. This 'effective height of rise' is used in the calculations for the mass flow rate of a plume entering the hot layer. It is an empirical value, based on the depth of the smoke layer, see Figure 5.7.

The factor, 1.26, represents the ratio of the smoke reservoir depth, measured by the visible smoke (when clearly stratified), to the depth measured by temperature, as in Equation 5.30:

$$d_{(\text{temperature})} = 1.26d_{(\text{visible})} \quad \text{m} \quad \text{Eq. 5.30}$$

This factor was found in experiments with relatively shallow smoke reservoirs with little variation in depth. If the reservoir depth is large, this additional 26 % represents a substantial reduction of the effective height of rise. For deep reservoirs with small actual heights of rise, a negative height of rise could be derived, therefore this factor may not be 1.26 consistently.

In the experimental work of Lee and Emmons (1961), Grella and Faeth (1975) and Liburdy and Faeth (1978), the apparatus had no smoke reservoir. The rigs were open topped. Thus there was no reservoir influence on the plume behaviour. The issue of the 'effective depth' did not arise

Hansell (1993) found that this factor varied considerably, and that for deep reservoirs, the depth measured by temperature became less than the visible depth, with visible reservoir depths over 1.2 m, for a 1/10 scale model.

Data from Marshall, Harrison and Morgan (1993) shows that this factor varies significantly, but that the depth by temperature is always slightly larger than by visible layer. The reservoir measured by temperature is usually 90 % to 140 % the visible depth. This has not been measured at full scale and could be a scaling and radiation problem.

These factors are all likely to be geometric specific. Hansell (1993) recommends further research into this problem. The effective depth is not noted in BR 258.

5.11.4 Entrainment into Line Plumes

α has been found to have a reasonably consistent value (0.077 for adhered plumes and 0.16 for double sided plumes) in other experimental work, for free plumes (round and line) and for adhered plumes (Liburdy and Faeth 1978).

Thomas (1989a) states that ' α ' is assumed to be constant for a plume's full height. This can create errors, as entrainment is proportional to the density of the gases.

5.11.5 Plume Widths by Temperature and Velocity

' λ ' represents the relative width of the plume measured by velocity and temperature, as shown below:

$$\lambda = b_{\theta}/b_w = 0.9 \qquad \text{Eq. 5.31}$$

where: $b_{\theta} \equiv$ the plume width based on temperature
 $b_w \equiv$ the plume width based on velocity

The edge of a weak plume is usually defined as the point where the velocity has fallen to 36.8 % (equivalent to $1/e$) of the maximum velocity. Similarly, the plume edge

based on temperature, is $1/e$ of the maximum. The width of a weak plume is usually defined by the velocity factor. The values reported for λ are less consistent than those reported for α , with values found by various researchers, to vary from 0.9 to 1.3 (Cox and Chitty 1980). Fewer empirical measurements are available for line plumes, Lee and Emmons (1961) assumed it to be 0.9, the value for round free plumes originally determined by Rouse, Yih and Humphreys (1952). Grella and Faeth (1975) and Liburdy and Faeth (1978) have confirmed this for wall plumes. There has been no other confirmation of this value for line plumes. The Fire Research Station did not measure it in experiments.

The variation in the ratio of plume widths, causes the mean temperature to vary, relative to the maximum in weak plumes as follows (Morgan and Marshall 1975):

$$\frac{\theta_1}{\theta} = \frac{(1 + \lambda^2)^{1/2}}{\lambda} \quad \text{Eq. 5.32}$$

where: θ_1 = maximum temperature
 θ = mean temperature

If ' λ ' can vary from 0.9 to 1.3, then the ratio of maximum to mean temperature can vary 1.5 to 1.26 respectively. This variation has great implications in analysis of experimental data and development of design calculations, as mass flow rate estimates based on this measurement will vary by 2 % at 50°C maximum temperature difference to 8 % at 300°C. Using $\lambda = 0.9$ for line plume calculations overestimates the mean temperature and underestimates the mass flow rate.

Thomas (1989a) comments on line plume theory. He states that Morton (1965), following Thomas et al (1963), used 'top hat' profiles to characterise strong plumes

and Gaussian profiles for weak plumes. The use of these profile forms is arbitrary. The flow profiles in the near and far fields do not match. A transformation of the strong (top hat) profile to a weak plume (Gaussian) profile, as a plume rises, creates calculation difficulties. There may be errors due to these differing profiles.

Morgan and al use Gaussian profiles for the full height of the plume. This leads to errors as the equivalent source may have a top hat profile. Thomas recommends further examination of the problem.

5.11.6 Other Limitations

Morgan's atrium plume calculation has other limitations, notably:

- It is not valid for actual heights of rise less than 3 m full scale. 4.2 m if the plume ends are enclosed by a side walls, so receive no entrainment. Below these heights the reservoir effects the plume development.
- It is limited to unobstructed 'atrium' spaces. Obstructions in the path of a plume have not been examined in any experimental work.
- Heat loss could be incorporated, in a simple form, although this is not incorporated in any spill plume models.

5.12 Alternative Atrium and Spill Plume Calculations

Thomas (1987) developed an alternative formula for calculating the entrainment into a line plume, treating the plume as a 'far plume' rising from a source some distance from the edge of the balcony or underside of downstand (where no balcony present). This was developed to simplify the design calculations for line plumes and to avoid difficulties with theoretical doubts regarding the entrainment of smoke as it passes around spill edges.

$$M_z = 0.58\rho \left[\frac{gQ_w L^2}{\rho c T_0} \right]^{1/3} (z_{res} + \Delta) \left[1 + \frac{0.22(z_{res} + 2\Delta)}{L} \right]^{2/3} \quad \text{kgs}^{-1} \quad \text{Eq. 5.33}$$

This equation was developed from theoretical analysis and from Morgan et al's empirical data. It reduces all of the formulae for the flows out of a compartment and for the rotation around the spill edge to an empirical factor 'Δ'. This is related to the height of the opening to the fire compartment, as follows:

$$\Delta = kH \quad \text{m} \quad \text{Eq. 5.34}$$

where 'k' ranges in value from 0.2 to 0.8, depending on analysis of data. According to Thomas's theoretical calculations, $k = 0.3$.

Marshall's, Harrison's and Morgan's (1993) empirical data, $k = 0.3$ for small heights of rise up to 3 to 4 m, but is 0.67 above these heights, when the plume ends are enclosed by side walls (i.e. no air entrains into the ends).

Thomas's formula is not applicable to adhered plumes. It could be adapted arithmetically, by changing a coefficient, but this revised formula would need to be compared to experimental data, as it is uncertain that some of Thomas's assumptions would hold for adhered plumes.

Law (1995) has also developed a simplified plume equation, to calculate the mass flux of a plume entering a smoke reservoir, based on Morgan's experimental data and Thomas's theory:

$$M_z = 0.31(Q_f L^2)^{1/3} (z_{res} + 0.25(Dd + h)) \quad \text{kgs}^{-1} \quad \text{Eq. 5.35}$$

where: Q_f = total heat output of the fire source (kW)
 z_{res} = height of rise of line plume (m)

This has few geometrical factors influencing the mass flow rate. Variations due to the location of the fire and compartment form (such as length, width or height) are not included, though could form a revised coefficient to the right hand side (i.e. the value 0.31 varies). It is not explicit what form of line plume it refers to, though it appears to be for a free plume.

In commenting on Law's (1995) paper, Thomas (1995) states that Δ , appears to be at $0.25(Dd+h)$ below the underside of the balcony.

As a final note, an American spill plume formulae has been developed, and is published in NFPA 92B, Smoke Management in Malls, Atria, and Large Areas (1991). This is an adaptation of Thomas's formula, so is based on Morgan's et al's data. It is adapted in part to fit the general form of American plume theory. Many authors have commented on it and have recommended that it needs revision. Comparison to FRS data reveals it to calculate mass flow rates very poorly (Marshall, Harrison and Morgan 1993).

5.13 Heat Output of the Fire and Heat Loss

A major problem in applying these formulae is to find reliable information on the relation of heat loss from the fire and smoke.

Radiation losses from flames usually amount to 20 to 30% of the total heat output (Lee and Emmons 1961). In experiments they found that radiation from a sooty flame reduced Q in a line plume, from a theoretical value by 50 %, up to 60 % for low values of Q .

Similar values are presented in other work, though no consistent values are found, with radiation from fire plumes estimated to vary from 60 to 80 % most often. So significant errors can occur when using smoke calculations with heat release rates.

In a design guide, following analysis of Morgan's experimental data, Law (1995c) defines the relationship of the heat release rate to the convective heat output as:

$$Q_c = Q_f / 1.5 \quad \text{kW} \quad \text{Eq. 5.36}$$

This provides a consistent estimate of the value of convective heat output, but not necessarily a truly accurate one.

The design guides avoid this problem, as the 1 MW and 5 MW design fire sizes in BR186 and BR258 are for convective heat output.

In all of the formula presented here, no account is made of the heat loss from the fire compartment. In general terms, the heat loss from a compartment is proportional to the area of the ceiling, where this area is the order of a magnitude larger than the plume impingement area.

Information on the effect of sprinklers on smoke in compartments and plumes is not readily available. This is the subject of continuing research. Basic methods are used to estimate the temperature of smoke in these situations, often assuming a 50 % heat loss to sprinklers or a reduction of the temperature down to the operating temperature of the sprinklers. The effect of sprinklers is not considered in this work.

5.14 Ventilation Controlled Fires

The formulae described in Section 5.5.2 are limited to FBC fire regimes (BR 258). The flow mechanism for Fully Involved Large Opening (FILO) or Ventilation Controlled (VC) fires is different. FILO fires occur where the area of openings is large enough to allow complete combustion, within a compartment. VC fires occur where there is insufficient size of opening to allow enough air to enter a compartment to allow complete combustion. The mass flow rate reaches a limiting value of $0.5 A^{H/2}$ (see Equation 5.37). These occur after flashover, and temperatures within the fire compartment are in excess of 800°C .

The mass flow rate is controlled by the differences of the weight of the hot gases produced in comparison to the cooler gases outside the compartment. Usually after flashover, developing into a fully developed fire, very approximately, as the gas layer approaches 600°C or when the heat flux at floor level reaches 20 kW/m^2 (c.f. Drysdale 1985), though this can vary greatly depending on the proximity of combustible materials to the hot gas layer. A simplified relationship of fire size and ventilation opening dimensions is presented in graphical form by Morgan and Hansell (1987), for an unsprinklered office. Other methods for determining the transition and quantities of hot gases flowing out of a compartment have been produced, including simplified zone models by Law (1989) and Thomas (1992a). No examination was made of these for this thesis.

An early model of the flow out of a compartment, from a VC fire was developed by Kawagoe (1958), from a large number of experiments, for a fully developed compartment fire. It is expressed in its simplified form in Equation 5.10.

$$M_a = 0.5 A H^{0.5} \quad \text{kgs}^{-1} \quad \text{Eq. 5.37}$$

Smoke flow calculations for the flow of smoke in atria for these fire regimes have not been developed, except in preliminary form, by Morgan and Hansell (1987), who state that much research is needed on this subject.

5.15 Summary of Atria Smoke Flow Models

- Spill plume models are available for steady state conditions, for Fuel Bed Controlled fires.
- The spill plume models give varying mass flow rates for particular geometries.
- All spill plume models are based on data by Morgan and others from experiments at the Fire Research Station. These are mainly 1/10 th scale experiments, but include some full scale work.
- A few large scale experiments appear to show that the final outcome of these formulae are reasonably accurate for design purposes.
- There has been little independent validation of these formulae.
- The FRS formula have accounted for the effect of downstands on the flow out of compartments, but not for openings without balconies in the atrium
- There is not a comprehensive range of coefficients to express the effects of compartment geometry on the flow out a compartment. The effect of compartment length has not been examined.
- There is much disagreement about the entrainment rate in the rotation region, from the w-plane to the y-plane.
- Certain aspects of spill plumes have not been examined such as heat loss, profile forms or the relationship between plumes width by temperature or velocity.
- The validity of the concept of the ‘effective height of rise’ is uncertain. It appears to have been dropped in BR 258.

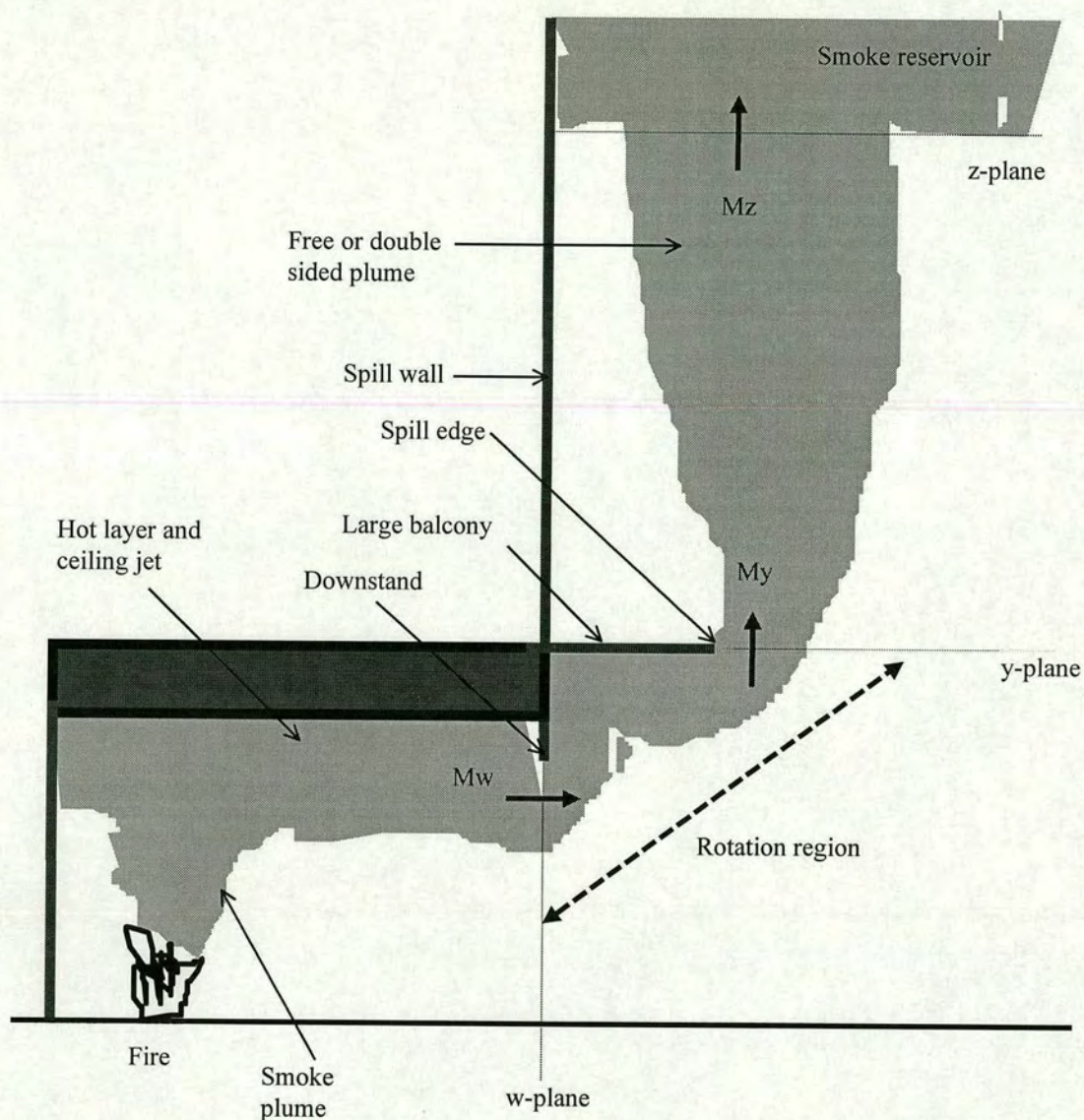


Figure 5.1(a) Basic Structure of a Spill Plume:

Double-Sided or Free Plume with Large Balcony

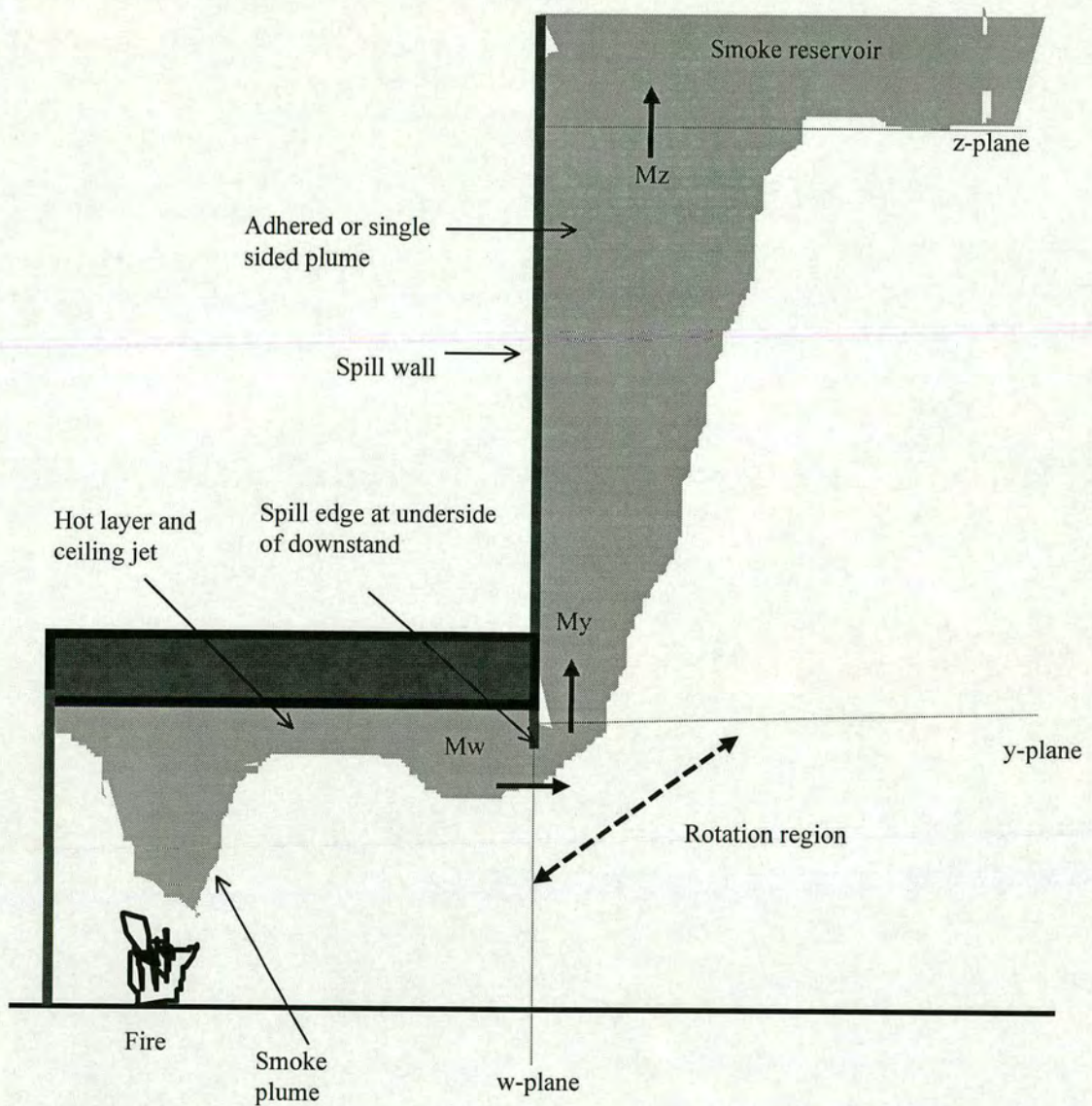


Figure 5.1(b) Basic Structure of a Spill Plume:

Single-Sided or Adhered Plume with No Balcony

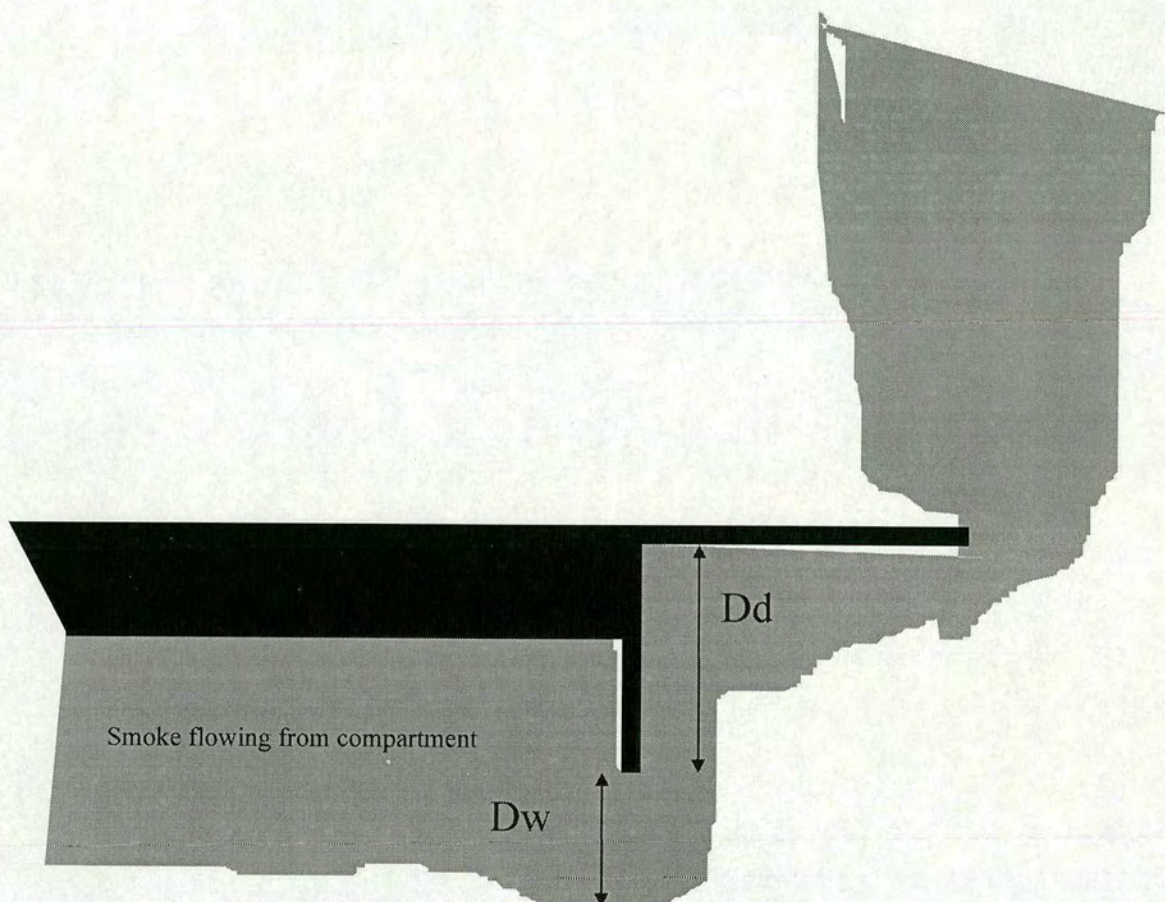
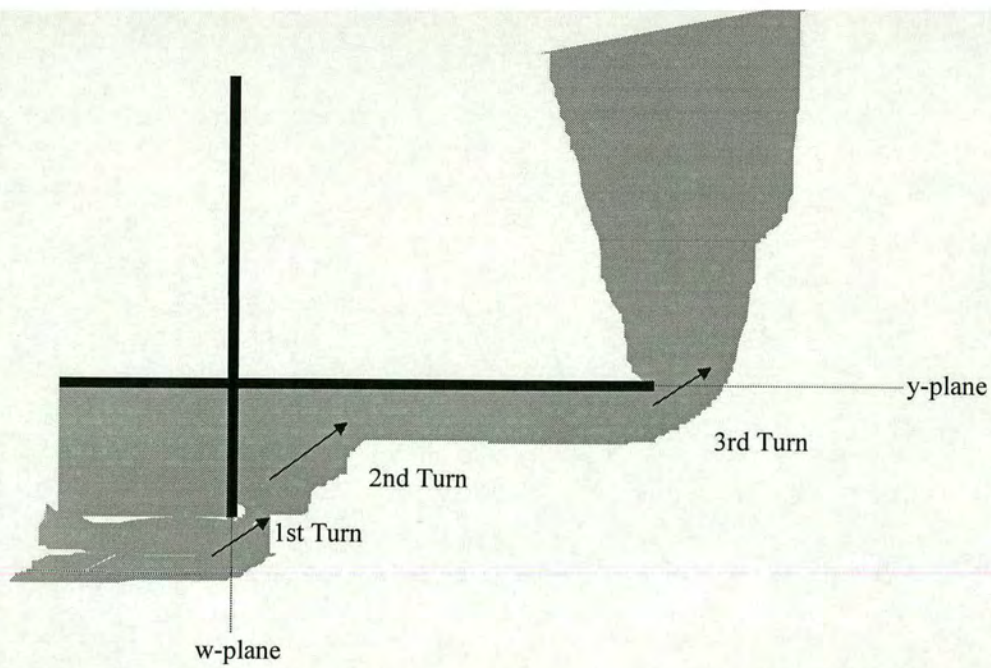
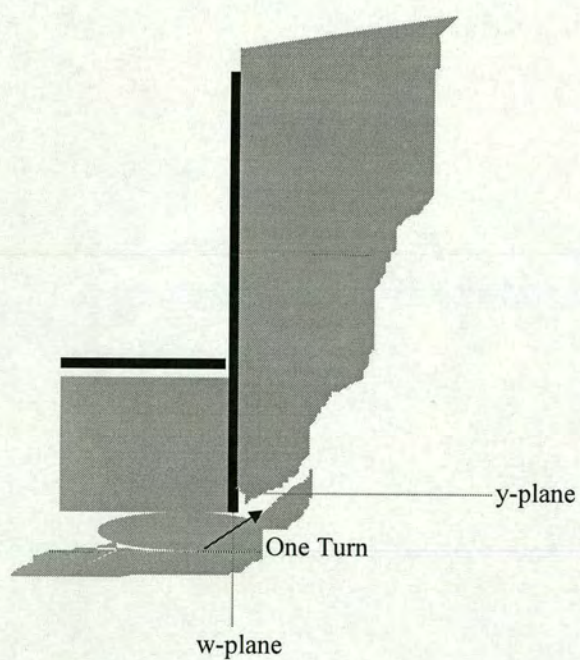


Figure 5.2 Location of Measurement of D_d (from BR 258).



a) Free Plume



b) Adhered Plume

Figure 5.3 Rotation Zones for Free and Adhered Plumes

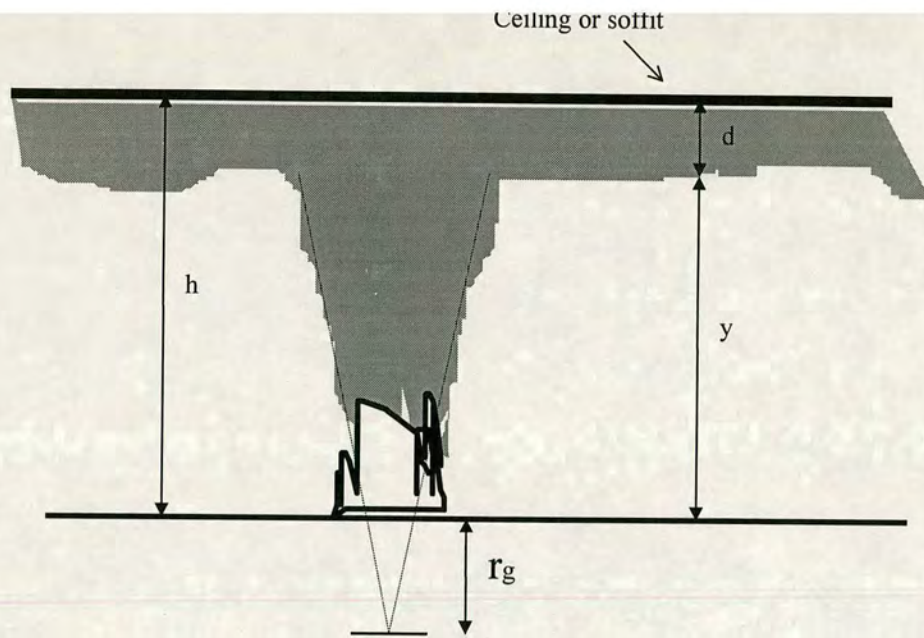
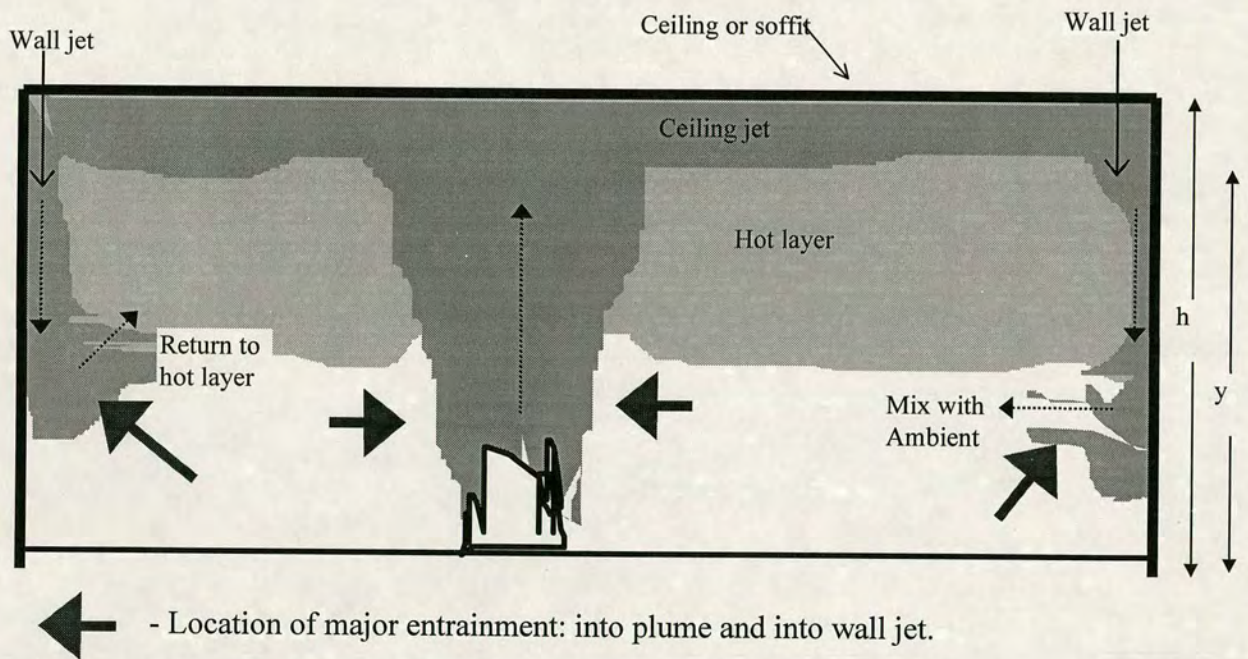


Figure 5.4 Virtual Source



A - buoyant wall jet, returns into hot layer

B - wall jet with low buoyancy, returns to hot layer after mixing with much air or 'fogs' compartment.

Figure 5.5 Significant Features of Entrainment in a Compartment Fire (Jaluria 1988)

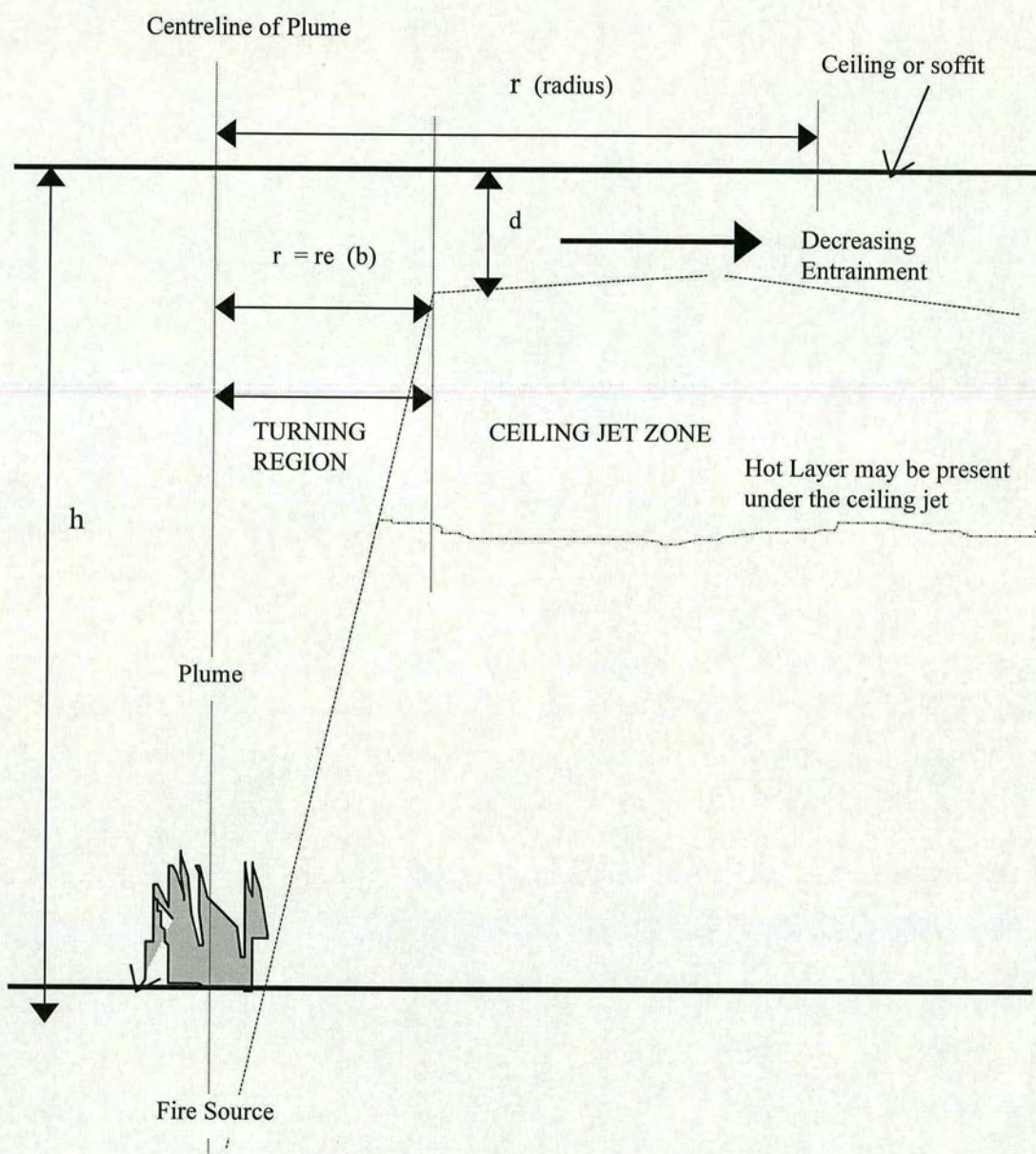
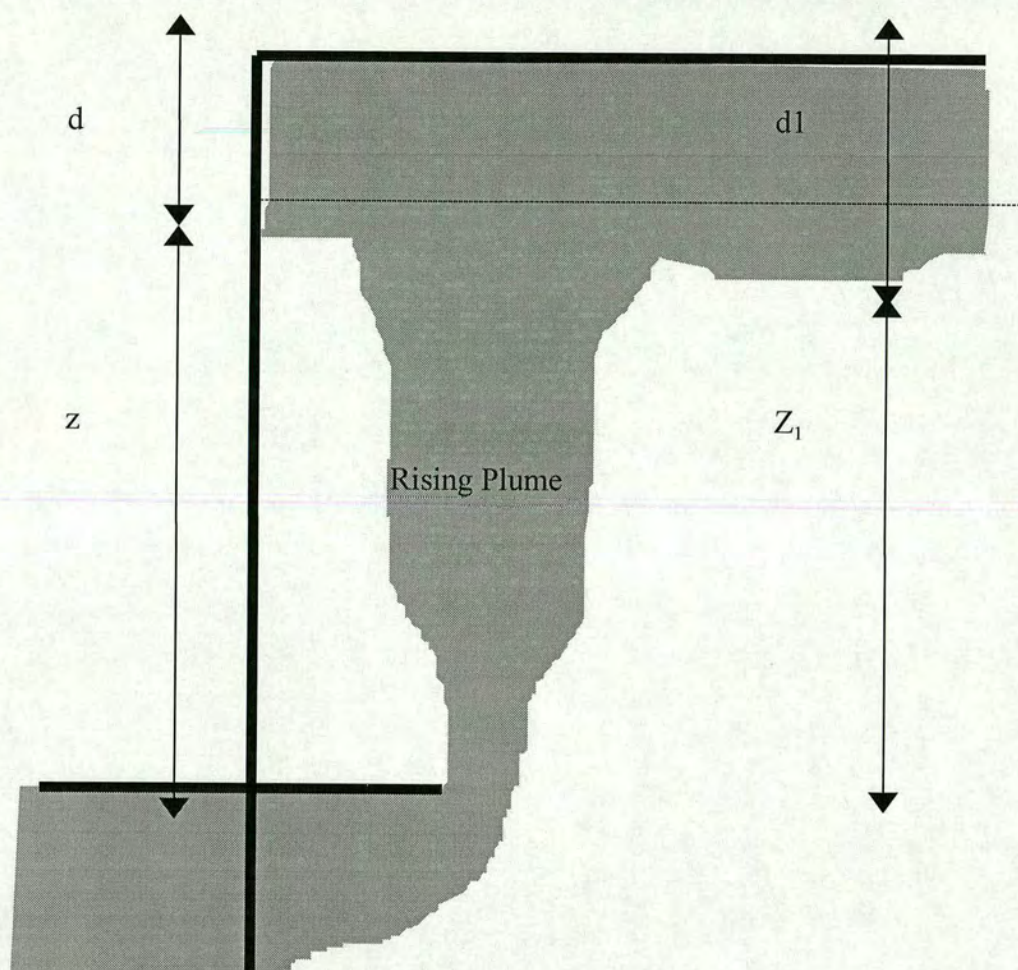


Figure 5.6 The Major Features of a Ceiling Jet (from Alpert 1974)



d	-	depth of smoke
d'	-	$1.26 d$
z	-	height of rise to visible layer
z'	-	$z-(d'-d)$

Figure 5.7 Effective Height of Rise

Chapter 6: Experimental Study of Smoke Movement in Atria

6.1 Introduction

In Chapter 5, it is demonstrated that various models for smoke flow in atria exist. Much of the experimental research into spill plumes has been conducted at the Fire Research Station, mainly involving 1/10th full scale experiments, but also some full scale work.

This Chapter presents the development of an experimental programme to investigate spill plumes, to provide independent experimental data.

6.2 Experimental Aims

This work sets out to investigate variations to the calculations developed by the Fire Research Station and to provide further information on the behaviour of smoke flow in atria. Two of the variations to the flow described theoretically in Chapter 5 are:

- The effect of downstand size when no balconies are present in the atrium.
- The effect of compartment length.

Several methods of instrumentation and measurement are used to provide additional information on certain issues; the entrainment rate in the rotation region, from the w-plane to the y-plane, when no balcony is present, and the structure of spill plumes.

6.3 Development of an Experimental Programme

The experimental programme was developed as follows:

6.3.1

Examination of the experimental methods used by the FRS, for research into spill plumes to assess how the data is derived, particularly what is measured directly and what is inferred.

6.3.2

Appraisal of instrumentation techniques to find alternative methods of measurement.

6.3.3

Examination of the scaling laws for turbulent flow to establish the limitations of reduced scale experiments.

6.3.4

Development and construction of a scale model of an atrium for spill plume experiments.

6.3.5

A preliminary set of experiments to refine the main experimental programme, and to assess the feasibility of intended instrumentation techniques.

6.3.6

The main set of experiments, results analysed and conclusions drawn.

6.4 Experiments on Spill Plumes in Atria and Malls at the Fire Research Station

6.4.1 General

The experiment was set up geometrically similar to the FRS's model, to avoid creating too many unidentifiable geometric discrepancies, and for ease of comparisons with results.

Discussions with Dr. Howard Morgan and Norman Marshall at the Fire Research Station (FRS) covered smoke flow theory (particularly spill plumes and areas requiring more research); experimental and instrumentation techniques used at the FRS, and the difficulties of measuring smoke flow (new measuring techniques are needed to provide greater insight into the mechanics of smoke flow).

6.4.2 The FRS 1/10th Scale Experiments

The information regarding the FRS 1/10th scale tests, discussed below, is from the visit to the FRS and from their publications, particularly CP 45/76, N 203/92 and N65/93 (N publications are notes prepared for circulation within the FRS).

The FRS scale model is shown in Figure 6.1. The model has a steel frame with ceramic glass fibre board attached, covered with ceramic fibre insulation. The geometry can be adapted as follows:

Fire Compartment

This has fixed dimensions. A downstand can be added at the exit to the atrium. Air enters the compartment from the rear. A shutter is raised so that only outflowing air can pass through the exit. No inflowing air enters the compartment this way.

Methanol is supplied into the space via a pipe, and is burned in a small metal tray. A flowmeter controls the flow to enable different rates of heat release within the fire compartment to be achieved.

Atrium

The side walls contain the smoke, so the bottom of the walls form the reservoir in the atrium and can be raised or lowered to change the height of rise of the plume. End walls could also be added to block entrainment to the sides of the plume. The top of the atrium is at a fixed height relative to the compartment.

A duct at the top of the atrium extracts the hot gases at a controlled rate. The fan speed is set so that the extraction rate matches the mass flow rate of the plume, at the reservoir height. If extraction is too slow, then the hot gases spill out under the walls, if too fast, the gases rise up rapidly away from the bottom of the walls. The hot gases are visualised using theatrical smoke.

Balconies of varying size can be fixed inside the atrium. Boards can be added to the fire compartment side of the atrium, to allow adhered plumes to form.

6.4.3 Instrumentation in the FRS Experiments

The measurements made in the FRS scale model were:

1. Inlet air velocity, in the duct, to the rear of the fire compartment measured by pitot tube and micromanometer.
2. Velocity of extracted hot gases, in the duct, measured by pitot tube, micromanometer and thermocouple.
3. CO₂ concentrations in the extract duct. CO₂ tracer gas is introduced into the inlet air, at levels many times higher than ambient (without inhibiting fuel combustion). The measurement of the CO₂ concentrations at various locations (including the extract duct), by infrared gas analysers to determine the entrainment in the plume.
4. Thermocouples for temperature profiles at the balcony edge and in the atrium.
5. Velocity measurements, at the compartment exit, using pitot tube, micromanometer and thermocouple. A bi-directional probe (see Appendix 6) is also used in some experiments, to measure maximum velocity only.

6.4.4 Experimental Method

Methanol is burned in the compartment at a controlled rate, so that the convective heat output can be estimated. The height of the shutter at the compartment exit is set so that no air flows back into the compartment. Pressure tapping at both sides of the shutter check that the shutter is not raised too high, causing the compartment to become pressurised, or set too low, so that all of the inlet air into the fire compartment can be measured.

The extraction rate is set so that the flow rate in the duct is equal to the mass flow rate of the plume, with a set height of rise. By setting the smoke reservoir at different heights, the variation of mass flow rate with height of rise can be found. The flow is visualised by theatrical smoke, observed from the underside of the atrium opening. Measurements are taken once the flow has reached a steady state condition and the extraction rate is set correctly.

6.4.5 Data from FRS Tests

These tests have provided the following direct measurements:

- velocity and temperature in the inlet duct (for inlet air mass flow rate).
- velocity and temperature at the shutter (w-plane) (mass flow rate and heat flux).
- velocity and temperature in the extract duct from the reservoir (for mass flow rate of the gases in the duct and the plume).
- CO₂ tracer concentrations in the hot gases at the shutter and in the extract duct, to determine the entrainment from the w-plane to the smoke reservoir.

6.4.6 Assumptions in the Spill Plume Experiments

There are several important assumptions used in these experiments.

- the velocity profile at the w-plane is uniform or semi-uniform.
- the velocity and temperature profiles in the spill plume are Gaussian.
- the smoke reservoir is a well mixed uniform layer.
- heat loss is zero.

6.4.7 Experiments at Cuijk, Netherlands

Experiments at Cuijk, Netherlands by Hansell (1993) and the FRS (Occasional Paper 55, Hansell, Morgan and Marshall 1993) provided additional data, examining different downstand and balcony conditions, using a 1/10 scale atrium model built for heating and ventilation research. The tests broadly follow the methods for the FRS 1/10th scale experiments.

The heat source was a bank of electric heaters, rather than by burning methanol, resulting in flow characteristics closer to those of a ventilation controlled fire rather than a fuel bed controlled fire.

6.4.8 Full-Scale Fire Tests at the Fire Research Station

Hansell (1993) conducted full-scale tests at the FRS, measuring the flow at the w-plane and the void edge (edge of balcony) using a bi-directional probe and thermocouple trees. Some unusual velocity profiles, and variations to C_d were found, but otherwise confirm the results of the 1/10th scale experiments.

6.4.9 Other Smoke Flow Experiments

Other methods of examining smoke flow have been used in related experiments. It would not be practicable to examine all of them here, but some researchers investigating ceiling jets and plumes have used methods that could be developed for this work. The limitations and benefits of particular experimental methods is examined later.

6.5 Scaling Laws

6.5.1 Froude Modelling

The experiment needs to satisfy the laws of scaling. Quintiere (1989) states that ‘three modelling strategies have been effectively used in fire research’, one of which, Froude modelling, is used for experiments conducted ‘in air at normal ambient conditions’.

Froude modelling allows the relations for temperature and velocity at corresponding points in models, having different sizes but similar shapes, to be determined (Thomas et al 1963). The characteristics of a plume will be similar at any scale.

Heskestad (1975) describes the essential characteristics of Froude modelling. The Froude number (Fr) needs to be kept constant, for the full scale application and reduced scale model, so that:

$$Fr = \frac{u^2 T_0}{Lg\theta} \quad \text{Eq. 6.1}$$

$$Fr_{\text{reduced scale}} = Fr_{\text{full scale}} \quad \text{Eq. 6.2}$$

where:

- u = velocity (m/s)
- T₀ = ambient temperature (K)
- L = characteristic length (m)
- g = gravity (m/s)
- θ = temperature rise above ambient (C)

The products of combustion generally recirculate around fires. Variations in the concentration of these affect the continuing combustion process. In Froude modelling the temperature difference (θ) is kept constant, therefore gas concentrations are kept constant.

If θ and T are kept constant then:

$$\left(\frac{u^2}{L}\right)_{\text{model}} = \left(\frac{u^2}{L}\right)_{\text{fullscale}} \quad \text{Eq. 6.3}$$

From which some simple relationships can be defined (Thomas et al 1963):

$$\begin{aligned} u &\propto L^{1/2} \\ m, Q &\propto L^{5/2} \end{aligned} \quad \text{Eq. 6.4}$$

If θ and T are constant, then Reynolds number cannot be constant. The Reynolds number is ignored ‘which is equivalent to ignoring flow effects dependent on viscosity’ (Heskestad 1975). Boundary layer phenomena cannot be accurately be modelled with this method, but with the ‘proper choice of the solid boundary materials, it is possible to partially preserve some of the boundary heat transfer effects even though Re is explicitly ignored in Froude scale modelling’ (Quintiere 1989). This is the principle of ‘partial modelling’ (Jolly and Saito 1992), in which the important parameters are identified ‘so that any desired outcome could be predicted with a reasonable degree of accuracy’.

The assumption that temperatures at full-scale and reduced-scale are equal, may not always hold. Thomas (1989) reports that work by Blay, Tourhault and Jourbert, found scaling factors can cause distortion of temperatures, at higher temperatures (above approximately 300⁰ C). In the experiments in this thesis, temperatures above 300⁰C, were only found close to the flame, therefore temperature errors were limited.

6.5.2 Other Methods of Conducting Reduced Scale Experiments

The other two methods used for smoke modelling are salt water (cf. Poreh 1994 and Thomas et al 1963) and pressure modelling. Salt water modelling simulates the buoyancy effects of hot gases and maintains the Reynolds number. This may be used

to model corridor smoke flows, when the boundary conditions could be critical. The Froude number is not maintained, so plume flows may not be simulated effectively.

Pressure modelling (in a pressure vessel at pressures at approximately 10 times atmospheric pressure) preserves both the Froude and Reynolds number. This method is rarely used due to practical limitations and excessive costs.

6.5.3 Application of Froude and Partial Modelling to Smoke Flow Experiments

6.5.3.1 Reynolds Number

For free plumes, the Reynolds effects are limited, because there is no boundary condition. Most reduced-scale plume experiments use Froude modelling.

Adhered plumes and ceiling jets have boundary conditions that could develop to a significant scale and cause major inaccuracy in the results. When modelling jets and adhered plumes, the model size and fire sizes need to be large enough to produce turbulent flow. Usually, turbulent flow is said to develop when Reynolds number, Re , is larger than 2000. This is for the 'classic' situation of a smooth bore pipe. In the more complex situation of a ceiling jet with many disturbances to the flow, then turbulent flow develops if Re is greater than 1000 to 1500. Marshall (1994) states that the FRS experiments are turbulent when Re is greater than 1000 to 1500. Other researchers (c.f. Chan et al 1993) found that experimental relationships were valid, above $Re = 1000$.

The Fire Research Station, using the 600 mm ceiling heights have produced mass flow rates, that achieve Re greater than 2000 for heat release rates of 4.5 kW and above (c.f. Marshall and Harrison 1992).

6.5.3.2 Radiation Effects

It has been shown that for Froude modelling;

$$Q \propto L^{5/2} \quad \text{Eq. 6.4}$$

If the model was scaled for radiation, then:

$$Q \propto L^2 \quad \text{Eq. 6.5}$$

At 1:8 scale, this Q would need to be 2.8 times greater in Froude modelling than in Radiation modelling. Radiation effects can be ignored, if thought to be negligible. This assumption is used for Froude modelling of ceiling jets and steady-state enclosures fires (Quintiere 1989). Radiation is a dominant factor in fire growth, therefore is more important when modelling growing fires (Quintiere 1989).

6.5.3.2 Empirical Rules for Modelling Ceiling Jets

Alpert (1971, 1973) has examined ceiling jets with reduced scale models. He has found that the viscous sublayer can become relatively large in small scale models. Some simple modelling rules were developed to avoid the viscous sublayer (boundary layer) becoming too thick in comparison to the ceiling jet or laminar flow:

- The minimum ceiling height should be 450 to 600 mm. The distance at which the flow stabilises could be reduced excessively, and the flow could become laminar if the ceiling height is too low.
- The length of flow of the ceiling must not extend too far to avoid an excessive sublayer developing. The maximum length of the ceiling flow is approximately three times the height of the compartment.
- The fire must be small enough to avoid flames from reaching the ceiling, because different scaling laws, such as radiation and thermochemical, are applicable to flames along a ceiling.

6.6 Instrumentation

6.6.1 General

Many smoke flow experiments require the measurement of temperature and velocity and it is not always possible to measure these directly. They can be derived from indirect flow measurements, other empirical data sources or existing formulae.

Indirect measurements are also used to simplify the experimental method. For example the duct measurements, to derive the mass flow rates in the FRS spill plume experiments, avoid the need to measure plume profiles. Additional measurements, such as CO₂ concentration, allow entrainment values in the plume to be derived.

Smoke flow in reduced-scale experiments can be difficult to measure. The flow is small-scale, with fine temperature and velocity gradients. It can be disturbed easily. There are rapid periodic changes, which can make measurement more difficult. Temperature measurement techniques are well established, providing data of adequate quality for smoke flow experiments. Velocity measurements of similar accuracy are difficult to obtain.

6.6.2 Velocity Measurements

The development and refinement of velocity measurement techniques is the subject of much experimental research in fluids. Different velocity measurement techniques have been assessed to find a suitable method to meet the aims of the experiment.

The maximum mean velocity predicted for this experiment was approximately 1.6 m/s. The maximum instantaneous velocity was estimated to be less than 2.1 m/s.

The lowest velocities of interest are found at the edge of the plume or ceiling jet, as defined by the relationships in Equations 5.27 and 5.28 and in Section 5.11.4. The plume edge is at the point where the mean velocity is :

$$u_{\text{edge}} = u_{\text{max}}/e \quad \text{m/s} \quad \text{Eq. 6.5}$$

If the lowest maximum mean velocity expected is 0.3 m/s, then the lowest edge mean velocity would be 0.11 m/s. To achieve reasonable accuracy, velocity measurements would need to be done at ± 0.01 m/s, for input to mass flow calculations.

Velocities need to be measured at a wide range of temperatures; ambient (15°) to 250° C, because the temperature in the compartment could vary within this range.

The measurement technique adopted should aim to:

- provide direct measurement of areas of interest
- minimise the disturbance to the flow
- measure a range of velocities, 0.00 to 2.1 m/s (at 0.01 m/s).
- measure velocities at a wide range of temperatures (15° to 300° C)
- have the potential to provide data of a quality higher than existing methods

6.6.3 Velocity Instrumentation

The methods examined were:

- pressure differential methods (pitot tubes and bi-directional tubes)
- hot wire anemometry
- vane anemometry
- temperature correlation
- laser doppler anemometry
- particle image velocimetry

This is a list of the velocity measurement techniques available for this experiment. The limitation of each technique is given in the next section.

6.6.3.1 Pressure Differentials

Pitot-static Tube

The most common form of pressure differential measurement uses the Pitot-static tube. This robust probe can be a small size, a minimum diameter of 2 mm for standard tubes. Smaller tubes could be constructed if necessary.

The flow is disturbed to a similar degree as a thermocouple tube. The temperature at the probe head needs to be measured to find the fluid density.

High errors are obtained at low velocities. A 2 % error at 0.6 m/s, for a standard, $K = 1.0$, pitot-static tube is reported by Ower and Pankhurst (1976), with increasing error at lower velocities. There will be an additional error at low velocities, as most transducers do not have the sensitivity to measure the low pressures created by standard pitot tubes. Ower and Pankhurst state that:

‘for an error limited to 1 per cent in the observation of velocity head for an air speed of 0.6 m/s we need a manometer sensitive to about 0.0002 mm of water column; and an instrument of this sensitivity had to be specially designed for the low-speed calibration of the National Physics Laboratory standard pitot-static tube. Numerous precautions are needed to ensure steady conditions. If 0.02 mm is taken as a reasonable limiting sensitivity for a manometer then the lowest air speed that can be observed with an error of 1 % with the pitot-static tube is about 4.5 m/s.’

Flow measurement with a pitot-static tube is uni-directional. If it is placed in flows that can reverse, then the ‘negative’ flow cannot be measured. Separate measurements would be required in the ‘reverse’ direction.

The effect of turbulence on pitot tubes is not fully accounted. The scale of the turbulence can cause readings to be higher or lower (Ower and Pankhurst).

The position and orientation of the tube need to be well controlled, although the effect of the angle of yaw is negligible when less than 30° . This can be an advantage in some circumstances where the maximum velocity, whatever the direction (within the 30°), needs to be measured. It is a disadvantage if the velocity component in a particular direction must be found, as the probe will measure the maximum velocity within 30° of the probe axis.

The accuracy of the measured velocity is reasonable (additional 1.5 % error) if close to a wall or within boundary layer (Ower and Pankhurst).

Bi-directional Probe

McCaffrey and Heskestad (1976) developed this probe to measure low flow velocities associated with small scale fires (see Appendix). It provides a robust measurement technique.

It can measure the velocity, whether flowing towards or away from the probe. It is also relatively insensitive to the angle flow. It measures velocity to $\pm 10\%$, if the approach flow is to within 50° of the probe axis. This can be an advantage where the maximum velocity is uncertain needs to be known, whatever the direction (within the 50° limit). It is a disadvantage if the velocity component in a particular direction must be found, as the probe will measure the maximum velocity within 50° of the probe axis.

Ceiling jet and hot layer flows through the w-plane are not parallel to the ceiling, and could be at angles of up to 30° . In this location a bi-directional probe measures the maximum velocity, not the velocity passing through the w-plane. The direction of maximum velocity needs to be found, to find the velocity across the w-plane.

A bi-directional probe can measure low velocities. McCaffrey and Heskestad (1976) found a maximum 7 % error for probes of 25 mm diameter, with a 0.304 m/s velocity. The error due to probe would only marginally increase with lower

velocities, but 'errors due to the resolution of the associated pressure transducers would become more significant' (McCaffrey and Heskestad 1976). Regular calibration of the transducers is necessary.

At higher velocities an error close to 5 % occurs. This rises to 10 % if the probe is not correctly aligned with the flow. Researchers at the FRS find that the angle of flow produces errors up to 15 %, at angles of up to 40° (Best and Williams 1991).

Some drawbacks exist with this method, for example thermocouples are needed in association with probe and the effects on the measurements of a boundary layer are not known.

6.6.3.2 Hot-Wire Anemometry

It is possible to measure velocities down to 0.4 m/s to an error of ± 1 % with this technique, but the probes are not robust, because low velocity hot wires are very delicate and are often damaged during handling.

A single hot-wire cannot measure the direction of the flow, so a more complex probe of 3 to 4 wires of differing orientation are needed, leading to greater risk of damage.

Hot-wires are unsuitable for the measurement of smoke flow as they need calibrating individually, at different temperatures (Gale). If thermocouples are used outside their designed temperature range (typically $\pm 20^{\circ}\text{C}$) then the error increases rapidly with temperature change (Lomas 1980). Compensation techniques can be used to reduce the error due to temperature variations. This generally improves the accuracy of the data, but a limiting temperature range is still present. Enquiries to manufacturers found that at best an anemometer could measure velocity in the range 20 to 120° C range, with limited accuracy and non-directional.

6.6.3.3 Vane Anemometry

Probes are commercially available, for velocities down to 0.4 m/s, but can only work in temperatures up to 140⁰ C. To operate at higher temperatures, measurements at lower velocities are less accurate.

The size of low velocity vane anemometers can make them unsuitable for reduced-scale smoke flow research. The probe measurements to within 13 mm of a wall.

6.6.3.4 Cross-Correlation Velocimetry (CCV)

The principles of this technique are described in Appendix 6. Cox (1977) demonstrated that this is an effective method of velocity measurement in the harsh conditions in flames and hot gases. It can measure low velocities, though to a minimum mean velocity of 0.2 m/s (Motevalli et al 1992). Interference can occur, for example due to local convection effects at lower velocities. This technique has the particular advantage of providing temperature and velocity measurements from one sensor, limiting disturbance to the flow. With certain forms of CCV instrument construction, only the velocity component in the direction of interest is measured.

Analysis (Motevalli et al 1992) demonstrated that the maximum accuracy is 5 %, if the sampling periods and distance between thermocouples are kept to a minimum. Greater errors are introduced if thermocouple sensors in each pair are not identical; if the distance between sensors is not set for the conditions in each experiment; and if measurements are made in the boundary layer.

6.6.3.5 Laser Doppler Anemometry

This technique has the advantage of being independent of temperature and it does not intrude into the flow. It is reported that it can give poor results below 0.3 m/s, though no published paper confirms this. It could be peculiar to instrument types.

The set up can be cumbersome. Glass panels may required on both sides of an experiment. The unit receiving the laser beam needs to be carefully aligned with the laser source optics. Without the use of expensive ancillary equipment, traversing a flow requires realignment of the laser for each position; a lengthy process.

6.6.3.6 PIV

PIV is a non intrusive flow visualisation technique, using moving particles illuminated by a bright light source and computational techniques to determine instantaneous spatially resolved velocity vectors by measuring particle displacements (de Laine 1995). Its general characteristics are noted in the summary of measurement techniques for comparison purposes. Section 6.7 provides a detailed description of the technique.

6.6.3.7 Summary

Method	Minimum Velocity	Temp Range	One Flow Direction ²	Boundary Layer	Intrusive into Flow	Robust
Pitot	0.6 m/s	no limit	no	yes	yes	yes
Bi-direct	0.3 m/s	no limit	no	yes	yes	yes
Hot-wire	0.4 m/s	±20 ⁰ C	varies	yes	yes	no
Vane	0.4 m/s	max140 ⁰ C	varies	no/varies ³	yes	yes
CCV	varies ¹	no limit	varies	no/varies	yes	yes
LDA	varies ¹	no limit	yes	yes	no	yes
PIV	varies ¹	no limit	yes	yes	no	yes

1. Depends on instrument set up, but is limited by the range of velocities to be measured.
2. Measurement in a single direction only is preferred.
3. Depends on instrument size and boundary layer thickness.

Table 6.1 Characteristics of the Methods of Velocity Measurement

Table 6.1 summarises the characteristics of the methods of velocity measurement, in relation to the requirements of reduced-scale smoke flow experiments. It can be seen that CCV, LDA and PIV techniques offer the best options for the measurement of

velocities in hot gas flows. PIV has two advantages over CCV and LDA. It provides qualitative as well as quantitative outputs. It can also provide time velocity data over a wide area, rather than single point time variant data.

CCV would be the cheapest option, although there would be developmental difficulties, but LDA and PIV systems were available for use in the University of Edinburgh.

6.7 Particle Imagery Velocimetry (PIV)

6.7.1 General

The Department of Mechanical Engineering to use Particle Imagery Velocimetry (PIV) a visualisation velocity measurement technique. The Encyclopaedia of Fluid Mechanics states:

The main advantages of visualisation vis a vis transducer measurement techniques in turbulent flows can be described as follows:

- 1. They usually describe relative fluid motions in an extensive flow region; under certain conditions, localised information is also provided. Mean flow and turbulence characteristics can be determined by statistical analysis of visualisation records.*
- 2. They normally introduce negligible physical disturbance of the flow.*
- 3. They can demonstrate the existence and define the boundary of 'irregularities' such as reverse flow regions and organised, 'coherent' structures.*
- 4. They permit the observation and recording of 'frozen' as well as evolving flow patterns as functions of both space and time*

6.7.2 Description of Particle Velocimetry Imagery (PIV)

PIV is the visualisation of moving particles using a bright light source and computational correlation techniques to determine instantaneous spatially resolved velocity vectors by measuring particle displacements (de Laine 1995). There are three main steps to PIV:

- illuminating the flow
- recording the flow
- analysing the images

Only the techniques used for this experimental work are described here. There is much associated theory that has been developed for PIV, but is beyond the scope of this work.

6.7.3 Illuminating the Flow

6.7.3.1 Requirements

A powerful laser is used to form a ‘pseudo’ sheet of light, to illuminate the particles in the flow. This illumination method must meet the following criteria (Bruce 1996):

1. A short pulse duration so that particles do not move significantly in the illumination period.
2. A time interval between pulses such that there is no significant acceleration of the flow field.
3. A flexible time interval (dependent on the seeding particle diameter and velocity) between pulses to ensure that the separation between successive particle images lies within the dynamic range of the PIV analysis system.
4. Suitably sized particles are introduced into the flow (seeded). These should be small enough to follow the flow, but large enough to be visible to the image capturing process. The seeding particles should also be approximately spherical and scatter light efficiently.

6.7.3.2 The PIV System at Edinburgh University

The light source in the Department of Mechanical Engineering's Fluids Laboratory is a Spectra Physics 171, 15 W, Argon Ion 514 and 488 nm (green and blue) continuous wave laser.

The light enters a fibre optic cable, which terminates with a scanning box. The fibre optic cable allows the laser to be permanently housed in a separate room in the laboratory, and the scanning box to be placed in any orientation, at any location within the laboratory.

The scanning box contains a 16 sided rotating polygonal mirror and a parabolic mirror. These translate the laser beam into a pseudo-light sheet. Each particle in the sheet is illuminated for a brief period of time as the laser beam passes. The rotation speed of the mirror can be altered to change the frequency of the 'pulses'. The beam is Gaussian across its width.

This arrangement allows controlled time intervals between pulses; relatively short pulses; uniform intensity of light throughout the flow field; and safe beam alignment. The basic arrangement of the laser and the scanning box is shown in Figure 6.2.

After many test recordings, 50 micron diameter bauxite was found to provide the best images of the flow, in comparison with other diameter sizes and materials. The seeding must be uniform throughout the flow. The density of particles in the flow needs to be carefully controlled, to ensure that enough particles are present to be analysed, but not too dense to prevent analysis of the flow.

The air is being extracted continually from the compartment. A continuous supply of the bauxite is needed during filming. After many attempts the best method found to introduce the bauxite, was via a tube and a plastic 'squeeze' bottle. The bottle was pressed at regular intervals, ejecting small amounts of bauxite powder.

The seeding was introduced at the rear of the fire compartment, into the ambient air being entrained into the fire. The amount of air introduced through the tubing was insignificant and did not affect the combustion process.

6.7.4 PIV Images

The PIV images were made until recently with photographs, but the procedure was time consuming. Video techniques have been developed to allow faster data acquisition and processing.

The flow was filmed using a S-VHS camera to provide fine definition, suitable for image capture and analysis. Many test films were made to find the correct scanning mirror speed, laser beam intensity and camera positions and settings. The camera was fixed to a rigid mounting to reduce vibrations. Markings at set dimensions were positioned inside the model, to provide a scale for the images.

Using 50 μm bauxite powder, in a reduced scale smoke flow experiment, it was found that with the laser power set to 12 W, a scan frequency of 100 Hz produced images of the best clarity.

6.7.5 PIV Images

For each experimental set up and at each location, at least 3 minutes of flow were videoed. From this the best quality 40 second sequence was selected and video frames at 5 second intervals were captured by Acrobat video software. These were then transformed into single frame bitmaps, with monochrome image depth of 8 bits (256 Grey Level), to enable the images to be processed.

The image was divided into 'interrogation' areas (grids), within which the velocity distribution is small. A vector (the 'mean' velocity) for all of the pairs within each grid was derived. The grid sizes needed to be as small as possible to provide detailed flow profiles. There was a limit to the minimum size of grid, based on the number of pixels per grid and particle sizes.

Three processes are available to quantify the velocities in the grid:

- Particle tracking
- Autocorrelation
- Crosscorrelation

The frames were analysed by VidPIV, a computer programme developed by Optical Flow Systems, the University of Edinburgh. Autocorrelation analysis was used. This is more accurate and reliable compared to particle tracking. It also provides signal-to-noise ratio information to reflect the validity of the data. Autocorrelation has disadvantages, as it is biased towards low velocities and requires the user to input the direction of flow (either in a positive or negative direction).

Crosscorrelation eliminates these disadvantages and reduces random correlation noise. This method requires more complex videoing and analysis techniques and was not available at the time of the experiment. Fortunately this experiment had well defined directions of flow. Local changes in direction of flow and hot gas edges were readily identified.

After initial analysis, filtering processes removed erroneous data. VidPIV does this by selecting data to be eliminated, by examining the velocity in each grid and comparing it to surrounding grids. Velocities that exceed neighbouring grid velocities by a set amount are eliminated. Velocities can also be filtered by vector quality (using the Signal to Noise Ratio). Manual editing was also done, to remove those erroneous velocities that were obviously missed by the filtering method.

The velocity data output was as vector maps and in tabular form, showing x- and y-velocities. These are in the Supplementary Appendix.

6.8 The Experimental Arrangement

6.8.1 General

The scale model was originally constructed in the Department of Civil and Environmental Engineering Laboratory. A preliminary set of experiments was conducted to investigate the range of conditions that would occur in the experiment:

- to find a suitable fire size
- to ensure that the construction would cope with the temperatures created within
- to refine the construction to ensure that no unexpected flow conditions are created
- to develop an initial comparison of results with atrium theory
- to investigate the suitability of the flow for PIV experiments
- to refine the experimental programme with the PIV work
- to identify any areas of interest

After these experiments, the scale model was dismantled and reassembled in the Fluids Laboratory. The design was altered to improve experimental operation.

In this thesis the preliminary set of experiments in the Civil Engineering Laboratory are referred to as the 'Preliminary Experiments'. Those in the Fluids Laboratory in the Department of Mechanical Engineering are referred to as the 'Main Experiments'

6.8.2 The Scale Model

6.8.2.1 General

It was a 1:8 scale model of a fire compartment and atrium., with similar dimensions to the FRS model (1:10 scale). The scale model construction is shown in Figure 6.3 and in Plates 6.1 to 6.8.

6.8.2.2 Construction Materials

The scale model was constructed of 12.7 mm plasterboard, fixed to a timber frame. Plasterboard provides similar boundary conditions to real models (Jolly and Saito 1992). The plasterboard was raised 15 mm thick from the face of the timber to allow

uniform heat loss from the face of the plasterboard. Dense 15 mm mineral board was used to construct the fire compartment to resist any flames, heat and chemical spills. The frame was made of timber, rather than proprietary steel framing, because it is economical and can give neat finishing and a rigid lightweight construction. The timber frame was also strong enough to support people, providing access to the high level extract fans and measurement points.

Thermal insulation was added to the outside of the model to reduce heat loss, for the Main Experiments. This prevented heat loss through the walls being dominant, which was found to cause excessive temperature loss in scale models (Jolly and Siato 1992). The insulation consisted of 100 mm mineral wool enclosed in aluminium foil. The foil acted as a non-combustible enclosure preventing laboratory occupant exposure to the mineral wool and reduced air movement through the wool. An additional layer of plasterboard protected the insulation and prevented laser reflections from the aluminium foil. The Preliminary Experiments were uninsulated.

A glass panel on one side of the atrium section allowed the smoke flow and reservoir depths to be observed and particles (illuminated by laser light) to be videoed.

Glass panels also formed a sidewall to each section of the compartment (except the fire compartment), to allow visualisation of the smoke along the length of the compartment. For the Main Experiments, these were covered with insulation, unless a particular section was to be viewed and no measurements to be taken.

The interior of the fire compartment and atrium was painted matt black, to provide a dark background for the videoing the flow particles and to reduce reflections.

The whole model was sealed at the plasterboard joints and glazing junctions to prevent hot gas losses. These were sealed with aluminium tape, covered with paper tape (to prevent local radiation effects from the aluminium tape. No significant leakage was found with tracer smoke.

6.8.2.3 Dimensions

The compartment had a fixed width and height, similar to the FRS model. This similarity allows a more accurate estimate of the conditions that could develop and an easy direct comparison of preliminary results. The fire compartment had the minimum height, as found by Alpert's ceiling jet investigations (see Section 6.5.2), to prevent the formation of an excessive boundary layer.

The fire compartment had removable sections, to vary the length, in 600mm steps; 660, 1260, 1860 and 2460mm. This differed from the basic form of the FRS's reduced-scale model, where the fire compartment length was fixed at 1000mm. According to Alpert (see Section 6.5.2), the maximum recommended length of a ceiling jet is approximately 3 times the compartment height. This suggests that the maximum compartment length should be 2100 mm (1800 mm jet length plus the 300 mm to the back of the fire compartment). A 2460 mm length does not greatly exceed this, so little additional error should develop compared to that in the recommended ceiling jet length limit.

At the compartment exit, downstands of 50, 100 and 200 mm could be fixed. The model also had hidden bolts to allow the easy fixing of various sizes of balconies (not used due to time restrictions). The downstand sizes were chosen based on an estimated ceiling jet thickness.

6.8.2.4 Air Movement within the Compartment

The model allowed the inlet air to enter the fire compartment from the atrium space. The incoming air passed under the opposing flow of the exiting air. In the FRS model the inlet air was introduced from the back of the compartment, and a shutter at the front prevented the entry of air under the exiting air.

In the Main Experiments, an external balcony, honeycombing and internal meshes were needed to reduce the turbulence in the atrium, without these the hot gases were

drawn down to the rear opening and mixed with the incoming air, preventing the formation of a stable hot layer, see Figure 6.4.

6.8.2.5 Smoke Reservoir and Height of Rise

The heights of rise of the spill plume and the depths of the smoke reservoir were similar to those used in recent experiments by the Marshall, Harrison and Morgan (1993). At these values, the reservoir depth, defined by the visible smoke layer, was similar to the depth defined by the temperature gradient. Therefore the effective height of rise was equal to the actual height of rise. The effective height of rise was approximately similar to the actual height of rise, as measured by the visible smoke layer in the Main Experiments.

6.8.2.6 Extraction System

In Preliminary Experiments, the smoke was to be extracted at a controlled rate, so that the smoke layer could be set to form at pre-determined height. Unfortunately, the extract ductwork had high pressure losses, so the extract system could not cope with the quantities of smoke. These measurements were made in the Main Experiment, using a better extract duct in the Fluids Laboratory.

For the Main Experiment, the extract ductwork and fan were connected to an existing open duct which terminated at roof level, with a protected roof cowl.

The smoke reservoir was visualised using the fibre board smoke, that was illuminated with a lamp. A fan controller set the extraction rate. The underside of the smoke was used to set the reservoir height to 750 mm or 550 mm above the bottom of the downstand. The underside of the smoke undulated by ± 50 mm. If greater rises and falls developed due to external wind pressures, the experiment had to be abandoned, until calmer wind conditions prevailed. Once the extraction rate was set and the conditions were steady, PIV or temperature recordings were made.

Velocities in the duct were measured using a pitot-static tube. The mean velocity was found with the 'log-linear rule' (Daly 1992). This was conducted at various extraction rates and temperatures. A consistent point of measurement was found, that was equal ($\pm 5\%$) to the mean velocity point. This point was used as a single measurement point for the mean velocity, to calculate the extract flow rate.

6.8.3 Instrumentation

The data from the instruments (except the Dantec probe) was recorded by a Windmill data logger system. The following were used to measure the flow in the experiments:

- k-type thermocouples in a mobile in the w-plane, y-plane, at set distances along the compartment and at low levels above the y-plane.
- single k-type thermocouples, on the external face of fire compartment, to gauge heat loss.
- a pair of thermocouples in the y-plane and w-plane to provide a continuous check that the fire and smoke were at steady-state.
- 2 mm diameter Pitot-static tube connected to a Furness FC011 Micromanometer in the extract duct.
- PIV system as described in section 6.7.
- ADC CO₂ Analyser Type SS-200 to measure profiles in the w-plane and y-plane. Reliable data was obtained in a limited number of tests in the Main Experiment.
- Dantec Flowmaster Precision Anemometer Type 54N60 to measure the velocities up the spill wall. Preliminary Experiments only.
- 2 mm diameter Pitot-static tube connected to a Furness FC011 Micromanometer to measure exit velocities from the compartment. Preliminary Experiments only.

6.9 Fire Sizes

6.9.1 General

The fire source needed to have the following characteristics:

- fuel bed controlled
- steady-state
- turbulent
- controllable heat output
- minimal safety risk

6.9.2 Choice of Heat Source

Different fuel sources were considered. These included electric heaters, wood cribs and gas burners. These methods are discussed in Appendix 6.

Methanol was used for these experiments, because it has complete (quantifiable) combustion, therefore the heat output can be controlled, using a flowmeter.

Complete combustion also prevents the production of soot particles and carbon monoxide. It should be noted that small amounts of impurities produced insignificant amounts of soot and carbon monoxide. With no soot being produced, less dirt is deposited on instruments and the internal plume structure is visible for PIV. A low luminosity flame reduces the amount of light reflections that would interfere with the PIV light sheet particle illumination.

Clean flames and hot gases emit less radiation, than sooty opaque smoke, typical of building fires, therefore the heat losses are less. This is important in reduced-scale experiments, because successful Froude modelling requires negligible radiation effects.

Lee and Emmons (1961) found that if acetone was used for their line plume experiments, rather than alcohol, much more soot was produced, and radiation losses

were increased significantly, which in turn reduced the temperature and increased the Froude number (Fr). In some experiments with acetone, Fr was over 1. This is a critical value above which entrainment is increased. Smoke produced in compartment fires with cellulosic material has a high concentration of smoke particles, but despite this, the Richardson number of the ceiling jet (an approximate inverse of the Froude number) away from the plume is above 0.8 (see Chapter 5), therefore entrainment is low. Reduced-scale experiments must have negligible radiation to avoid excessive radiative heat loss and consequential changes in entrainment rates. This is achieved with clean burning fuels such as methanol.

Jolly and Saito (1992) found that the radiative heat flux between full-scale and reduced-scale models differed from expectations, due to differing quantities of soot particles in the hot gases. For reduced scale experiments, a fuel source that produces a low concentration of soot particles should be used to minimise radiative heat losses.

6.9.2 Early Fire Tests

These tests were conducted to find the best method for burning the methanol and an ideal fire size. The fires for the spill plume experiments need to have a known area and heat output. These need to remain constant for the duration of the experiment.

The series of tests conducted included:

- methanol fires with differing fuel trays and cooling methods, in an open laboratory space.
- methanol fires in the rig, to determine the fire sizes to use for the experiment.

6.9.2.1 Theoretical Considerations

The combustion of methanol has been examined by many researchers. For most pool fires over 200 mm diameter, radiation is the dominant factor affecting the combustion rate. It is also a major factor at lower diameters. Methanol burns with a clear flame and produces relatively little radiation (compared to other fuels), so radiation effects are limited. It burns at a constant rate, $0.017 \text{ kg/m}^2\text{s}$ (the regression

rate) irrespective of the pool diameter for diameters of 50 mm up to 20 m (Babrauskas 1988), because radiation does not become a major heat transfer process for this range. Below 100 mm diameter, higher burning rates occur due to relatively higher levels of heat loss due to conduction (Nakakuki 1994).

If the methanol pool area is constant, then the burning rate is constant. This assumption is used in the Fire Research Station's smoke control experiments. In their reduced-scale tests, the methanol was burned in a tilted metal 'plate', providing an approximate steady area.

There is a risk that conduction from the fuel tray and radiation from surrounding surfaces could cause the fuel rates to vary, even cause very rapid 'boiling-off of the fuel. In the full-scale tests at the Fire Research Station, methanol was burned in water cooled metal trays (1 m by 1 m), to prevent overheating of the methanol (Hansell 1993).

At reduced-scale, conduction and radiation (in enclosures) to the fuel tray may increase the tray temperature, therefore increase the combustion rate. Thus, the heat output and fire area could vary during the course of an experiment. Some researchers have placed a water cooling jacket underneath the fuel tray to ensure that the temperature remains constant (e.g. Lee and Emmons 1961). Beyler (1986) used a water cooled tray to burn methanol, when studying flames in compartment fires, to reduce the affects of radiation and conduction, to ensure that the combustion rate was constant.

6.9.2.2 Laboratory Fires

A set of methanol fire experiments were conducted, in an open laboratory space, to discover if the using a simple burning tray would be sufficient to provide a controlled burning rate and heat output.

By placing a tray on a wire cage, approximately 25 mm above the table top (to encourage air cooling around the tray), a steady burning rate could be obtained. A constant combustion rate of 0.199 g/s (3.97 kW) was obtained, when using a flat bottomed Pyrex 150 mm diameter, 12 mm deep dish. The regression rate was 0.0113 kg/s, less than that commonly reported ((Babrauskas 1988)). This could be, in part, due to the cooling affects of the air flow.

6.9.2.3 Heat Source in the Scale Model

In the spill plume model fire compartment, the combustion rate varied considerably and a steady state condition could not be maintained, when using the flat bottomed Pyrex plate. The combustion rate was found by maintaining a constant mass of methanol in the Pyrex dish and using a flowmeter to measure the amount of methanol required to replace the burned methanol.

A set up, similar to the FRS compartment fire method was used. This allowed the flow rate to be controlled with the flow meter and a constant fire area to develop. The tray was placed on a wire mesh raised 25 mm above the floor of the fire compartment (see Figure 6.5).

Different fire sizes were investigated. It was found that 4.67 kW was a reasonably sized standard fire, being turbulent, with flames below ceiling height and temperatures that were not excessive. A larger fire size, 6.09 kW, was also used. This had flames that were just below ceiling height and produced temperatures at the limit of the tolerance of the rig.

6.9.2.4 Visualisation of Hot Gas Flow

The hot gases were visualised so that the depth of the hot layer in the compartment and reservoir depth could be measured against discrete scales. The flow structure was also visualised to help explain some of the data gathered. Visualisation was not done when instrument readings were being recorded or when PIV work was being conducted.

The most efficient method of visualising the hot gases produced by the fire, was found to be cool smoke from smouldering fibre board (10 x 10 mm). This smoke had very low heat output and low buoyancy in comparison to the methanol fire, therefore it was drawn into the hot gases without affecting the flow structure.

A proprietary hot oil mist probe was used, but the smoke was too hot and its small plume 'penetrated' the ceiling jet and not mixing effectively with the hot gases.

6.10 Experimental Programme

6.10.1 Preliminary Experiments

The fire compartment geometries were the same the Main Experiments, shown in Figure 6.6 were examined, with a 4.67 kW fire source. The experiments were conducted for adhered plumes only.

6.10.1.1 Measurements

The measurements, located in Figure 6.6, were:

- Horizontal and vertical thermocouple tree readings to measure the temperatures at the exit, within the compartment and up the spill wall.
- Pitot tube readings at the exit and anemometer readings up the atrium wall, using 2 mm diameter Pitot-static tube connected to a Furness FC011 Micromanometer.

Velocity measurements were made with the Dantec anemometer and CO₂ measurements made with the ADC analyser. Difficulties with the instruments gave poor results, so are not included.

6.10.1.2 Quantitative Results of Measurements

The following smoke characteristics (method of calculation and results shown in Chapter 7) were calculated:

- Mass flow rates for the w-plane and y-plane.
- Heat fluxes for the w-plane and y-plane.

The heat flux and mass flow rates at the z-plane were not found due to instrument and extract duct problems.

6.10.1.3 Other Flow Characteristics

The Preliminary Experiments verified that the following conditions existed. These are shown in Chapter 7:

Turbulence

The flow appeared to be turbulent, so that Reynolds number and boundary layer effects would be minimal, therefore Froude modelling would be effective.

Two-dimensional

The flow was approximately two-dimensional, therefore would be suitable for PIV analysis. The temperature profiles in the w-plane and y-plane measured at different distances from the centreline of the fire compartment, see Figure 6.7, were similar, varying by less than $\pm 8\%$. Visual observations with smoke found insignificant lateral flow, see Chapter 7.

Within 50 mm of the sidewall, the hot gases were deeper than along the central section of the exit, this phenomenon is examined in Chapter 7.

Periodicity

There was a large scale periodicity of approximately 45 seconds, due to large eddies. Smaller scale periodicity occurred (due to smaller eddies). A 90 second sampling time was adopted for thermocouples and other instruments. Comparisons with 120 and 180 second sampling periods found insignificant differences (1-2 %). Sampling was at 5 second intervals. Insignificant variation was found by increasing the sampling rate from 5 seconds to 2 seconds. Similar sampling periods were used at

the FRS. A 40 second sampling time was adopted for the PIV analysis, to prevent excessive periods of videoing and processing.

Time to Steady State Conditions

The time to steady state was found, by temperature analysis. It took approximately 8 to 10 minutes for steady state conditions to develop.

The external surface temperature of the rig reached steady state within 15 minutes, with a continuing temperature rise, 1° to 2° C, over the next half an hour.

6.10.1.4 Consequential Developments for Main Experiment

The Preliminary Experiment also revealed areas where the detailing and methodology of the Main Experiment could be improved:

- The Dantec anemometer results were unreliable. The probe overestimated the velocity of the plume, measuring all velocity components. It also gave inconsistent temperature readings. This was not used in later experiments.
- The CO₂ readings were difficult to obtain, because the sampling probe could easily disturb the flow and the length of time that it took for the analyser to
- Heat loss through the single sheet of plasterboard could be significant. To reduce this insulation was added to the scale model for the Main Experiments.
- Thermocouple tree layouts were rationalised.
- An improved extraction system was developed.

6.10.2 The Main Experiment

The Main Experiments were conducted with the geometries and measurement at the locations shown in Figure 6.8. The following measurements were made:

1. Mass flow in the extract duct.
2. Thermocouple tree (the thermocouple tree is shown in Figure 6.9).
3. PIV analysis of the flow at the w-plane, y-plane and z-plane, (see Supplementary Appendix for exact location of images).
4. CO₂ analysis, at the w-plane and at set heights above the y-plane.

The PIV videoing was conducted after the temperature measurements had been completed. To ensure that similar conditions were created during the two experimental runs, the mass flow rate in the ducts was checked during the PIV experiments, and was found to vary by $\pm 10\%$, from the set of experiments measuring temperature. The temperature varied by less than $\pm 2\%$.

6.10.2.2 Instrumentation

The data (except from Dantec probe) was centrally recorded by a Windmill data logger system. The following were used to measure the flow in the Main Experiments:

- PIV system

Spectra Physics 171, 15 W, Argon Ion 514 and 488 nm (green and blue) continuous wave laser. Laser output set to 12 W.

Beam transmitted to scanning box via fibre optic cable.

Scanning box by Optical Flow Systems. Set to frequency of 200 Hz.

Seeding: 50 μm diameter bauxite powder.

Images on S-VHS video camera. Minimum of 3 minutes of flow recorded. Images captured with Acrobat video software, in monochrome with depth of 8 bits (256 Grey Level). Video frames sampled at 5 second intervals for velocity data. Frame by frame analysis to visualise flow patterns. Image analysis by VidPIV programme, from Optical Flow Systems, using autocorrelation technique (Interrogation grid data see Supplementary Appendix). Filtering and manual editing to remove erroneous velocities.

- k-type thermocouples.
- 2 mm diameter Pitot-static tube connected to a Furness FC011 Micromanometer.
- ADC CO₂ Analyser Type SS-200 to measure profiles in the w-plane and y-plane.

6.11 Experimental Safety Procedures

6.11.1 Fire Spread

The construction of the model was such that heat transfer to the timber frame was minimal. The fire sizes used during the experiments were limited. The temperature on the outside face of the inner sheet of plasterboard was less than 80° C.

The greatest fire risk was from the methanol. A leak from either the fire compartment, or the reservoir tank or tubing, would cause a rapid spread of methanol across the floor. Figure 6.3 includes the detailing inside the fire compartment to contain of methanol spills within the compartment, using sand and bunding.

To prevent fire spread up the methanol supply piping, the copper tube feeding the methanol to the tray had loose fitting wire wool plugs at both ends. The methanol supply pipes were encased in reinforced plastic petrol piping.

The methanol reservoir sat in a metal frame. The frame was lined with plasterboard and mineral wool insulation. By placing ice packs around the reservoir, the temperature was reduced to below the flashpoint, 12° C. This was to reduce the risk of ignition of methanol vapour in the top of the reservoir and to reduce the amount of methanol vapour entering the laboratory.

Water and CO₂ extinguishers were on hand, and a safety procedure developed. This was posted on the side of the rig, a copy is in Appendix 6.

6.11.3 Laser Safety

To ensure safe operation of the laser and other parts of the PIV system, all established laser safety measures were followed. Everyone working with the experiment attended a laser safety course, and followed relevant procedures. Adaptations to the design of the rig, to avoid laser reflections have been described earlier.

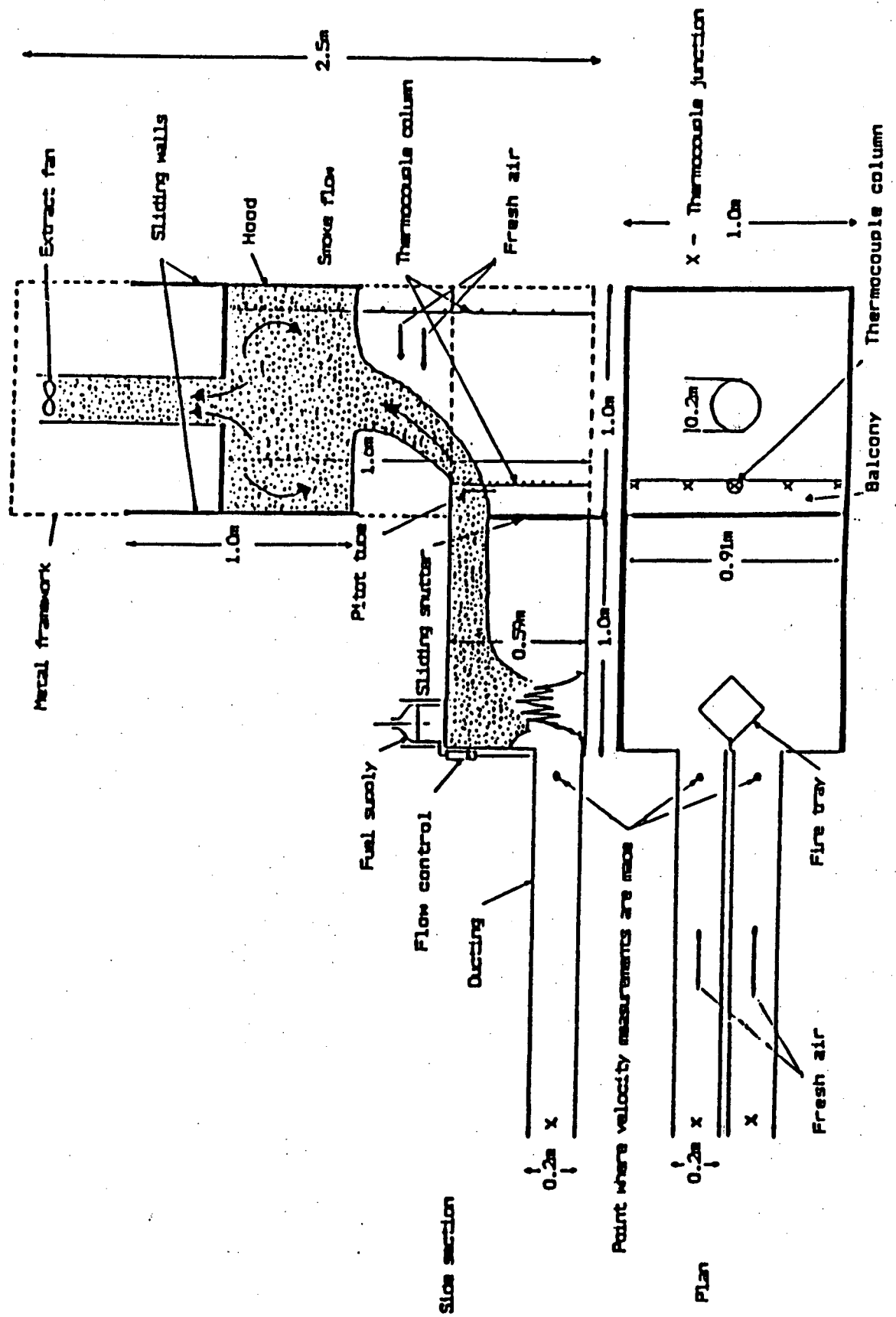


Figure 6.1 The FRS Reduced Scale Model Atrium (Morgan, Harrison and Morgan (1993))

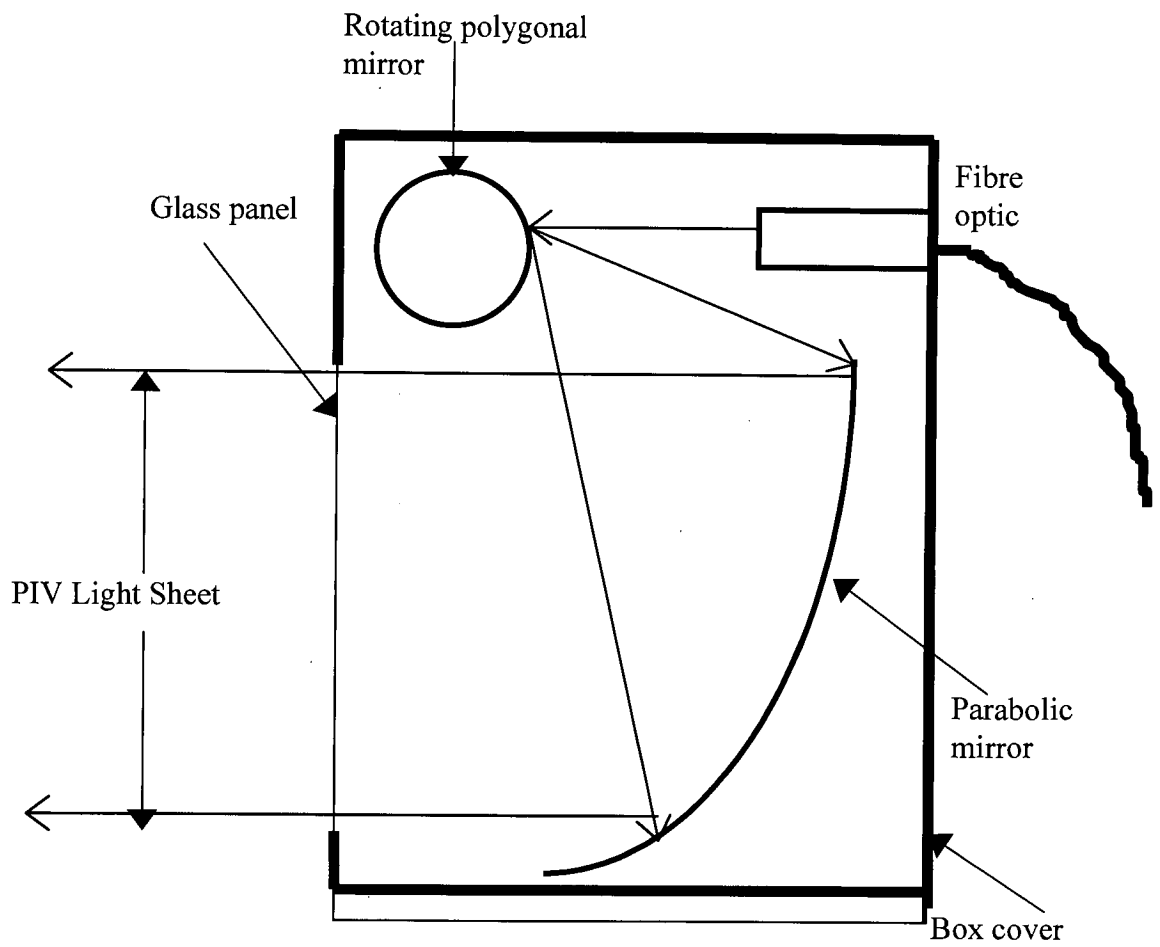


Figure 6.2 Typical Scanning Beam Illumination Method (Bruce 1996)

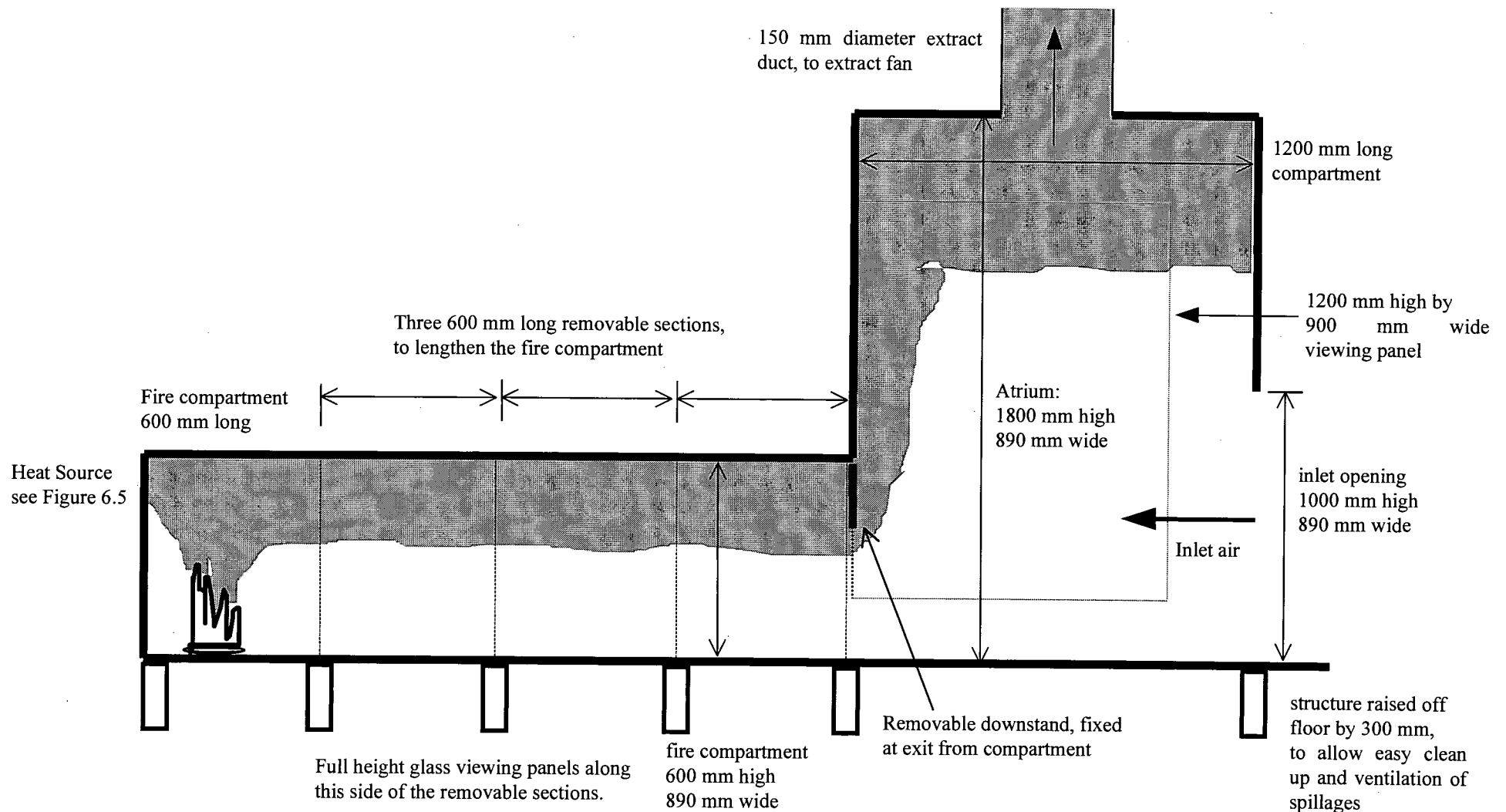
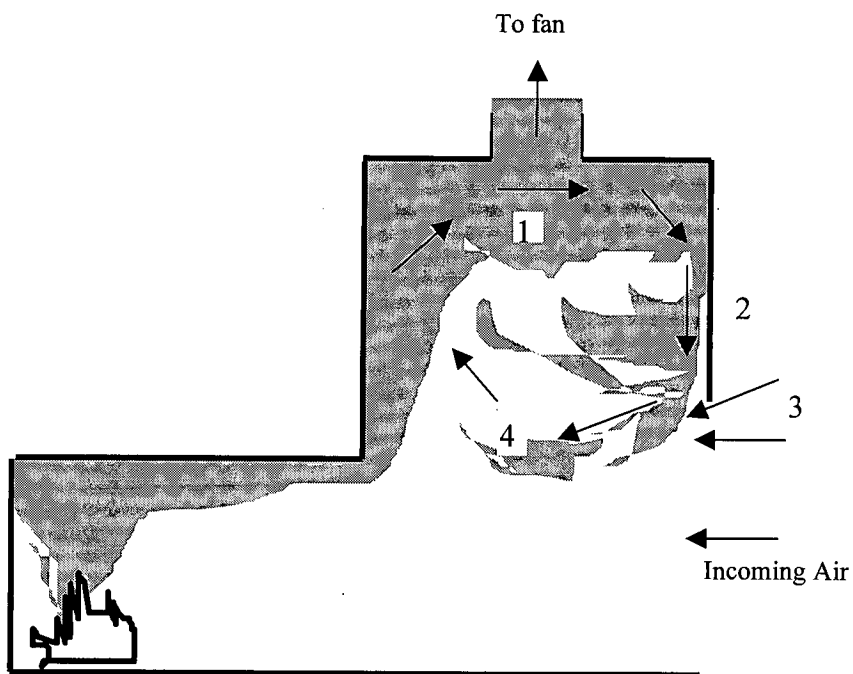


Figure 6.3 The Model used for Experimental Analysis of Smoke Movement in Atrium

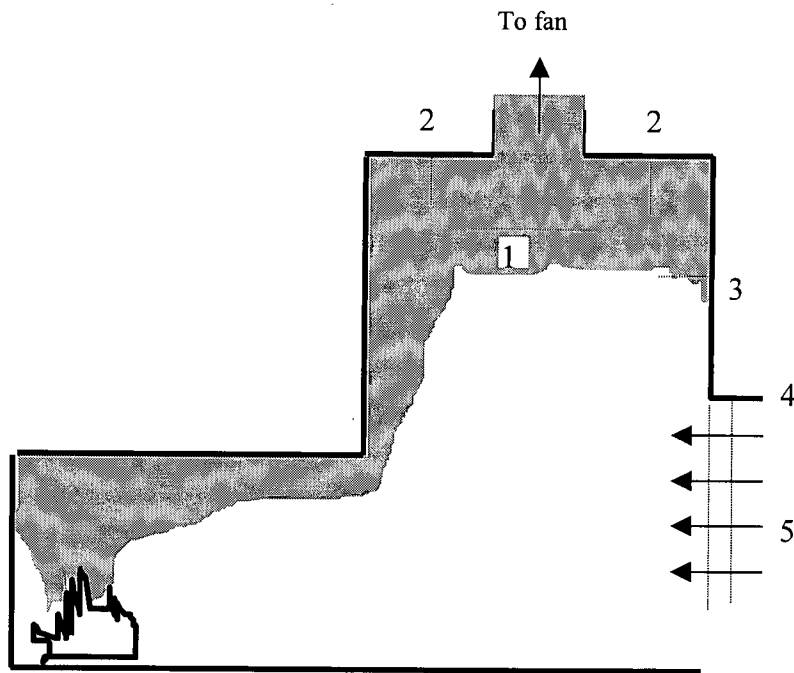


Large vortices form in the atrium, due to the following key features:

1. Momentum and buoyancy of plume converted into strong velocity of ceiling jet.
2. Strong negative gravity current (wall jet), as ceiling jet hits wall.
3. Rapid acceleration of inlet air around top edge of into atrium.
4. Wall jet and inlet air mix together

No clear layer forms in the atrium.

**Figure 6.4 a Smoke and Air Movement within the Atrium
without Turbulence Reduction Measures**



Vortices minimised in the atrium, due to the following key features:

1. Fine mesh (1 mm diameter holes) 250 mm beneath the outlet to the fan to minimise disturbance to the smoke layer.
2. Fine mesh barrier extending 50 mm below the ceiling, to reduce ceiling jet velocities.
3. Fine mesh barrier extending 250 mm from wall, to reduce wall jet velocities.
4. External balcony to prevent air accelerating around inlet edge.
5. Honey combing to break up large eddies. Metal honeycomb sheet, 50 mm thick, with 10 mm diameter holes. Creates reasonably parallel flow, with small eddies.

Figure 6.4b Turbulence Reduction Measures to Prevent Large Vortices

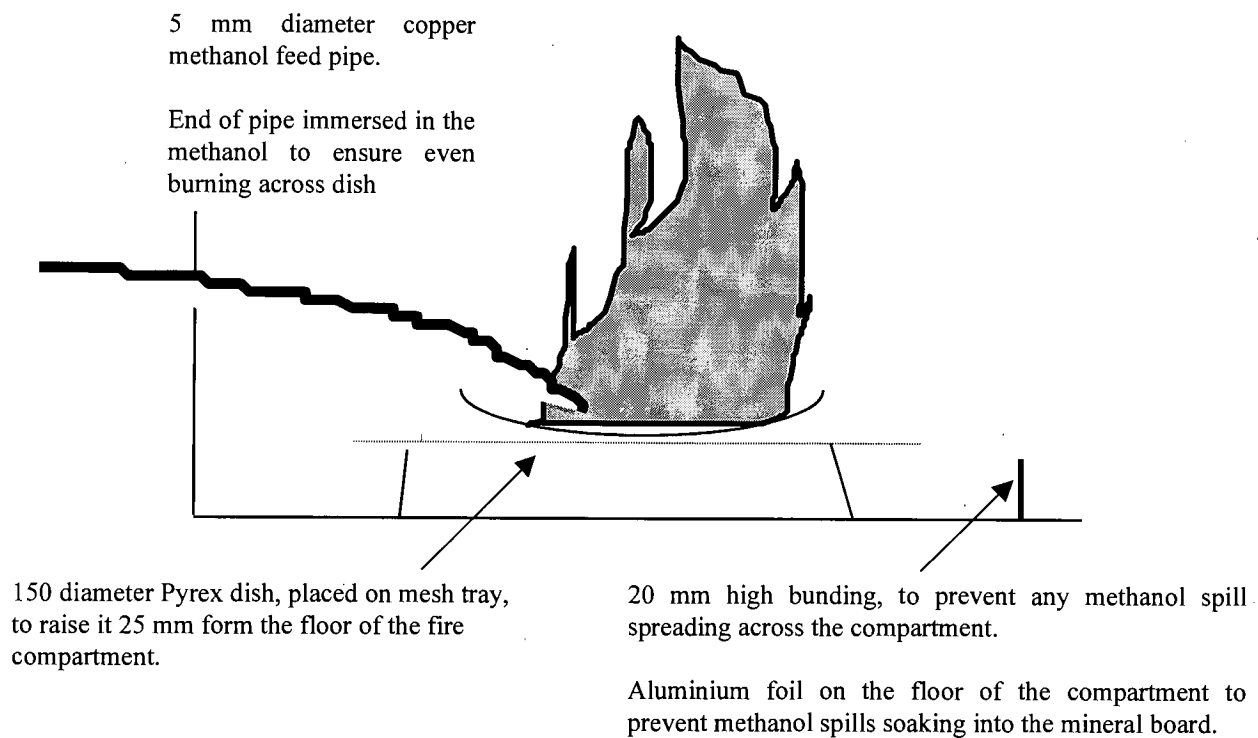


Figure 6.5 Methanol Supply and Fire Tray

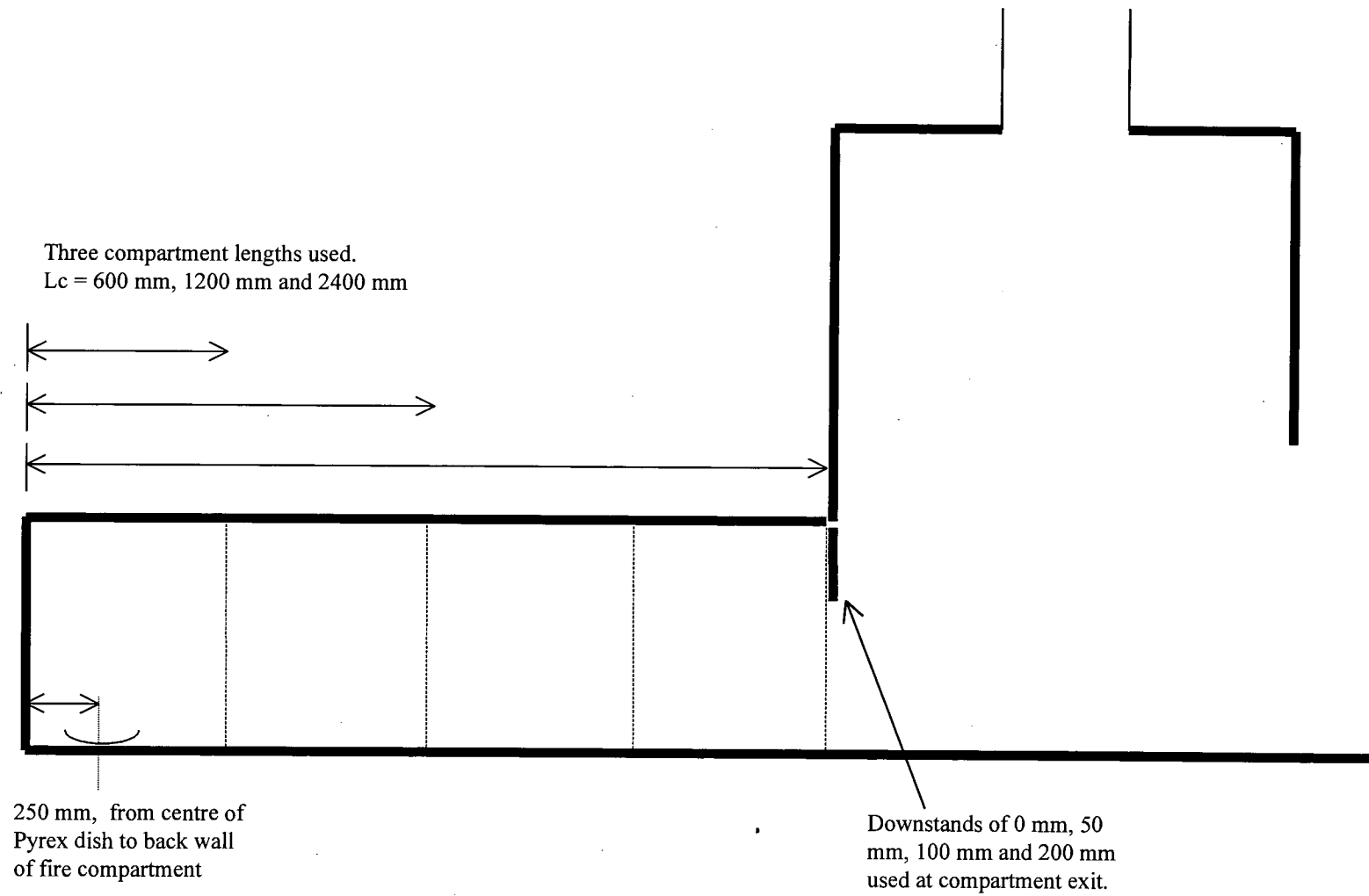


Figure 6.6 The Geometries used for the Preliminary Experiments

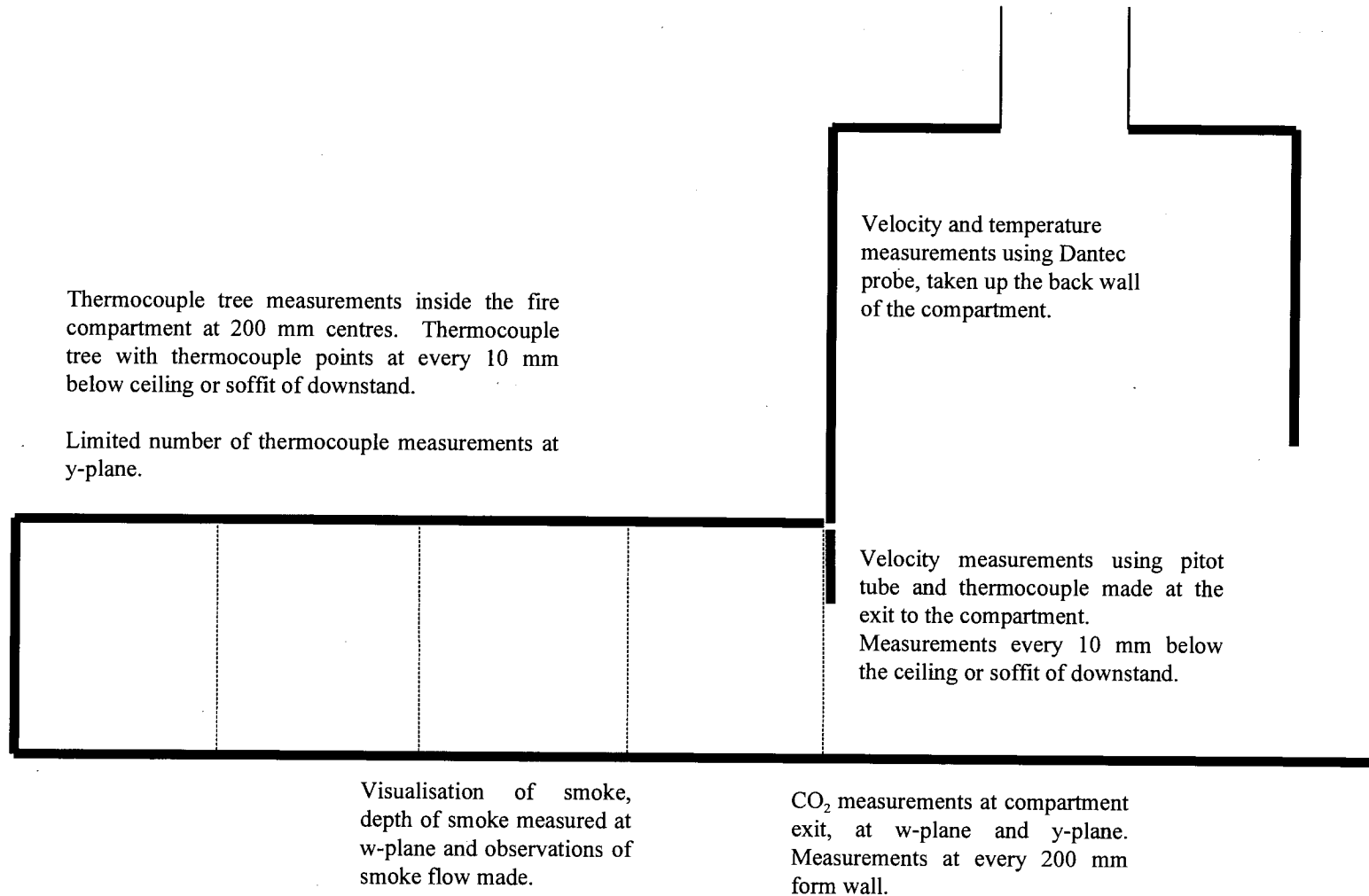


Figure 6.7 The Instrumentation used for the Preliminary Experiments

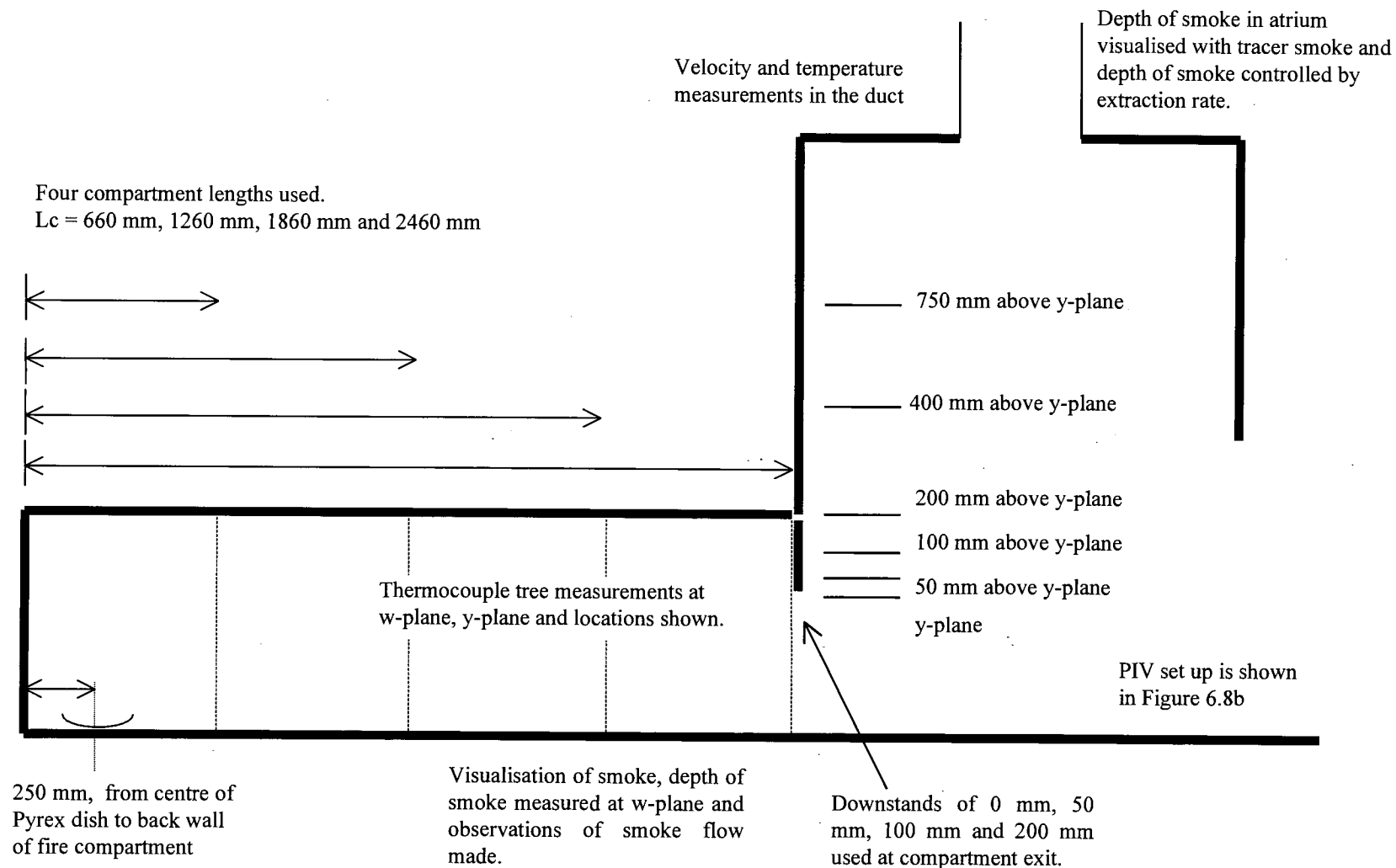


Figure 6.8 a The Geometries and Instrumentation used for the Main Experiments

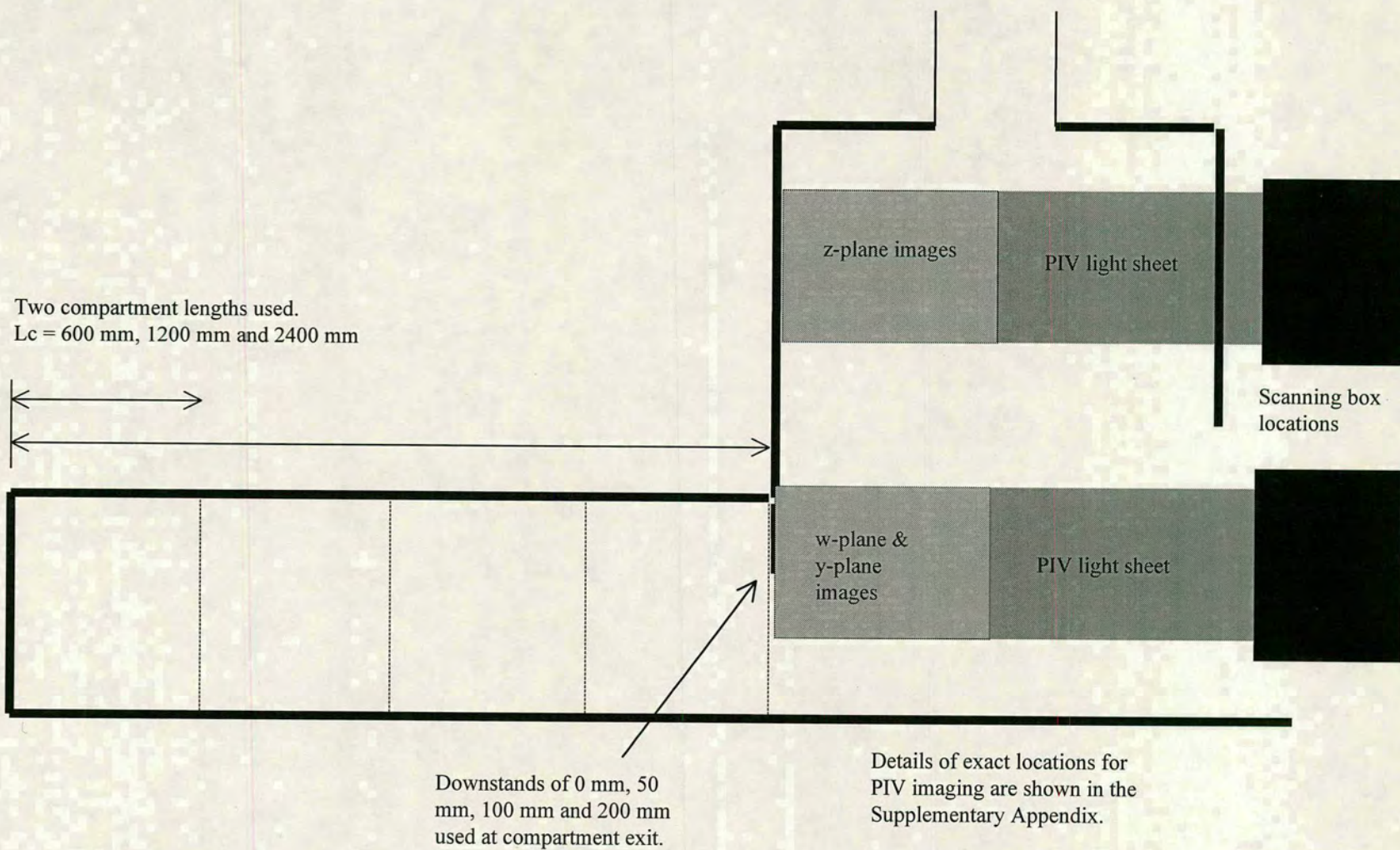


Figure 6.8b The Arrangement of the PIV Measurements

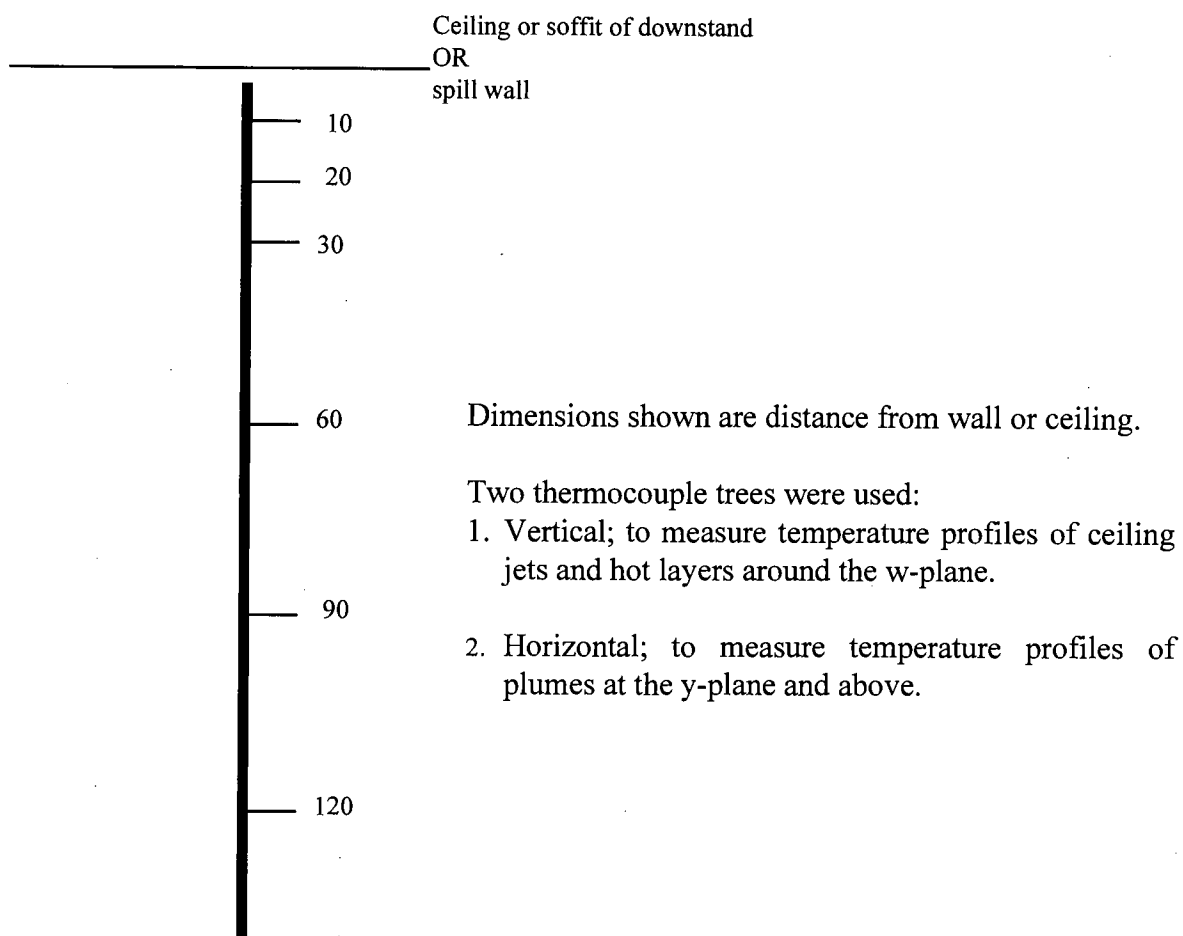


Figure 6.9 Thermocouple Trees

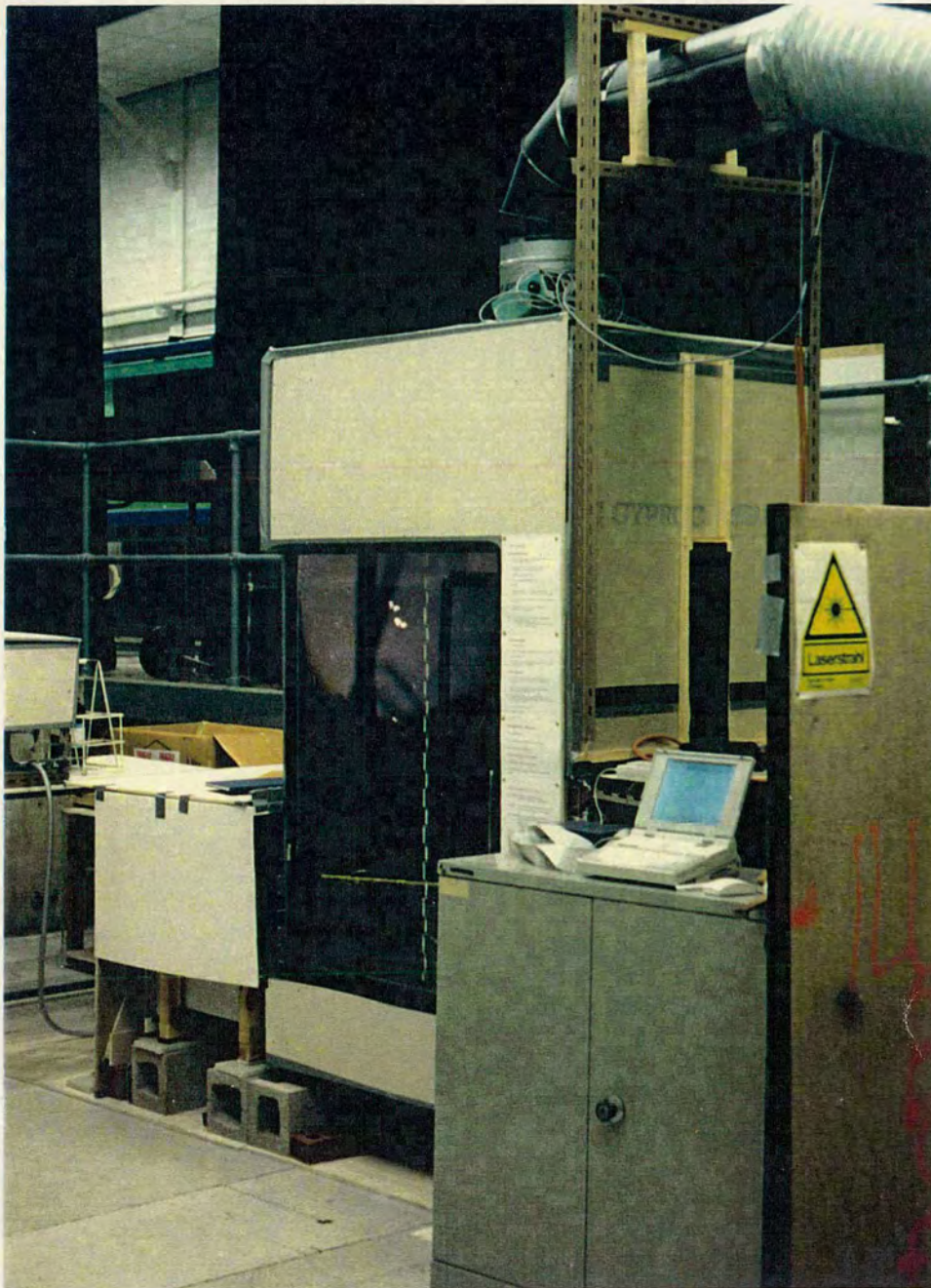


Plate 6.1:

General set-up for short compartment length, $L_f = 0.41$ m.

Glass viewing panel in side of atrium. Interior of structure painted black to minimise reflections. Narrow front panel for PIV light entry.

Extract duct at high level.

Methanol reservoir to rear.

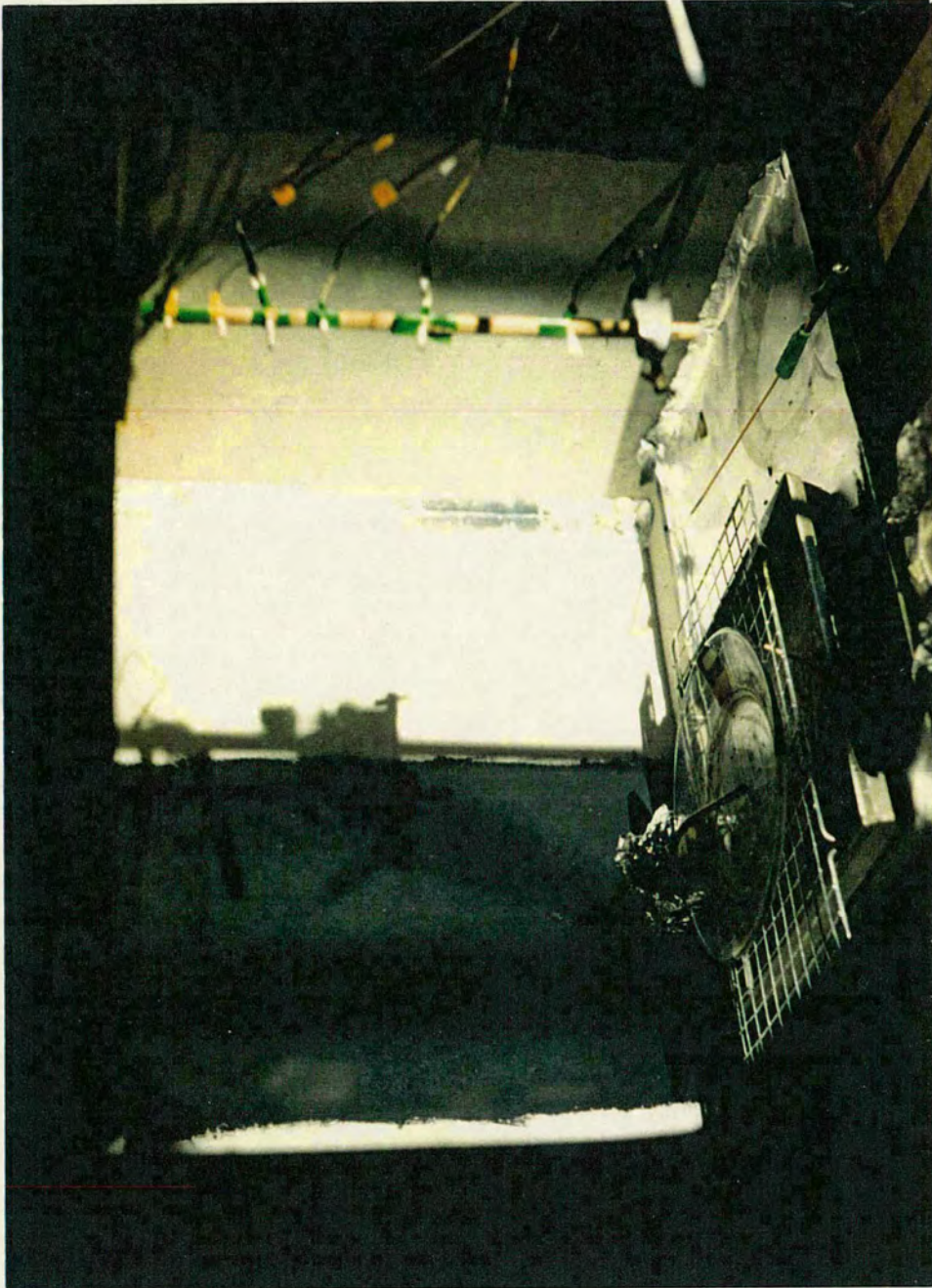


Plate 6.2:

Inside view of the fire compartment. Much of interior painted black minimise light reflections.

Thermocouple tree visible.

Plate methanol fire placed on wire mesh. Copper tube for methanol supply to rear.

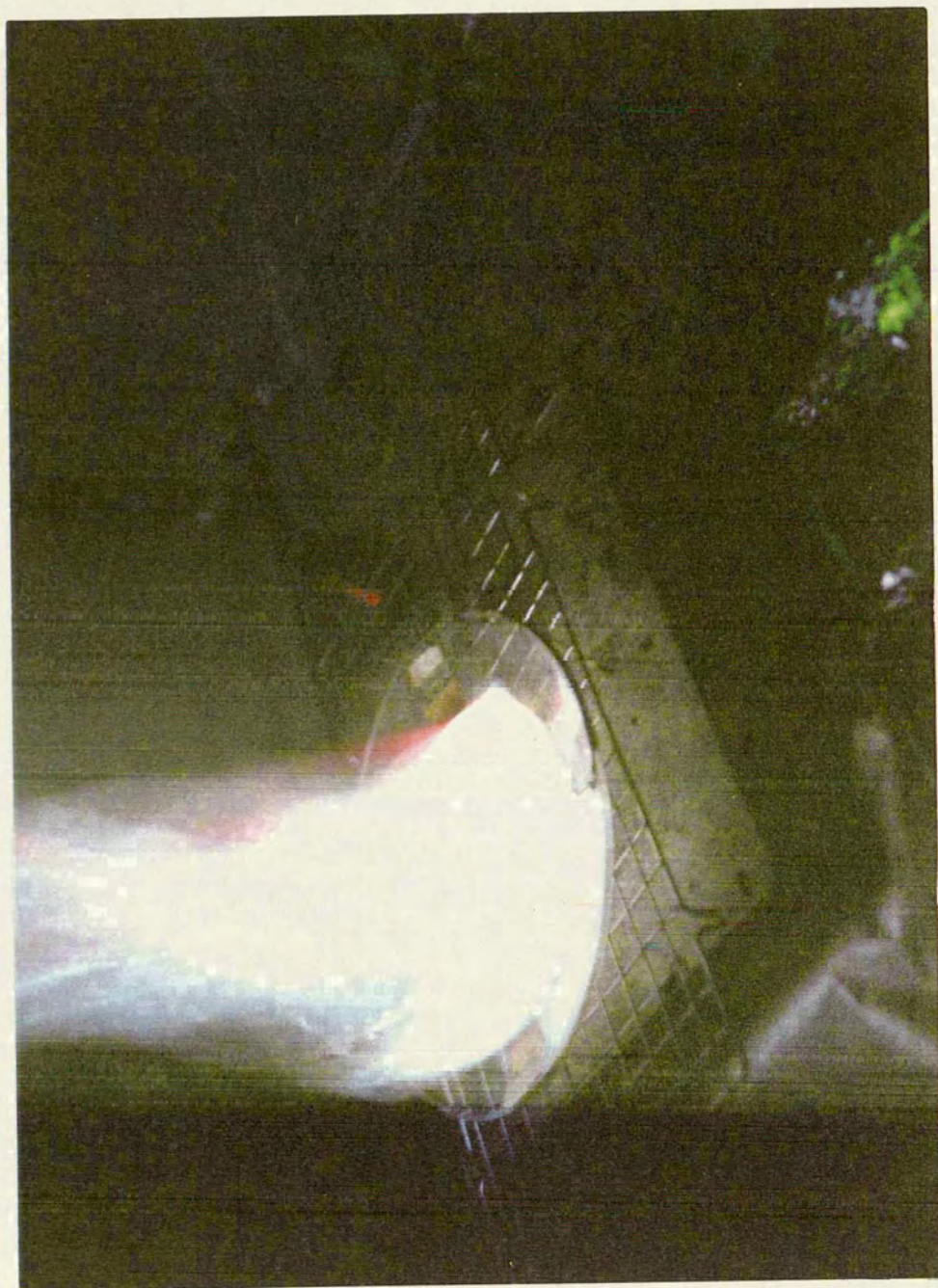


Plate 6.3:
Methanol fire (4.61 kW).

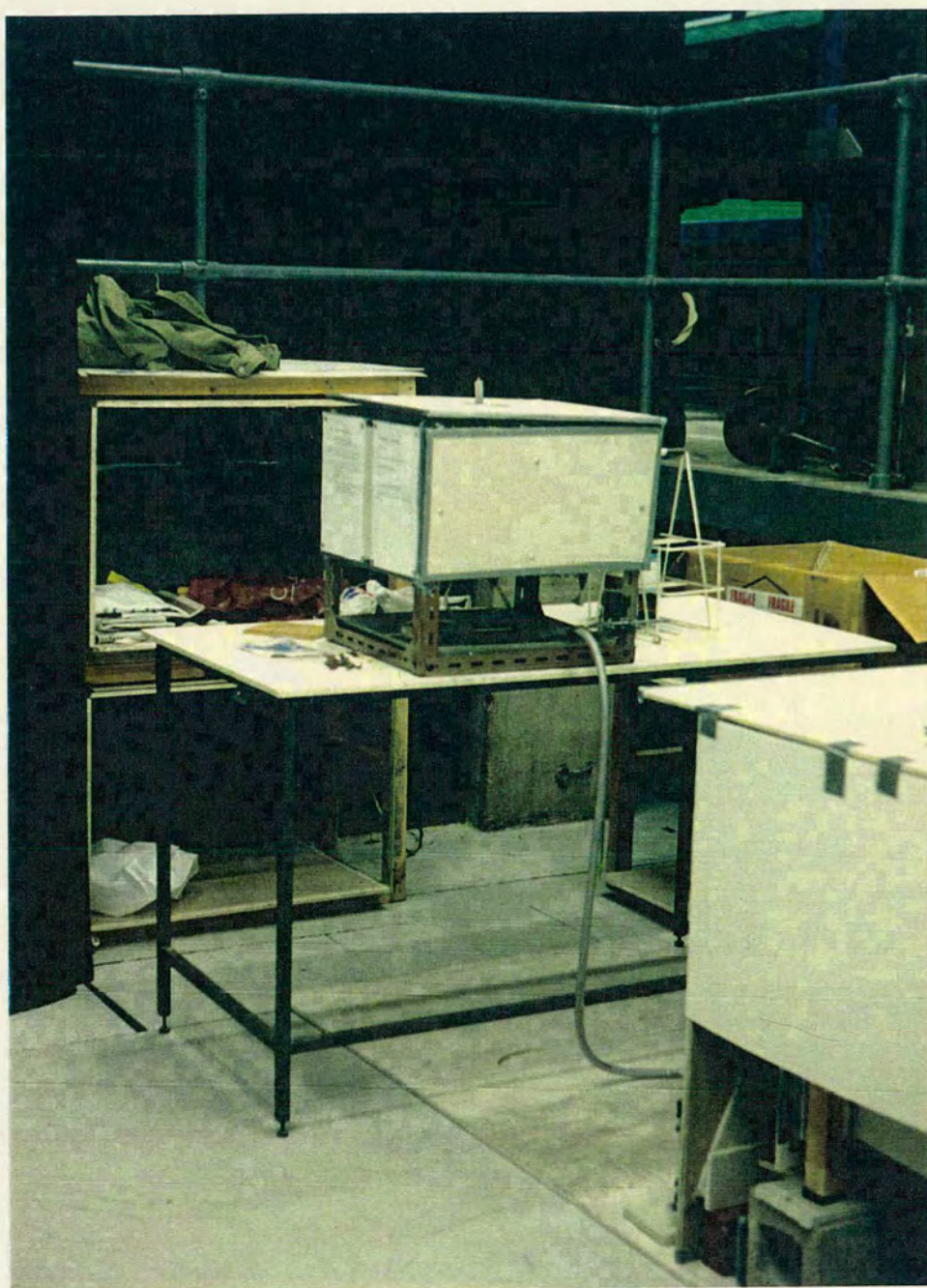


Plate 6.4:

Methanol reservoir and supply pipe. Pipe enclosed in reinforced petrol pipe. Insulated plasterboard casing around copper tank. Ice packs placed around tank to keep temperature below 7°C .

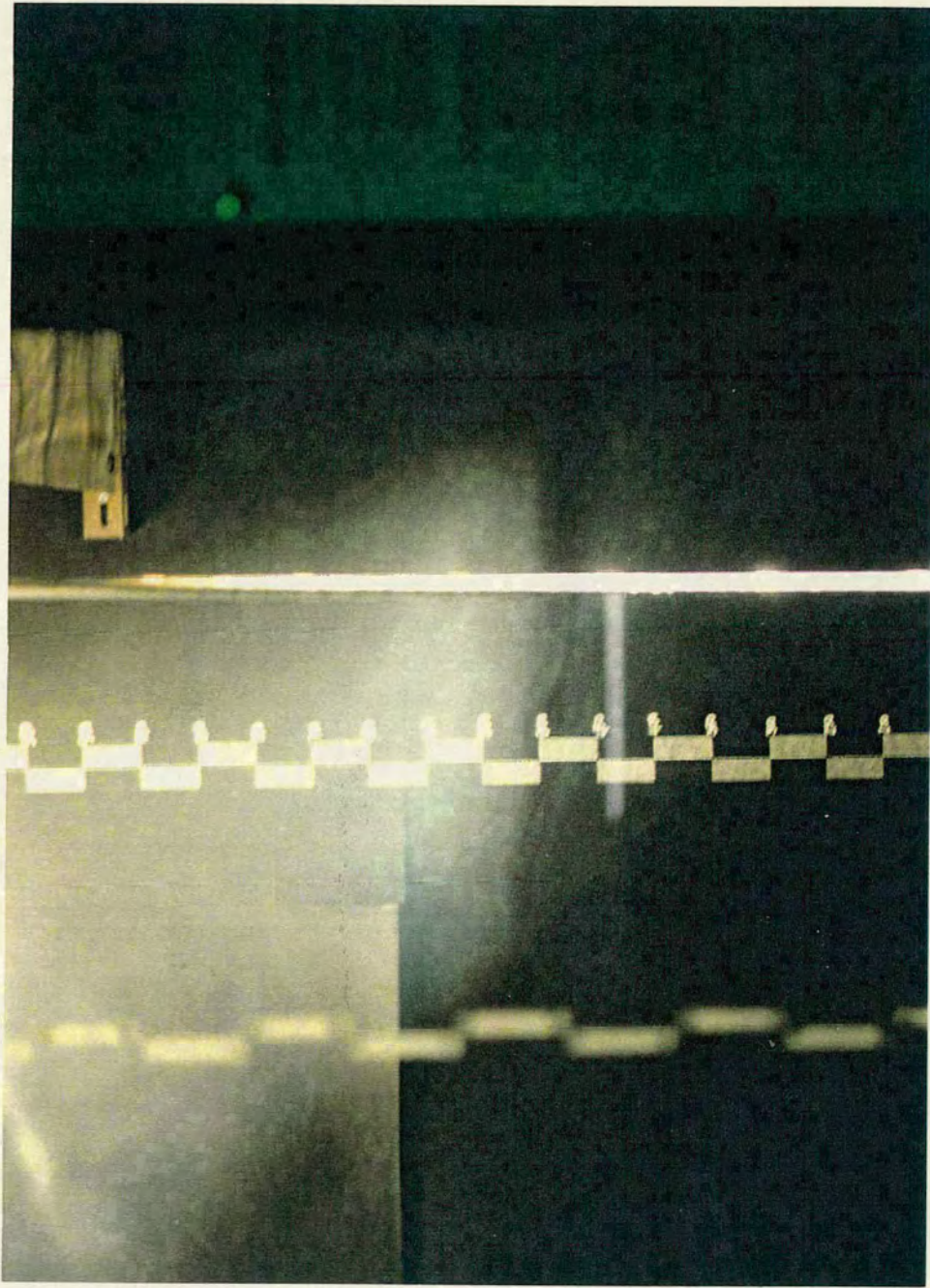


Plate 6.5:

Scales in atrium, for sighting the smoke reservoir height. Scales are in 50 mm.

Note that the smoke in photograph has not formed a suitably stratified layer for measurement purposes.

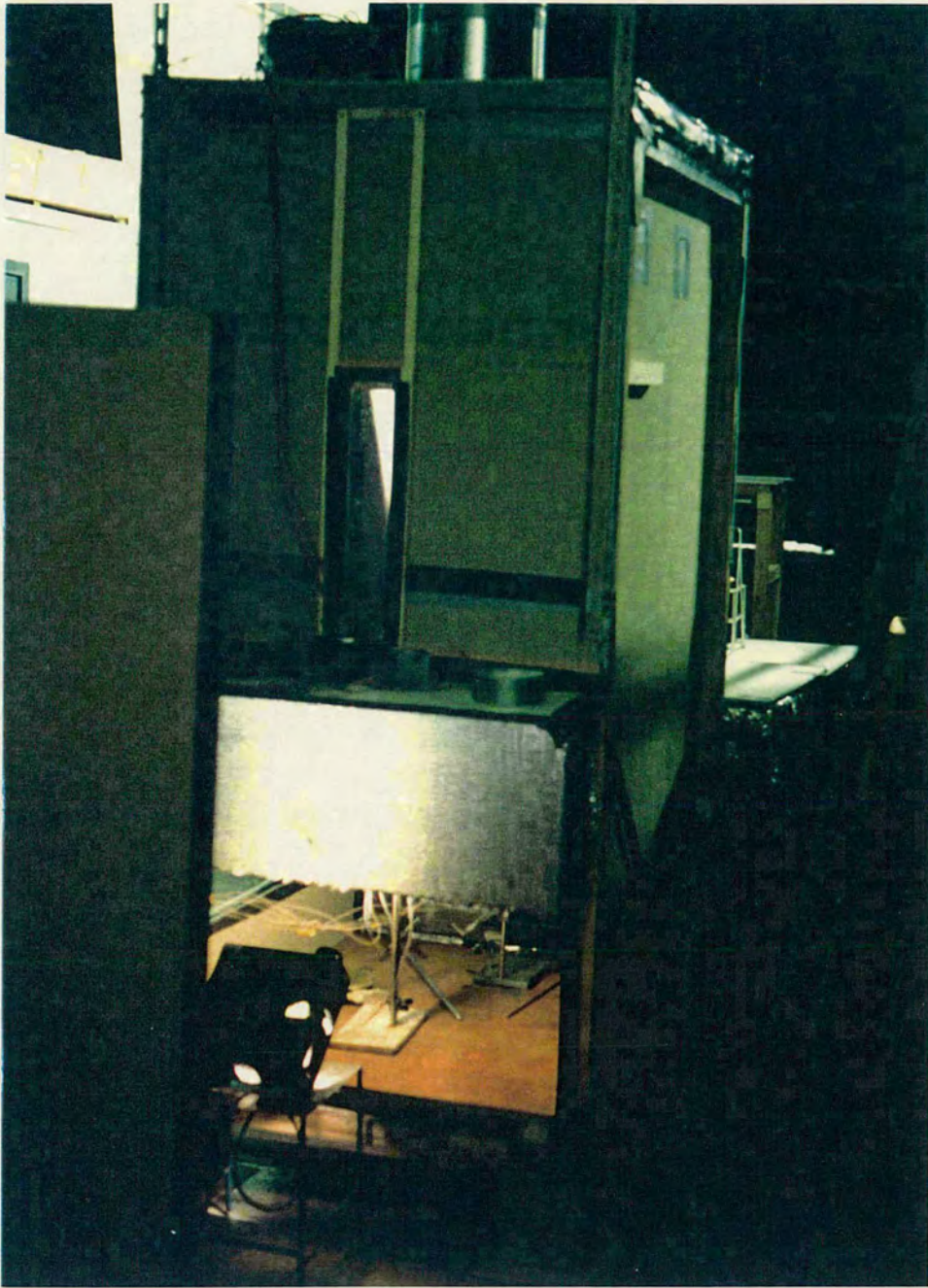


Plate 6.6:

Front view of the rig.

Honeycombing at high level in the atrium entrance, to reduce scale of vortices.

High level window for laser light entry.

Projector provides light source for smoke visualising.

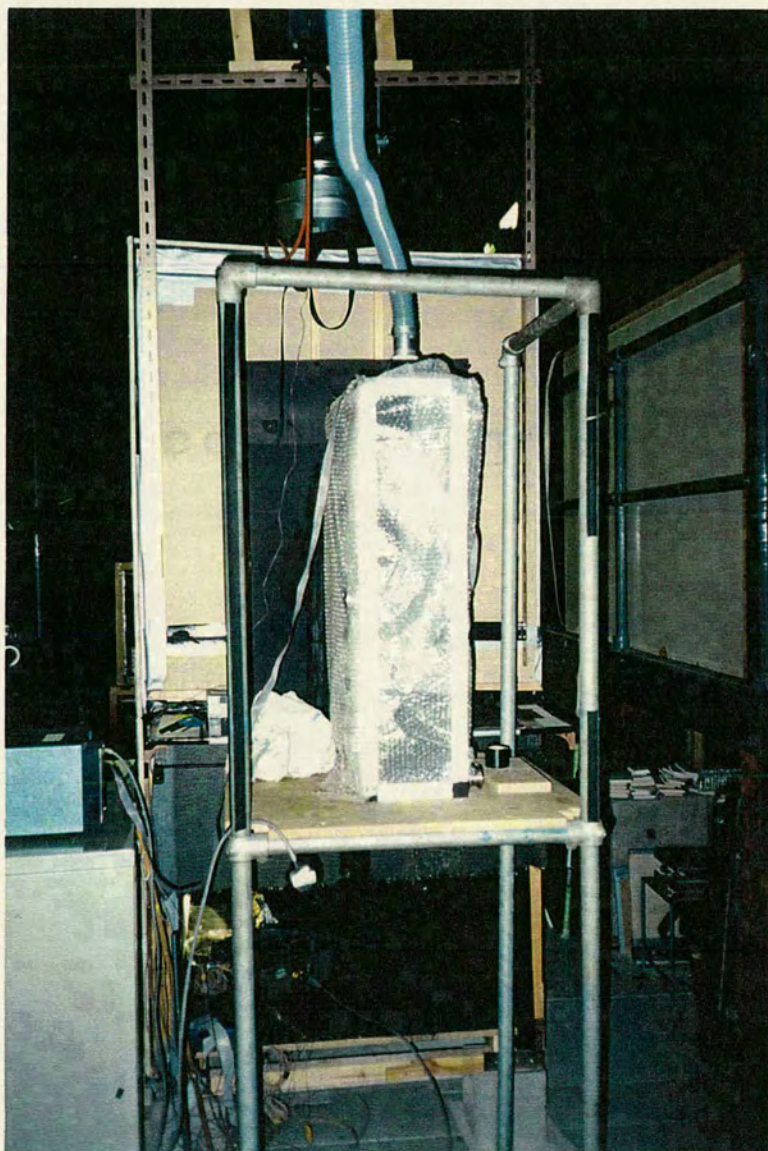


Plate 6.7:
Scanner box at high level, for z-plane velocity measurements.

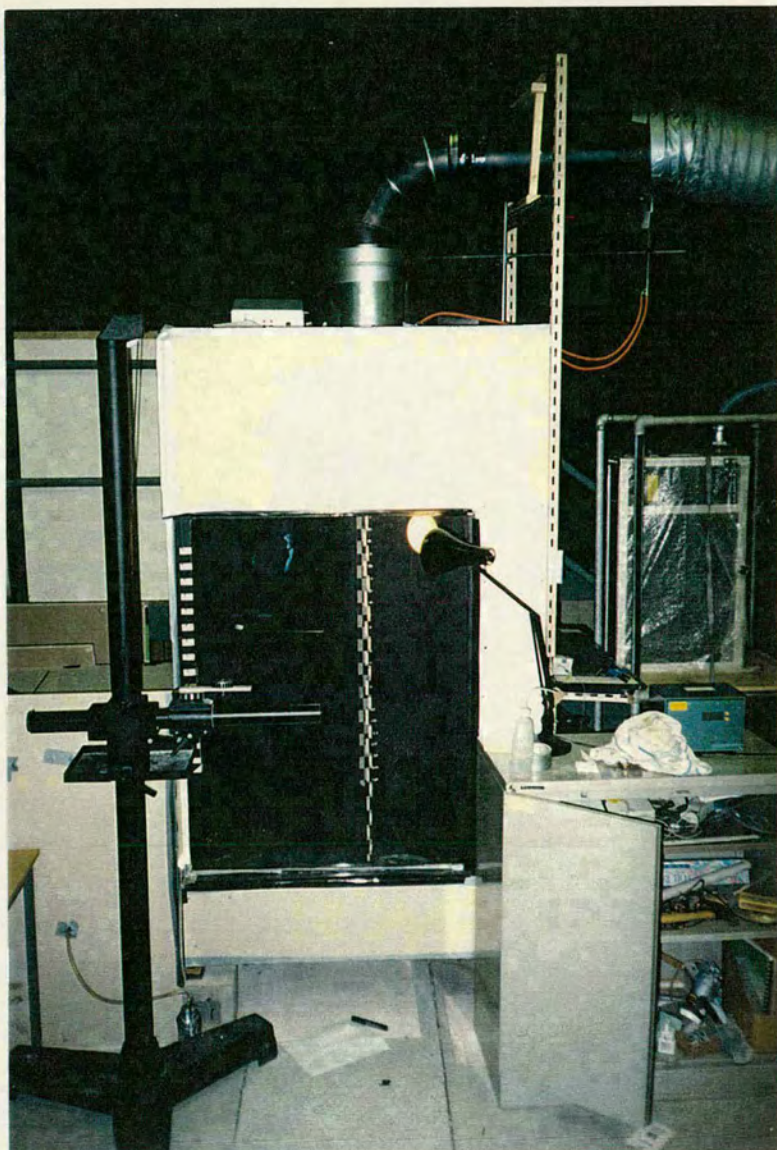


Plate 6.8:

Side view of scanner box, located at high level, for z-plane velocity measurements.

Video camera support frame positioned for z-plane velocity measurements.

Chapter 7 Experimental Results

7.1 Introduction

This chapter presents the results of the scale model atrium tests. Comparison to values derived from BR 258 are shown.

The results are summarised as follows:

- **Section 7.2** Mass Flow Rates in the Duct
- **Section 7.3** PIV Velocities and Related Thermocouple Data
- **Section 7.4** Thermocouple Data
- **Section 7.5** CO₂ Measurements
- **Section 7.6** Assumptions Necessary for Experiment
- **Section 7.7** Error Analysis

7.1.1 Notes on Chapter 7

7.1.1.1 Theory

The experimental results are compared against theoretical calculations. In this chapter the methods from BR258 are used to calculate the spill plume mass flow rates: as below:

w-plane - Equations 2 to 4 from BR258 (Equations 5.1,2 and 3 in Chapter 5)

y-plane - Equation B9 from BR258 (Equation 5.4 in Chapter 5)

z-plane - Equations B6 to B25 from BR 258, shown in Appendix 5

7.1.1.2 Fire Size

The fire size has been calculated from the flow rate of the methanol, through the flowmeter. The heat release rate (total heat produced combustion) has been calculated as 20 MJ/kg. The convective heat flux of the gases is calculated as follows (Law 1995c):

$$Q_c = Q_f/1.5 \qquad \text{kW} \qquad \text{Eq.7.1}$$

7.1.1.3 Nomenclature

A general list for the nomenclature used is listed below:

- Dd - Depth of downstand (m)
- Lc - Distance from back face of fire compartment to w-plane (m)
- Lf - Distance from axis of fire to w-plane (m)
- m - Mass flow rate (kg/s)
- Qc - Convective heat flux (kW)
- Qf - Heat release rate (kW)
- u - Velocity (m/s)
- z - Height above y-plane (m)
- θ - temperature rise above ambient (C)

The distance from the plume axis marks the stages of the plume development, not the total length of the fire compartment, therefore Lf is used rather than Lc when plotting trends for mass flow rate and other data.

7.2 Mass Flow Rates in the Duct

In this section the mass flow rates derived from the Pitot-static tube and thermocouple measurements in the duct are shown. Tables 7.1, 2 and 3, and Graphs 7.1, 2 and 3 show the mass flow, for different downstand conditions and compartment lengths, in comparison to values derived from BR 258.

No spill plume theories include a term to vary mass flow rate with the compartment length, so only one theoretical value, for each downstand depth is shown.

7.2.1 Mass Flow Rates

7.2.1.1 $Q_f = 4.67 \text{ kW}$, $z = 0.750 \text{ m}$

	Theory	Duct Measurement			
Dd (m)		Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	0.176	0.210	0.192	0.179	0.167
0.05	0.186	0.171	0.156	0.183	0.161
0.10	0.166	0.145	0.145	0.146	0.135
0.20	0.138	0.123	0.120	0.132	0.132

sumvel02.xls

Table 7.1 Mass Flow Rate of Plume (kg/s); Comparison of Theory to Experiment: Heat Release Rate: $Q_f = 4.67 \text{ kW}$ Height of Rise: $z = 0.750 \text{ m}$

Table 7.1 and Graph 7.1

The measurements made in the duct show similar values and trends with the spill plume theory. The 1.86 m long compartment ($L_f = 1.61 \text{ m}$) shows the maximum difference of 12.5 %, with theoretical results.

In general the spill plume model overestimates the mass flow rate, except when no downstand ($D_d = 0$) is present. In this situation, a maximum 20 % difference occurs. A greater range of values for the mass flow rate is found for this downstand condition. This is discussed in Chapter 9.

Table 7.1 and Graph 7.2

The influence of the compartment length on mass flow rate, is best illustrated in Graph 7.4. In general, the larger downstand ($D_d = 0.1$ and 0.2 m) depths showing little variation for most lengths of compartment, whereas, the smaller downstand depths (0 and 0.5 m) show a decline in mass flow rate for as the compartment lengthens. The longest compartment ($L_f = 2.21 \text{ m}$) length appears to produce lower mass flow rates for downstand depths of 0 , 50 , and 100 mm .

7.2.1.2 $Q_f = 4.67 \text{ kW}$, $z = 0.550 \text{ m}$

	Theory	Duct Measurement			
Dd (m)		Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	0.148	0.155	0.149	0.150	0.127
0.05	0.159	0.131	0.131	0.134	0.116
0.10	0.143	0.123	0.116	0.118	0.101
0.20	0.118	0.106	0.102	0.101	0.097

sumvel02.xls

Table 7.2 Mass Flow Rate of Plume (kg/s); Comparison of Theory to Experiment: Heat Release Rate: $Q_f = 4.67 \text{ kW}$ Height of Rise: $z = 0.550 \text{ m}$

Table 7.2 and Graph 7.3

There is a greater difference between the theoretical mass flow rate and the duct measurements, than was found with a 750 mm height of rise ($z = 0.75 \text{ m}$). The variation of the mass flow rate with depth of downstand, for the theory and experimental values have similar trends though. The 2.46 m long compartment ($L_f = 2.21 \text{ m}$), with a 200 mm downstand shows the greatest difference (29 %).

In general the spill plume model overestimates the mass flow rate, except when no downstand ($D_d = 0$) is present. In this situation, a maximum 15 % difference occurs, when the compartment is 2.46 m long ($L_f = 2.21 \text{ m}$). Shorter compartment lengths produce little (less than 5 %) difference compared to the theory.

Table 7.2 and Graph 7.4

The influence of the compartment length on mass flow rate, is shown in Graph 7.5. In general, for all downstand depths, there is little variation in mass flow rate for most compartment lengths, except with the longest compartment length of 2.46 m ($L_f = 2.21 \text{ m}$) for downstand depths of 0, 50, and 100 mm. This gives lower mass flow rates for all downstand sizes.

7.2.1.3 $Q_f = 6.09 \text{ kW}$, $z = 0.750 \text{ m}$

	Theory	Duct Measurement			
Dd (m)		Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	0.189	0.242	no data	no data	0.165
0.05	0.205	0.197	no data	no data	0.155
0.10	0.186	0.163	no data	no data	0.137
0.20	0.150	0.127	no data	no data	0.135

sumvel02.xls

Table 7.3 Comparison of Theory to Mass Flow Rates in Extract Duct:

Heat Release Rate: $Q_f = 6.09 \text{ kW}$ Height of Rise: $z = 0.750 \text{ m}$

Table 7.3 and Graph 7.5

The measurements made in the duct show similar values and trends with the spill plume theory. The 0.65 m long compartment ($L_f = 0.41 \text{ m}$) shows a maximum 33 % difference with theoretical results. This results appears to be anomalous, but this configuration also produces high values for the 4.67 kW fire ($L_f = 0.41 \text{ m}$).

In general the spill plume model overestimates the mass flow rate, except when no downstand ($D_d = 0$) is present. In this situation, a maximum 20 % difference occurs. A greater range of values for the mass flow rate is found for this downstand size.

Table 7.3 and Graph 7.6

The influence of the compartment length on mass flow rate, is not so well illustrated in Graph 7.6, as only two compartment lengths were used. In general, the overall effect of compartment length on mass flow rate is similar, with the decreasing effect on mass flow rate with increasing downstand depth.

7.2.3 Temperatures and Heat Flux in the Plume and the Duct

The temperature in the duct and the temperature in the plume differ. The heat flux, Q is determined, to determine whether these differences are due to excessive heat loss.

Two sets of values of Q_{duct} (shown in Tables 7.4, 7.5 and 7.6) have been derived:

1. Using the mass flow rates and temperatures measured in the duct.
2. Using the mass flow rates in the duct and the mass weighted temperatures in plume, at the reservoir height, either 750 or 550 mm above the y-plane.

Lf	Dd	θ_{duct}	Q_{duct}	$Q_{\text{dt}}/Q_f \%$	$\theta_{(z=0.75)}$	$Q_{(z=0.75)}$	$Q_z/Q_f \%$
0.41	0.00	35.0	3.07	66	38.1	3.73	80
0.41	0.05	37.0	3.01	64	38.2	3.22	69
0.41	0.10	41.0	2.92	65	48.1	3.96	85
0.41	0.20	41.0	2.60	56	48.3	3.50	75
1.01	0.00	33.0	2.41	52	44.7	4.65	100
1.01	0.05	38.0	2.74	59	50.3	4.66	100
1.01	0.10	33.5	1.89	40	49.2	4.18	89
1.01	0.20	38.0	2.10	45	49.4	3.47	74
1.61	0.00	34.0	2.48	53	46.3	4.70	101
1.61	0.05	34.5	2.61	56	44.5	4.43	95
1.61	0.10	35.0	2.18	47	46.3	3.83	82
1.61	0.20	34.0	1.83	37	40.2	2.65	57
2.21	0.00	32.0	2.52	54	43.4	4.44	95
2.21	0.05	34.0	2.76	59	45.6	4.64	99
2.21	0.10	34.0	2.22	47	40.9	3.14	67
2.21	0.20	34.5	2.24	48	43.1	3.38	72

1. Derived from Duct Temps

2. Derived from Plume Temps

Table 7.4 Mass Heat Flux in Duct for $z = 0.750$ m, $Q_f = 4.67$ kW

Lf	Dd	θ_{duct}	Q_{duct}	$Q_{\text{dt}}/Q_f \%$	$\theta_{(z=0.55)}$	Q_z	$Q_z/Q_f \%$
0.41	0.00	38.5	2.81	60	40.6	3.13	67
0.41	0.05	40.5	2.77	59	41.7	2.93	63
0.41	0.10	44.0	2.83	61	43.6	2.79	60
0.41	0.20	43.5	2.50	53	68.6	5.16	111
1.01	0.00	40.0	2.93	63	42.9	3.37	72
1.01	0.05	40.0	2.56	55	75.1	7.18	154
1.01	0.10	35.5	1.74	37	41.9	2.49	54
1.01	0.20	40.0	2.00	43	49.8	3.01	64
1.61	0.00	38.5	2.75	59	57.3	5.58	119
1.61	0.05	38.5	2.47	53	47.2	3.64	78
1.61	0.10	36.0	1.88	40	59.2	4.64	99
1.61	0.20	39.0	1.91	41	58.4	3.88	83
2.21	0.00	36.5	2.50	53	45.6	3.67	88
2.21	0.05	40.0	2.69	58	51.6	4.05	87
2.21	0.10	40.5	2.32	50	49.5	3.23	69
2.21	0.20	37.0	1.89	41	49.7	3.13	67

1. Derived from Duct Temps

2. Derived from Plume Temps

Table 7.5 Mass Heat Flux in Duct for $z = 0.55$ m, $Q_f = 4.67$ kW

Lf	Dd	θ_{duct}	Q_{duct}	$Q_{\text{dt}}/Q_f \%$	$\theta_{(z=0.75)}$	Q_z	$Q_{\text{dt}}/Q_f \%$
0.41	0	36.5	3.89	64	43.8	5.65	93
0.41	0.05	38.0	3.67	60	40.8	4.22	69
0.41	0.1	40.5	3.20	52	42.5	3.53	58
0.41	0.2	43.0	2.93	48	52.6	4.15	68
2.21	0	33.5	2.74	45	42.3	4.20	69
2.21	0.05	36.0	2.97	49	49.2	5.03	82
2.21	0.1	37.5	2.73	45	43.0	3.49	57
2.21	0.2	38.0	2.76	45	46.2	3.87	64

1. Derived from Duct Temps

2. Derived from Plume Temps

sumq02

Table 7.6 Mass Heat Flux in Duct for $z = 0.75$ m, $Q_f = 6.09$ kW

7.2.3.1 Temperature Differences

The turbulent flow in the duct, ensures that the temperature distribution is uniform, therefore the mean temperature is approximately equal to the maximum temperature.

The mean temperature of the plume has been calculated by assuming that it is 67 % of the maximum temperature found in experiments. This 67 % has been calculated using the assumptions in Equation 5.32 (from Chapter 5):

$$\frac{\theta_1}{\theta} = \frac{(1 + \lambda^2)^{1/2}}{\lambda} = 1.495 \quad \text{Eq. 5.32}$$

where $\lambda = 0.9$
 θ_1 = maximum temperature rise ($^{\circ}\text{C}$)
 θ = mean temperature rise ($^{\circ}\text{C}$)

The temperatures measured in the plume, compared to the measurements in the duct are different. A significant temperature drop occurs between the plume as it enters the smoke reservoir and the point of measurement in the duct.

7.2.3.2 Heat Flux

The values for the heat flux have been calculated from the figures for the mass flow rate in the duct, and the temperature rise in the duct and the plume. The duct temperature based heat flux values are a true measurement of the heat flux, excluding allowances for experimental accuracy. The plume heat flux figures show a much higher heat flux, therefore additional entrainment must occur beyond the plume height of rise. To demonstrate the relationship between the sets of values, the heat flux has been plotted as a percentage ratio in Graphs 7.7, 7.8 and 7.9. The percentages represent:

$$\frac{Q_{\text{duct}}}{Q_f}$$
$$Q_z / Q_f$$

where Q_f = heat release rate
 Q_{duct} = heat flux in duct
 Q_z = nominal heat flux in plume

They are plotted as ratios to allow easy comparison between the two heat release rates and height of rises used, and to indicate the heat loss from the plume.

Graph 7.7 $Q_f = 4.67 \text{ kW}$; $z = 0.75$

This shows a good relationship for the duct based heat flux values. Very similar values are obtained at $L_f = 1.01, 1.61$ and 2.21 . $L_f = 0.41$ is different, it follows the same trend, but less heat loss is apparent.

There is a greater range in values for the plume based 'nominal' heat fluxes than duct based measurements, but similar trends exist, where heat loss increases by approximately 10 % with increasing depth of downstand and length of compartment.

Graph 7.8 $Q_f = 4.67 \text{ kW}$; $z = 0.55$

This shows poorer relationships for the duct based heat flux values. Similar values are obtained at $L_f = 1.01, 1.61$ and 2.21 , which are within $\pm 6 \%$. $L_f = 0.41$ is different, it follows the same trend, but less heat loss is apparent. Heat flux is greater by approximately 10 %.

There is a much greater range in values for the plume based 'nominal' heat fluxes, than the duct based measurements, but similar trends exist. Heat loss increases by approximately 15 % with increasing depth of downstand and length of compartment.

To plot Graph 7.8, 3 values that are obviously in error were not plotted. These are:

$D_d = 0.00, L_f = 1.61$; $D_d = 0.05, L_f = 1.01$ and $D_d = 0.20, L_f = 0.41$

Graph 7.9 $Q_f = 6.09 \text{ kW}$; $z = 0.75$

This shows relationships for the duct based heat flux values, similar to Graph 7.7.

Values for $L_f = 2.21$ and 0.41 differ to a similar degree as Graph 7.7. They follow the same trend, but heat loss is less by approximately 5 to 20 % when $L_f = 2.21$.

Obviously, fewer data are points available, so fewer conclusions can be drawn.

7.2.3.3 Summary

There is a much greater range in values for the plume based 'nominal' heat fluxes, than the duct based measurements, but similar trends exist. Heat loss increases by approximately 15 % with increasing depth of downstand and length of compartment.

7.3 PIV Velocity and Thermocouple Data

7.3.1 General

The PIV analysis was conducted with a 750 mm height of rise ($z = 0.75$ m), using a 4.67 kW heat source ($Q_f = 4.67$ kW). Four depths of downstand (0, 50, 100 and 200 mm) were used for a 660 mm long compartment ($L_f = 2.21$) and two (0 and 200 mm) for a 2460 mm long compartment ($L_f = 2.21$).

7.3.2 Velocity Measurements

		Dd = 0.00	Dd = 0.05	Dd = 0.10	Dd = 0.20
Theory	w-plane	0.623	0.462	0.522	0.658
Lf = 0.41	w-plane	0.666	0.475	0.568	0.661
Lf = 2.21	w-plane	0.793	no data	no data	0.660

Theory	y-plane	0.442	0.466	0.468	0.468
Lf = 0.41	y-plane	0.660	0.613	0.736	0.458
Lf = 2.21	y-plane	0.510	no data	no data	0.645

Theory	z = 0.75	1.170	1.142	1.162	1.199
Lf = 0.41	z = 0.75	0.898	0.864	1.050	1.243
Lf = 2.21	z = 0.75	0.920	no data	no data	1.124

Table 7.7 Maximum Velocities ($U_{\max}$ m/s) at W-Plane, Y-Plane and Z-Plane

Table 7.7 shows the time averaged velocities for the hot gas flow at the w-plane, y-plane and z-plane, derived from the PIV analysis. The process of reducing the values derived from the analysis into this form is described in the Supplementary Appendix.

Graph 7.10 shows the variation of the maximum velocity with the depth of downstand, at the three planes of interest. The theoretical values for the velocity are derived from the formula in Appendix B of BR258 (shown in Appendix 5 of this thesis):

w-plane velocity - Equation B5, BR 258
y and z-plane velocity - Equation B24, BR 258

These show good agreement with the theoretical velocities at the w-plane, particularly for the short compartment ($L_f = 0.41$), where a maximum difference occurs.

At the z-plane a greater difference is found. The values for $D_d = 0.2$ m show good agreement, for both compartment lengths. This difference increases as the downstand depth decreases. When there is no downstand ($D_d = 0$ m), a difference of 23 % between the theoretical and experimental value is found.

It should not be expected that the y-plane velocity predictions would match. The formula used is not intended to be used at the y-plane and is only valid when the height of rise is greater than 4.2 m full-scale, 0.53 m at reduced-scale. The theoretical values have been under-predicted by approximately 30 %. A significant degree of acceleration has occurred as the gases start to leave the fire compartment.

The velocities are under-predicted at the y-plane and are over-predicted at the z-plane, for the smaller downstand sizes, therefore a slower rate of acceleration exists in the experiment than in the spill plume calculations.

Little variation occurs with compartment length at the w and z-planes. At the y-plane a greater difference is produced by the increase in compartment length, but with little data no clear conclusion can be made.

7.3.3 Temperature Variations

Temperatures at the w, y and z-planes were measured for all experimental configurations. In this section only those used for the PIV analysis are shown, to allow comparison of velocity and temperature data. The temperature rise is plotted against Dd.

7.3.3.1 Maximum Temperature Rise

		d = 0.00	d = 0.05	d = 0.10	d = 0.20
Theory	w-plane	72.5	90.8	101.0	133.1
Lf = 0.41	w-plane	71.9	82.8	96.9	128.5
Lf = 2.21	w-plane	67.2	no data	no data	99.5

Theory	y-plane	48.7	43.7	52.3	76.3
Lf = 0.41	y-plane	77.1	84.0	96.1	127.1
Lf = 2.21	y-plane	65.2	no data	no data	96.8

Theory	z = 0.75	31.8	30.0	33.6	40.4
Lf = 0.41	z = 0.75	23.4	24.8	35.9	37.5
Lf = 2.21	z = 0.75	35.0	no data	no data	33.8

Table 7.12 Maximum Temperature Rise ($\theta_{\max}$; °C)

Table 7.12 and Graph 7.13 shows good agreement between the theoretical and experimental temperatures at the w-plane, except for the 2460 mm (Lf = 2.21 m) long compartment, with the 200 mm downstand (Dd = 0.20).

There is good agreement at the z-plane (z = 0.75), except for the 660 mm (Lf = 0.41) compartment, where there is no downstand (Dd = 0.00).

The values at the y-plane are not in agreement with the theory. The experimental values at the y-plane are almost the same as at the w-plane, whereas the theoretical values are approximately 30 to 50 % less.

7.3.3.2 Mean Temperature Rise

These have been calculated as follows:

$$\theta_{\text{mean}} = Q_c / m$$

⁰C

Eq.7.3

where:

θ_{mean}

-

mean temperature ⁰C

Q_c

-

heat flux at plane of interest kW (see Section 7.3.5)

m

-

mass flow rate (kg/s)

The results are shown in Table 7.13.

		d = 0.00	d = 0.05	d = 0.10	d = 0.20
Theory	w-plane	53.0	66.3	73.8	97.3
Lf = 0.41	w-plane	52.7	56.5	78.7	79.8
Lf = 2.21	w-plane	60.9	no data	no data	62.7

Theory	y-plane	40.3	36.2	43.3	63.2
Lf = 0.41	y-plane	59.5	60.1	86.7	95.0
Lf = 2.21	y-plane	59.0	no data	no data	71.6

Theory	z = 0.75	26.4	25.0	28.0	33.6
Lf = 0.41	z = 0.75	17.2	20.4	30.8	29.7
Lf = 2.21	z = 0.75	27.6	no data	no data	26.7

Table 7.13 Mean Temperature Rise (θ_{mean} ; ⁰C)

A greater variation in temperatures appears to occur. Trends are not so clear, especially at the w-plane. This could be caused by a greater degree of error in the PIV measurements influencing the mean temperature results.

7.3.4 Depth of Hot Layer and Plume Widths

The depth of smoke in a compartment or the width of a line plume can be measured by the temperature or velocity gradient. Conventionally it is measured using the velocity gradients. The edge of the plume being defined as the point where the velocity is 27 % of the maximum velocity (equivalent to 1/e). These Tables show the different depths derived by these methods of measurement, and the ratio of these values.

Table 7.14 shows the depth measured by velocity.

Table 7.15 shows the depth measured by visible depth.

Table 7.16 shows the depth measured by temperature.

Table 7.17 shows λ , where;

$$\lambda = b_{\theta}/b_w$$

Eq. 5.31

where: b_{θ} $\equiv$ the layer depth or plume width based on temperature

b_w $\equiv$ the layer depth or plume width based on velocity

		D = 0.00	d = 0.05	d = 0.10	d = 0.20
Theory	w-plane	0.104	0.123	0.102	0.069
Lf = 0.41	w-plane	0.098	0.109	0.087	0.096
Lf = 2.21	w-plane	0.075	no data	no data	0.097

Theory	y-plane	0.280	0.295	0.250	0.179
Lf = 0.41	y-plane	0.103	0.094	0.078	0.090
Lf = 2.21	y-plane	0.108	no data	no data	0.085

Theory	z = 0.75	0.174	0.188	0.166	0.135
Lf = 0.41	z = 0.75	0.119	0.112	0.088	0.097
Lf = 2.21	z = 0.75	0.104	no data	no data	0.118

Table 7.14 Depth of Smoke (m) Measured by Velocity at Point where $u = u_{max} e^{-1}$

In Table 7.14 and Graph 7.15, the depth at the w-plane shows the best agreement between theory and experiment, although differing trends are evident.

There is poor agreement at the y-plane because the theoretical values derived are for an 'imaginary' source, and good agreement would not be expected until $z = 0.5\text{ m}$, approximately. The y-plane data is not plotted in Graph 7.15.

At $z = 0.75\text{ m}$, there is poor agreement, with the values derived experimentally being approximately 60 % of theoretical values.

Compartment length appears to have little influence upon plume width or hot layer depth.

		d = 0.00	d = 0.05	d = 0.10	d = 0.20
Lf = 0.41	w-plane	0.128	0.156	0.107	0.133
Lf = 2.21	w-plane	0.104	no data	no data	0.130

Lf = 0.41	y-plane	0.136	0.120	0.121	0.095
Lf = 2.21	y-plane	0.121	no data	no data	0.102

Lf = 0.41	z 0.75	0.199	0.156	0.161	0.162
Lf = 2.21	z 0.75	0.135	no data	no data	0.131

Table 7.15 Depth of Smoke (m) Measured by Visible Depth

The average depth of the visible hot layer depth or plume width is related to the velocity width shown in Table 7.15, as it is derived from PIV images.

		d = 0.00	d = 0.05	d = 0.10	d = 0.20
Lf = 0.41	w-plane	0.107	0.105	0.102	0.075
Lf = 2.21	w-plane	0.090	no data	no data	0.070

Lf = 0.41	y-plane	0.111	0.090	0.131	0.070
Lf = 2.21	y-plane	0.112	no data	no data	0.070

Lf = 0.41	z 0.75	0.198	0.145	0.214	0.176
Lf = 2.21	z 0.75	0.180	no data	no data	0.204

**Table 7.16 Depth of Smoke (m) Measured by Temperature;
at Point where $\theta = \theta_{\max} e^{-1}$**

In Table 7.16 and Graph 7.16, the depth of the hot layer and plume widths, measured by temperature are slightly wider than those measured by velocity, but have approximately the same range as the theoretical values. There is no clear relationship with downstand depth, the 100 mm downstand ($Dd = 0.1\text{ m}$). There is an overall decrease in the depth of the hot layer at the w-plane and the width of the plume at the y-plane, and a slight increase at the z-plane. Much higher values occur with a 100 mm downstand ($Dd = 0.1\text{ m}$) at the y and z-plane, the opposite effect to the velocity width measurements.

The compartment length appears to have little influence on plume width or hot layer depth.

		d = 0.00	d = 0.05	d = 0.10	d = 0.20
Lf = 0.41	w-plane	1.092	0.963	1.167	0.781
Lf = 2.21	w-plane	1.208	no data	no data	0.722

Lf = 0.41	y-plane	1.075	0.957	1.679	0.778
Lf = 2.21	y-plane	1.037	no data	no data	0.824

Lf = 0.41	z = 0.75	1.669	1.291	2.420	1.811
Lf = 2.21	z = 0.75	1.734	no data	no data	1.729

Table 7.17 Ratio of Smoke Depths λ (Dd_g / Dd_u or b_g / b_u)

λ is constant at 0.9, in the FRS spill plume calculations and in the line plume analysis of Lee and Emmons (1961). There is quite a significant variation in the values shown here. There is a rapid transition in λ , as Dd increases from 0.05 to 0.1 m. This appears not to be random, as the same trends exist for all curves. λ appears to be almost constant with changing compartment length.

7.3.5 Mass Flow Rates from PIV and Thermocouple Data

The mass flow rate ($\dot{m}$) has been calculated from the PIV profiles and thermocouple profiles. The method is shown in Section 7.7.

7.3.5.1 Mass Flow Rate in the W-Plane

		d = 0.00	d = 0.05	d = 0.10	d = 0.20
Theory	w-plane	0.0585	0.0467	0.0420	0.0319
Lf = 0.41	w-plane	0.0440	0.0412	0.0365	0.0372
Lf = 2.21	w-plane	0.0359	no data	no data	0.0407

Table 7.18 Mass Flow Rates from PIV Data at the W-Plane (kg/s)

The mass flow rates shown in Table 7.18 and Graph 7.18, for the w-plane show limited agreement with the theoretical values. Experimental conditions could account for the mass flow rates being generally 15 % lower than theory. The trend for mass flow rate with increasing downstand is different. The mass flow rate decreases with increasing depth of downstand, except for a small increase in the mass flow rate, with a 200 mm downstand ($D_d = 0.2$ m). With increased compartment there is a greater difference in experimental values compared to theoretical values.

7.3.5.2 Mass Flow Rate in the Y-Plane

		d = 0.00	d = 0.05	d = 0.10	d = 0.20
Theory	y-plane	0.1153	0.1284	0.1074	0.0736
Lf = 0.41	y-plane	0.0518	0.0426	0.0334	0.0250
Lf = 2.21	y-plane	0.0352	no data	no data	0.0401

Table 7.19 Mass Flow Rates form PIV Data at the Y-Plane (kg/s)

Table 7.19 and Graph 7.19 show a great difference between the theoretical and experimental mass flow rates at the y-plane. The mass flow rate at the y-plane, for most downstand conditions is over 65 % less than predicted with spill plume theory. The closest agreement with values is 55 % of the theoretical value.

There is a similar trend in mass flow rate. An overall decline is found with increasing depth of downstand. The increasing the compartment length does not cause any significant change in mass flow rate.

7.3.5.3 Mass Flow Rate in the Z-Plane

		d = 0.00	d = 0.05	d = 0.10	d = 0.20
Theory	z 0.75	0.1759	0.1862	0.1663	0.1383
Lf = 0.41	z 0.75	0.1163	0.0943	0.0754	0.1066
Lf = 2.21	z 0.75	0.0761	no data	no data	0.1049

Table 7.20 Mass Flow Rates form PIV Data at the Z-Plane (kg/s)

In Table 7.20 and Graph 7.20, there is little agreement with theory, except a similar trend in mass flow rate, with increasing depth of downstand. As the depth of downstand increases, the degree of difference between experimental and theoretical mass flow rates decreases, from 34 to 57 % to 24 to 25 %.

If comparisons are made to the values obtained in the duct, then large differences are also seen (Table 7.21).

		Duct	Duct	PIV	PIV
Dd (m)	Theory	Lf = 0.41	Lf = 2.21	Lf = 0.41	Lf = 2.21
0.00	0.176	0.210	0.167	0.116	0.076
0.05	0.186	0.171	0.161	0.094	no data
0.10	0.166	0.145	0.135	0.075	no data
0.20	0.138	0.123	0.132	0.107	0.105

Table 7.21 Variations in Mass Flow Rates (kg/s) at Z-Plane Measured in the Duct and the Directly in the Plume. $Q_f = 4.67 \text{ kW}$ $z = 0.750 \text{ m}$

The duct measurements show better agreement with the theoretical plume values and are only 5 to 15 % lower than the theoretical values.

7.3.6 Heat Flux from PIV and Thermocouple Data

By calculating the heat flux at the w, y and z-plane, heat loss can be estimated. The magnitude of experimental error using PIV can also be estimated. Table 7.23 shows the convective heat flux at these planes.

	d = 0.00	d = 0.05	d = 0.10	d = 0.20	mean
Theory	3.11	3.11	3.11	3.11	3.11
All planes					
w-plane	2.33	2.34	2.88	2.99	2.64
y-plane	3.00	2.55	2.90	2.37	2.71
z 0.75	2.01	1.93	2.34	3.18	2.37
Mean	2.45	2.27	2.71	2.93	2.57
Variation	± 22 %	± 15%	± 14 %	± 19 %	

Table 7.22 Heat Flux at W, Y and Z-Planes (kW); Lf = 0.41 m

	d = 0.00	d = 0.20	mean
Theory	3.11	3.11	3.11
All planes			
w-plane	2.19	2.56	2.64
y-plane	2.09	2.88	2.71
z 0.75	2.12	2.82	2.37
Mean	2.14	2.75	2.45
Variation	± 2 %	± 7 %	

Table 7.23 Heat Flux at W, Y and Z-Planes (kW); Lf = 2.21 m

Variation due to experimental error is evident. The total heat loss would be expected to increase, as in Equation 7.4, as the hot gases pass the w-plane, the y-plane and then the z-plane. The heat flux increases in some instances. Negative heat loss cannot occur, therefore experimental error must be creating significant differences in measured temperatures and velocities.

$$Q_w \geq Q_y \geq Q_z$$
Eq.7.4

where:

Q_w
-convective heat flux at w-plane
kW

Q_y
-convective heat flux at y-plane
kW

Q_z
- convective heat flux at z-plane
kW

The heat loss in this model could be insignificant beyond the fire, so that Q_w , Q_y and Q_z are approximately equal. For each downstand condition, the heat flux varies about a mean. A decrease in heat loss with increasing depth of downstand and a increase heat loss with length of compartment, but without more experimental data, the results are inconclusive. The trends evident in Tables 7.22 and 7.23 could be due to experimental error.

7.3.7 Other Flow Characteristics from PIV and Thermocouple Data

Other characteristics have been examined to demonstrate that the conditions for Froude modelling have been met and there are similar characteristics to large scale smoke flow.

7.3.7.1 Reynolds Number

Successful Froude modelling requires the flow to be turbulent. Reynolds number at the w, y and z-planes are shown in Table 7.24.

		d = 0.00	d = 0.05	d = 0.10	d = 0.20
Theory	w-plane	3226	2503	2215	1604
Lf = 0.41	w-plane	2424	2207	1927	1881
Lf = 2.21	w-plane	1978	no data	no data	2054

Theory	y-plane	5990	6673	5577	3822
Lf = 0.41	y-plane	2857	2035	1839	1376
Lf = 2.21	y-plane	1941	no data	no data	2211

Theory	z = 0.75	8934	9456	8447	7023
Lf = 0.41	z = 0.75	6734	5463	4367	6175
Lf = 2.21	z = 0.75	4408	no data	no data	6074

Table 7.24 Reynolds Number (Re)

Reynolds number is generally lower than in theoretical predictions. This is mainly due to mass flow rates being lower than predicted. The flows all have Re values that indicate turbulent flow, except at the y-plane, when $Dd = 0.2$ and $Lf = 2.21$. The latter has an intermediate value for these conditions. It appeared to be turbulent in the PIV image sequences. It also had a similar turbulence intensity to the other geometric conditions used, see Table 7.25.

7.3.7.2 Turbulence Intensity

		d = 0.00	d = 0.05	d = 0.10	d = 0.20
Lf = 0.41	w-plane	0.21	0.43	0.41	0.17
Lf = 2.21	w-plane	0.21	no data	no data	0.18

Lf = 0.41	y-plane	0.30	0.12	0.12	0.18
Lf = 2.21	y-plane	0.35	no data	no data	0.25

Lf = 0.41	z = 0.75	0.28	0.35	0.25	0.19
Lf = 2.21	z = 0.75	0.28	no data	no data	0.16

Table 7.25 Streamwise Turbulent Intensity at Point of Maximum Velocity

There is little published data on the values for turbulence intensity in smoke flow. In a study of turbulence intensity in round buoyant plumes, Shabbir and George (1994) found that it ranged from 0.25 to 0.33. There have been no studies on line plumes or ceiling jets. The values derived here have a wider range, but are closer than expected to the values from Shabbir and George. These values could be described as being indicative of the turbulence intensity, rather than true values. A greater sampling rate would be needed to provide a more accurate measurement of the variations in the flow. They are indicative of the flow having similar turbulence characteristics to other buoyant plume studies.

7.3.7.3 Richardson Number

		d = 0.00	d = 0.05	d = 0.10	d = 0.20
Theory	w-plane	0.32	0.88	0.70	0.48
Lf = 0.41	w-plane	0.97	1.79	1.09	1.54
Lf = 2.21	w-plane	0.95	no data	no data	1.03

Table 7.25 Richardson Number (Ri)

Section 5.9 of Chapter 5, states that entrainment is negligible when $Ri > 0.8$. The experimental values at the w-plane are > 0.8 . This indicates that little additional entrainment would be expected to occur at the w-plane. The theoretical values are around 0.8, or lower, indicating that more entrainment would be expected.

These values are only of limited value in relation to understanding the probability of entrainment, because they are for unstable flow passing the spill edge. At this point the flow characteristics could change and differing entrainment could occur.

When downstands are present the values of Ri are for flow around an obstruction (a downstand). Ri for the ceiling jet inside the fire compartment would be different if the horizontal flow was to continue, rather flow up past the spill edge.

7.3.7.4 Velocity Profiles

A complete set of velocity profiles, for all geometries, is shown in Appendix 7. The white lines show the velocity profiles for each image and the black line the mean value. The velocities for each image, at the w-plane appear to have a random variation about a mode velocity, except close to the ceiling where the ceiling jet is at its maximum velocity. The changing depth of the smoke is the cause of the period variations in velocity. This variation produces a time-averaged reduction in mean velocity with depth. In the example shown here, a Gaussian profile has not formed. This profile is more typical of a hot ceiling jet. Other downstand sizes give Gaussian profiles. These different profile forms could be due to limited a experimental range, or different profile characteristics.

At the y-plane the profile forms are relatively uniform, producing the 'top-hat' profile of strongly buoyant gases. The profile is detached from the wall, by approximately 30 mm. This 30 mm 'zone' forms part of an area of recirculation evident during the PIV experiments (see Chapter 8).

At the z-plane typical Gaussian profiles were found. Similar to the w-plane plume structure, the mean profile of the plume is formed by variations to the plume width, not the plume velocity. The plume velocity has a mode value about which there is limited difference in velocity. The flow at the w-plane and z-plane is characteristic of bursts of hot gases passing the line of measurement. This typical of large scale vortices, whose width is equivalent to the hot layer depth or plume width forming the basic flow mechanism (Kotsovinos 1977).

The flow at the y-plane is different with a much more steady flow pattern. The visual observations of the flow are in Chapter 8.

7.4 Thermocouple Data

7.4.1 W-Plane Temperatures

Length	Dd = 0.00	Dd = 0.05	Dd = 0.10	Dd = 0.20
Theory	72.5	90.8	101.0	133.1
Lf=0.41	71.9	82.8	96.9	128.5
Lf=1.01	70.6	73.5	87.6	110.2
Lf=1.61	70.5	74.2	84.3	98.7
Lf=2.21	67.2	72.8	77.9	97.8

Table 7.26 Maximum Temperature Rise at W-Plane; $Q_f = 4.67 \text{ kW}$

Table 7.26 shows the variations in maximum temperature due to differing depths of downstand (Dd). The trend for the temperature variation with downstand depth shows good agreement between theory and experimental results, Graph 7.24.

The temperatures for the short compartment condition ($L_f = 0.41$) show good agreement with the theoretical values. Increasing the compartment length reduces the maximum temperature, Graph 7.25. The PIV results did not produce such clear trends for the increase in compartment length, due to limited experimental range. Similar results are found with the 6.09 kW fire, shown in Table 7.27 and Graph 7.26.

Length	Dd = 0.00	Dd = 0.05	Dd = 0.10	Dd = 0.20
Theory	86.5	109.1	121.2	158.5
Lf=0.41	87.9	97.0	111.6	144.9
Lf=2.21	72.6	80.4	82.7	113.9

Table 7.27 Maximum Temperature Rise at W-Plane; $Q_f = 6.09 \text{ kW}$

The plume temperature profiles are Gaussian (see Graphs A7.21 to 24) for all compartment lengths, except the shortest ($L_f = 0.41 \text{ m}$), which has a linear relationship between the depth of smoke and temperature.

7.4.2 Y-Plane Temperatures

Length	Dd = 0.00	Dd = 0.05	Dd = 0.10	Dd = 0.20
Theory	32.4	29.1	34.8	50.8
Lf=0.41	77.1	84.0	95.1	125.9
Lf=1.01	62.2	71.0	83.9	109.2
Lf=1.61	67.4	71.9	81.8	96.8
Lf=2.21	66.1	70.3	75.3	96.8

Table 7.28 Maximum Temperature Rise at Y-Plane; $Q_f = 4.67 \text{ kW}$

Table 7.28 shows the variations in maximum temperature due to differing depths of downstand. The trend for the temperature variation with downstand depth shows good agreement between theory and experimental results, Graph 7.27, but the experimentally derived temperature rise at the y-plane is twice as much as the theoretical values. Increasing the compartment length reduces the maximum temperature, Graph 7.28.

These results confirm the PIV results, which demonstrated that little entrainment was occurring between the w-plane and the y-plane. There was no definite trend for the increase in compartment length, due to limited experimental range. Similar results are found with the 6.09 kW fire, shown in Table 7.29 and Graph 7.29.

Length	Dd = 0.00	Dd = 0.05	Dd = 0.10	Dd = 0.20
Theory	36.9	32.7	39.1	57.7
Lf=0.41	89.1	95.9	109.8	139.1
Lf=2.21	69.8	79.2	69.6	110.9

Table 7.29 Maximum Temperature Rise at Y-Plane; $Q_f = 6.09 \text{ kW}$

The plume temperature profiles are Gaussian (see Graphs A7.29 to 32) for all compartment lengths, except the shortest ($L_f = 0.41 \text{ m}$), which has a more linear relationship between the depth of smoke and temperature.

7.4.3 Z-Plane Temperatures (at 0.75 m above y-plane)

Length	Dd = 0.00	Dd = 0.05	Dd = 0.10	Dd = 0.20
Theory	22.0	20.8	22.5	28.0
Lf=0.41	23.4	35.9	37.5	24.8
Lf=1.01	32.0	38.0	38.2	39.4
Lf=1.61	34.6	34.5	26.4	32.2
Lf=2.41	35.0	30.8	33.8	37.9

Table 7.30 Maximum Temperature Rise at Z-Plane; $Q_f = 4.67$ kW

Table 7.30 shows the variations in maximum temperature due to differing depths of downstand. The trend for the temperature variation with downstand depth shows poor agreement between theory and experimental results (Graph 7.30). The experimental results appear to be erratic, particularly the results for the short compartment condition ($L_f = 0.41$ m). In general the results show that the experimentally derived temperature rises at the z-plane are much greater than the theoretical values, but there is a limited trend of the temperature rise increasing with depth of downstand, as with the theory.

Increasing the compartment length does not have a clear affect on the temperature rise, Graph 7.31. The results are erratic. It would appear that the temperature rise is, on average, almost constant with varying compartment lengths. There could be another factor dominating the results at the z-plane, because the temperature rises at the w and y-planes show clear trends with depth of downstand (D_d) and compartment length (L_f). The reservoir characteristics (geometry, depth, wind affects on the extract duct and so on) could be dominating the entrainment in to plume as it rise through the atrium.

These results confirm the PIV results, which found limited variation occurring at the z-plane with varying downstand depth. Similar results are found with the 6.09 kW fire, shown in Table 7.31 and Graph 7.32.

Length	Dd = 0.00	Dd = 0.05	Dd = 0.10	Dd = 0.20
Theory	25.7	23.8	26.1	32.6
Lf=0.41	30.8	33.5	42.6	43.0
Lf=2.21	28.2	28.5	33.7	37.9

Table 7.31 Maximum Temperature Rise at Z-Plane; $Q_f = 6.09$ kW

The plume temperature profiles are weakly Gaussian (see Graphs A7.29 to 32) for all compartment lengths. The magnitude of the temperature profiles varies, although there is no trend with compartment length.

7.4.6 Comparison of the Maximum Temperature Rises at the W-Plane for Insulated and Uninsulated Fire Compartments

The preliminary set up for the experiment was conducted in part without any insulation. The heat loss through the compartment wall was through one sheet of plasterboard only, rather than two sheets of plasterboard and 100 mm of glass fibre insulation. The results are shown in Table 7.36.

Length	Dd = 0.00		Dd = 0.05		Dd = 0.10		Dd = 0.20	
Theory	72.5		90.8		101.0		133.1	
Insulated	Yes	No	Yes	No	Yes	No	Yes	No
Lf=0.41	71.9	70.3	82.8	79.6	96.9	88.4	128.5	105.4
Lf=1.01	70.6	63.2	73.5	74.9	87.6	80.4	110.2	104.5
Lf=2.21	67.2	58.9	72.8	61.2	77.9	70.7	97.8	87.5

Table 7.36 Comparison of Max Temp Rise ($^{\circ}\text{C}$) at W-Plane with Insulated and Uninsulated Compartments; $Q_f = 4.67$ kW

Heat loss is higher from the uninsulated compartment, as expected. Although it is not excessive. The compartment was insulated to minimise heat loss effects, to allow entrainment in the ceiling to be examined. Similar trends with downstand depth and compartment length were found for both conditions.

7.5 Comparison of CO₂ Measurements in the Spill Plume

The CO₂ measurements made in the hot layer flowing from the compartment and in the spill plume show similar results as the temperature measurements. Table 7.37 shows the actual increase in CO₂ above ambient, as a percentage of the volume.

Flow from Compartment	Spill Plume; height above y-plane (m)				
w-plane	0.01	0.06	0.12	0.47	
0.89	0.86	0.76	0.70	0.43	

Dd = 0.00

Flow from Compartment	Spill Plume; height above y-plane (m)				
w-plane	0.01	0.06	0.17	0.37	0.57
0.99	0.97	0.76	0.67	0.54	0.47

Dd = 0.05

Flow from Compartment	Spill Plume; height above y-plane (m)				
w-plane	0.01	0.06	0.10	0.22	0.62
1.10	1.04	1.00	0.89	0.79	0.56

Dd = 0.10

Flow from Compartment	Spill Plume; height above y-plane (m)				
w-plane	0.01	0.06	0.20	0.32	0.72
1.55	1.33	1.27	1.03	0.95	0.65

Dd = 0.20

Table 7.37 Maximum Rise in CO₂ Concentrations (%) above Ambient,
at W-Plane and Heights above Y-Plane; Lf=0.41 m, Qf=4.67 kW

7.6 Assumptions for Experiment

Section 6.10.1.3, of Chapter 6, states that the Preliminary Experiments verified that the essential conditions for the experiment existed. The results are shown below, with data from the Main Experiment included.

7.6.1 Turbulence

Re was over 1800, for all configurations except one, as shown in Table 7.24. These values are indicative of turbulent flow. The low value, of 1376 could be anomalous. Even if is the true Re value, turbulent flow could still develop. Visualisation of the flow with the PIV technique (see Chapter 8) showed that it appeared to be turbulent.

Approximate values of the turbulent intensity of the flow were derived and are shown in Table 7.25. These are close to the range of values found by Shabbir and George (1994). The degree of turbulence found in this experiment is close to that in round turbulent plumes.

7.6.2 Two-dimensional

The flow was approximately two dimensional, comparisons of the temperature profiles across the w-plane, at varying distances from the centreline of the compartment are shown in the tables below in Graphs 7.39 and 7.40 (data in Tables A7.23). The temperature profiles of the hot gases are in good agreement across the width of the compartment, except close to the sidewalls. The 400 mm offsets are 35 mm from the compartment wall. The depth of the hot gases here are deeper than across most of the width of the compartment. Approximate pitot tube velocity measurements indicated that the gases are slow moving, and would contribute to less than 5 % error to the overall estimate of the flow out of the compartment. This phenomena of lateral smoke deepening is discussed in Chapter 8 and Chapter 9.

Introducing fine smoke trails into the ceiling flow indicated that rapid lateral spread of disturbances occurred, but the flow was dominated by velocities towards the w-

plane in the ceiling jet and by vertical velocities in the plume. Lateral velocities towards the sidewalls represent a minor part of the flow.

The successful application of the PIV technique also indicated that the flow was two-dimensional. If lateral movement had been relatively larger, then the PIV imaging would not have been successful.

In certain parts of the flow, a three dimensional flow pattern was found, such as at the hot gas and ambient interface at the y-plane. Here the vertical velocities are very low, and lateral velocities are relatively large. The flow, as found by the PIV technique, is represented by near static particles.

7.6.3 Periodicity and Time to Steady State Conditions

These are discussed in Chapter 6.

7.6.4 Repeatability

7.6.4.1 Mass Flow in Ducts

A summary of the variations found is in Table 7.38, shown below (full in Appendix 7). The mass flow rates in the ducts are within $\pm 10\%$ of a mean value.

L_f	D_d	θ	m
m	m	C	kg/s
0.41	0.00	+ 2.9	+ 16.9
0.41	0.05	- 2.7	+ 0.2
0.41	0.10	0	+ 19.5
0.41	0.20	+ 1.2	+ 2.6
2.21	0.00	+ 1.6	- 6.8
2.21	0.20	+1.4	- 16.8

Table 7.38 Mass Flow Rate in Duct Comparison of Repeated Measurement;

$$Q_f = 4.67 \text{ kW}; \qquad z = 0.75 \text{ m}$$

7.6.4.2 PIV Velocity Measurements

Due to time limitations, a full range of PIV repeat measurements were not possible. Two sets of measurements were obtained at the y-plane though, because the images made for the w-plane also included the y-plane. The plume width is measured from the point of the maximum velocity to the point where the velocity is equivalent to 0.368 of the maximum velocity.

	Images 1-8	Images 9-16	Variation $\pm$ %
plume width (mm)	49	65	-14.0
velocity (m/s)	0.58	0.74	-12.5

$D_d = 0.00$ m; $L_f = 0.41$ m

	Images 25-32	Images 33-40	Variation $\pm$ %
plume width (mm)	52	53	1.0
velocity (m/s)	0.66	0.69	2.1

$D_d = 0.05$ m; $L_f = 0.41$ m

	Images 49-56	Images 56-64	Variation $\pm$ %
plume width (mm)	53	42	-11.6
velocity (m/s)	0.79	0.69	-6.7

$D_d = 0.10$ m; $L_f = 0.41$ m

	Images 73-80	Images 81-88	Variation $\pm$ %
plume width (mm)	53	58	4.5
velocity (m/s)	0.39	0.53	15.2

$D_d = 0.20$ m; $L_f = 0.41$ m

	Images 129-136	Image137-144	Variation $\pm$ %
plume width (mm)	50	53	2.9
velocity (m/s)	0.62	0.67	3.5

$D_d = 0.20$ m; $L_f = 2.21$ m

Only one set of images at y-plane and w-plane for configuration $D_d = 0.00$ m and $L_c = 2.21$ m

Table 7.39 Y-plane Plume Width and Velocity Variation with Two Sets of Images

The maximum velocity difference is 15 %, suggesting a maximum deviation from the mean of 7.5 %. The maximum difference in smoke depth is 14 %, suggesting a maximum deviation from a mean of 7 %.

7.6.4.3 Temperature Measurements

The temperature at the w-plane was recorded separately, for two periods of 90 seconds, the last starting 240 seconds after the first. The two sets of readings have been compared. Table 7.40 shows a summary of the variation in these readings.

Most ceiling jet layer temperature variations are less than 2.9 %. In most cases the maximum temperature rise corresponds to the point where $D = 0.01$ or 0.02 m. The temperature here is subject to fewer fluctuations. The maximum temperature is ± 1.5 % about a mean.

Higher variations are apparent further from the ceiling. The base of the smoke layer lie within a depth of 0.06 and 0.12 m below the ceiling. Small changes in the smoke layer depth over long periods, result in large temperature differences.

Lf	D = 0.01	D = 0.03	D = 0.06	D = 0.09	D = 0.12	D = 0.18
mean difference	100	101	105	105	106	100
standard deviation	2.7	2.9	7.4	9.1	8.2	6.4

D = depth below ceiling or soffit of downstand (m)

Table 7.40 Summary of Variation in Temperature Difference

7.7 Error Analysis

7.7.1 Measurement Error

Systematic errors were avoided as far as possible. The estimated error for dimensional and instrument readings are shown in Tables 7.41 and 7.42.

Controlled Unit	Instrument Error
Compartment Dimensions	2 mm
Instrument Locations	0.5 mm
Reservoir Height	25 mm
Flowmeter	4 %

Table 7.41 Estimates of Error for the Controlled Conditions

	Instrument	Sampling	Combined
Smoke depth ¹	3 ²	7	8
Duct velocity ³	4	10	11
Thermocouple	1	2	2
PIV velocities	5	8	9
CO ₂ analyser	6	2	6

1. From video images 2. ≈ 2 mm for shallowest smoke layer 3. Measured with pitot-tube

Table 7.42 Smoke Measurement Error (+/- %)

The controlled conditions represent those dimensions used to define the geometry and fire sizes for the experiment. The instrument errors are derived from manufacturers information and published data, described in Chapter 6. The PIV error is estimated from the pixel size and particle size relative to the displacement during the period of each PIV image (Bruce 1996).

The flow is turbulent, therefore a sampling error is introduced. The differences between repeated measurements provide an estimate of this. The sampling errors and instrument errors are independent of one another. The combined error is the root of the sum of the square of each error (Taylor 1991).

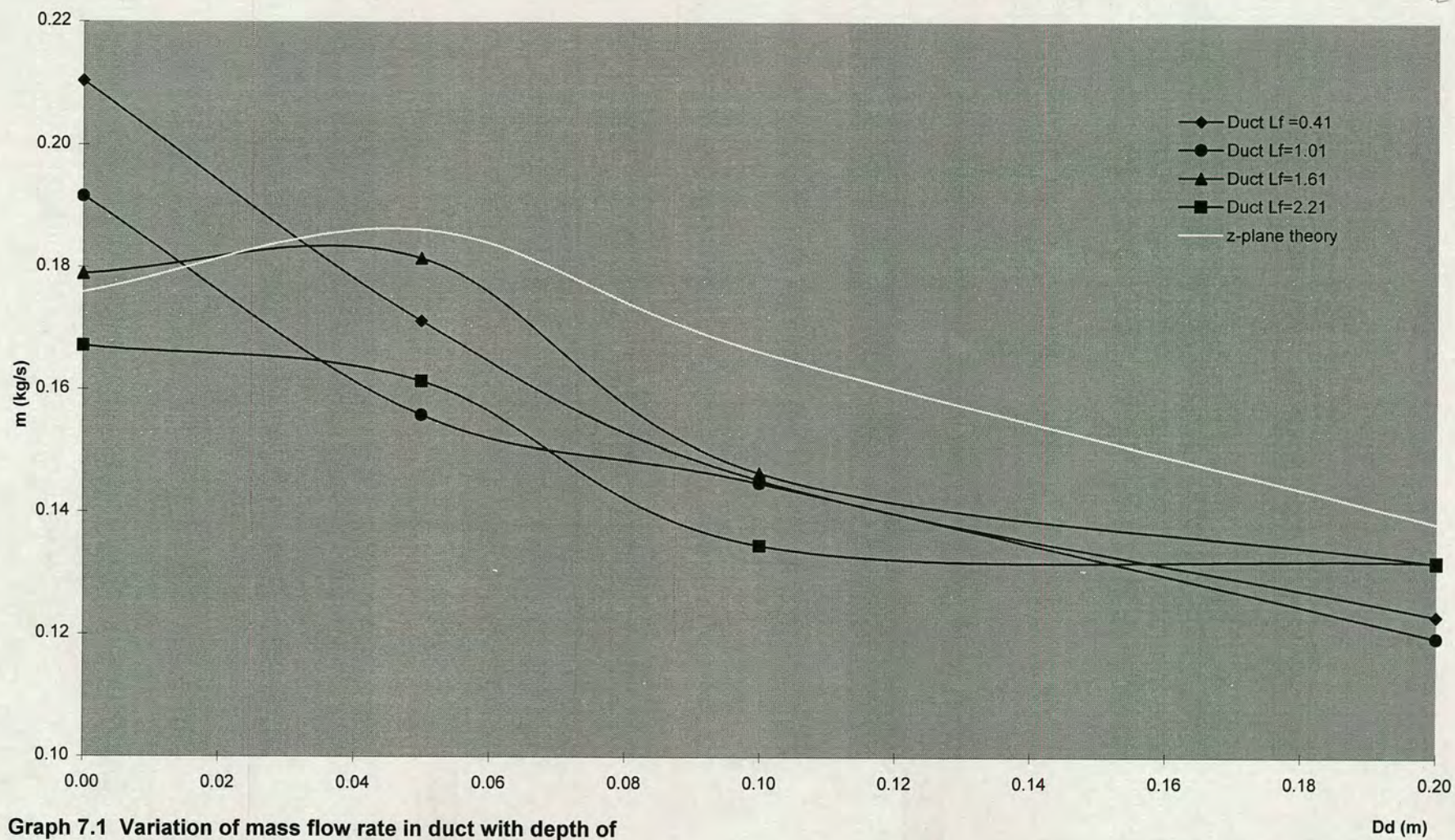
7.7.2 Error in dimensional units

The estimated error (excluding systematic and random errors) for the dimensional units of interest in these results are as follows:

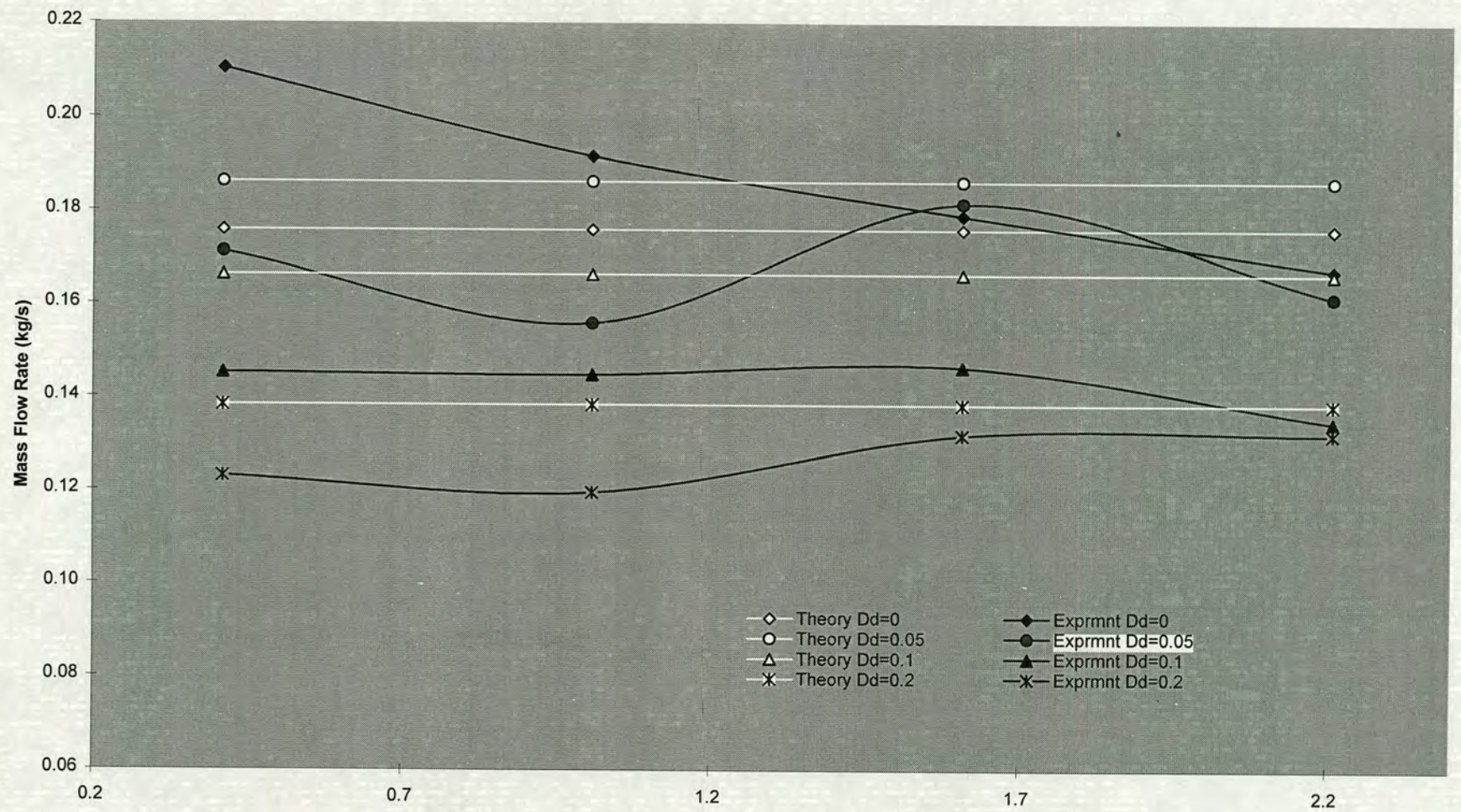
D	8 %	measured from video images
Dd	2 mm	scaled
H	2 mm	scaled
z	25 mm	visual estimate of average height between two scales
H	2 mm	scaled
m	11 %	measured in duct
	13 %	measured by PIV (includes estimated 2 % due error in estimating the edge of the plume)
Q_f	4 %	measured with flowmeter
Q_c	13 %	measured in duct
	15 %	measured by PIV and thermocouples
T	2 %	direct measurement
$u_{\max}$	9 %	from direct measurement
W	2 mm	scaled
$\theta_{\max}$	2 %	direct measurement
θ_{mean}	28 %	derived from Q_c and m from PIV

7.8 Graphs

There is no Graph 7.11, 7.21 to 7.23, and 7.33 to 7.40.

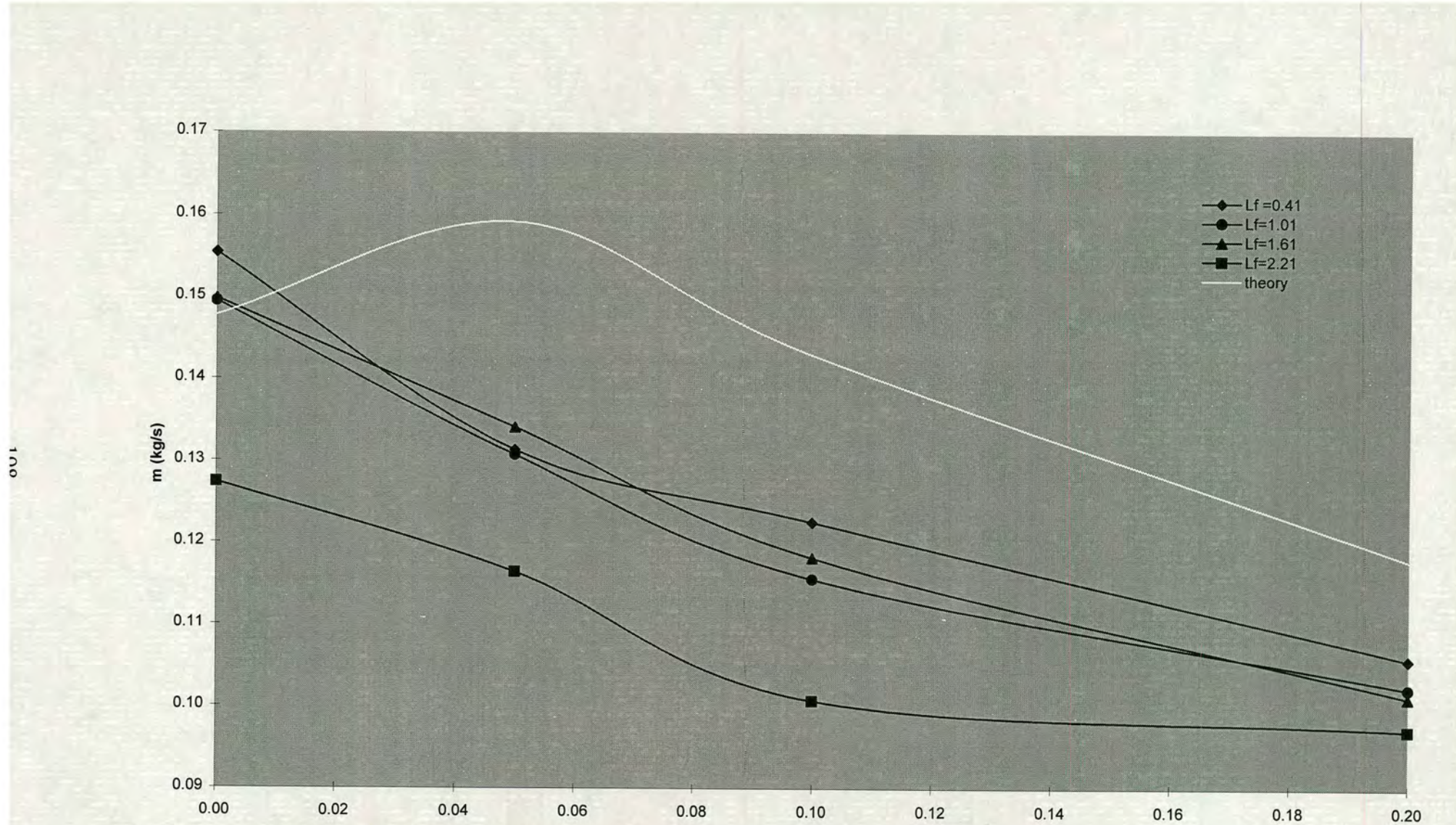


Graph 7.1 Variation of mass flow rate in duct with depth of downstand (Dd); $Q_f = 4.67\text{kW}$; $z = 0.75$



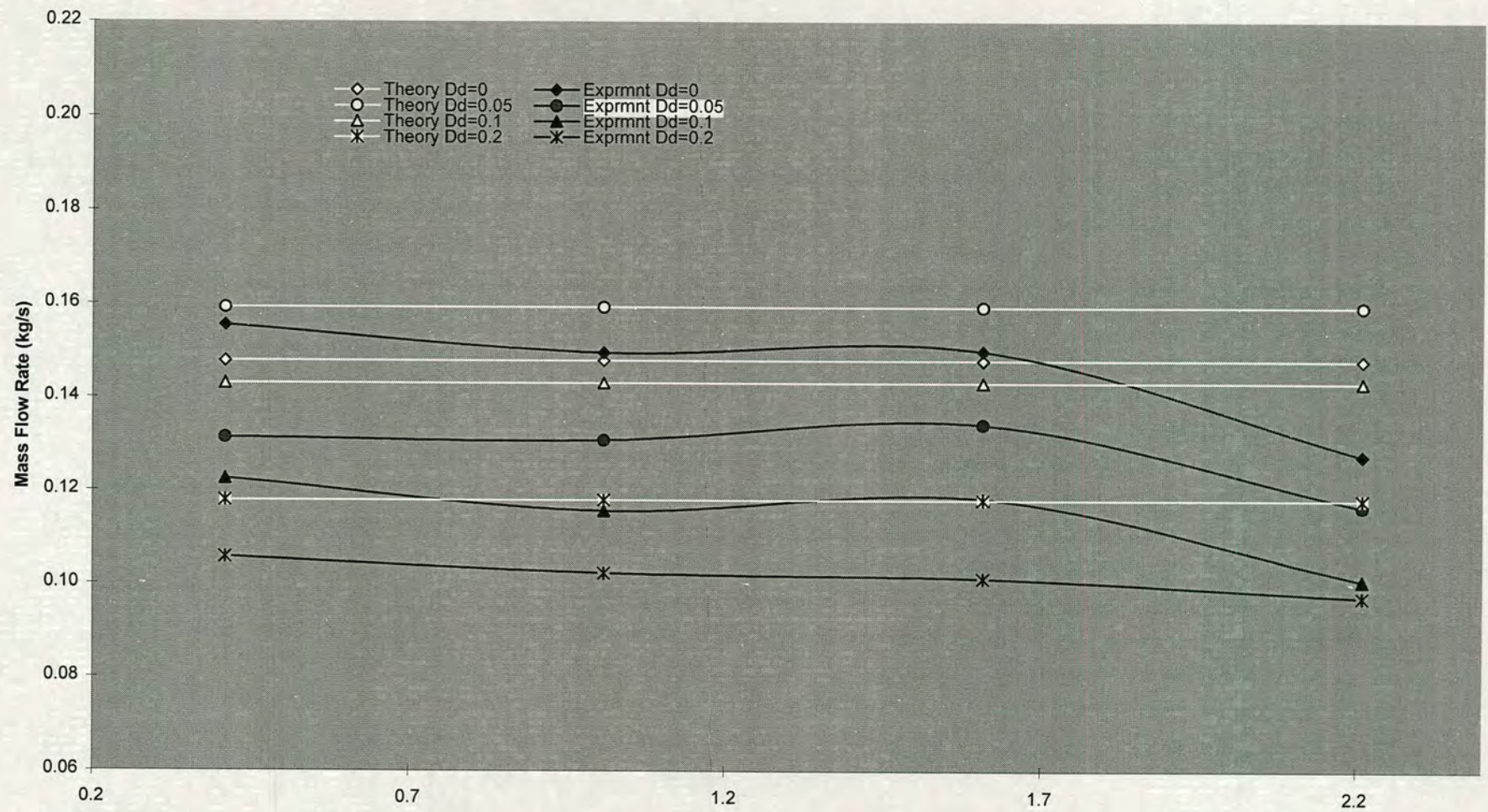
Graph 7.2. Variation: m v. L_f ; $z = 0.75$; $Q_f = 4.67$ kW

L_f (m)



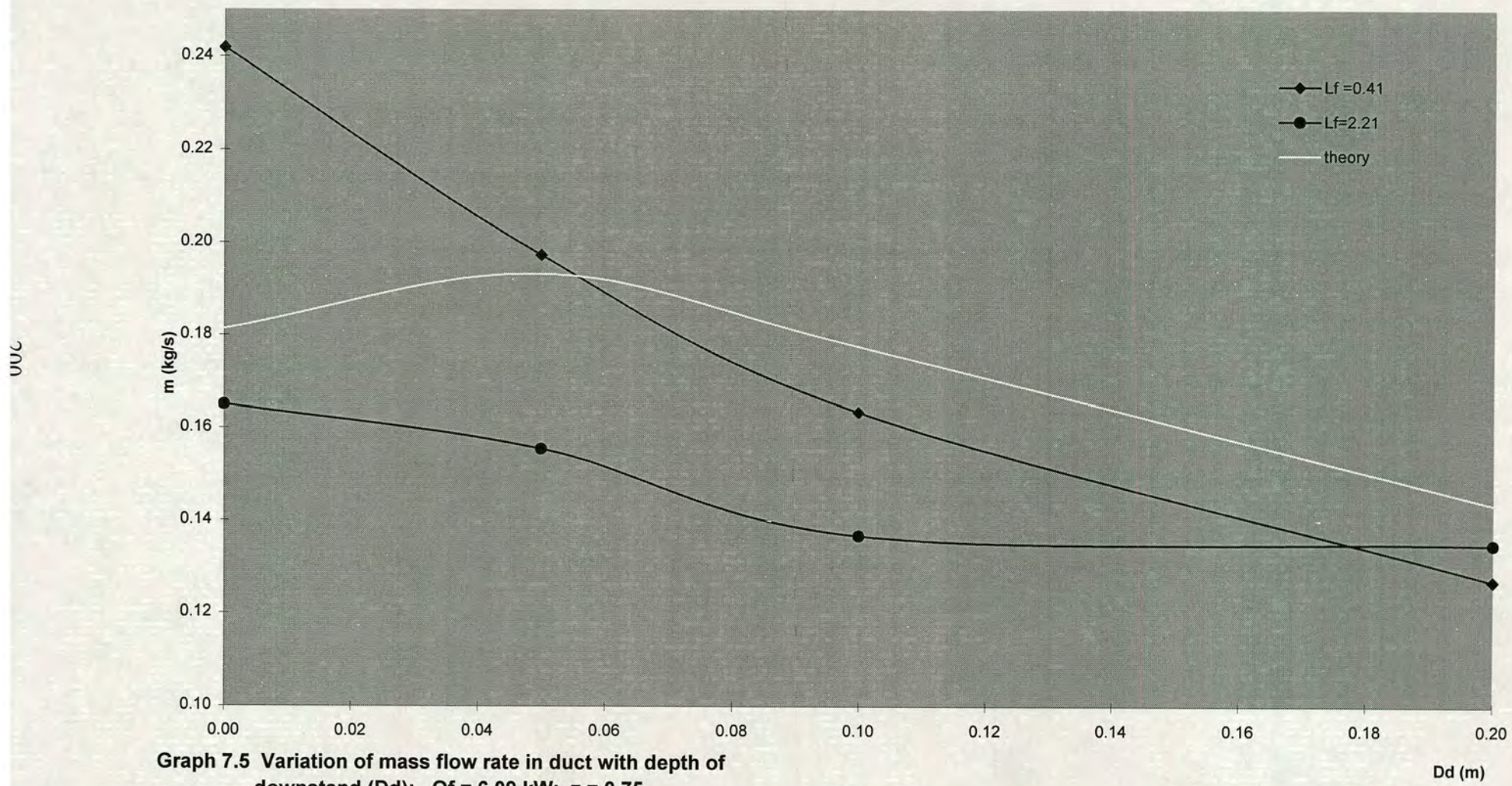
Graph 7.3 Variation of mass flow rate in duct with depth of downstand (Dd); $Q_f = 4.67\text{kW}$; $z = 0.55$

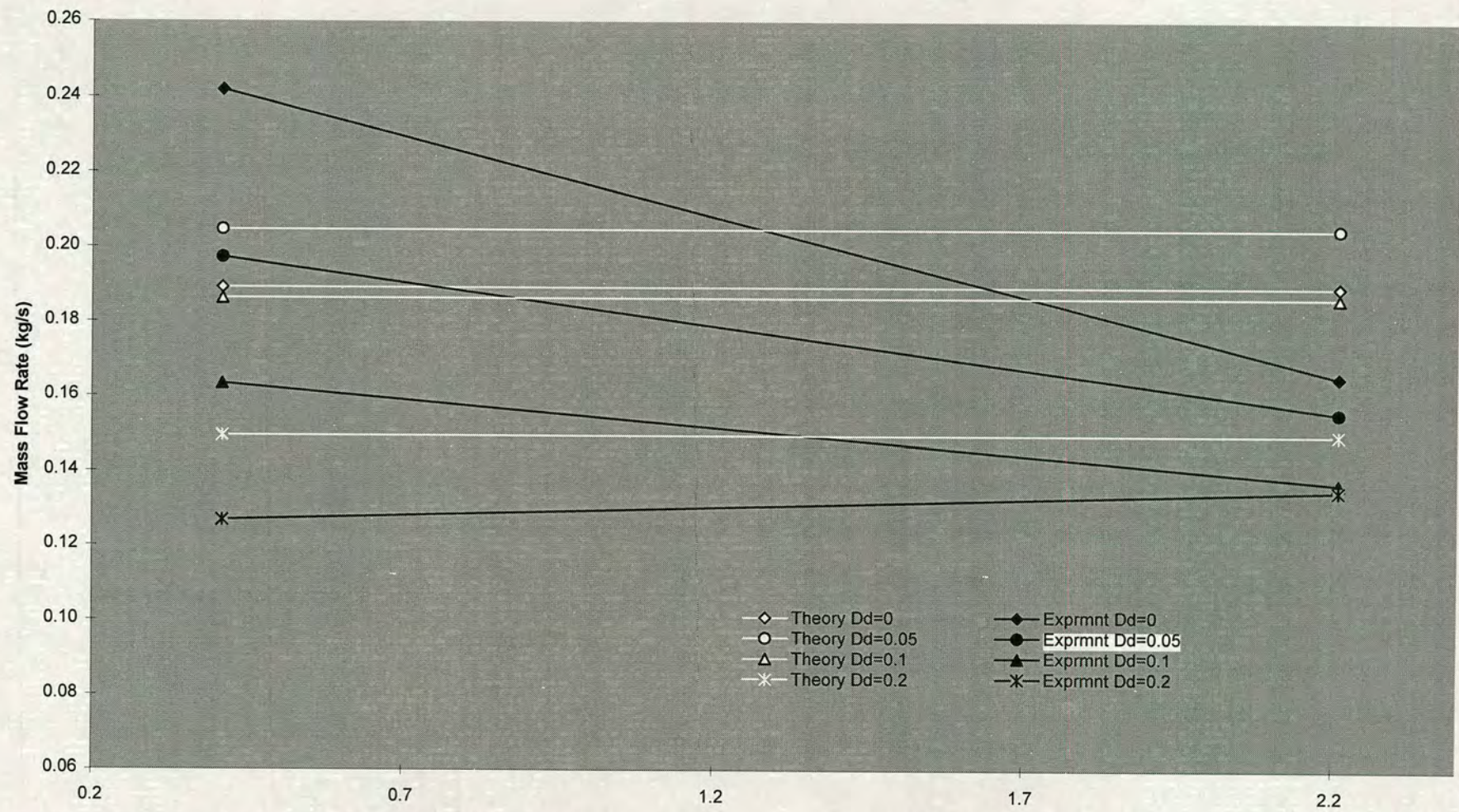
Dd (m)



Graph 7.4. Variation: m v. L_f ; $z = 0.55$; $Q_f = 4.67$ kW

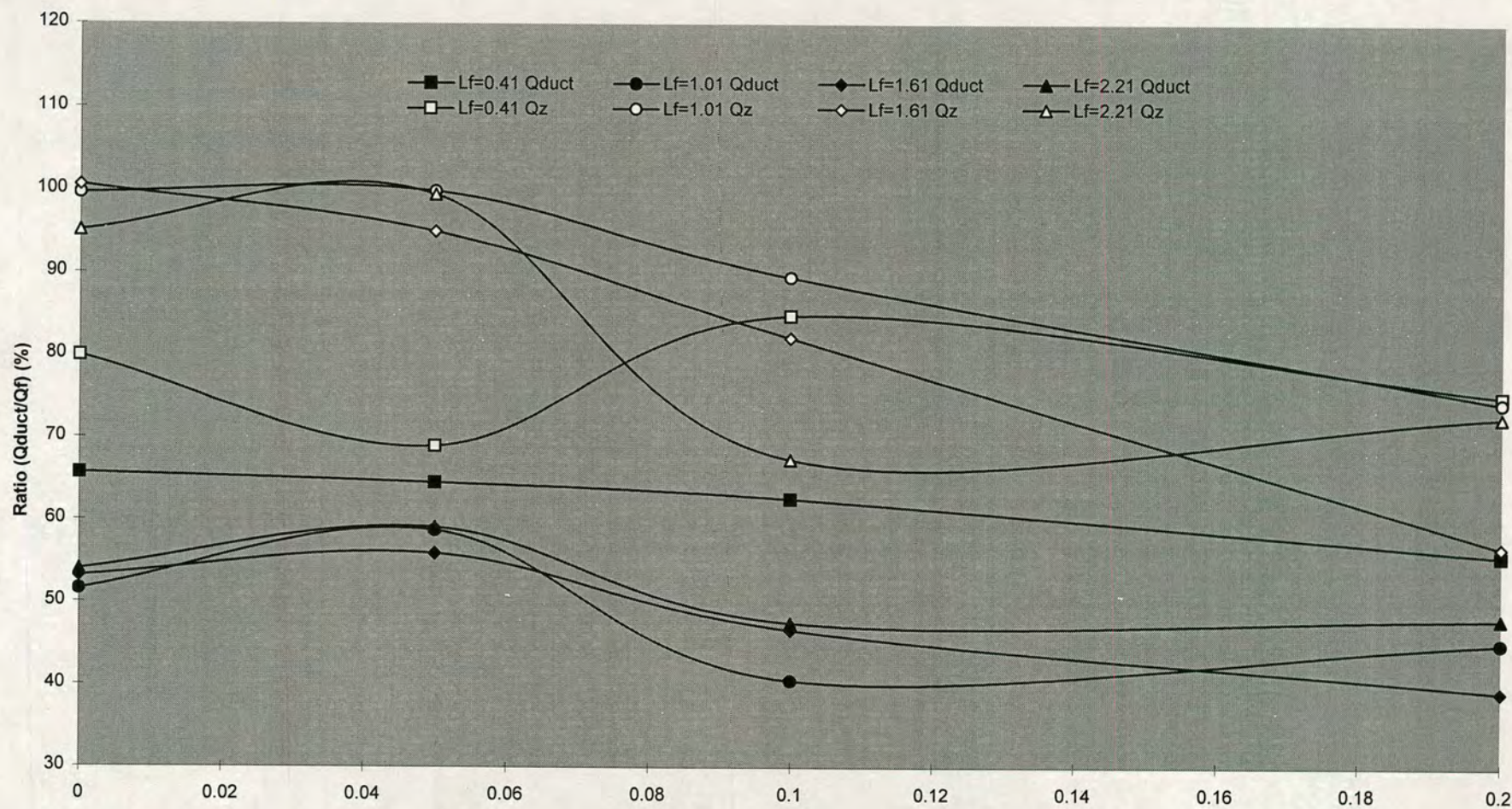
L_f (m)





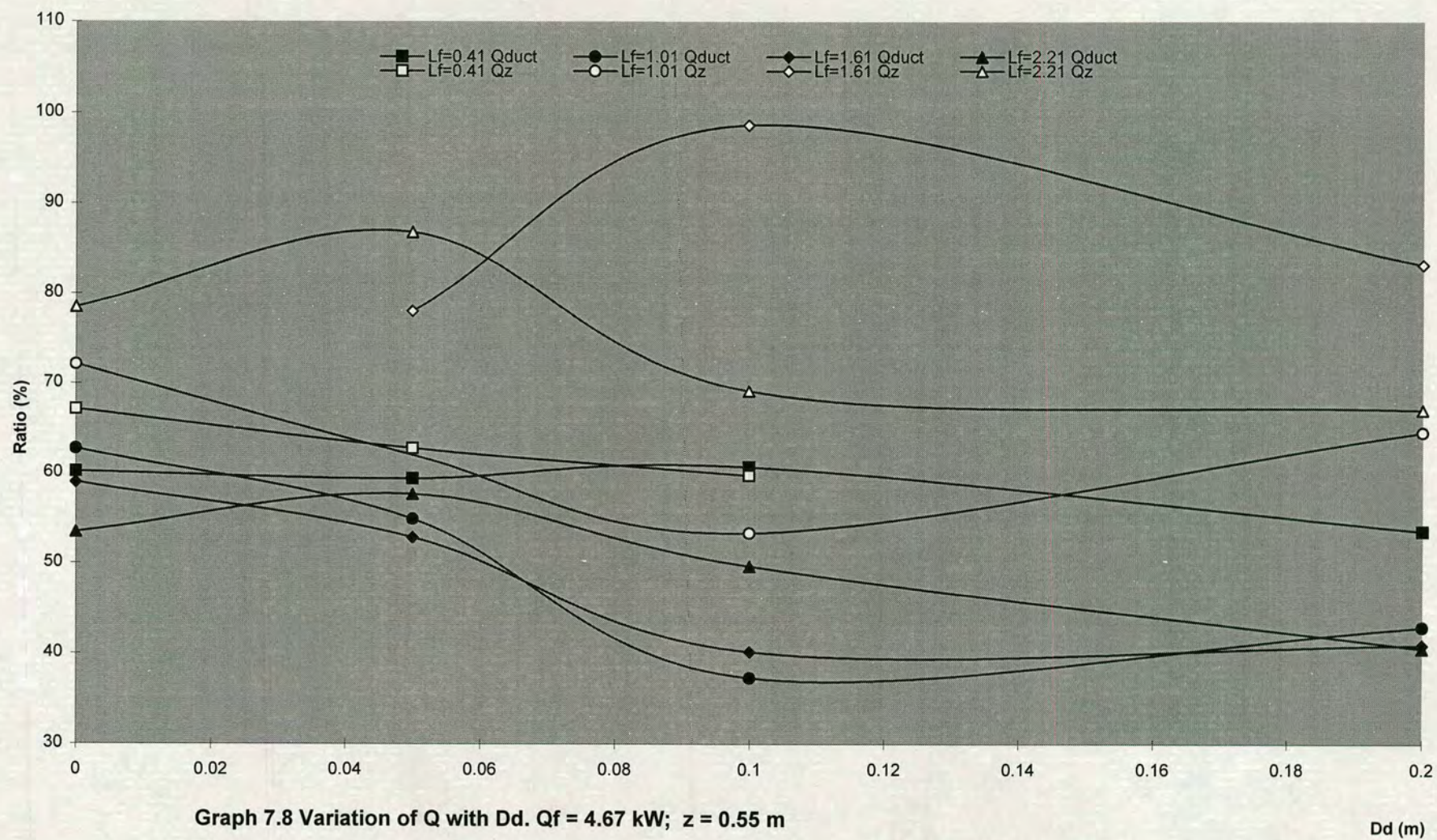
Graph 7.6. Variation: m v. L_f ; $z = 0.750$; $Q_f = 6.09$ kW

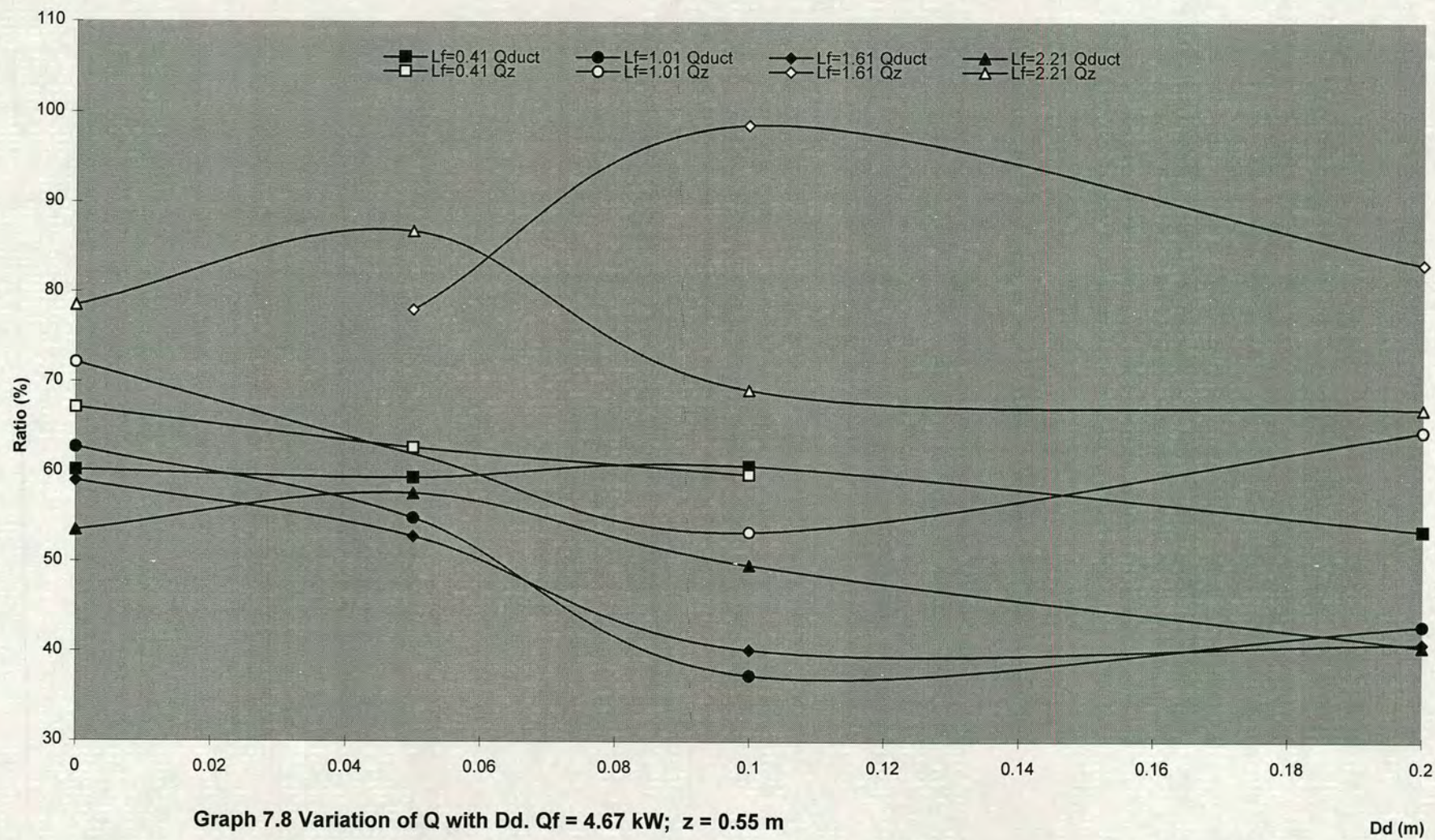
Lf (m)

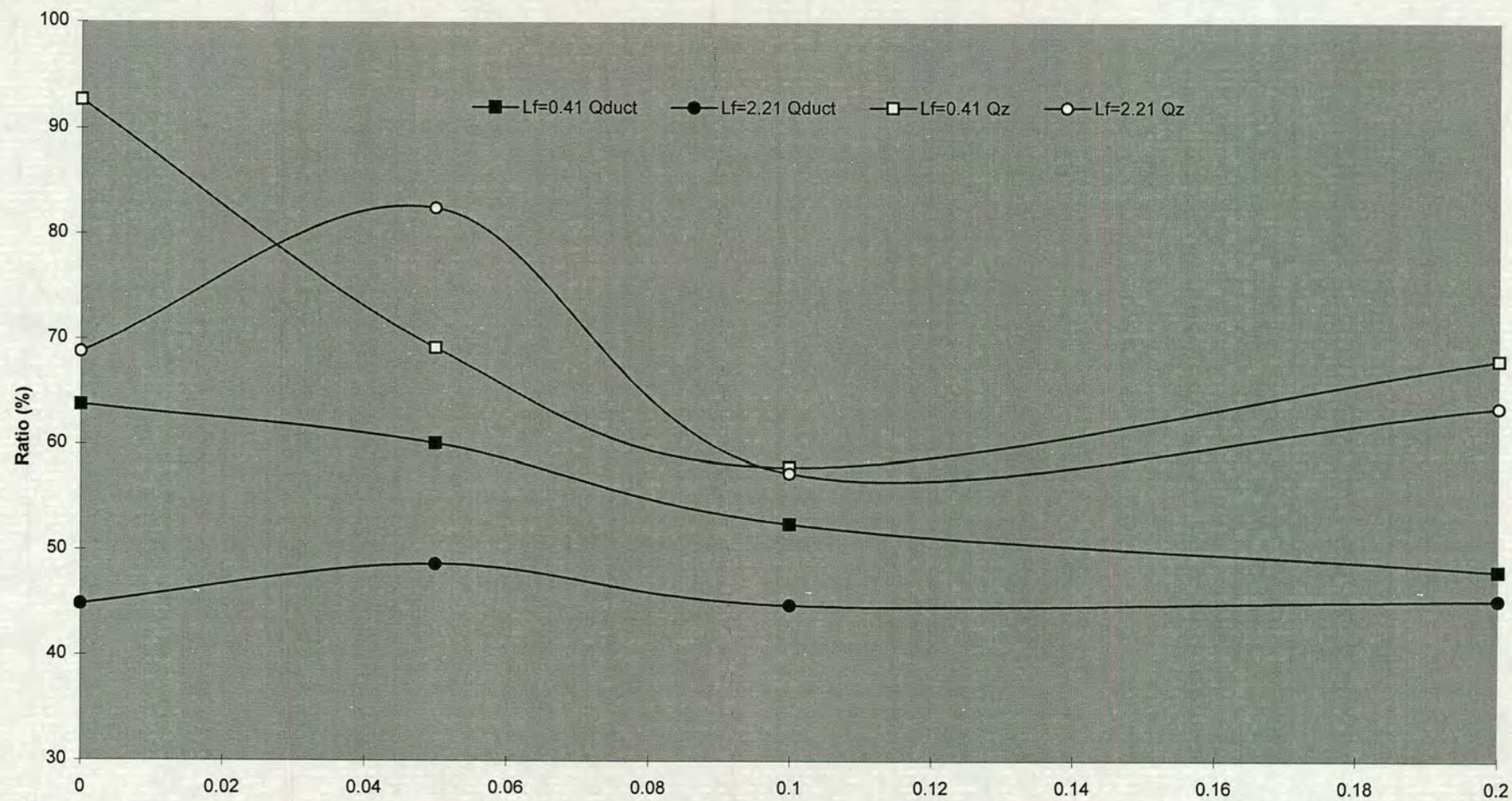


Graph 7.7 Variation of Q with D_d . $Q_f = 4.67$ kW; $z = 0.75$ m

D_d (m)

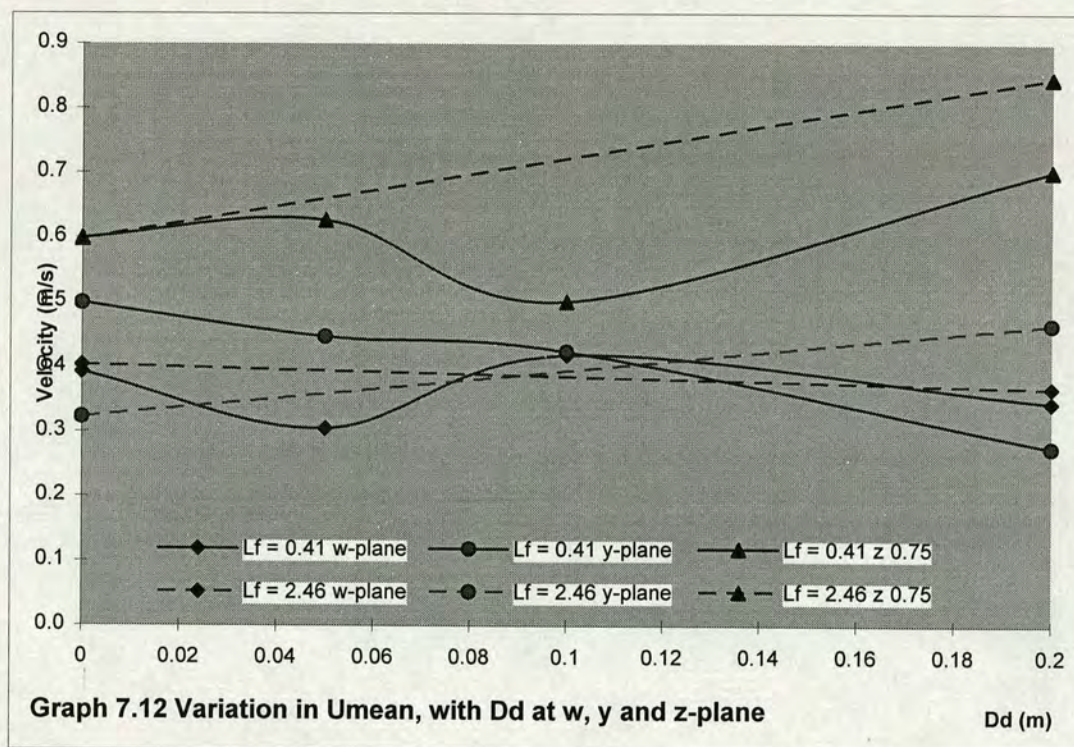
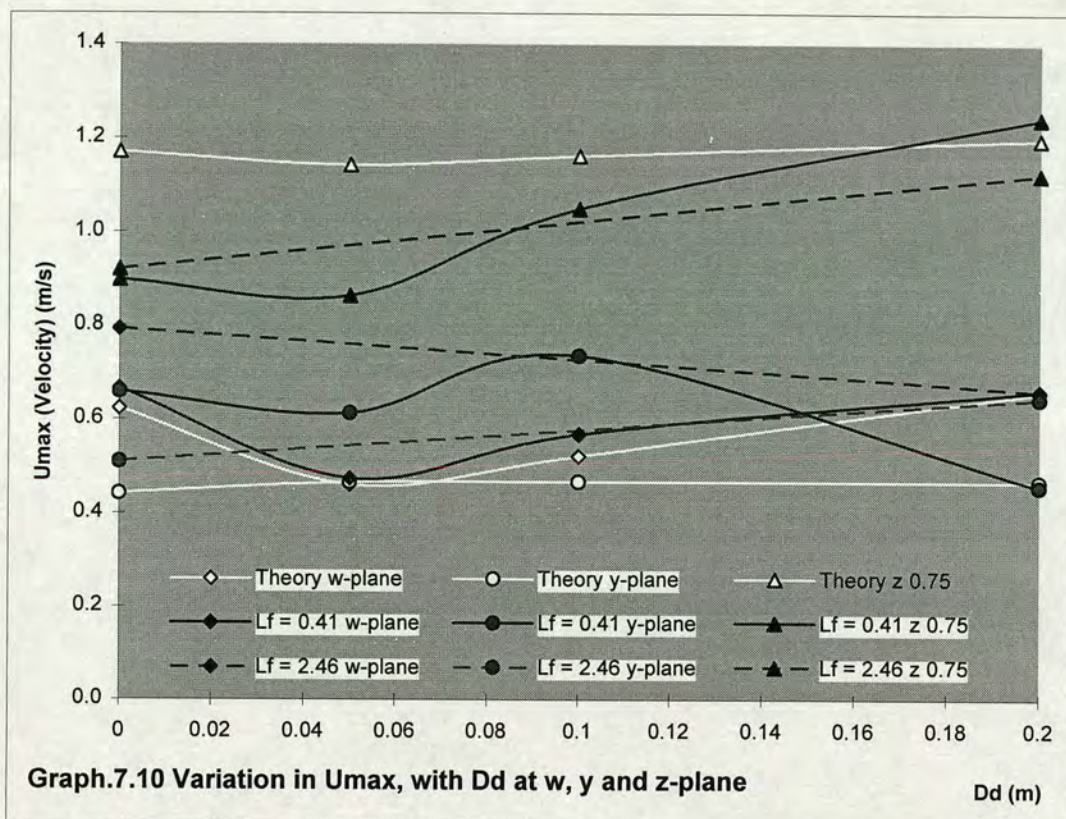


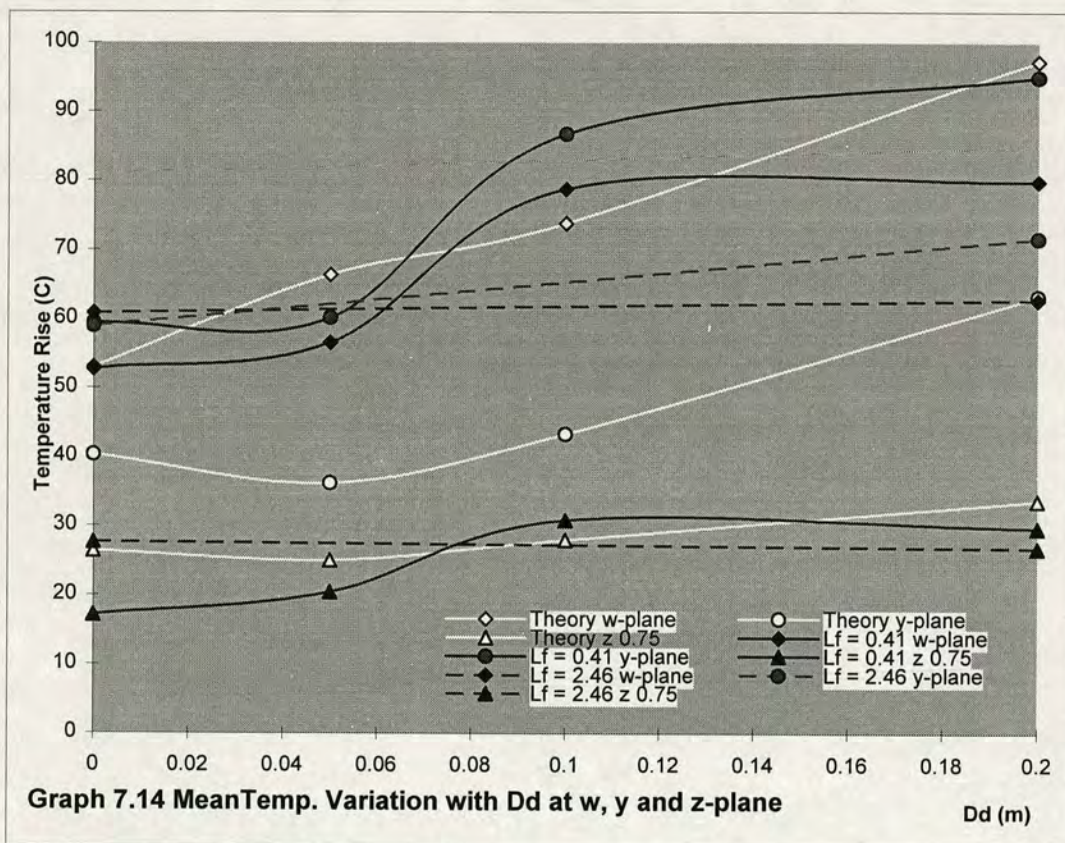
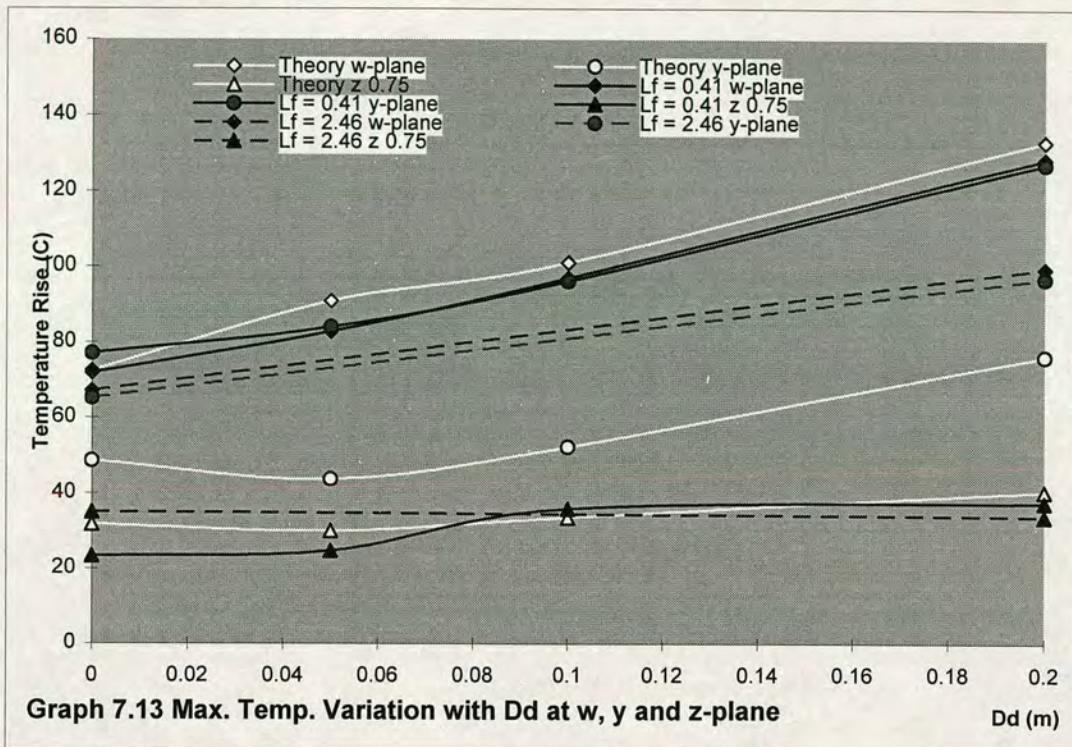


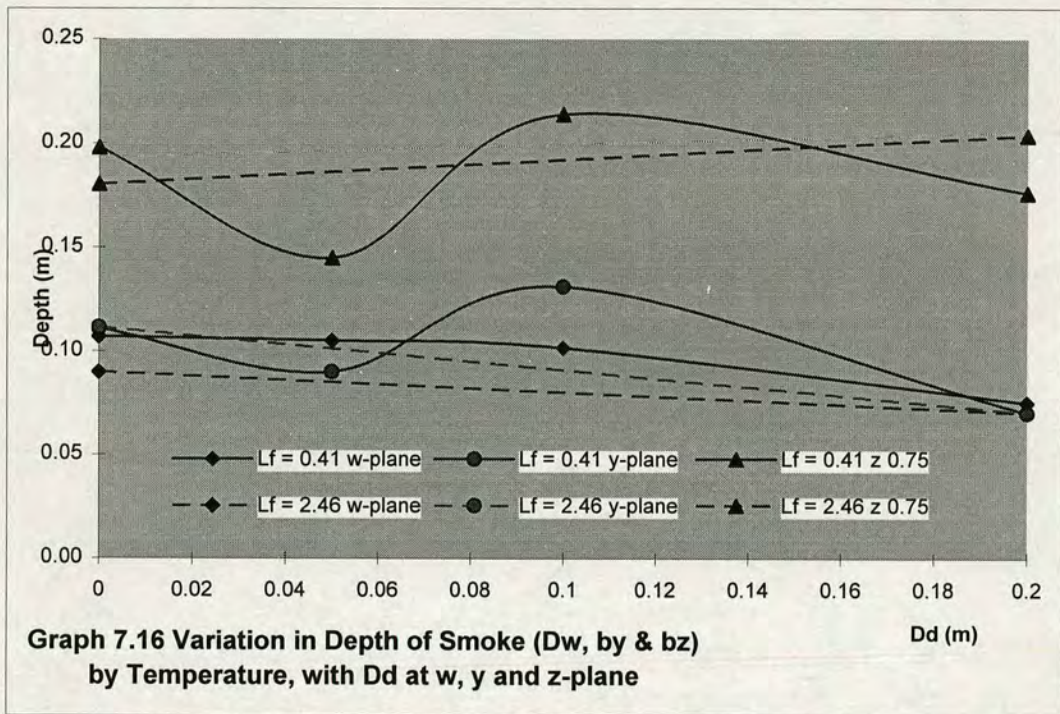
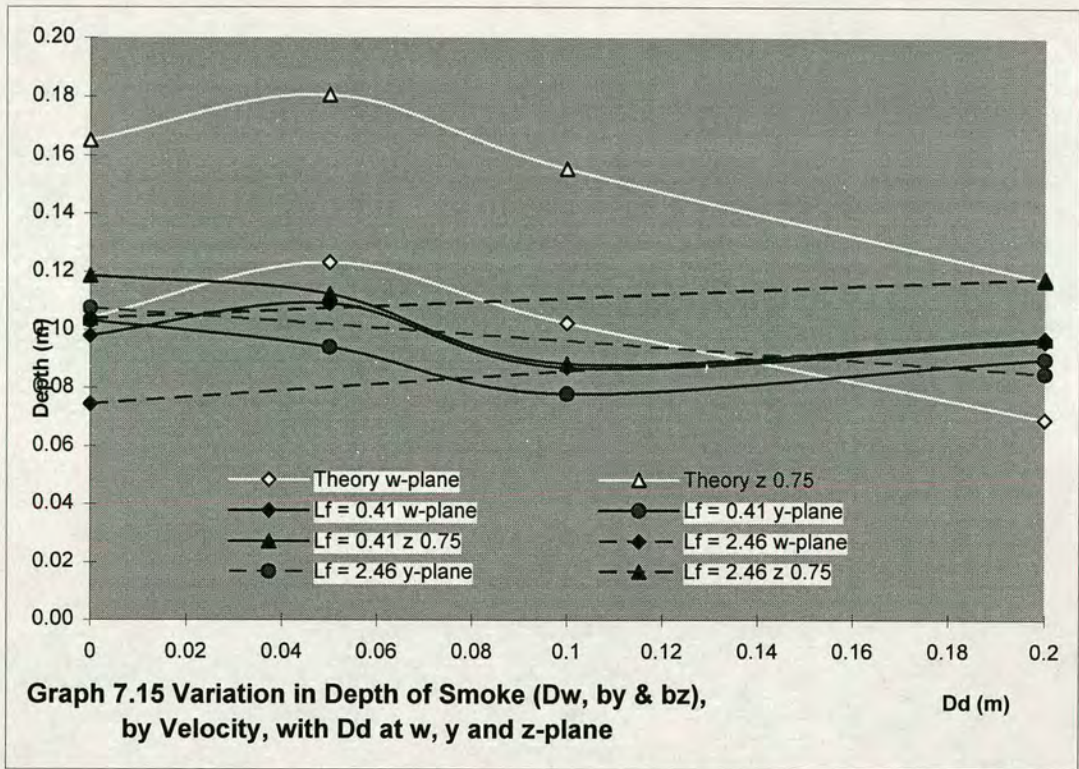


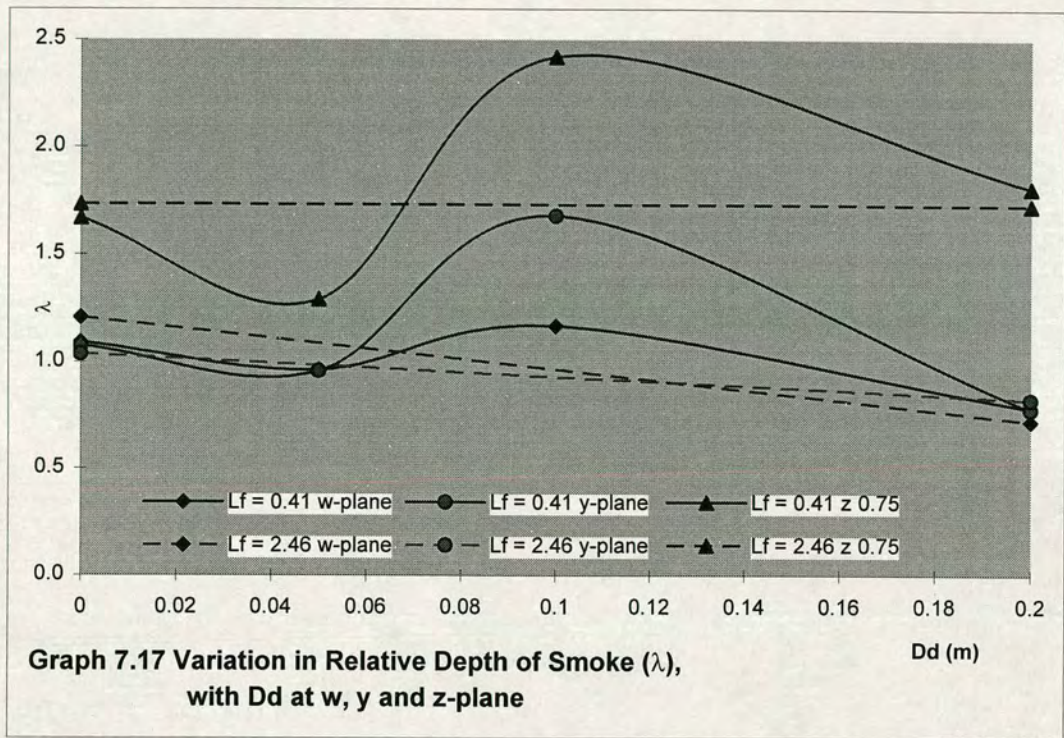
Graph 7.9 Variation of Q with Dd. $Q_f = 6.09 \text{ kW}$; $z = 0.75 \text{ m}$

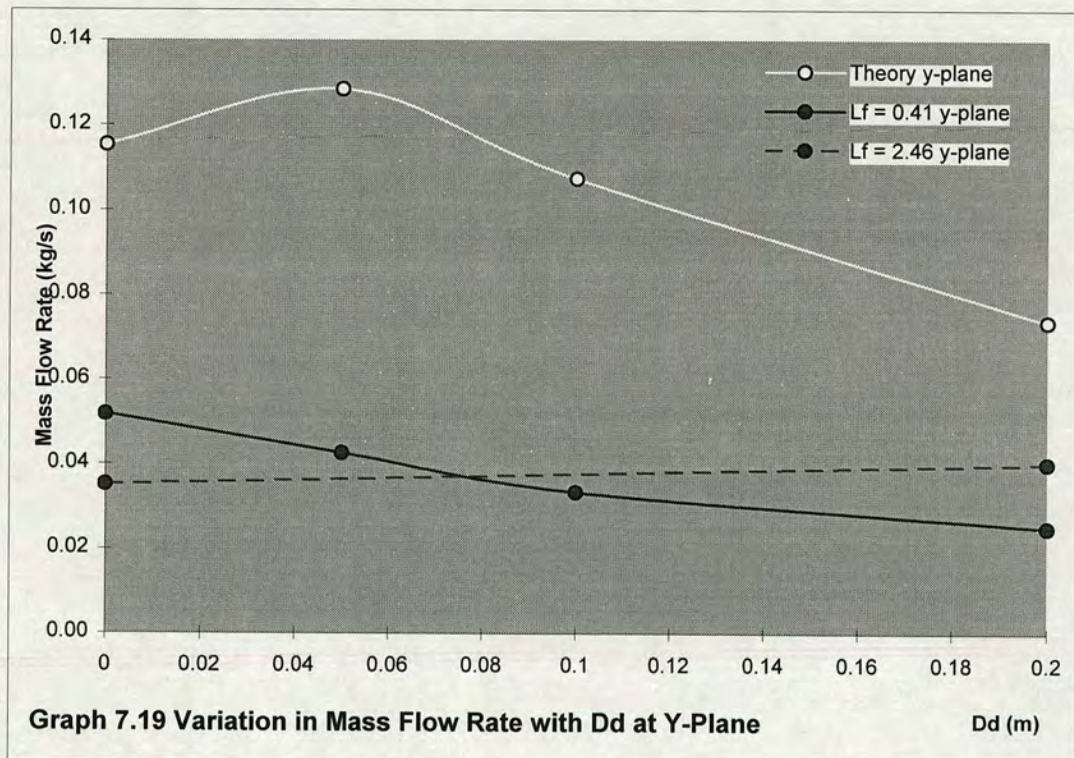
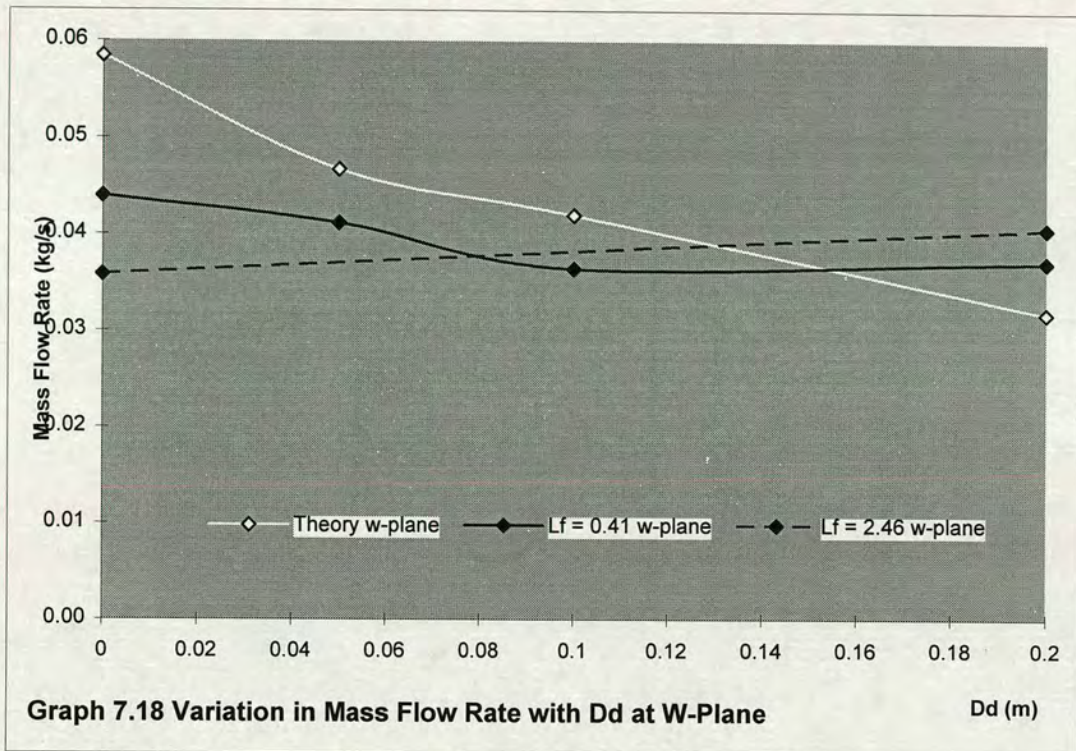
Dd (m)

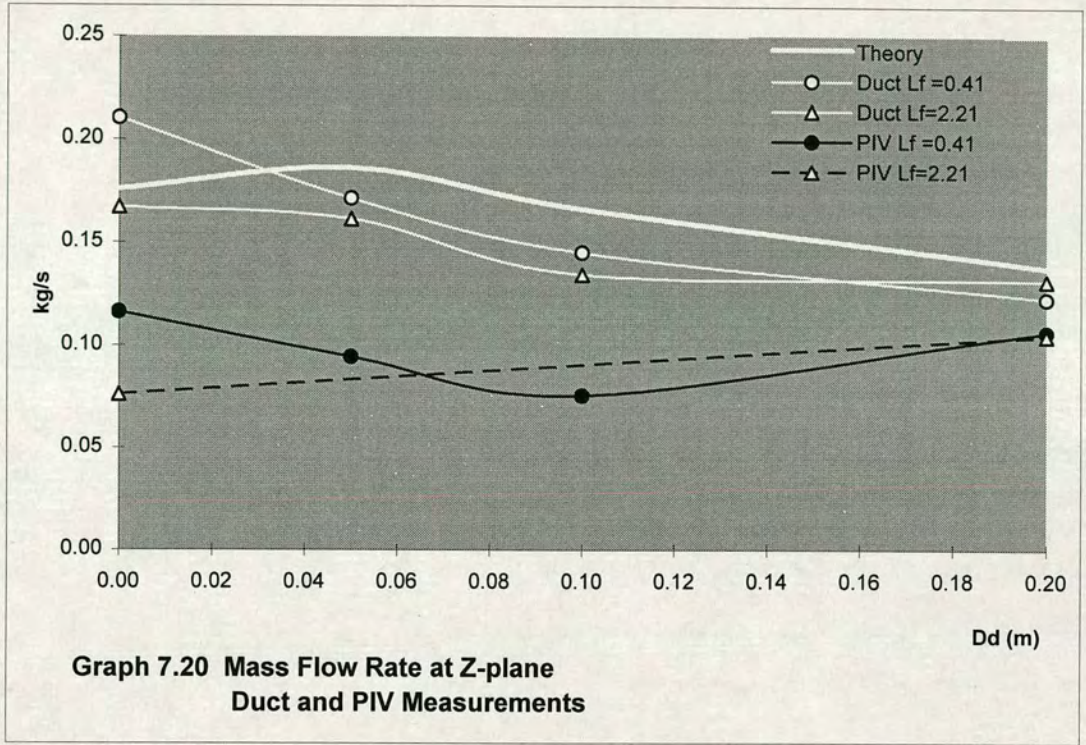


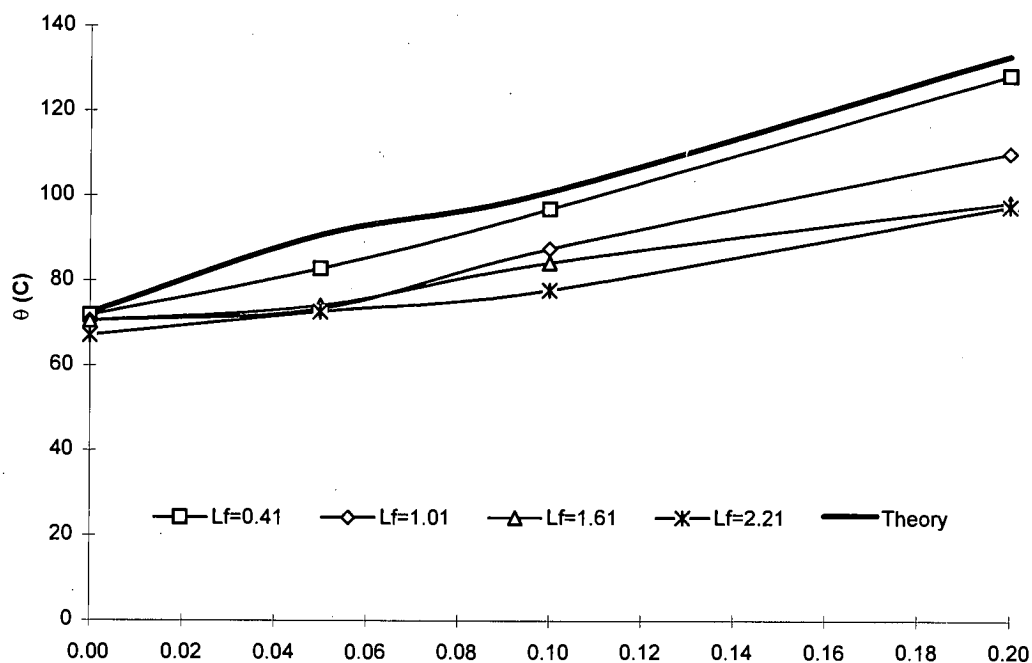








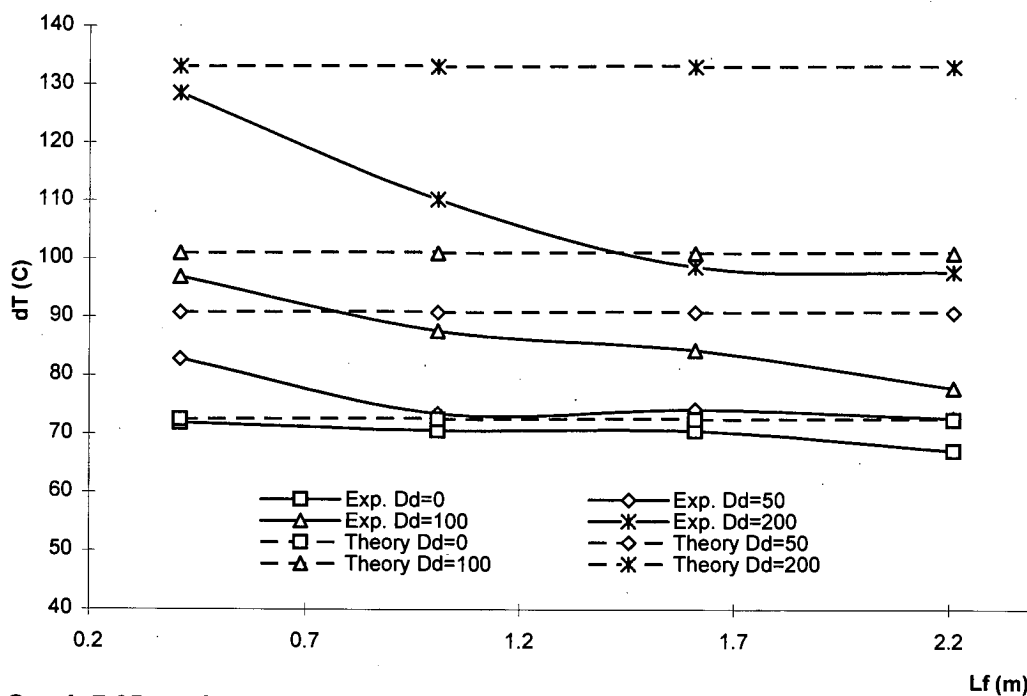




**Graph 7.24 Maximum Temperature Rise (θ) at W-Plane,
with Varying D_d ; $Q_f = 4.67$ kW**

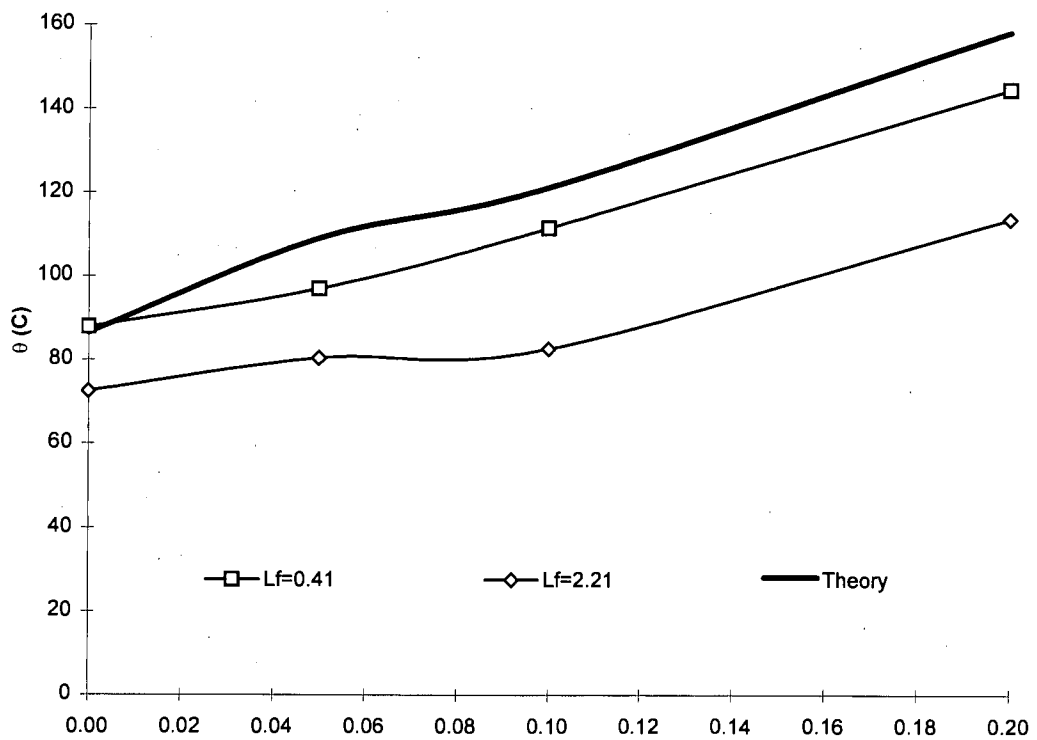
D_d (m)

sumtrmwpl



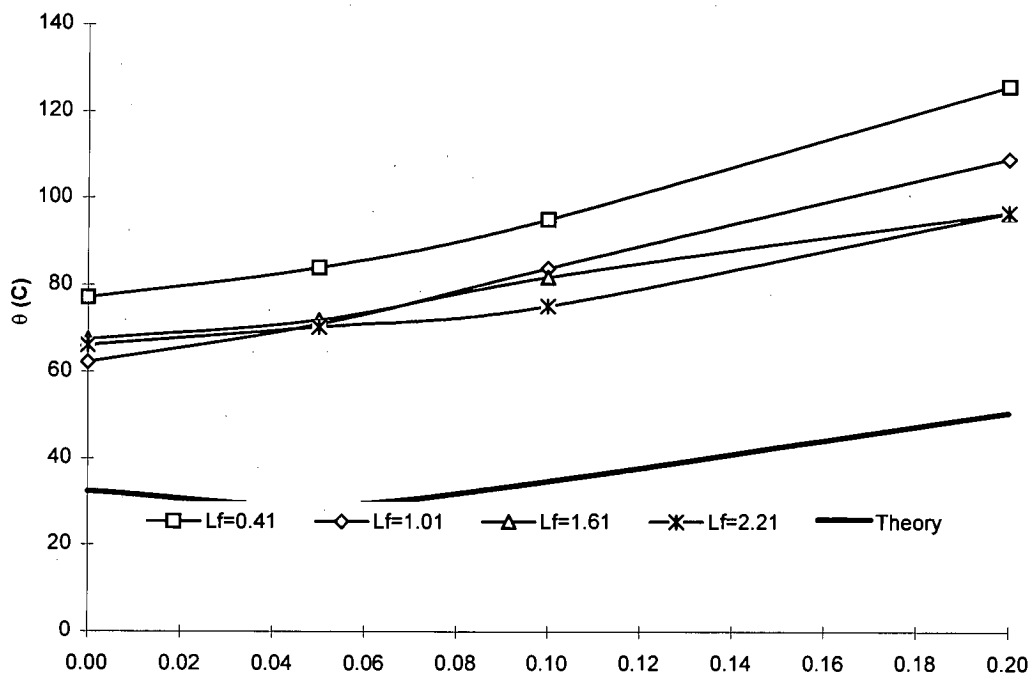
**Graph 7.25 Maximum Temperature Rise (θ) at W-Plane,
with Varying L_f ; $Q_f = 4.67$ kW**

L_f (m)



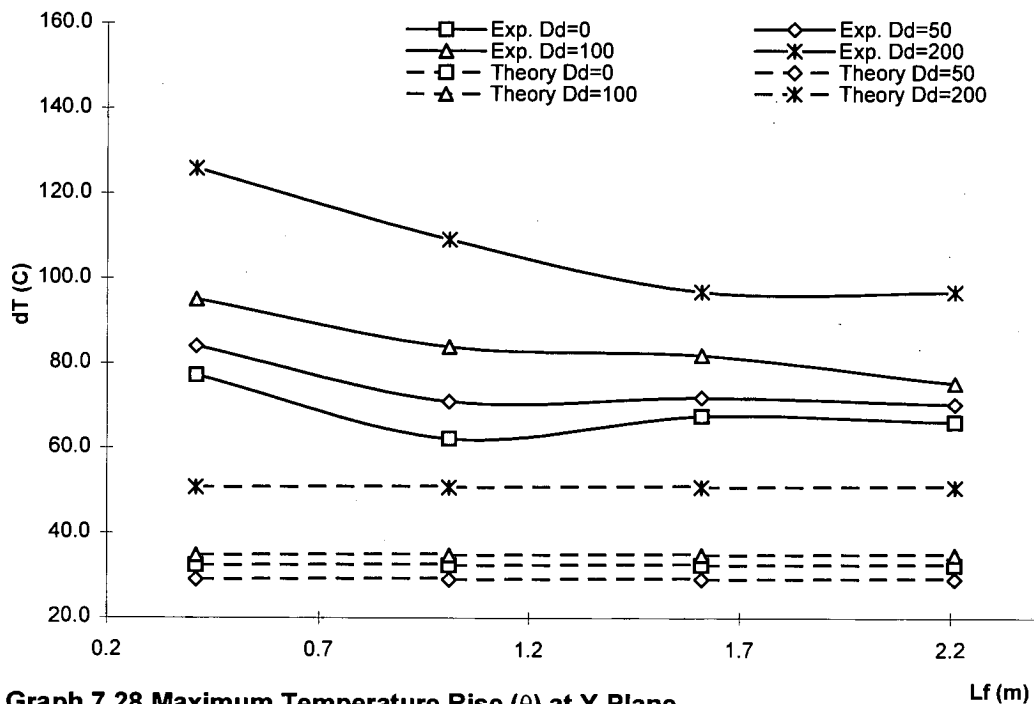
**Graph 7.26 Maximum Temperature Rise (θ) at W-Plane,
with Varying Dd ; $Q_f = 6.09$ kW**

Dd (m)



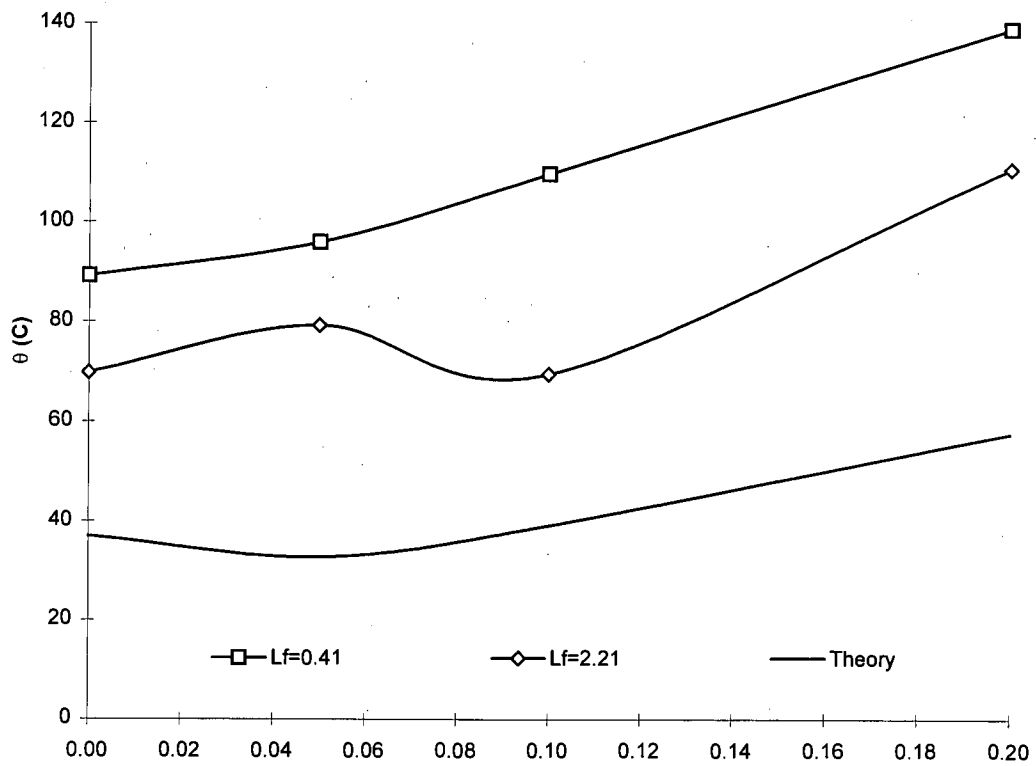
**Graph 7.27 Maximum Temperature Rise (θ) at Y-Plane,
with Varying Dd ; $Q_f = 4.67$ kW**

Dd (m)



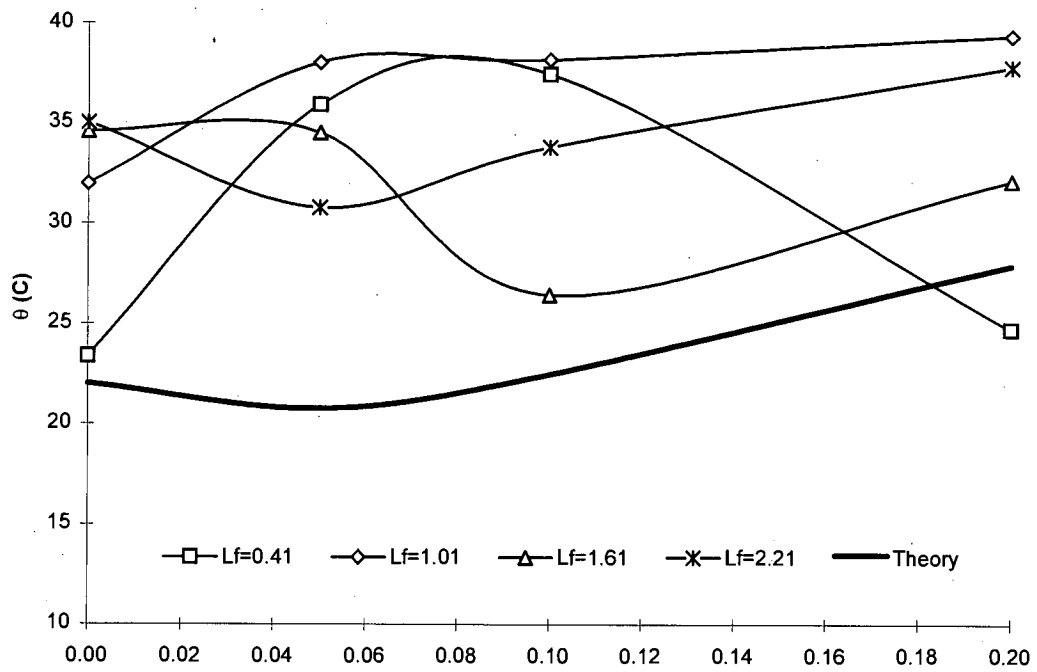
**Graph 7.28 Maximum Temperature Rise (θ) at Y-Plane,
with Varying Lf ; $Q_f = 4.67$ kW**

Lf (m)



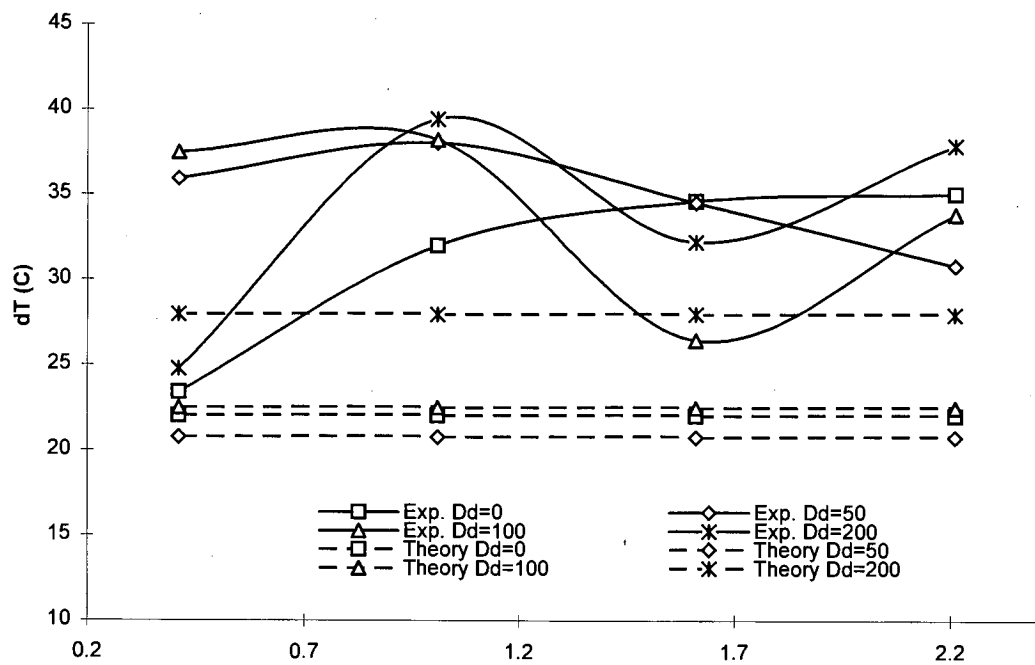
**Graph 7.29 Maximum Temperature Rise (θ) at y-Plane,
with Varying Dd ; $Q_f = 6.09$ kW**

Dd (m)



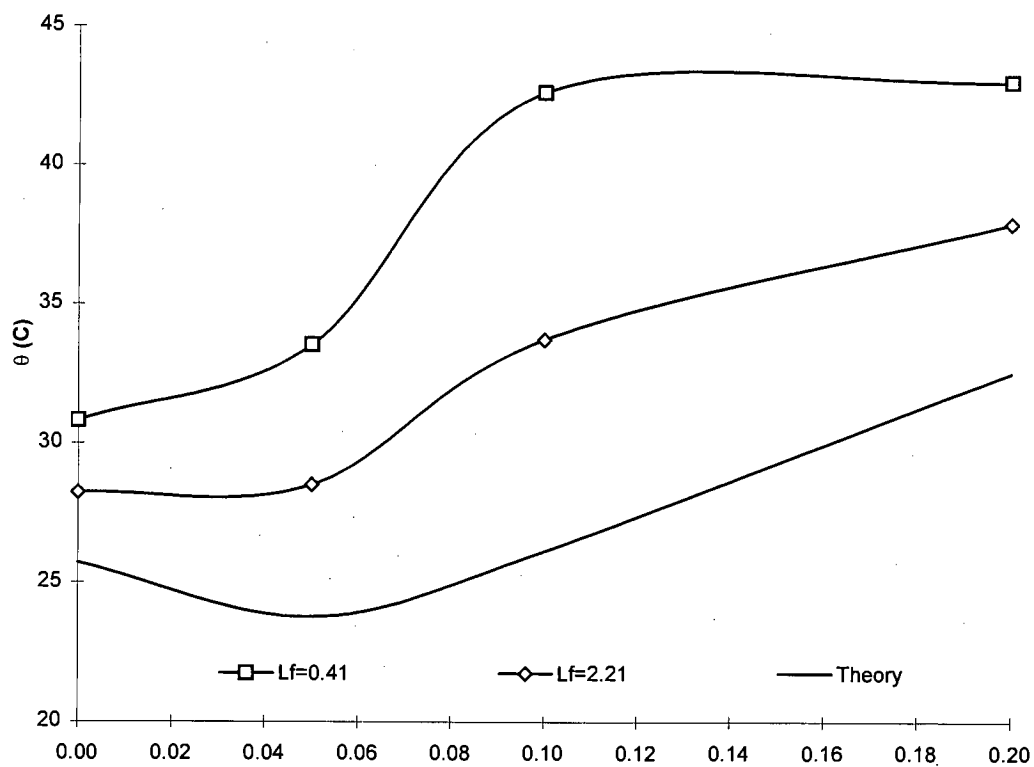
Graph 7.30 Maximum Temperature Rise (θ) at z-plane, with Varying Dd; $Q_f = 4.67$ kW

Dd (m)



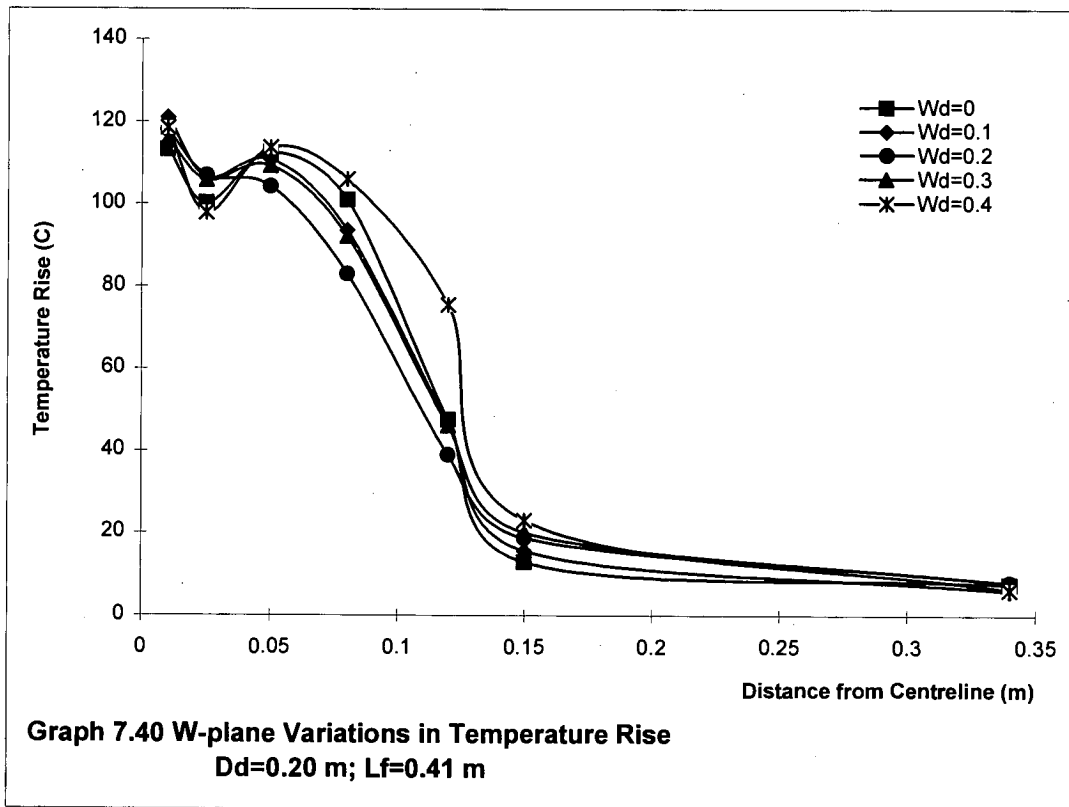
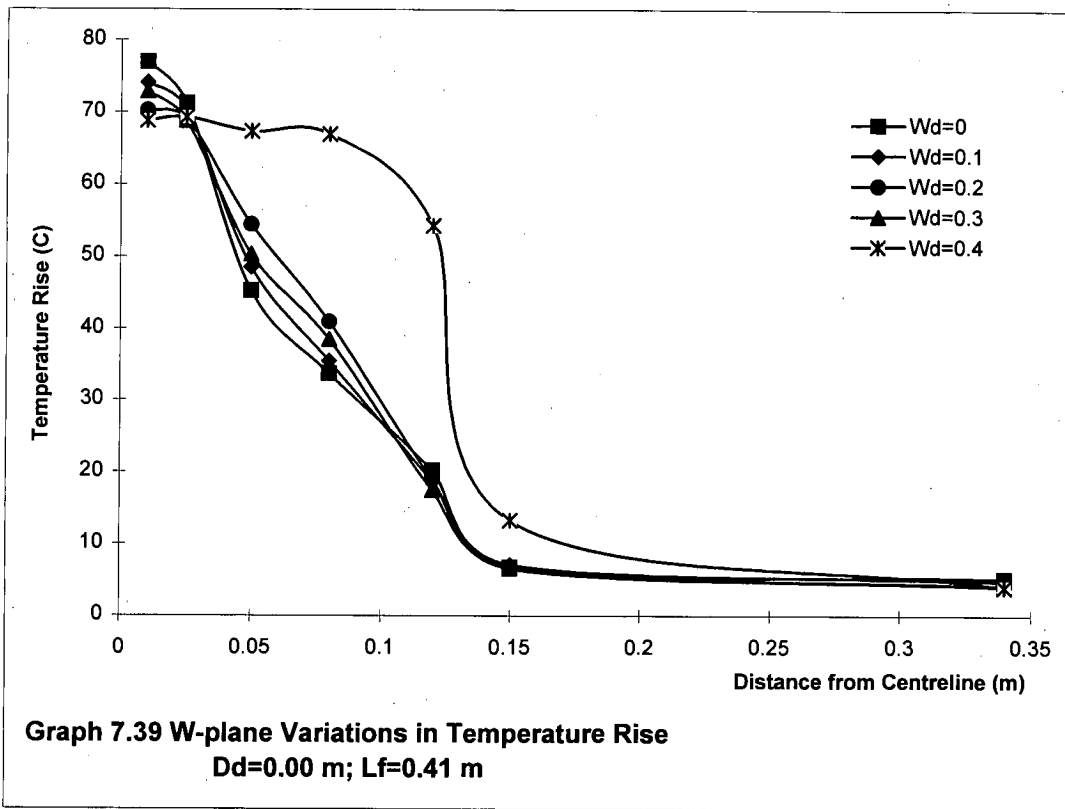
Graph 7.31 Maximum Temperature Rise (θ) at z-plane, with Varying Lf; $Q_f = 4.67$ kW

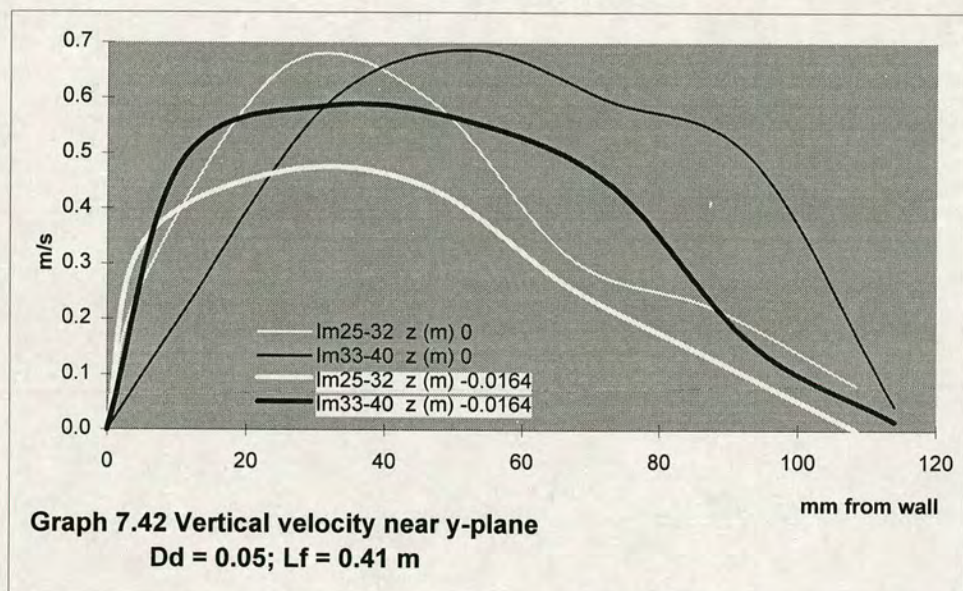
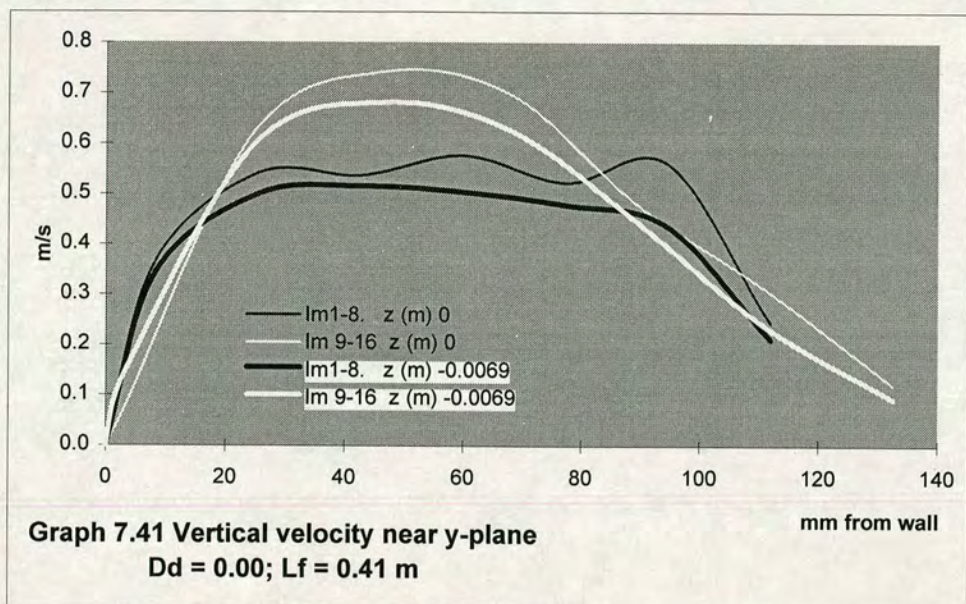
Lf (m)

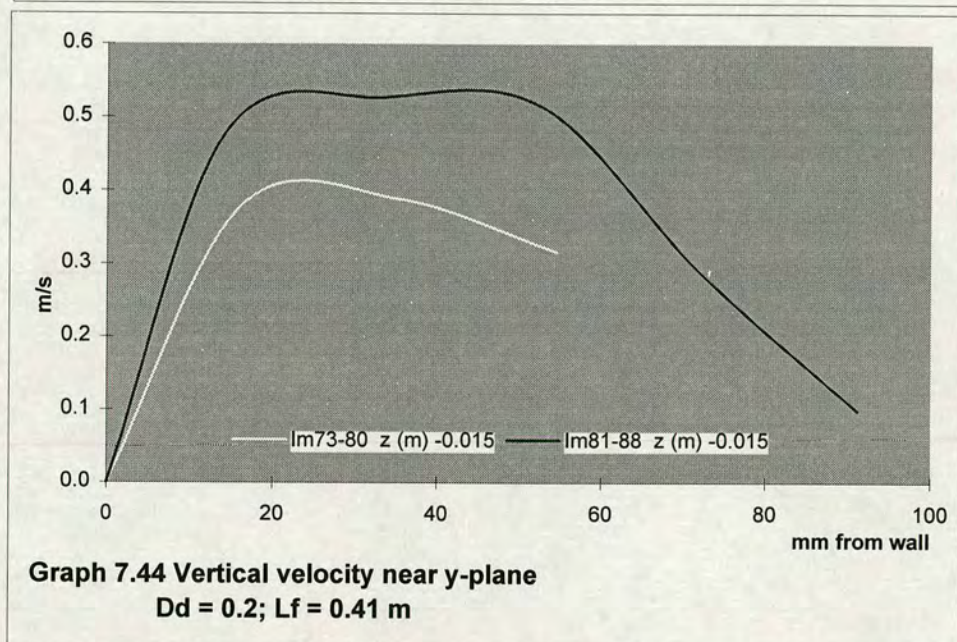
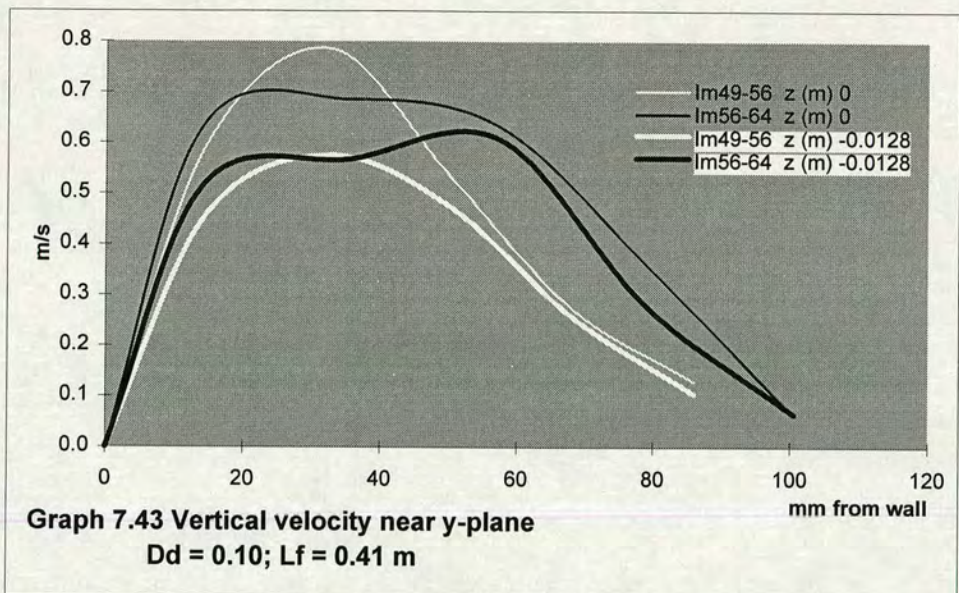


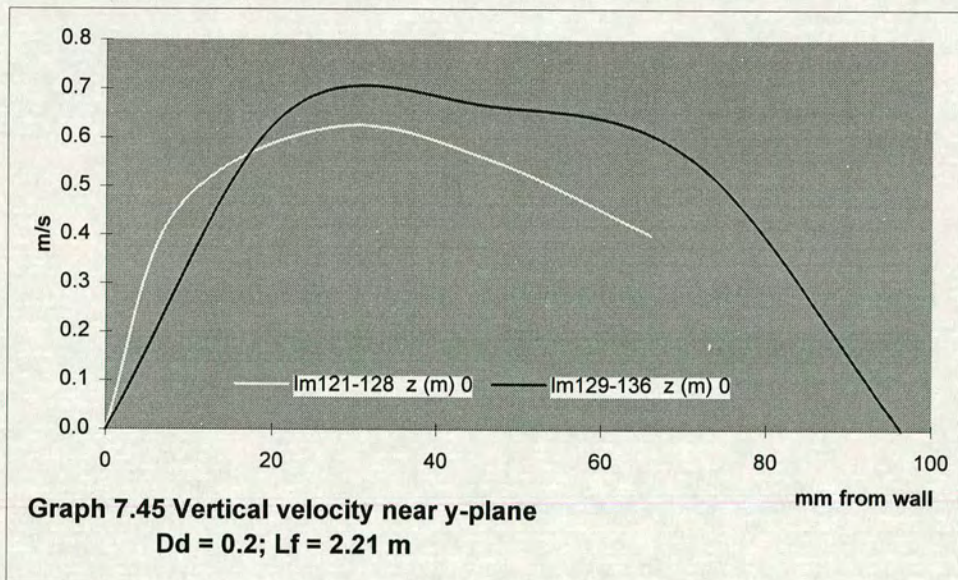
**Graph 7.32 Maximum Temperature Rise (θ) at z-Plane,
with Varying Dd ; $Q_f = 6.09$ kW**

Dd (m)









Chapter 8 Visual Observations from Experiments

8.1 Introduction

Visualisation allows explanations for the data from the experimental measurements to be developed and to highlight areas where additional measurements may be required. The visual records for the following experimental arrangements are presented:

- Preliminary Experiment; using tracer smoke and lamp illumination
- Main Experiment; using tracer smoke and lamp illumination
- Main Experiment; using PIV imaging

One particular aspect of the flow that requires visualisation is the flow in the rotation region, to provide additional evidence for whether major entrainment is occurring.

8.2 Preliminary Experiment

The observations of the flow conditions observed are discussed in this section. These were made possible by using tracer smoke, illuminated by a bright lamp.

8.2.1 Flame

The methanol fire was not fully turbulent, but created turbulent conditions that were suitable for the experiment.

8.2.2 Ceiling Jet and Hot Layer

Rapid lateral spread of tracer smoke, from a smouldering piece of fibreboard immersed in the ceiling jet, was observed for all ceiling jets and hot layer conditions.

As expected, when no downstand was present a rapidly flowing jet was observed to flow beneath the ceiling. Its depth appeared to vary between 60 and 80 mm for the shorter compartment, $L_f = 0.41$ m and 70 and 90 mm for longer compartments.

When downstands were fixed at the compartment exit, a hot layer formed, as expected. For the short compartment condition, $L_f = 0.41$ m, a stable but rapidly fluctuating hot layer formed. With greater compartment lengths, the stable hot layer was observed to be gently undulating, away from the plume.

Differences between the hot layers for the 50, 100 and 200 mm downstand depths were observed, for the longest compartment length ($L_f = 2.21$ m). When a 50 mm downstand was used, there was no clearly defined ceiling jet and hot layer. They appeared to be mixed together for most of the length of the fire compartment.

With a 100 mm downstand, a clearly defined, 80 mm deep ceiling jet was observed to flow along most of the length of the compartment. The jet appeared to breakdown and mix with the hot layer, 300 mm before reaching the downstand. Closer examination showed that smoke was being pulled back along the walls, before rising back into the hot layer 100 mm from the exit.

With a 200 mm downstand, this mixing occurred as the jet was forced downwards to pass under the downstand, 150 mm back from the downstand, see Figure 8.1.

8.2.3 Smoke Flow Along Walls

At the compartment exit, for all downstand conditions, the smoke was observed to be flowing along the compartment walls, forming localised deepening of the smoke layer close to the walls. The depth of this local deepening below the smoke layer appeared to be greater for smaller downstand. There was less local deepening for greater compartment lengths. This is shown in Figure 8.1.

8.2.4 Compartment Exit

A region of shedding vortices was observed at the compartment exit, around the rotation zone from the w-plane to the y-plane, for all downstand conditions and compartment lengths. These are shown in Figure 8.2. There appeared to be a fast flowing layer, directly under the downstand and up the spill wall. Vortices were shed

from the outer edge of the flow, which was characterised by large scale turbulence. Below a point in the flow, vortices flowed back into the compartment. Above that point, the vortices flowed up into the atrium. This point, at which vortices were shed in different directions, appeared to drift by approximately 200 mm.

8.3 Main Experiment

The following flow conditions were observed, using tracer smoke, illuminated by a bright lamp. Phenomena were observed that were similar to the flows described in the Preliminary experiment. In addition several other features were found:

8.3.1 Smoke Flow Along Walls

Less smoke flow along the fire compartment walls was observed. The extent to which the smoke descended down the walls was much less. A more uniform flow out of the compartment was observed, possibly due to reduced cooling along the walls.

8.3.2 Reservoir Flow

In the Main Experiment the measures described in Chapter 6 (6.8.2.4) were necessary to reduce the turbulence in the flow. The resulting flow of hot gases and ambient air within the compartment are shown in Figure 8.3.

An important feature of the flow is the ambient air that appears to be drawn up into the plume as it enters the hot layer (at point (1) in Figure 8.3) and the mixing that occurs as the smoke is drawn down the rear wall.

The plume is turbulent, for its full height above 100 to 200 mm above the y-plane.

8.4 PIV Observations

8.4.1 General

In Chapter 6 (6.7.1), the advantages of visualisation techniques were described. The PIV images from the experiments provided much evidence for understanding the complexity of the flow, but also helped to confirm and provide explanations for some of the quantitative results shown in Chapter 7.

8.4.2 Fire Compartment Observations

Although the internal flow within the compartment was not quantified using PIV, the flow was observed with the seeding particles, when no downstand was present ($D_d = 0.00$ mm). With a downstand installed, the ceiling jet zone was in shadow, so only the lower part of the hot layer was visible.

In both the long and short compartment conditions ($L_f = 0.41$ and 2.21 m), when there was no downstand ($D_d = 0.00$ mm) the ceiling jet was visible as a fast moving stream of particles, with small scale turbulent structures. No large rolling vortices were observed.

The inlet mixing occurs between the jet and the inlet air, by the formation of large vortices. Particles of bauxite were observed to be mixed into in the airflow, incoming and outgoing, for the full depth of the compartment. The underside of the ceiling jet was not as clearly defined as indicated by the tracer smoke observations. The boundary appeared to be defined by the centre of larger vortices between the inlet air and the jet, see Figure 8.4. Quantified measurements would provide a confirmation of this observation. This recirculation structure occurred with all compartment lengths and downstand depths.

In the long compartment, with and without a downstand, a line of shear stress was observed to form intermittently, approximately 10 % of the time. This line of shear stress defined the boundary between the outflow and inflow. It would usually break up with the sudden changes in flow rate, due to the periodic fluctuations of the flow.

8.4.3 The W-Plane and Y-Plane

The laser illumination and slow motion video film revealed the flow structure shown in Figure 8.5. This shows the general flow pattern. Figure 8.6 shows an idealised form of the periodic gas flow that occurs at the compartment exit. This was typical for all compartment configurations. The frequency of each burst is approximately 3 per second.

Images 3, 64 and 5, used for PIV analysis are examples of the patterns that appear at Stage 1, 2 and 3 respectively. A full range of PIV images and velocity maps are shown in the Supplementary Appendix.

These confirm the observations from the tracer smoke techniques, that fast flow is passing around the spill edge, with an extended depth of large, slower vortices on the outer edge. The majority of the measured mass flow is in the fast stream of hot gases.

The intermittent disappearance of any hot gases above the y-plane, during the 'bursting' of the hot gases from the exit, is not detectable with ordinary tracer techniques. This only occurs with 10 to 20 % of the bursts. It is unlikely to be occurring for the full width of the plume. Often the bursting appears as rapid fluctuations in the gas layer depth and plume width.

There does not appear to be large scale flow structures, that would indicate the entrainment of ambient air into the hot gases in the rotation region between the w and the y-plane. Indications of significant entrainment only appears to be visible at approximately 60 mm above the y-plane, where the bursting results in the rapid spread of the plume out into the ambient air. The structure of this flow is described in the section describing the images at the z-plane.

8.4.4 Megaplug Images

Another PIV imaging process was available for a limited period. This provided 1000 by 1000 pixel images, rather than the 320 by 240 images provided by S-VHS images. This greater quality of resolution gave more detailed information on the flow structure in the plume. Two typical examples are shown in Figures 8.7 to 8.12.

The rapid flow from the compartment in closely parallel streamlines around the downstand are clearly evident. The finer details of the vortices at the edge of the flow are visible. In the enlarged images, the vortices that form at the interface of the gases leaving the compartment and the gases entering the compartment are clearly evident. The appearance is of gases being pushed against the ambient air, and being forced to diverge.

The vector maps also show the gases recirculating above the y-plane. Figure 8.11 extends much higher, than Figure 8.8, and shows the plume being pushed up against the wall by the entraining air.

For the purposes of these experiments, the data from the Megaplug images was not used, to provide consistency. However, the images confirm the flow patterns found in the video images.

8.4.5 The Z-plane

This was more difficult to visualise with the tracer smoke techniques, due to rapid fluctuations in the flow. PIV allowed better visualisation of the flow. A typical cycle for the flow structure is shown in Figure 8.7. This composite image was derived from Images 44.0 to 44.16 in the Supplementary Appendix.

The characteristic description of a line plume structure is a rounded, upwardly moving series of masses of hot gases. These images appear to rotate about a central

point, with the outer edge moving downwards, relative to the plume mass. The 'masses' of hot gases appear to expand as they rise, by engulfing ambient air.

When the PIV images are examined, these round structures do not appear to rotate, but have cycles of 'bursts' of hot gases. A volume of gas bursts upwards, appearing to expand as it rises. As this burst passes, ambient air rushes in underneath it, with a thin layer of hot gas continuing to rise up the spill wall. Soon after this another burst of hot gas appears, and the process continues. Each cycle of bursts has a frequency of approximately 3 per second. This pattern is found from 60 to 100 mm above the y-plane, and up to and inside the smoke reservoir.

It is possible that this bursting pattern may not scale up with full scale fire plume. This bursting feature could form a small scale structure within the plume, rather than a major feature within the plume. Even as a small scale structure within full scale plumes, it could still provide the action necessary for entrainment.

8.5 Summary of Visualisation of the Flow

- There appears to be significant entrainment into the reservoir at the point where the adhered plume meets the smoke layer and where smoke from the reservoir descends down the rear wall of the atrium.
- The flow of smoke in the fire compartment revealed by tracer smoke techniques matches existing theory, with a fast moving ceiling jet, with small scale turbulence, when no downstand is present. When downstands are present then a clear stratification between the hot layer and the inward flowing ambient air occurs. The hot layer gently undulates. Little evidence of entrainment into the hot layer is visible.

- PIV imaging reveals a fast moving stream of gases in the ceiling jet, with larger scale vortices extending down to the bottom of the compartment. Recirculation is evident with these images, that is not evident with tracer smoke techniques.
- The majority of the flow from the compartment is in a fast stream, with close parallel streamlines. At the edge of this large vortices form, these rotate from the flow, re-entering the fire compartment or flowing up with the plume.
- At the y-plane the flow structure has not changed significantly from the w-plane. No major increase in turbulence was observed here.
- At 60 to 100 mm above the y-plane a bursting pattern develops with the flow. This pattern shown in Figure 8.7 is evident for the full height of the plume, and into the reservoir.

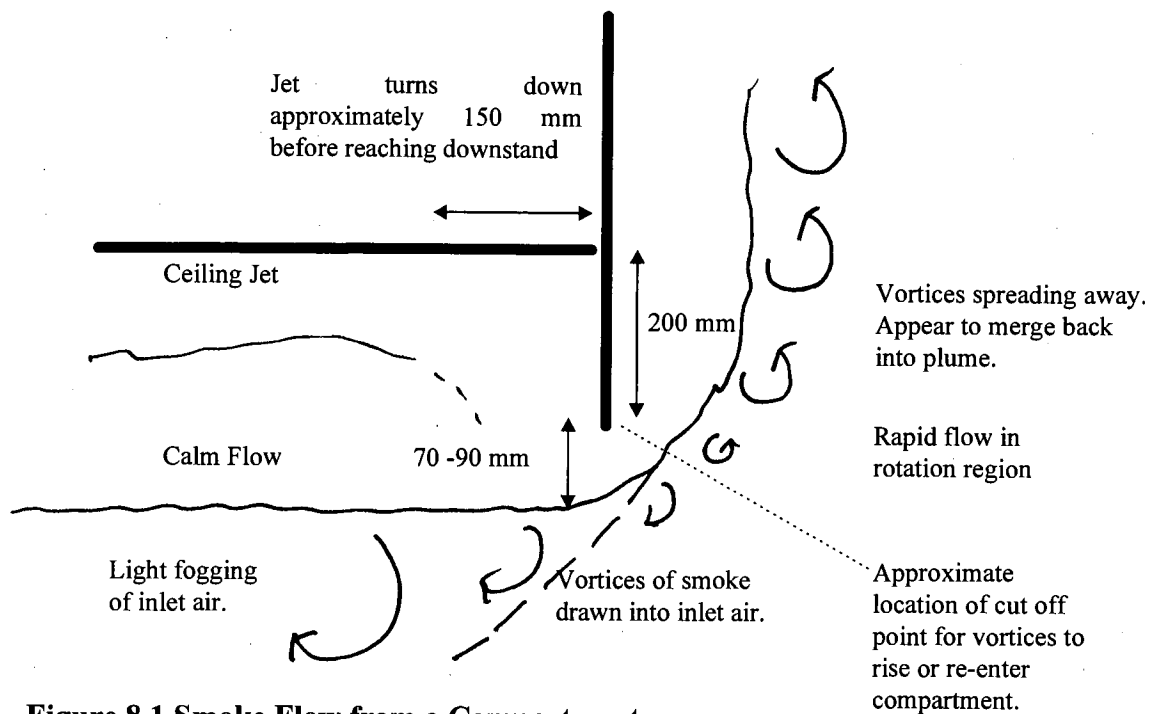


Figure 8.1 Smoke Flow from a Compartment

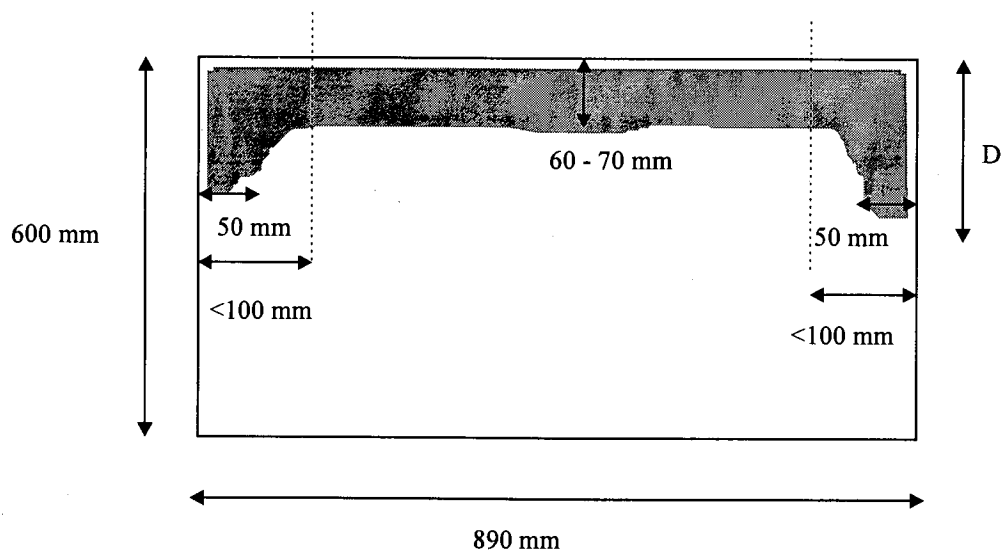
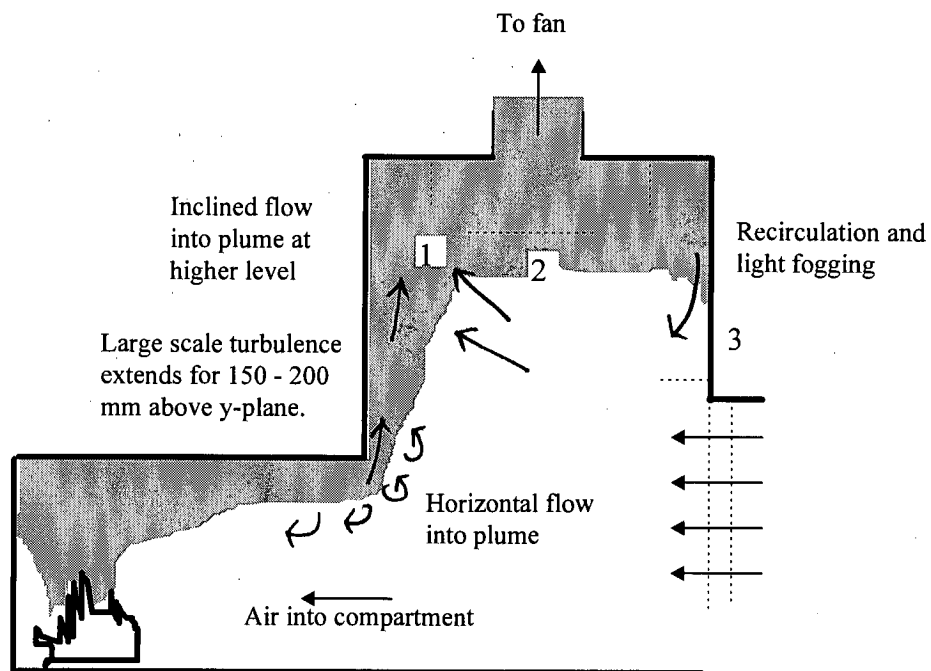


Figure 8.2 Smoke Layer Depth Across Fire Compartment

$L_f = 0.41\text{m}$; $D = 200\text{ mm}$; $L_f = 1.01\text{m}$; $D = 150\text{ mm}$; $L_f = 1.61\text{m}$; $D = 120\text{ mm}$



Vortices minimised in the atrium, due to the following key features:

1. Plume enters reservoir creating turbulent zone. Ambient air drawn up with plume into reservoir.
2. Stable underside to the smoke layer forms. Rise and fall; maximum ± 50 mm. If greater experiment abandoned. In this section of the atrium, the smoke slowly rises and falls.
3. Wall flow - small amount of smoke with continuing momentum down wall.

Figure 8.3 Air Circulation in an Atrium

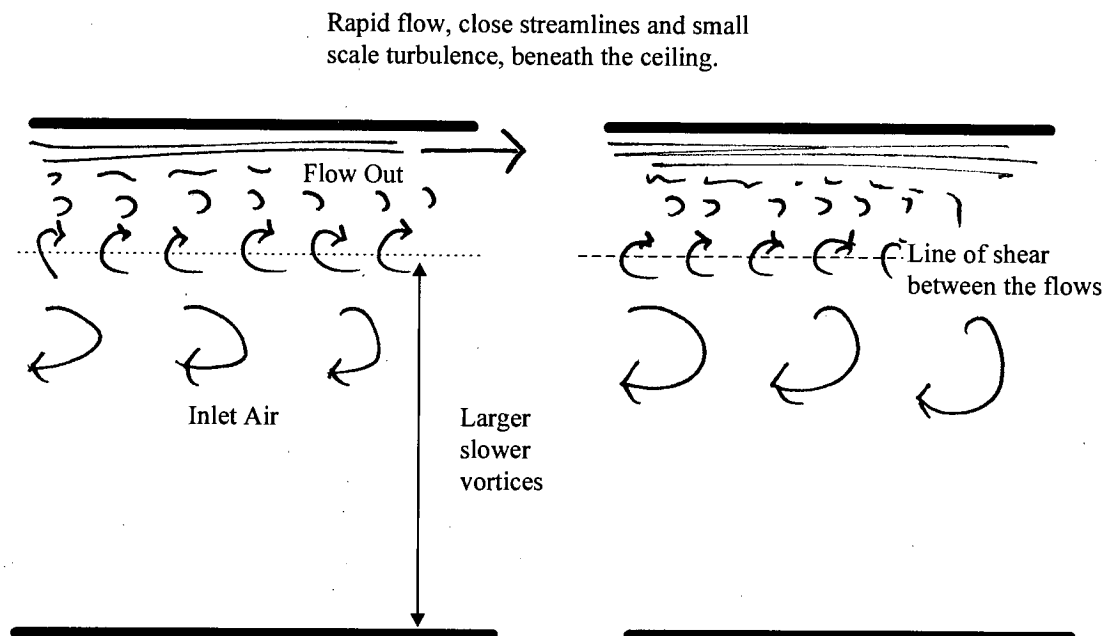


Figure 8.4 Flow Structures in a Fire Compartment (Section of Compartment)

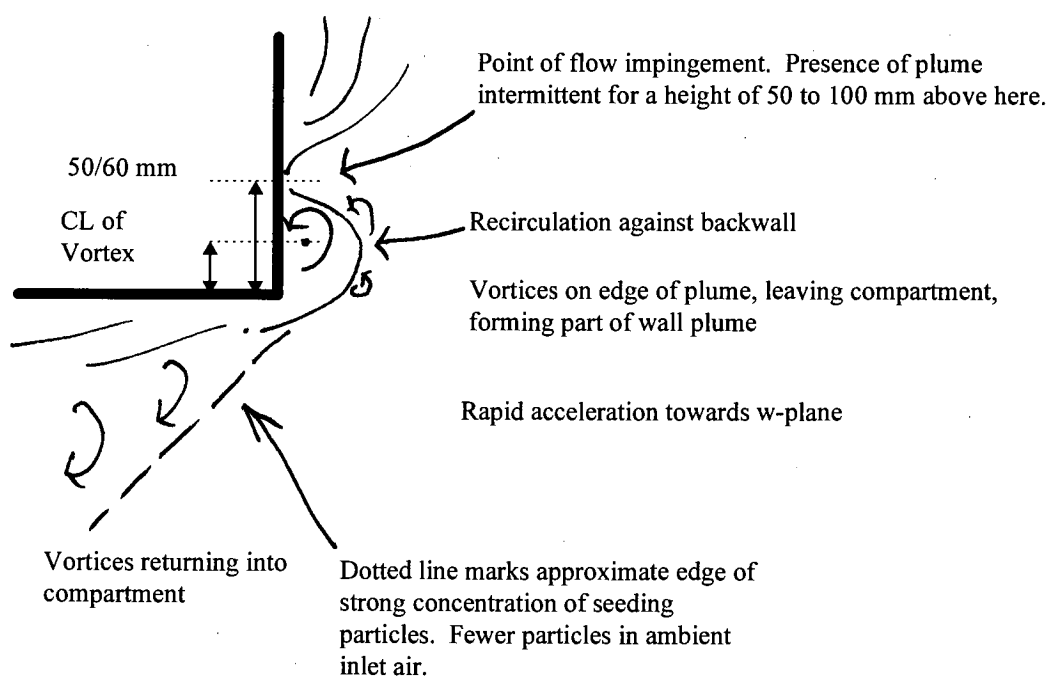
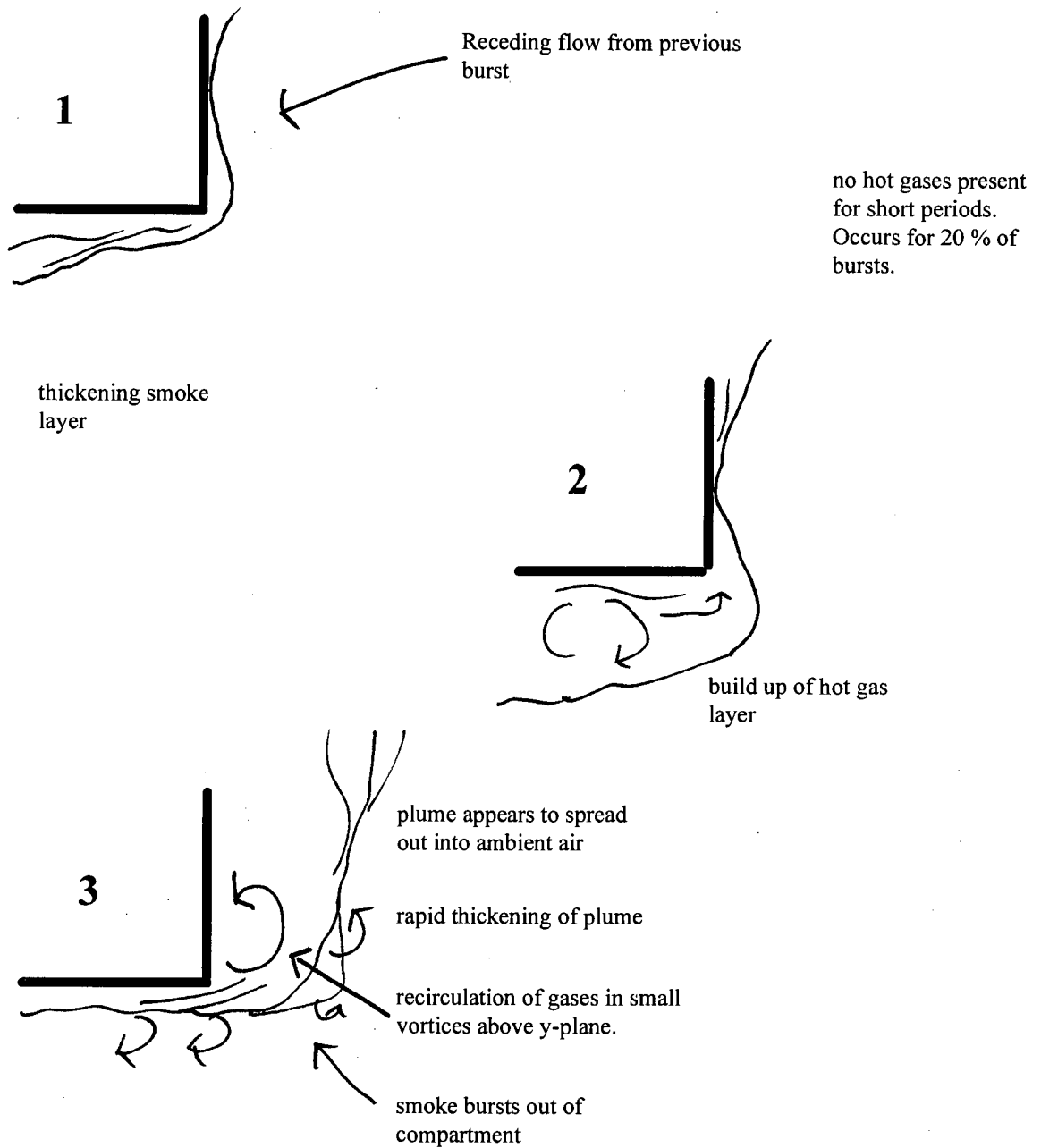


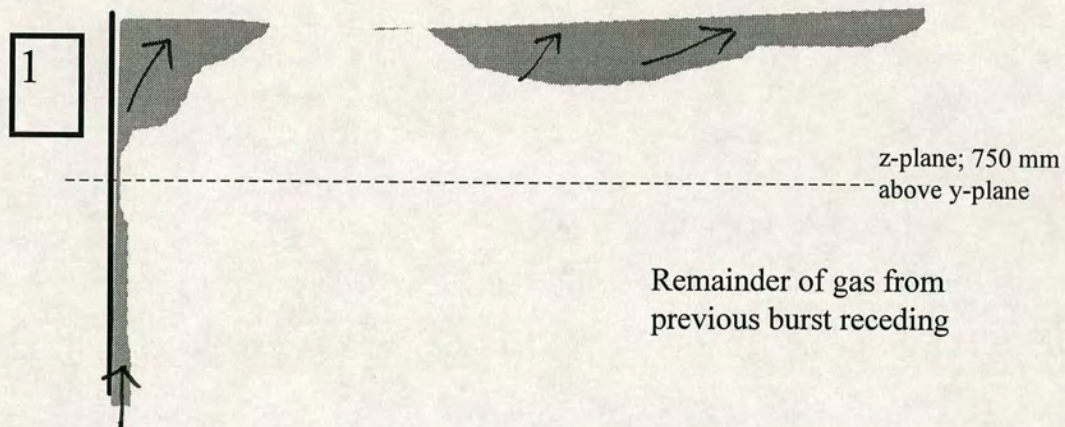
Figure 8.5 General Smoke Movement Observed in Main Experiment



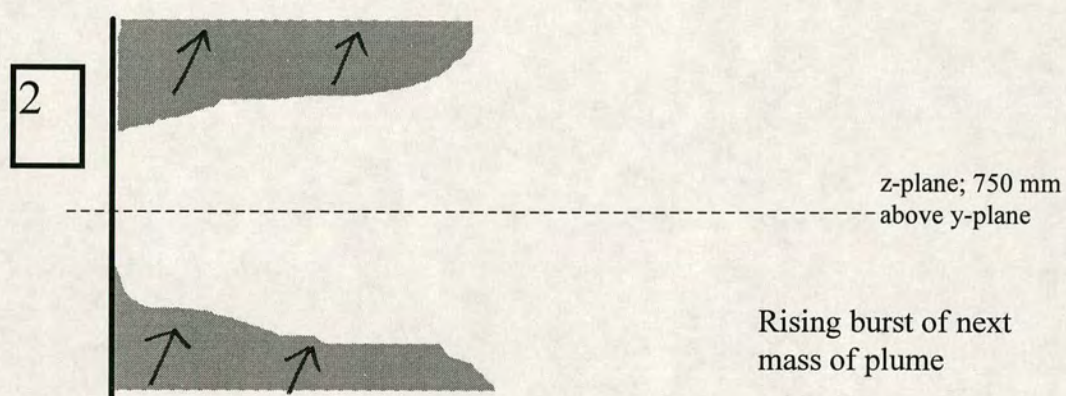
After stage (3), gas rapidly recedes.

This phenomenon may not occur uniformly across the width of the atrium

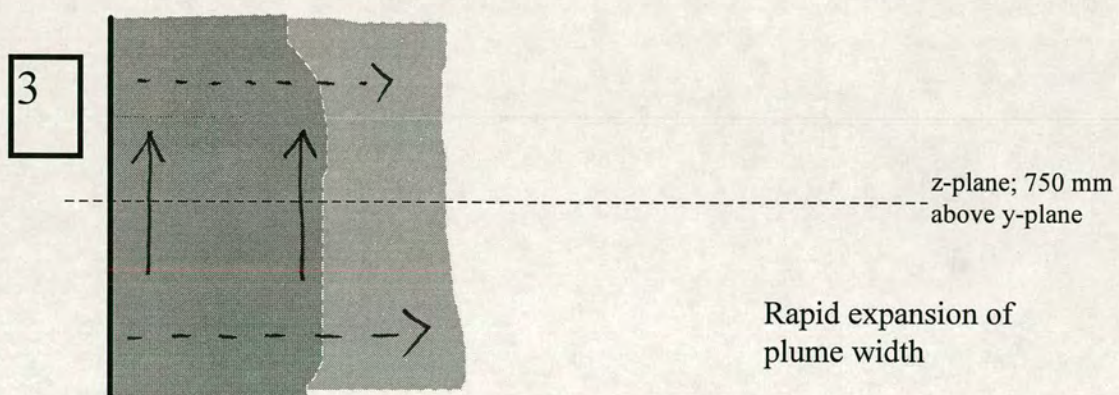
Figure 8.6 Periodic Gas Flow at w and y-plane



Images 44.9



Images 44.10



Images 44.11 and 44.12

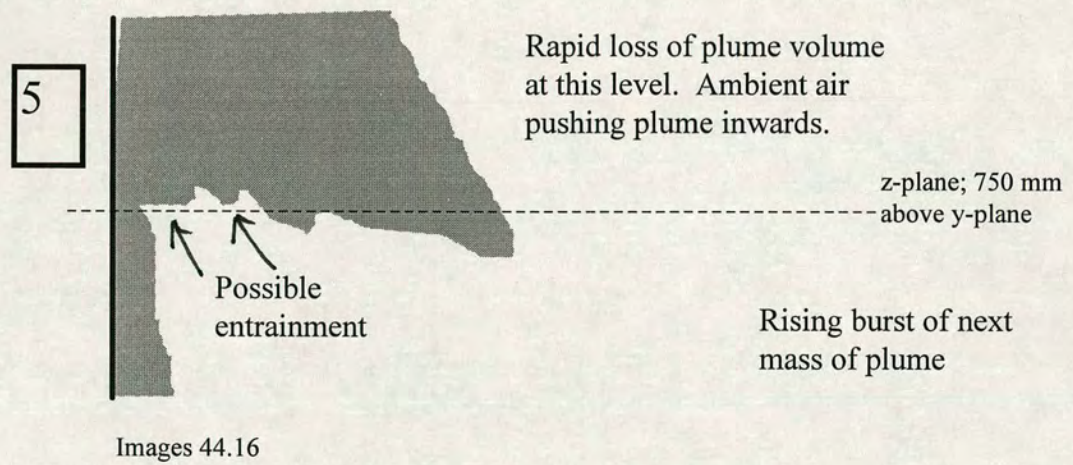
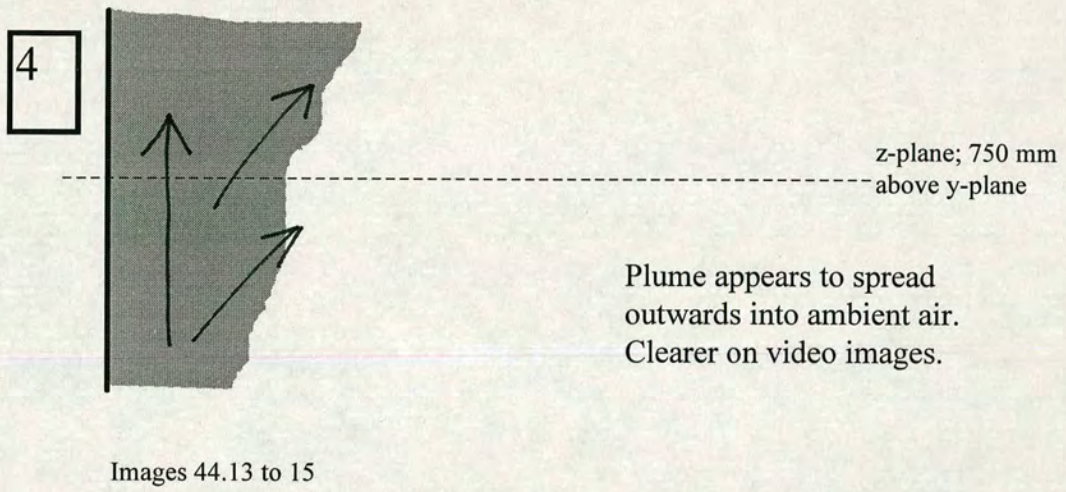
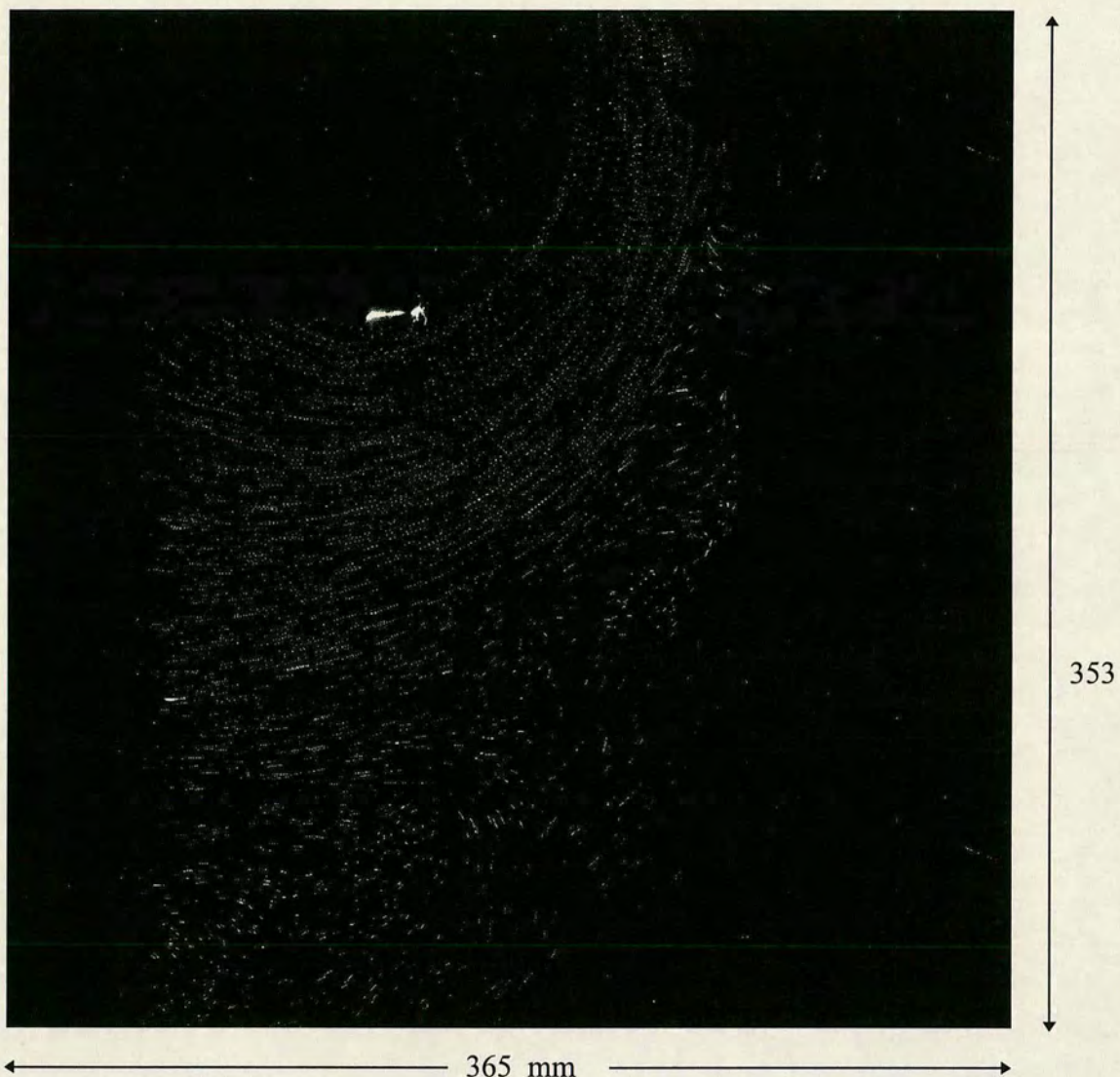


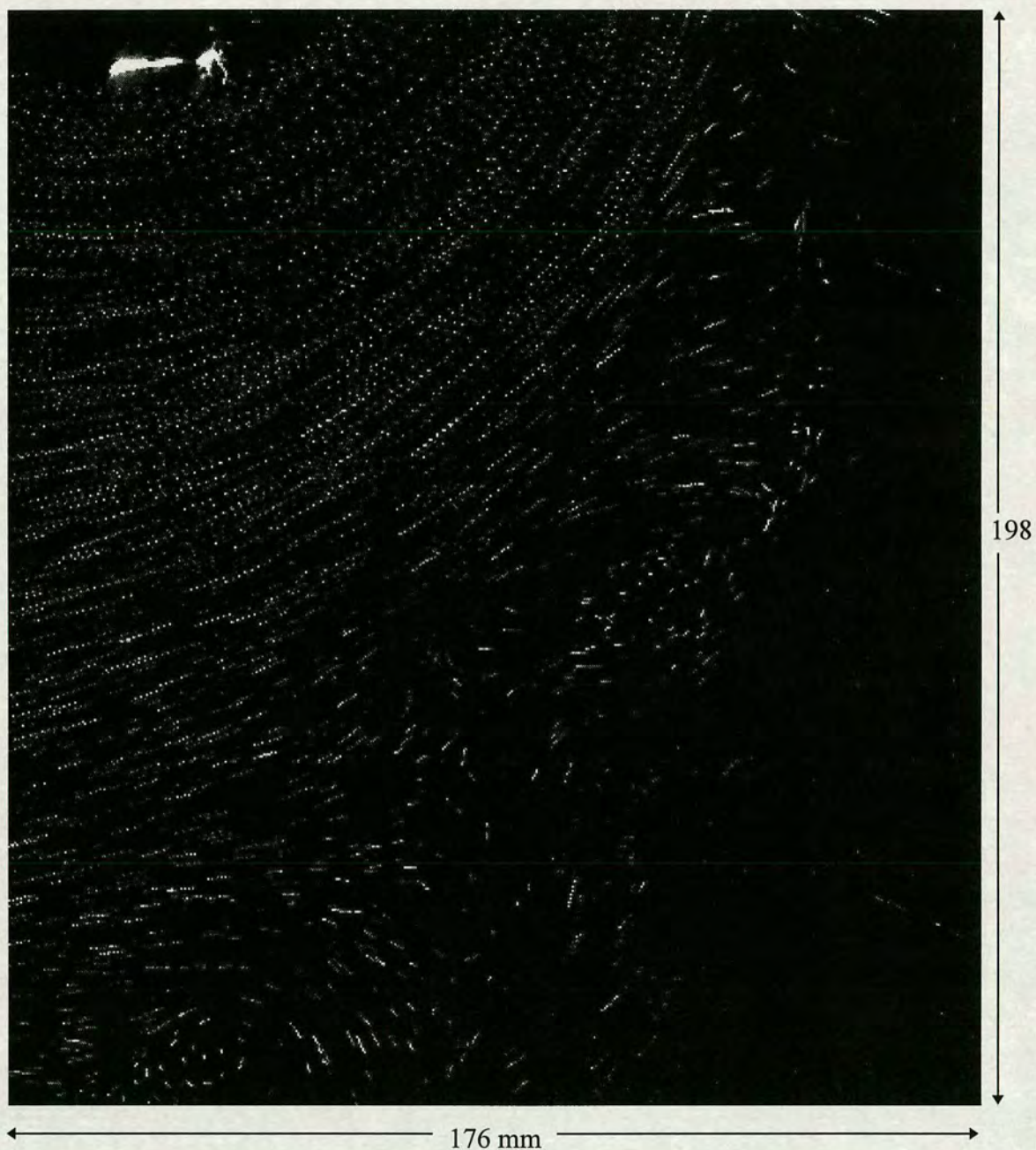
Figure 8.7 Flow Structure in Rising Wall Plume, from PIV Images 44.9 to 44.16



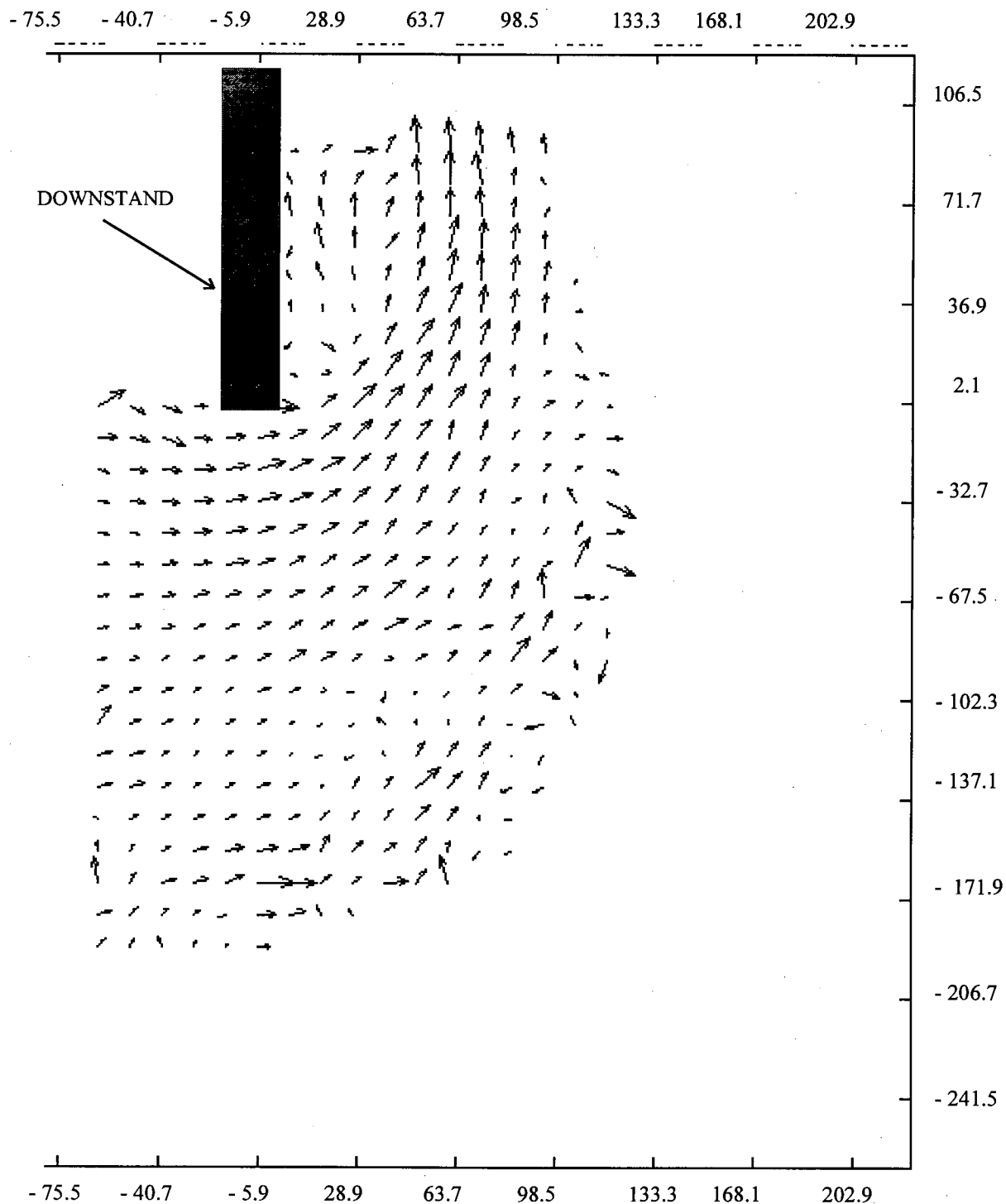
ORIGINAL IMAGE

MEGA IMAGE 01

2460 MM LONG COMPARTMENT; 200 DOWNSTAND



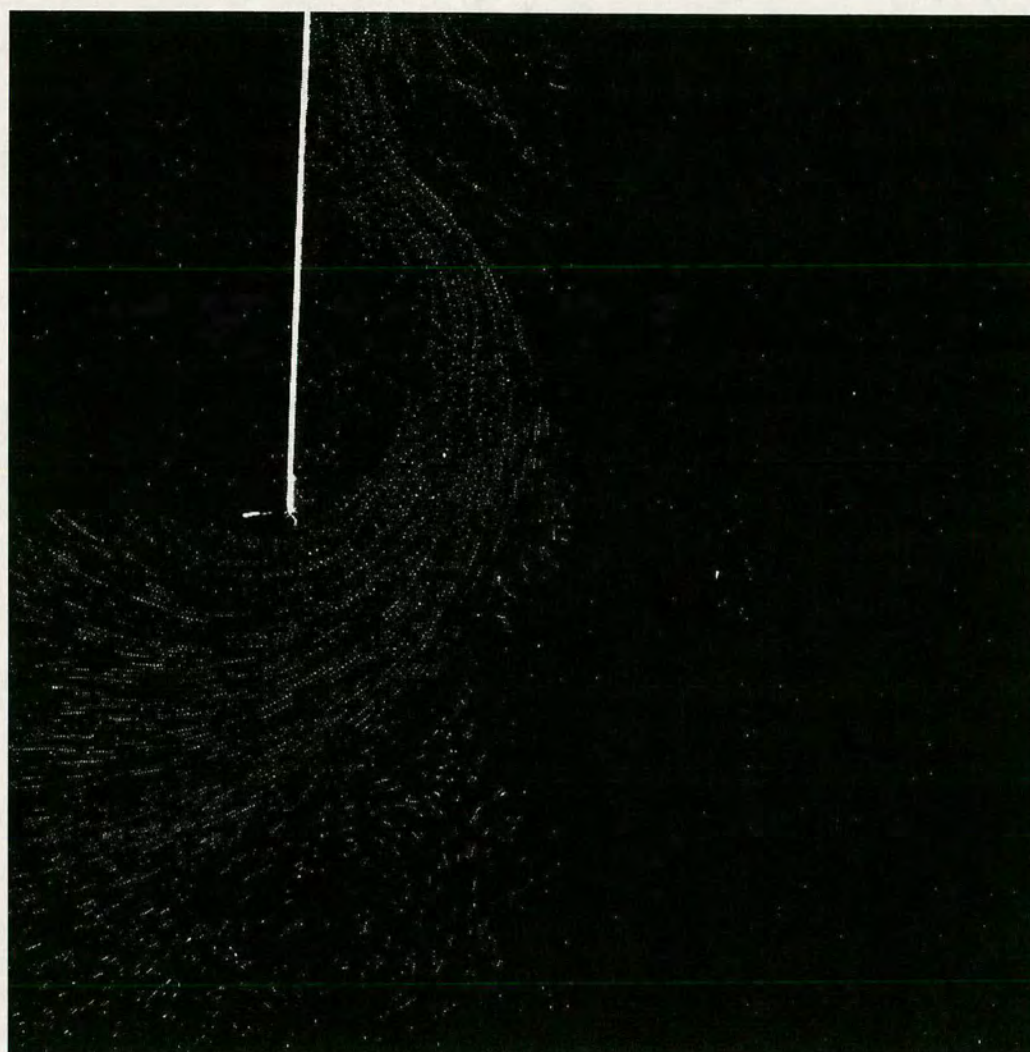
ENLARGEMENT OF MEGA IMAGE 01, SHOWING DETAIL OF FLOW THROUGH W-PLANE; WITH VORTICES FORMING AT INTERFACE OF GASES EXITING AND GASES ENTERING THE COMPARTMENT. RECIRCULATION OF GASES IS CLEARLY EVIDENT.



VECTOR MAP

MEGA IMAGE 01

2460 MM LONG COMPARTMENT; 200 DOWNSTAND



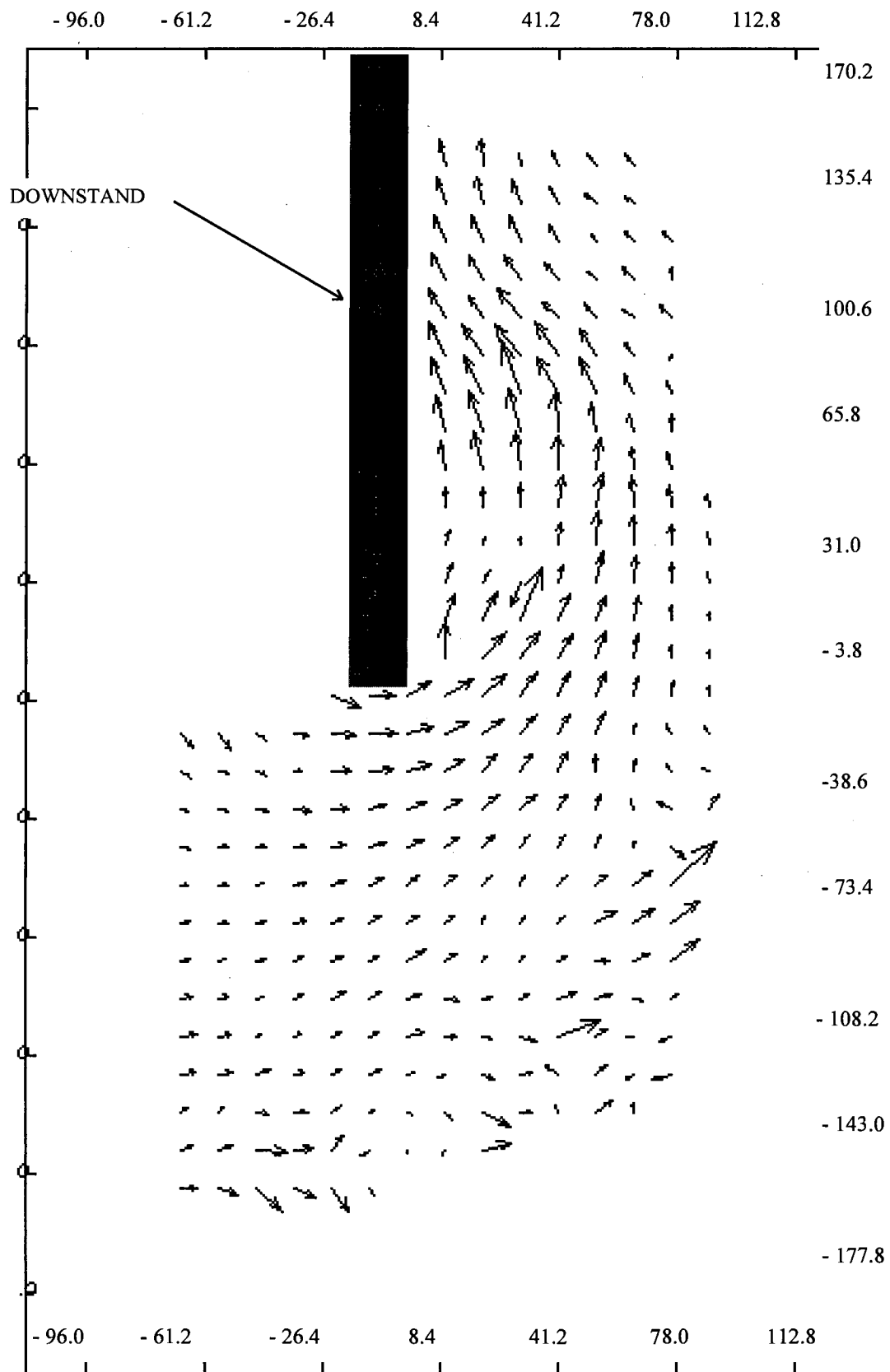
353

← 365 mm →

ORIGINAL IMAGE

MEGA IMAGE 02

2460 MM LONG COMPARTMENT; 200 DOWNSTAND



VECTOR MAP

MEGA IMAGE 02

2460 MM LONG COMPARTMENT; 200 DOWNSTAND

Chapter 9. Discussion of the Results

9.1 Introduction

The aim of the experiment was to investigate variations to the formulae developed by the Fire Research Station, presented in Chapter 5, and to provide further information on smoke flow in atria. Two potential variations to the flow were examined:

- The effect of downstand depth when no balconies are present in the atrium void.
- The effect of compartment length.

Alternative methods of instrumentation and measurement were used in these experiments. These provided additional information on certain aspects of smoke flow such as entrainment in the rotation region, from the w-plane to the y-plane, where no balcony is present and the relationship between plume widths (distance from wall to edge of plume), gauged by temperature or velocity. Additional information has also been obtained on entrainment into the smoke reservoir. Chapters 7 and 8 presented the results of the experiment with a brief discussion.

9.2 The Effect of Depth of Downstand on Smoke Flow

9.2.1 The Depth of Downstands and the Coefficient of Discharge

In BR 258 a formula is presented to calculate the mass flow, M_w from compartments. This is shown in Chapter 5, as Equation 5.1. It contains the coefficient, C_d , the coefficient of discharge, which can be calculated from the formulae in Equations 5.2 and 5.3. These were developed by Hansell and Morgan. Hansell (1993) explains their derivation. A basic assumption in these formulae, is that D_d is measured from the bottom of a downstand to the underside of a balcony. A maximum value of 1.0 m is used, see Chapter 5.

In BR258 it is not clear how to derive C_d , when no balcony is present. Hansell (1993) states that where the height from the bottom of a balcony exceeds 1.0 m, then the

coefficient of discharge is determined by the characteristics of the flow up the spill wall. The coefficient of discharge is determined by the height at which it reaches terminal velocity (approximately 1.0 m above the spill edge). It can be inferred that C_d is constant, when there is no balcony.

The mass flow rate and temperature rises measured at the w-plane were compared to the theoretical values derived from the formulae in BR 258. The experiment investigated the effect of the downstands, by measuring:

- mass flow rates measured in the duct and by PIV
- temperature rises
- the carbon dioxide concentrations
- visible flow structures

9.2.2 Mass Flow Rate in the Extract Duct

Most mass flow rates in the duct derived in the experiment are 5 % to 20 % below theoretical values, except when $D_d = 0.00$ m, which generally range from 5 to 10 % higher. For the larger fire size a greater range of differences are found. The range of differences could be due to range of other variables in the smoke flow system.

The mass flow rates are converted to ratios for ease of comparison. The mass flow rate for downstands, $D_d = 0.05, 0.10$ and 0.20 m are compared to $D_d = 0.00$, thus:

$$R = \frac{M_w (D_d = 0.05, 0.10 \text{ or } 0.20 \text{ m})}{M_w (D_d = 0.00 \text{ m})} \quad \text{Eq. 9.1}$$

where: M_w is the mass flow rate at the w-plane

Table 9.1 compares the ratios for the theoretical values derived from BR 258 spill plume calculations to the experimental results.

		Duct Measurement			
Dd (m)	Theory	Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	1.00	1.00	1.00	1.00	1.00
0.05	1.06	0.81	0.81	1.02	0.96
0.10	0.94	0.69	0.76	0.82	0.81
0.20	0.78	0.59	0.63	0.73	0.79

Heat Release Rate: $Q_f = 4.67$ kW Height of Rise: $z = 0.750$ m

Note: $L_f = 1.61$ m and $D_d = 0.05$ m, the ratio (and actual mass flow rate could be anomalous).

		Duct Measurement			
Dd (m)	Theory	Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	1.00	1.00	1.00	1.00	1.00
0.05	1.07	0.85	0.86	0.89	0.91
0.10	0.97	0.79	0.78	0.79	0.80
0.20	0.80	0.68	0.68	0.67	0.76

Heat Release Rate: $Q_f = 4.67$ kW; Height of Rise: $z = 0.550$ m

		Duct Measurement			
Dd (m)	Theory	Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	1.00	1.00	1.00	1.00	1.00
0.05	1.08	0.81	no data	no data	0.94
0.10	0.98	0.67	no data	no data	0.83
0.20	0.79	0.53	no data	no data	0.82

Heat Release Rate: $Q_f = 6.09$ kW; Height of Rise: $z = 0.750$ m

Table 9.1 R for Theoretical (BR 258) and Experimental Mass Flow Rates

The ratio, R , reveals different trends for the experimental mass flow rates compared to theoretical values from BR 258, for varying downstand depths.

Statistical analysis of the mass flow rates in Tables 7.1 to 7.3 is summarised as follows in Table 9.1A. These tables correlate the values predicted by the calculation method in BR258 and the mass flow rates in the experiment.

Qf = 4.67 kW z = 0.750 m	Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
a	0.979	0.922	0.963	0.891
r²	0.524	0.537	0.840	0.607
se_(y)	0.0258	0.0203	0.0099	0.0112
m (min)	0.123	0.120	0.132	0.132
se_(y) (%)	21.0	16.9	7.6	8.5

Qf = 4.67 kW z = 0.550 m	Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
a	0.906	0.877	0.886	0.774
r²	0.477	0.5657	0.631	0.425
se_(y)	0.0147	0.0132	0.0128	0.0105
m (min)	0.106	0.102	0.101	0.097
se (%)	13.9	13.0	12.7	10.8

Qf = 6.09 kW z = 0.750 m	Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
a	1.00	no data	no data	0.81
r²	0.455	no data	no data	-0.004
se_(y)	0.0362	no data	no data	0.0145
m	0.150	no data	no data	0.135
se_(y) (%)	24.1	no data	no data	10.7

a - a co-efficient (see below)
se_(y) - standard error (kg/s)

m - mass flow rate, minimum, (kg/s)
se_(y) (%) - **m/se_(y)** (%)

Table 9.1A: Correlation of Theoretical Mass Flows with Experimental Results

In Table 9.1A, the experimental results are correlated with theoretical mass flow rates thus:

$$m_{(\text{experiment})} = a m_{(\text{theory})} + b \quad \text{kgs}^{-1}$$

In the correlation a varied from 1.4 to 0.4, and b from -0.094 to 0.074 (mean -0.007). This relatively small value for ' b ' meant that reanalysis having the zero intercept, $b = 0$, could be carried out. Setting $b=0$, also reduced the variation to the values of ' a '. The values for a , for each set of experiments are shown in the table. If there is perfect correlation between the theoretical values and experimental values, then ' a ' should be equal to 1.0. The average value of ' a ' is approximately equal to 0.9. This indicates that the mass flow rates in the experiment are approximately 10% less than theoretical values.

The value ' r^2 ', the coefficient of determination, provides an indication of the validity of the correlation. This compares the estimated values (from the regression analysis) to the actual values from the experimental results. A value of 1 indicates perfect correlation, and 0 indicates no correlation. Most of the values are between 0.42 and 0.66. This indicates that there is a reasonable level of correlation, but better relationships may be found.

The standard error (S.E) for the experimental mass flow rates are equivalent to 8% to 24% of the mass flow rates (S.E %). Most of the values are close to the estimated error of 11% (see Section 7.7). The experimental results are in reasonable correlation with the theoretical results. However, the analysis does not account for the differing trend for the mass flow rates, for small values of D_d .

There may be a constant value for C_d for all depths of downstand. The relationship between the mass flow rate and compartment exit height and downstand depth can be simplified, using a form of Law's formula (1995), as shown in Equation 9.2 (for a free plume without free ends to the plume):

$$M_z = 0.31(Q_f L^2)^{1/3} (z + 0.25(D_d + h)) \quad \text{kgs}^{-1} \quad \text{Eq. 9.2}$$

where:

Q_f = total heat output of the fire source kW
 z_s = height of rise of line plume m
 D_d = depth of downstand m
 h = height of opening m
 L = width of the opening m

Statistical analysis of the results, comparing the experimental results to Law's (1995) formula is shown in Table 9.1B. The analysis has been conducted as follows:

$$m = a (Q_f^{1/3} L^{2/3} (z + 0.25 (D_d + h))) + b$$

Statistical analysis gives a mean value of -0.015 for 'b', a relatively small value. Therefore the data has been analysed with the intercept 'b' assumed to be zero. This gives less variation to values of 'a',

	Compartment Length			
	0.41	1.01	1.61	2.21
a	0.210	0.180	0.186	0.191
se_(b)	0.00986	0.00347	0.00541	0.00425
r²	0.593	0.846	0.830	0.895
m	0.106	0.102	0.101	0.097
se_(y)	0.0262	0.0092	0.0116	0.0091
(se_(y)/m) %	24.7	9.0	11.5	9.4

Table 9.1B Regression Analysis of Mass Flow Rates

The results show a better correlation, than using the formula from BR258, because the range of figures for the coefficient of determination (r^2) has higher values. The standard error (expressed as a percentage of the mass flow rate) also has a lower range, than when using the formula from BR258. For lengths $L_f = 1.01, 1.61$ and

2.21 the error is within the range of the estimated experimental error (11 %). When $L_f = 0.41$, the standard error appears to be much larger. The cause of this is uncertain.

The coefficient, 'a', derived from the experiment is different from the value for Law's (1995) formula. In Law's formula, for free plumes, with free ends, it is 0.31. The experiment used an adhered plume, with ends enclosed by walls, giving a range of values from 0.18 to 0.21. The range of values are due to compartment length, these are discussed in Section 9.3.

9.2.3 Mass Flow Rates PIV Results

The PIV results measured the velocity at the w-plane, so that the influence of downstand depth can be calculated directly. Table 7.7 in Chapter 7 shows good similarity between the experimental and theoretical velocities, except when $D_d = 0.00$ m, and $L_f = 2.21$ m.

The experimental mass flow rates for the shorter compartment length differ by up to 25 % from the theoretical amounts. The error was estimated to be ± 13 %. The sampling rate may be such, that larger errors are introduced.

Dd (m)	Theory	Mass Flow from PIV	
	BR 258	Lf = 0.41	Lf = 2.21
0.00	1.00	1.00	1.00
0.05	0.80	0.94	no data
0.10	0.72	0.83	no data
0.20	0.55	0.85	1.13

Table 9.2 Mass Flow Rates: Theoretical and Experimental (PIV) at the W-plane

Table 9.2 shows these mass flows rates reduced to the ratio R, shown in Equation 9.1. The experimental values of R have a much narrower range, than the theoretical ratios.

In Table 9.3, the mass flow rates at the y-plane are very different from the theory. The more complex spill plume theory, from BR 258, appears to over-estimate the entrainment in the rotation region from the w-plane to the y-plane. R from the experiments is in good agreement with R from BR 258, for the w-plane, in Table 9.2.

	Theory	Mass Flow from PIV	
Dd (m)	BR 258	Lf = 0.41	Lf = 2.21
0.00	1.00	1.00	1.00
0.05	1.11	0.82	no data
0.10	0.93	0.64	no data
0.20	0.64	0.48	0.88

Table 9.3 Mass Flow Rates: Theoretical and Experimental (PIV) at the Y-plane

Table 9.4 shows the mass flow rates at the z-plane, reduced to the ratio R. At the z-plane there is limited similarity between the theoretical from BR 258 and experimental results.

	Theory	Mass Flow from PIV	
Dd (m)	BR 258	Lf = 0.41	Lf = 2.21
0.00	1.00	1.00	1.00
0.05	1.06	0.81	no data
0.10	0.95	0.65	no data
0.20	0.79	0.92	1.38

Table 9.4 Mass Flow Rates: Theoretical and Experimental (PIV) at the Z-plane

Statistical analysis of the results, comparing the experimental results to Law's formula (1995) as shown in Equation 9.2 (for a free plume) is shown in Table 9.4A. The analysis has been conducted as follows:

$$m = a (Q_f^{1/3} L^{2/3} (z + 0.25 (D_d + h))) + b$$

As in previous sections, the intercept b is assumed to be zero.

a	0.112
se_(a)	0.0105
r²	0.688
m	0.0761
se_(y)	0.0220
(se_(y)/m) %	19.6

Table 9.4A Regression Analysis of Mass Flow Rates

The results show a better correlation, than using the formula from BR258, because the range of figures for the coefficient of determination (r^2) has higher values.

The standard error (expressed as a percentage of the mass flow rate) is outside the range of the estimated experimental error (13 %).

The coefficient, a , derived from the experiment is different from the values derived from the mass flow rates in the duct, which gave a range of values from 0.18 to 0.21. Here, ' a ' is 0.112. This is in good agreement with a statistical correlation by Thomas and Poreh (Thomas 1997) of the data from the Fire Research Station (by Morgan et al). The difference between the measurements in the duct and the plume is discussed in Section 9.5

9.2.4 Temperature Rise

The mean temperature is assumed to be proportional to the maximum temperature. The mean temperature is proportional the mass flow rate given a constant heat output. Therefore the maximum temperature is assumed to be proportional to the mass flow rate, thus:

$$m \propto 1/\theta_{\text{maximum}} \quad \text{Eq. 9.3}$$

The maximum temperatures can be used to provide the ratio R, used in Section 9.2.4.

At the w-plane R (see Table 9.5) shows good agreement with the spill plume theory and the round plume theory, for the 4.67 kW fire size, with the short compartment ($L_f = 0.41$ m), but poor agreement for the longer compartments.

The intermediate compartment length of 1.01 m shows good agreement, with the measurements of the mass flow in the duct, but the temperature measurements for this length are not in such good agreement. This could be, in part due, to additional heat loss with increasing compartment length.

	Spill Plume Theory	Round Plume	Experiment			
Dd (m)			Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	1.00	1.00	1.00	1.00	1.00	1.00
0.05	0.80	0.87	0.87	0.75	0.95	0.92
0.10	0.72	0.74	0.75	0.81	0.84	0.86
0.20	0.55	0.54	0.56	0.64	0.71	0.69

Heat Release Rate: $Q_f = 4.67$ kW Height of Rise: $z = 0.750$ m

	Spill Plume Theory	Round Plume	Experiment			
Dd (m)			Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	1.00	1.00	1.00	no data	no data	1.00
0.05	0.79	0.87	0.91	no data	no data	0.90
0.10	0.71	0.74	0.79	no data	no data	0.88
0.20	0.55	0.54	0.61	no data	no data	0.64

Heat Release Rate: $Q_f = 6.09$ kW Height of Rise: $z = 0.750$ m

Table 9.5 Mass Flow Rate Ratios at the W-plane, based on the Maximum Temperature Rise

At the y-plane (see Table 9.6) R shows good agreement with the round plume theory, for the 4.67 kW fire size, with the intermediate compartment length ($L_f = 1.01$ m), but poor agreement for the longer compartments. The short compartment does not have such good agreement as at the w-plane, but the values are close, for both fire sizes.

	Spill Plume Theory	Round Plume	Experiment			
Dd (m)			Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	1.00	1.00	1.00	1.00	1.00	1.00
0.05	1.11	0.87	0.92	0.88	0.94	0.94
0.10	0.93	0.74	0.81	0.74	0.82	0.88
0.20	0.64	0.54	0.61	0.57	0.70	0.68

Heat Release Rate: $Q_f = 4.67$ kW Height of Rise: $z = 0.750$ m

	Spill Plume Theory	Round Plume	Experiment			
Dd (m)			Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	1.00	1.00	1.00	no data	no data	1.00
0.05	1.13	0.87	0.93	no data	no data	0.88
0.10	1.00	0.74	0.81	no data	no data	1.00
0.20	0.63	0.54	0.64	no data	no data	0.63

Heat Release Rate: $Q_f = 6.09$ kW Height of Rise: $z = 0.750$ m

Table 9.6 Mass Flow Rate Ratios at the Y-plane, based on the Maximum Temperature Rise

At the z-plane (see Table 9.7 below) R shows good agreement with the spill plume theory, rather than simple round plume theory, for the 4.67 and 6.09 kW fire sizes, especially with the longer compartment lengths.

	Spill Plume Theory	Round Plume	Experiment			
Dd (m)			Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	1.00	1.00	1.00	1.00	1.00	1.00
0.05	1.06	0.87	0.84	1.00	1.14	1.06
0.10	0.94	0.74	0.84	0.76	1.04	0.98
0.20	0.78	0.54	0.81	0.93	0.92	0.79

Heat Release Rate: $Q_f = 4.67$ kW Height of Rise: $z = 0.750$ m

	Spill Plume Theory	Round Plume	Experiment			
Dd (m)			Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	1.00	1.00	1.00	no data	no data	1.00
0.05	1.08	0.87	0.88	no data	no data	1.13
0.10	0.98	0.74	1.00	no data	no data	0.94
0.20	0.79	0.54	0.63	no data	no data	0.64

Heat Release Rate: $Q_f = 6.09$ kW Height of Rise: $z = 0.750$ m

Table 9.7 Mass Flow Rate Ratios at the Z-plane, based on the Maximum Temperature Rise

9.2.5 Carbon Dioxide Concentrations

The carbon dioxide concentrations are proportional to the mass flow rate thus:

$$m \propto 1/C_c \quad \text{Eq. 9.4}$$

where: $C_c \equiv$ the concentration of the CO_2

The carbon dioxide concentrations can then be used to provide ratios, R , of the mass flow rate, as used in Section 9.2.4.

At the w-plane R (Table 9.8 below) shows reasonable agreement with spill plume theory and the round plume theory, for the 4.67 kW fire size, with the short compartment ($L_f = 0.41$ m).

Dd (m)	Spill Plume Theory	Round Plume Theory	CO₂ Measurement
0.00	1.00	1.00	1.00
0.05	0.80	0.87	0.89
0.10	0.72	0.74	0.81
0.20	0.55	0.54	0.58

Heat Release Rate: $Q_f = 4.67$ kW; Height of Rise: $z = 0.750$ m; $L_f = 0.41$

Table 9.8 Mass Flow Rate Ratios at the W-plane, based on the Carbon Dioxide Concentrations

9.2.6 Visual Records

Although differing flow regimes were visible within the compartment, such as the ceiling jet not being clearly defined in some conditions (when $Dd = 50$ mm), there was a strong similarity in patterns of hot gas flow outside the compartment. For all downstand depths, recirculation of the gases was observed, with vortices being shed from the flow as it passed the w and y-planes.

A strong vortex always formed at the bottom of the spill wall, with a similar size in all experiments of approximately 50 mm diameter. A rapid flow of hot gases was observed to pass around this. Above this, at approximately 60 to 90 mm above the y-plane, rapid expansion and regression in the flow was observed to occur, as described in Section 8.4.2.

9.2.7 Summary

The effect of depth of downstand (D_d) on the coefficient of discharge (C_d) for the flow of smoke from a compartment can be summarised as follows:

1. The mass flow rates, temperature rises and rise in concentrations of carbon dioxide derived from the experiment have been reduced to a non-dimensional ratio, R as shown in Equation 9.1.
2. There is limited agreement between the experimental results and the spill plume theory from BR 258. Statistical analysis shows that there is better agreement with the form Law's (1995) spill plume formula.

$$M_z = a(Q_f L^2)^{1/3} (z + 0.25(D_d + h)) \quad \text{kgs}^{-1}$$

The coefficient 'a' varies, 0.18 to 0.21 for measurements made in the duct (dependent on compartment length) and 0.112 when calculated using PIV data. This is in good agreement with a recent statistical correlation by Thomas and Poreh of data by Morgan et al (Thomas 1997).

3. The experiments show reasonable agreement with values from BR258, for the flow at the w-plane.
4. The apparent increase in mass flow rate, predicted by the spill plume models, at the y and z-planes does not occur when introducing a small downstand at the w-plane.
5. The variations to the mass flow from the compartment, when the depth of downstand is varied appear to be primarily determined by the total height of rise from the fire floor to the atrium smoke reservoir. Therefore, C_d , the coefficient of discharge could be approximately constant when no balcony is present in the atrium.
6. There is a similar flow pattern at the w-plane for all depths of downstand and compartment lengths. No major differences in the flow structure are seen.

9.3 The Effect of Compartment Length on Smoke Flow

9.3.1 Compartment Lengths and Mass Flow Rates

As shown in Chapter 5, there is no factor included in the spill plume models to account for compartment length.

Research, particularly that by Alpert (1972 and 1974) has shown that there are three stages in the development of the flow of a ceiling jet. The flow is fully developed once it has reached 2 to 3 times the radius of the plume. Little entrainment into the ceiling is expected beyond this point (Alpert 1974).

If a hot layer is present under this ceiling jet, then the rate of entrainment is reduced and fully developed flow develops over a greater distance (Evans 1988). This is described in more detail in Section 5.9 of Chapter 5.

9.3.2 Mass Flow Rate in the Extract Duct

When $Q_f = 4.67$ kW and $z = 0.75$ m, and $D_d = 0.05, 0.10$ and 0.20 m, the greatest overall difference to the mass flow rates is 15 %, which is within the range of experimental error. When no downstand is present, $D_d = 0.00$ m, there is a reduction in the flow rate, there is a 20 % reduction in the mass flow rate with increasing compartment length.

When $Q_f = 4.67$ kW and $z = 0.55$ m, for all depths of downstand, there is limited variation except when $L_f = 2.21$ m (less than 10 %). Greater differences (up to 20%) are found, from the mass flow rates for shorter compartment lengths.

When $Q_f = 6.09$ kW and $z = 0.75$ m, a greater variation to the mass flow rates is found (less than 10 %). With no downstand ($D_d = 0.00$ m), the mass flow rate is 31 % less than predicted by theory.

When $D_d = 0.05$ and 0.10 m, there is a 20 % reduction in the mass flow rate with increasing compartment length. These variations are more than expected with experimental error. When $D_d = 0.20$ m, there is a slight increase in mass flow rate.

Statistical analysis of the effects of downstand depth in Section 9.2 showed limited variation due to compartment length. The regression analysis, using Law's (1995) formula showed a range for the coefficient 'a' of 0.18 to 0.21.

$$M_z = a(Q_f L^2)^{1/3} (z + 0.25(Dd + h)) \quad \text{kgs}^{-1}$$

The values for 'a' are summarised in Table 9.8A below.

	Lf=0.41	Lf=1.01	Lf=1.61	Lf=2.21
mean	0.193	0.185	0.190	0.172
stdev	0.01831	0.01434	0.01152	0.00879
% stdev	9.48	7.76	6.06	5.10

Table 9.8A: Variation of Coefficient 'a' for Adhered Plume

The variations for 'a' lie within the range of experimental error, found for the measurement of the mass flow rate in the ducts. However, there appears to be a decline in the value of 'a' as the compartment length increases. Regression analysis of the data shows that 'a' varies as follows:

$$a = 0.198 - 0.00962 L_f \quad \text{Eq. 5.5A}$$

where L_f is the distance of the compartment exit from the fire (m).

The standard error is 0.0067. The coefficient of determination is 0.65, indicating a reasonable level of accuracy in the formula in predicting 'a' for varying compartment length. This formula only applies to these experimental results, and needs to be confirmed at full-scale.

An increase in the compartment length generally causes a small reduction in mass flow rate, which is within the range of experimental error. For the purposes of design, it could be ignored

9.3.3 Mass Flow Rates PIV Results

No overall trend is apparent with the velocity, at the w, y and z-planes, with increasing compartment length. Significant velocity variations were found. These could be due to experimental error.

Variations of the depth of smoke with varying compartment length were limited, well within the range of experimental error.

The mass flow rate, when $D_d = 0.00$ m, shows a large decrease at the w, y and z-planes, with increasing compartment length. When $D_d = 0.20$ m, there is a large increase at the w and y, and a small decrease at the z-plane, with increasing compartment length. These variations could be due to experimental error.

Limited variations to the length of the fire compartment were found with PIV. The results are inconclusive, but indicate that there are variations at the w and y-planes, due change in compartment length.

9.3.4 Temperature Rise

The temperature rises measured at the w, y and z-planes vary due to differing heat loss and entrainment into the hot gases. The Graphs 7.24 to 7.32 in Chapter 7 show a rapid decrease in temperature rise, as the compartment length, L_f is increased from 0.41 m to 1.01 m. This initial, large temperature decrease could be due to the entrainment into the plume, as it develops into a stable ceiling jet.

Further increases in compartment length resulted in smaller decreases in temperature rise, at the w and y-plane, possibly, in the main, due to heat loss. At the z-plane, the effect of increasing the compartment length is variable. No trend is discernible.

It can be concluded that limited heat loss is occurring from the ceiling jet and significant levels of entrainment occur as the ceiling flow stabilises.

9.3.5 Visual Records

Few significant differences were observed between the flow patterns for the different downstand depths, when the compartment length was increased, except the ceiling jet (and hot layer) were well established at the w-plane for the longer compartments.

The scale of recirculation of the hot gases was similar in all instances. The total amount of recirculation would be greater with the longer compartment lengths.

9.3.6 Summary

1. Limited variation due to the change in length of compartment is evident in the mass flow rate, measured in the duct.
2. Significant variations are found when measured at the w, y and z-planes with PIV, but these could be due to experimental error.

It appears, from the limited data available, that:

- at the w and y-planes, increasing the compartment length increases the mass flow rate for the deep downstand condition ($D_d = 0.20$ m), but decreases the mass flow rate when no downstand is present ($D_d = 0.00$ m).
- at the z-plane there is a slight reduction in mass flow rates.
- More experiments are needed to clearly determine the effect of increasing the compartment length.

9.4 The Rotation Zone from the W-plane to the Y-plane

9.4.1 Entrainment into the Rotation Zone

In BR 258 formulae are presented to calculate the mass flow, M_y , at the y-plane. These are shown in Chapter 5, as Equations 5.6 and 5.7. Equation 5.6 gives rise to a doubling of the mass of the smoke as it passes from the w-plane to the y-plane. Equation 5.7 results in a 70 to 150 % increase in the mass flow rate.

$$M_B = 2M_w \quad \text{kgs}^{-1} \quad \text{Eq. 5.6.}$$

$$M_y = \frac{2}{3} \rho_o W \alpha' \left[2g \frac{\theta_c}{T_o} \right]^{1/2} d_w^{3/2} + M_w \quad \text{kgs}^{-1} \quad \text{Eq. 5.7.}$$

As shown in Chapter 5, it is not clear whether these formulae apply to flows into atria from compartments with no balconies and the high rate of entrainment ($\alpha = 1.1$) is disputed by other authors (Thomas 1987 and Law 1995).

The experimental mass flow rates and temperature rises at the w-plane and y-plane were compared to the theoretical values derived from the formulae in BR 258.

The entrainment in the rotation region is examined with the following:

- mass flow rates measured by PIV at the y-plane and z-plane
- temperature at the w-plane and z-plane
- carbon dioxide concentrations at the w-plane and z-plane
- visualisation techniques at the w-plane and z-plane

9.4.2 Mass Flow Rates Measured by PIV

PIV measures the velocity at the w-plane and y-plane, so that the entrainment in the rotation region can be calculated directly. As shown in Chapter 7, the mass flow rates at the w-plane are approximately 15 % below that predicted by BR258 shown as

Equation 5.1 in Chapter 5. The mass flow rates at the y-plane are approximately 30 to 55 % of that predicted by Equations 5.6 and 5.7.

Table 9.9 shows these mass flow rates reduced to ratios of the mass flow rate at the w-plane compared to the mass flow rates at the y-plane. To eliminate unknown variables, the mass flow rates are converted to ratios. The mass flow rate for downstands, $D_d = 0.05, 0.10$ and 0.20 m are compared to $D_d = 0.00$, thus:

$$R = \left(\frac{m_w}{m_y} \right) \tag{Eq. 9.5}$$

where: R is the ratio of the mass flow rate at the w-plane compared to the y-plane.
The ratios are subject to an error of ± 19 %.

	Theory	Mass Flow from PIV	
Dd (m)	BR 258	Lf = 0.41	Lf = 2.21
0.00	0.51	0.85	1.0
0.05	0.36	0.97	no data
0.10	0.39	1.09	no data
0.20	0.43	1.49	1.0

Table 9.9 Theoretical and Experimental Entrainment into the Rotation Region

The results do not show the high degree of entrainment predicted by BR258. From these results, R is approximately 1.0. It is higher than 1 in some instances, either due to experimental error or due to a reduction in mass from the w-plane to the y-plane.

9.4.3 Temperature Rise

The maximum temperature is inversely proportional to the mass flow rate thus:

$$m \propto 1/\theta_{\text{maximum}} \tag{Eq. 9.6}$$

The maximum temperatures can then be used to derive the ratio, R, for the mass flow rate, shown in Section 9.4.2. The heat flux measurements, from the PIV results, shown in Chapter 7 (7.3.7), show insignificant heat loss from the w to the y-plane.

Table 9.10 shows the values for R, based on the maximum temperature rise in the hot layer. The maximum temperatures are assumed to be inversely proportional to the mass flow rate.

R = q_y / q_w		Dd (m)			
z = 0.75 m		0.00	0.05	0.10	0.20
Qf=4.67	Lf=0.41	1.07	1.01	1.00	0.98
Qf=4.67	Lf=1.01	0.88	0.97	0.96	0.96
Qf=4.67	Lf=1.61	0.96	0.97	0.97	0.98
Qf=4.67	Lf=2.21	0.98	0.97	0.97	0.99
Qf=6.09	Lf=0.41	1.01	0.99	0.98	0.96
Qf=6.09	Lf=2.21	0.96	0.99	0.84	0.97
Qf=4.67	Theory	0.45	0.32	0.34	0.38
Qf=6.09	Theory	0.43	0.30	0.32	0.36

Table 9.10 Ratio R, Derived from Maximum Temperature Rise at W and Y-plane

In Table 9.10, the experimentally derived ratio of the maximum temperature at the w-plane compared to the maximum temperature at the y-plane is approximately 0.98 for all downstand conditions, fire sizes and compartment lengths, indicating that the maximum entrainment that would occur in the rotation region is approximately 2 %. The ratios have a surprisingly limited range.

9.4.4 Carbon Dioxide Concentrations

The carbon dioxide concentrations are inversely proportional to the mass flow rate as shown in Equation 9.4, therefore the carbon dioxide concentrations can then be used to provide ratio of the mass flow rate, R.

$R = q_y / q_w$		Dd (m)			
$z = 0.75 \text{ m}$		0.00	0.05	0.10	0.20
Qf=4.67	Lf=0.41	0.97	0.98	0.95	0.86
Qf=4.67	Theory	0.45	0.32	0.34	0.38

Table 9.11 Ratio, R, from Carbon Dioxide Concentrations at W and Y-plane

As shown in Chapter 7 (7.5) the ratios derived from the carbon dioxide concentrations show good agreement with the temperature rise ratios. R, in Tables 9.10 and 9.11 show good agreement. Entrainment in the rotation zone is approximately 2 to 5 %.

9.4.5 Visual Records

Although differing flow regimes were visible within the compartment, there was a strong similarity in patterns of hot gas flow outside the compartment. Most of the hot gases passed from the w to the y-plane in a fast moving turbulent stream. Larger scale turbulence was found outside this zone. For all downstand depths, recirculation of the gases was observed, with vortices being shed from the flow as it passed the w and y-planes.

There was little evidence of large scale entrainment in the rotation zone, certainly no large scale vortices engulfing ambient air. The larger vortices observed with the PIV technique at the edge of the hot layer may form up to 20 % of the mass flow. Approximately 30% of these appear to re-enter the fire compartment. Therefore up to 10 % of the mass flow measured at the w-plane could re-enter the fire compartment. If little entrainment occurs in the rotation zone, then this could account for apparent decreases in the mass flow rate as the hot gases pass from the w to the y-planes.

When observed with standard tracer smoke techniques, only the outside of the smoke flow from the fire compartment is visible, giving the impression of large scale turbulence for the full depth of the smoke layer and plume. This would be the large

scale vortices noted by Morgan and Marshall (1976) and Hansell (1993). The PIV images reveal the true nature of the flow.

The rapid flow of hot gases was observed to pass around the strong vortex that forms at the bottom of the spill wall. At approximately 60 to 90 mm above the y-plane, rapid expansion and regression of turbulent flow was observed to occur, as described in Section 8.4.2. At this level, higher rates of entrainment may occur, and the rate may be constant above this height.

9.4.6 Summary

The mass flow rates, temperature rises and rise in concentrations of carbon dioxide derived from the experiment have been reduced to non-dimensional ratios as shown in Equation 9.5. These quantify the entrainment into the smoke as it rotates from the w to the y-plane. The PIV images reveal the nature of the flow in this region. The following is a summary of these measurements and observations:

1. Entrainment in the rotation zone is approximately 2 to 5 % in most experiments.
2. There may be mass loss in some cases, as some smoke passing the w-plane is stripped from the main flow and re-enters the fire compartment.
3. Large scale entrainment may not occur until 60 to 90 mm above the y-plane (at this scale).

9.5 Entrainment into the Adhered Plume and Smoke Reservoir

9.5.1 General

Although not an objective of these experiments, information on the entrainment into the plume and the reservoir has been provided. The experiment demonstrates the effect of the downstands on:

- the mass flow rates in the duct
- mass flow rates measured by PIV
- temperatures in the plume and the duct
- visible flow structures

9.5.2 Mass Flow Rate in the Extract Duct and the Plume

The quantification of the volumes of smoke produced by a fire, in a compartment adjoining an atrium, is a major objective of main smoke flow calculations. As stated previously, most mass flow rates in the duct derived in the experiment are 5 to 20 % below the theoretical values, except when $D_d = 0.00$ m, for which the mass flow rates are generally ± 10 %.

As in previous sections, the mass flow rates are converted to ratios to eliminate unknown variables. The mass flow rate for downstands, $D_d = 0.05, 0.10$ and 0.20 m are compared to $D_d = 0.00$, thus:

$$R = \frac{M_{z \text{ PIV}}}{M_{z \text{ Duct}}} \quad \text{Eq. 9.1}$$

where: R is the ratio of the mass flow rates

$M_{z \text{ Duct}}$ the mass flow rate in the duct

$M_{z \text{ PIV}}$ the mass flow rate in the plume, at 750 mm above the y-plane.

Dd (m)	Lf = 0.41	Lf = 2.21
0.00	0.55	0.46
0.05	0.55	no data
0.10	0.52	no data
0.20	0.87	0.80

Table 9.12 Ratio R of the Mass Flow Rates (kg/s) at Z-Plane:
Qf = 4.67 kW z = 0.750 m

The mass flow rate in the duct is almost double that measured in the plume, except when $D_d = 0.20$ m. This could be due to additional entrainment occurring beyond the point of measurement at the z-plane.

It could also be due to experimental error. If the flow is not two-dimensional, then at the plane of measurement (the centreline of the atrium), the mass flow rate could be less than that found at the edges of the compartment. This would give an apparent low mass flow rate. This could account, in part, for the low heat flux at the z-plane compared to the heat flux in the duct, see Appendix 9, Tables A9.3 and A9.6.

9.5.3 Temperatures in the Extract Duct and the Plume

There are significant differences between the temperature in the extract duct and in the plume. The maximum temperature is inversely proportional to the mass flow rate thus:

$$m \propto 1/\theta_{\text{maximum}} \quad \text{Eq. 9.6}$$

The maximum temperatures can then be used to derive the ratio, R, for the mass flow rate, shown in Section 9.4.2. The heat loss from the z-plane to the measurement point in the duct will be small, as shown in Tables A9.5 and 9.6, in the Appendix. In Tables 7.4 to 7.6 (Chapter 7) it was shown that calculation of the heat flux by the duct temperature and mass flow rate gives a reasonable measurement of the heat flux.

$$R = \frac{q_{\text{Duct}}}{q_{\text{Plume}}} \quad \text{Eq. 9.1}$$

Table 9.13 (next page) shows the ratios for the duct and plume temperature measurements. The ratios when $L_f = 1.01, 1.61$ and 2.21 m, indicate that the mass flow rate in the plume is approximately 75 % of the mass flow rate in the duct. There appears to be less difference when $L_f = 0.41$ m, when the mass flow rate in the plume is approximately 85 % of the mass flow rate in the duct.

There is an inconsistency in the ratios, when $z = 0.55$, but a similar ratios are derived.

	Duct Measurement			
Dd (m)	Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	0.92	0.74	0.73	0.74
0.05	0.97	0.76	0.77	0.75
0.10	0.85	0.68	0.76	0.83
0.20	0.85	0.77	0.85	0.80

Heat Release Rate: $Q_f = 4.67 \text{ kW}$ Height of Rise: $z = 0.750 \text{ m}$

	Duct Measurement			
Dd (m)	Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	0.95	0.93	0.67	0.80
0.05	0.97	0.53	0.82	0.78
0.10	1.00	0.85	0.61	0.82
0.20	0.63	0.80	0.67	0.74

Heat Release Rate: $Q_f = 4.67 \text{ kW}$; Height of Rise: $z = 0.550 \text{ m}$

	Duct Measurement			
Dd (m)	Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	0.83	no data	no data	0.79
0.05	0.93	no data	no data	0.73
0.10	0.95	no data	no data	0.87
0.20	0.82	no data	no data	0.82

Heat Release Rate: $Q_f = 6.09 \text{ kW}$; Height of Rise: $z = 0.750 \text{ m}$

Table 9.13 Ratio of Plume and Duct Temperatures

9.5.4 Visual Records

The smoke tracer technique revealed a complex flow pattern in the smoke reservoir. Figure 8.3 shows the points where additional entrainment into the smoke may occur:

1. Ambient air is drawn up into the reservoir, as the plume enters the reservoir. This form of entrainment is similar to that occurring under balconies, as indicated in Figure 5.3 of Chapter 5. It could account for a large part of the entrainment into the reservoir.
2. Mixing occurs at the walls of reservoir. This occurs due to a ceiling jet hitting the walls and being driven down below the base of the smoke layer. This smoke mixes with ambient air and rises up into the smoke reservoir. This is known to occur in the more vigorous smoke flow within a compartment fire.
3. Little mixing was observed to occur at the underside of the smoke layer away from the plume and walls. The smoke formed a stable and well stratified layer.

The PIV image sequences shown in Figure 8.7 show the entrainment structure above the z-plane. This could be entraining the ambient air drawn into the smoke layer.

9.5.5 Summary

1. The mass flow rate measured in the plume as it enters the reservoir is less than the mass flow rate in the duct.
2. Additional entrainment of 20 to 50 % may be occurring in the smoke reservoir.
3. The flow in the plume may not be uniform across its width.

9.6 The Adhered Plume

9.6.1 General

The experiment did not aim to examine the characteristics of line plumes. Previous sections in this chapter have shown that the mass flow rates at the y-plane and the z-plane in the experiment are less than predicted in BR258. The main body of the plume, approximately 60 mm above the y-plane, shows an entrainment rate close to theoretical values. The temperature measurements show the change in mass flow rate with height above the y-plane.

9.6.2 Temperature Rise in the Adhered Plume

In Table 9.14, the ratio, R represents the following:

$$R = \frac{q_{\text{experiment}}}{q_{\text{theory}}} \quad \text{at heights above the y-plane}$$

where:

R is the ratio of temperature rises at heights above the y-plane

$q_{\text{experiment}}$ temperature rise from experiment

q_{theory} temperature rise from theory

z = 0.75 m		Dd = 0.00	Dd = 0.05	Dd = 0.10	Dd = 0.20
Qf=4.67	Lf=0.41	0.30	0.30	0.38	0.30
Qf=4.67	Lf=1.01	0.51	0.54	0.45	0.35
Qf=4.67	Lf=1.61	0.51	0.45	0.42	0.27
Qf=4.67	Lf=2.21	0.53	0.53	0.41	0.35
Qf=6.09	Lf=0.41	0.35	0.29	0.26	0.31
Qf=6.09	Lf=2.21	0.48	0.54	0.49	0.34
Qf=4.67	Theory	0.68	0.72	0.65	0.55
Qf=6.09	Theory	0.70	0.73	0.67	0.56

Table 9.14 Comparison of Maximum Temperature at z-plane to y-plane

Higher values of R represent lower amounts entrainment between the y -plane and the z -plane. Experimentally derived values of R vary from 0.29 to 0.54 for the different compartment geometries and fire sizes (an entrainment rate 80 to 250 %), whereas they range from 0.55 to 0.75 for the theoretical values of R , (an entrainment rate of 130 to 180 %).

Entrainment into the plume generally decreases with depth of downstand and compartment length, for the theoretical and experimental results. The larger fire size produces higher ratios, which equate to reduced entrainment into the plume. These results fit in with general plume theory, which states that entrainment into strongly buoyant, hotter plumes is less than into weakly buoyant cooler plumes (Thomas 1964, 1989 and 1992). The gases leaving the compartment are hotter when the fire size is larger, the downstand is deeper or the compartment length is longer, therefore the overall entrainment into the plume will appear to decrease.

When the temperature ratios up the spill wall are examined, the experimental temperature gradients do not match the theoretical values, as shown in Tables A9.7 to A9.9 in Appendix 9 and in Graphs 9.1 and 9.2.

In all cases the entrainment into a plume of this height of rise is much greater in the experiment than predicted by the theory. BR 258 states that spill plume calculations are not valid for heights of rise is less than 4.2 m full-scale, for a plume contained by two side walls, 0.53 m, at 1/8th scale. This is indicated by the line on the graph.

Graphs 9.1 and 9.2, show that the experimental temperature rises at the z -plane (0.75 m above the y -plane) are approximately 40 % higher than the theoretical values. This appears to be due to the theory predicting much more entrainment in the rotation zone (from the w to the y -plane). Above the rotation zone, from approximately 0.2 m above the y -plane, the entrainment rate (related to the gradient of the line) is approximately constant. The experimental gradient, hence the entrainment rate, is in reasonable agreement with theoretical values.

9.6.3 Carbon Dioxide Concentrations

A comparison of the CO₂ concentrations to the temperatures is in Graphs 9.3 to 9.6.

The ratios are: temperature rise ratio: $\theta_{z\text{-plane}} / \theta_{w\text{-plane}}$
 carbon dioxide ratio: $d\text{CO}_2_{z\text{-plane}} / d\text{CO}_2_{w\text{-plane}}$

where: $\theta_{z\text{-plane}}$ - maximum temperature rise at a height above y-plane
 $\theta_{w\text{-plane}}$ - maximum temperature rise at w-plane
 $d\text{CO}_2_{z\text{-plane}}$ - maximum CO₂ rise at a height above y-plane
 $d\text{CO}_2_{w\text{-plane}}$ - maximum CO₂ rise at w-plane

The rate of decline of the CO₂ concentration is less than for temperature. This could be due to the heat loss from the plume, in addition to the entrainment into the plume. There could be errors in these ratios due to the method of extracting the CO₂ from the gases. At most locations the sample tube was aligned with the flow, and the flow was reasonable well established. The samples extracted were representative of the gases at that point. At $z = 0.01$ m, the flow is unstable, and the sample tube draws gases through the horizontal flow below the y-plane. This includes concentrations below the maximum value at the y-plane, resulting in a lower measured CO₂ concentration.

9.6.3 Summary

Entrainment, between the y-plane and the z-plane is greater in the experiment than in theory. Well above the y-plane the entrainment rates are similar. The entrainment close to the y-plane (in the experiment) appears to be higher than predicted by BR258. However, the high level of entrainment predicted in the rotation region, by BR258, results in the plume having approximately similar mass flow rates (± 10 %).

9.7 An Assessment of Experimental Techniques

9.7.1 General

This spill plume experiment attempted to provide new data using some different techniques to those used at the Fire Research Station. Some similar techniques were used. Therefore an opportunity was provided to compare these techniques.

9.7.2 PIV

The experiment has demonstrated the benefits and limitations of the technique for smoke flow experiments. A restricted programme of experiments and lengthy developmental problems prevented the technique from being used to its optimum. At the time of the experiments, the technique was in a transitional phase. Until recently, it was primarily conducted using still photographs. It is now rapidly developing into a more robust reliable method available for industrial research, especially the image and data processing methods.

The experiment was a useful step in the development of PIV techniques. It demonstrated that video imaging could provide an effective method for PIV analysis, particularly sequences of images for flow and vector maps. This was an important step for all PIV fluids work, as sequential images (video frames and vector maps) have not been produced before. The experiment an effective method of seeding the low velocity hot gas flow for video images was developed.

Other researchers have started using PIV in smoke and fire experiments (Zhou, M and Garner 1996 and Zhou, X and Gore 1997). These are yielding useful information to improve the understanding the dynamics of the flow.

The technique was used reasonably successfully for time averaged flow measurements. In certain respects it is not best suited to these measurements, because it provides instantaneous velocities, rather than velocities integrated over a small time period, such as with pressure transducer techniques. In this experiment, a large part of the error generated is sampling error. A larger number of images need to be

processed to reduce the sampling error. The number of images processed at present is limited by the analysis techniques.

9.7.2.1 Advantages of PIV for Smoke Flow Experiments

PIV analysis of the smoke flow can quantify the hot gas flow in an extensive zone, but can also provide detailed information within that zone. The mean flow and turbulence characteristics can be determined by statistical analysis of the data from a particular experimental configuration. Often, this data has been produced with conventional velocity measurement techniques, but interpretation of the data has been difficult without understanding how this applies to changing flow structures. PIV images and vector maps help to demonstrate the existence and define the boundaries of the flow regions. It also provides 'frozen' images as well as evolving flow patterns of the flow. This has provided information on the recirculation of gases at the w-plane and the flow at the rotation zone around the y-plane.

An important advantage of PIV is that it causes little disturbance to the flow. In the rotation region it is difficult to measure the flow with a probe, such as a pitot tube, without changing the nature of the flow.

9.7.2.2 Disadvantages of PIV for Smoke Flow Experiments

The technique is generally limited to two-dimensional flows. If the smoke flow is fully three dimensional, then poor quality images are obtained, as particles disappear from the camera image, between each pass of the laser beam. In this experiment, it appears to effect the images obtained at the edge of the plume at the y-plane and in the smoke reservoir (away from the plume).

The scanning rate of the laser and its light output, and the camera settings, need to be set for particular velocities and seeding types. If strong velocity variations occur within the region being analysed, then the settings need to be adjusted for a particular range of velocities. Some areas of the flow, with different velocities, may not provide suitable particle images for analysis. This had little affect on this experiment, because

the peripheral flow structures at the edges of the plumes did not need to be quantified accurately. The main flow and peripheral flow may have required separate images to be recorded for analysis, if accurate data of both areas was required.

These images were analysed using auto-correlation, rather cross-correlation. The former requires the experimenter, when analysing the data, to decide the direction of the flow. It is not difficult to know the direction flow in the main part of a ceiling jet, but it is difficult to define in peripheral areas of flow where reverse flow and recirculation occur, such as below the ceiling jet, at the w-plane. Fortunately, much of the mass flow occurs in the well defined flow of a ceiling jet. Checking and correcting the direction of flow for each image can be a lengthy process, especially where the flow changes direction in the rotation zone (w to y-plane).

Processing of the data (including the step discussed above) is time consuming. This limits the number of images that can be analysed, reducing the amount of data that can be obtained for a particular experimental configuration. This in turn increases the scale of the sampling error, as the sampling frequency is reduced.

The quality of the video images is not as good as 'still' photographs. The detail is limited. A comparison with the Megaplug digital 'still' images shows the degree of detail that is lost with video images. The Megaplug images provide an excess of detail, but the velocity data provided from the video images is not as accurate as other data from, for example, thermocouples. The grid resolution, in analysing the images limits the number of points of measurement within the depth of the flow. For example, the ceiling jet velocity profile is often derived from six points.

9.7.2.3 Development of the Technique for Smoke Flow Experiments

Some of the problems discussed above will not be applicable, as PIV technology develops. New video cameras and data processing techniques are being developed that produce more detailed information, more rapidly. Optical Flow Systems, a technical development group within the University of Edinburgh, have developed a

video camera that can provide instantaneous cross-correlation analysis of PIV images, reducing the processing time. Cross-correlation also determines the direction of flow.

New cameras are also being developed that can improve the resolution of the images, therefore provide smaller grid sizes and more data points for flow profiles.

9.7.3 Other Techniques

Other more established techniques were also used for these experiments. These had the following benefits and limitations.

9.7.3.1 Mass Flow in Duct Measurement

The pitot tubes and thermocouples allowed rapid and reliable measurement of the mass flow rate in the duct. The mass flow rates may not be an accurate measurement of the mass flow rate in the plume, due to entrainment into the reservoir entrainment. It is a suitable method for comparative measures and direct modelling of extraction rates required for smoke control systems, but as an experimental technique, needs other data to supplement it, to describe the flow away from the reservoir.

9.7.3.2 Carbon Dioxide Measurement

The carbon dioxide measurements provided direct measurement of the entrainment into the plume. Unfortunately the gas analysis is slow due to the time to pull gas through tube and limitations on the number of measurement points.

There is also uncertainty about what is being measured. The sample tube may be extracting through fine gas gradients, therefore not receiving a true sample of the carbon dioxide levels.

9.7.3.3 Thermocouple Measurements

This has been a simple and effective method of measurement in the flow. If used in conjunction with other instruments, to demonstrate the scale of heat loss, they can provide accurate data, with ease.

9.8 Conclusions

These apply to results apply to adhered plumes only. Note that a wider range of experimental configurations, geometry and fire size, need to be used to show that these results hold for a wide range of conditions.

9.8.1 Experimental Aims

9.8.1.1 The Effect of Downstand Depth on the Coefficient of Discharge

1. The depth of a downstand has a limited effect on the flow from a compartment. The coefficient of discharge (C_d) is approximately constant for an adhered plume.
2. Good agreement is made with the form of Law's formula (1995), which was developed from Yokoi's (1960) data correlation. The coefficient for the formula differs due to the experiment using an adhered plume.
3. Using the data from the duct measurements, the formula for adhered spill plumes (with free ends) has been correlated as:

$$M_z = 0.19(Q_f L^2)^{1/3} (z + 0.25(Dd + h)) \quad \text{kg s}^{-1}$$

The constant is 0.11 using PIV plume data.

9.8.1.2 The Effect of Compartment on the Mass Flow Rate

1. There is a slight reduction in the mass flow rate, at the z-plane, due to increasing compartment length.

9.8.1.3 Entrainment into the Rotation Zone (W to Y-plane)

1. Entrainment in the rotation zone is approximately 2 to 5 %.
2. There may be mass loss in some cases, as some smoke passing the w-plane is stripped from the main flow and re-enters the fire compartment.
3. Entrainment into the plume close to the y-plane (up to 1.5 m full-scale) is higher than predicted by the theory in BR 258, possibly accounting for some of the assumed 'doubling' of mass in the rotation zone.

9.8.2 Additional Information Derived from the Experiments

9.8.2.1 Design Mass Flow Rates

1. When downstands are present, mass flow rates in the duct are 5 to 20 % below theoretical values.
2. When there is no downstand, mass flow rates are 5 to 10 % above theoretical values.

9.8.2.2 Entrainment into the Smoke Reservoir

Additional entrainment to the mass flow rate of 20 to 50 %, may be occurring in the smoke reservoir.

9.8.2.3 Three-dimensional Flow

The flow of smoke from a compartment and in a plume may not be uniform across its width. It is estimated that the mass flow rate could vary laterally by 10 %.

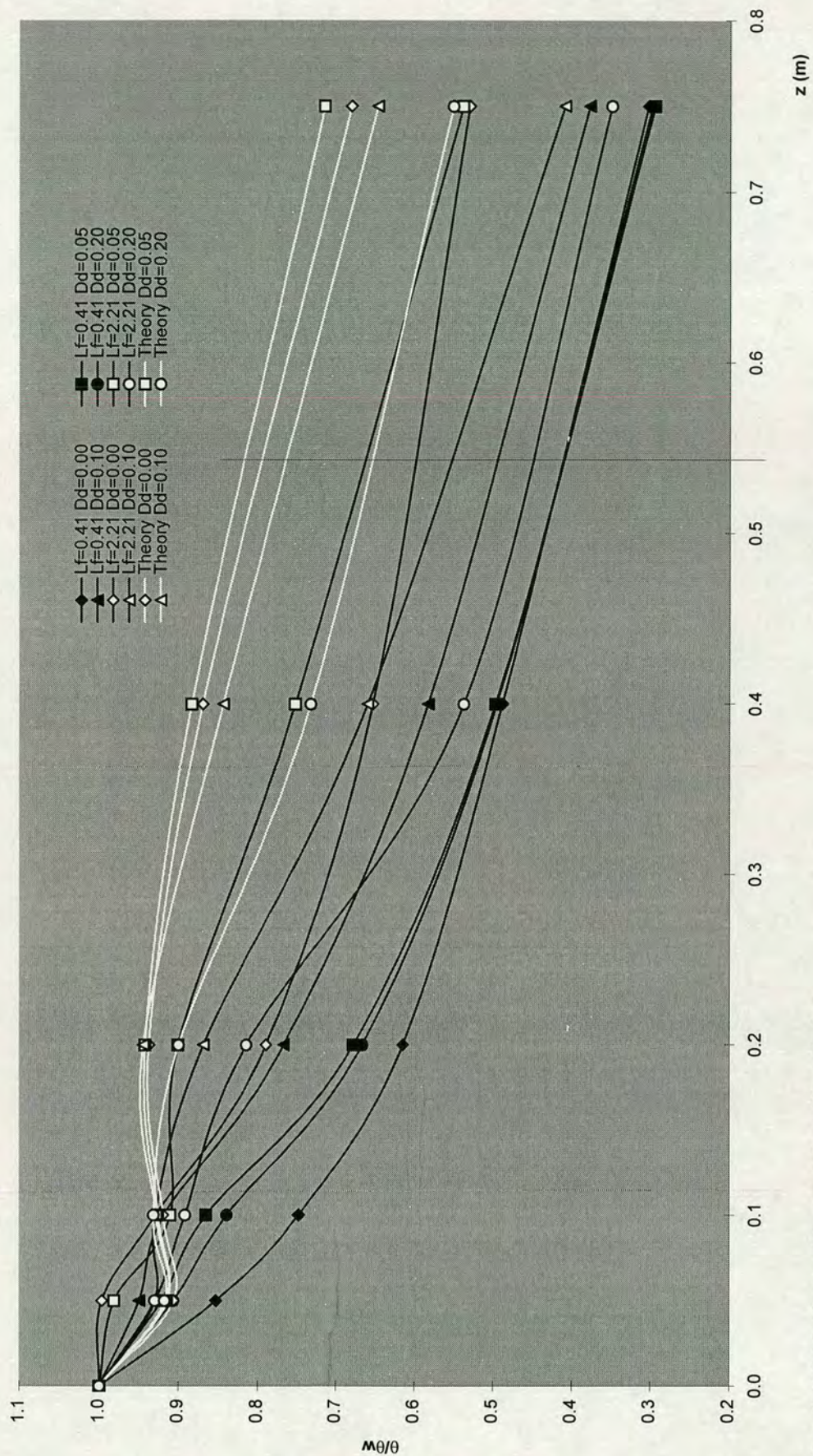
9.8.3 Summary

The results are significant as they demonstrate the following:

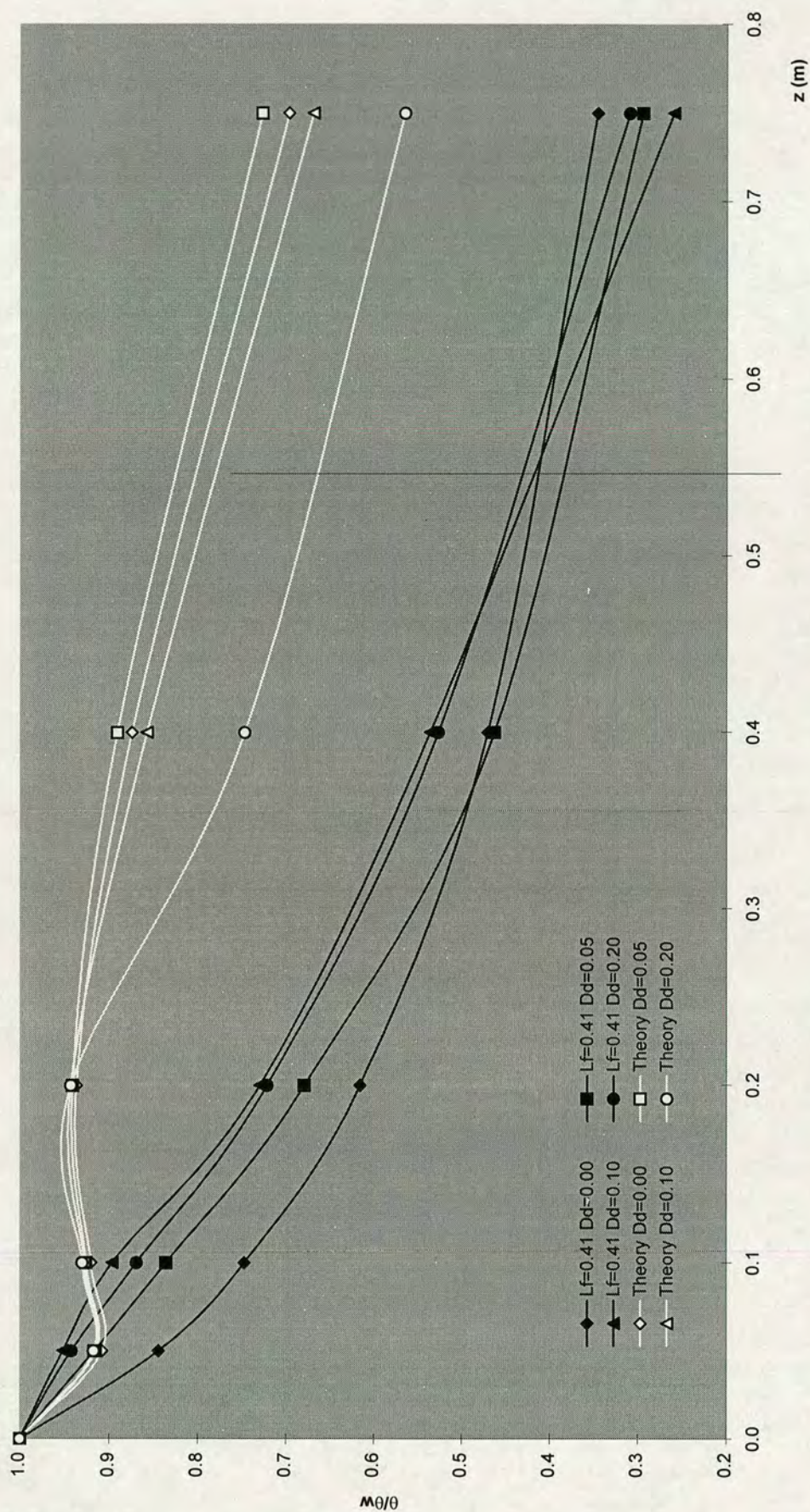
- The experimental results differ from the values predicted the spill plume theory in BR258.
- the effectiveness of the experimental techniques, and their limitations

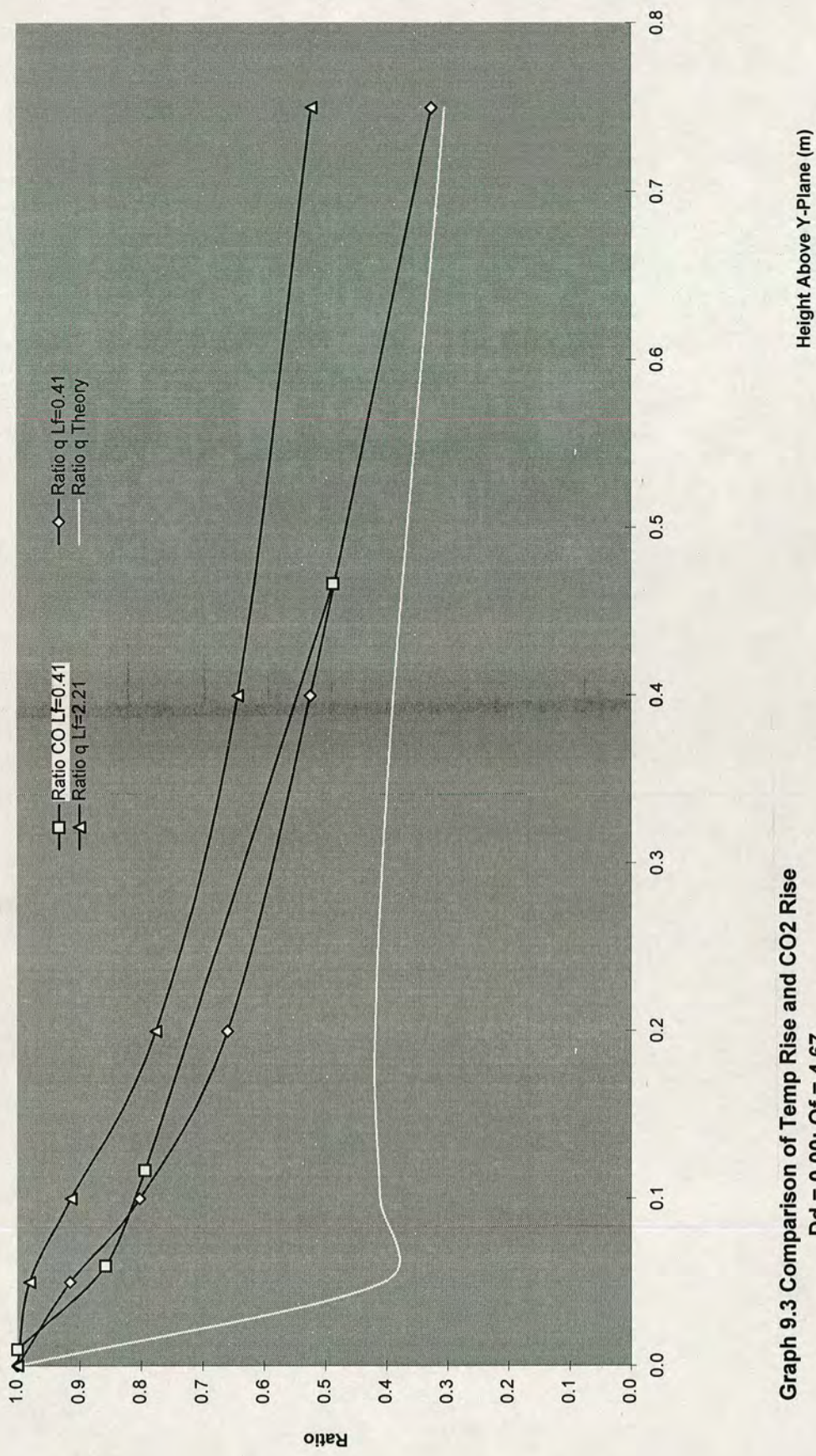
The measurements have been able to provide information on the characteristics of smoke flow from compartments into atria. This data demonstrates some limitations to the existing theories and identifies areas requiring further research.

The design implications of the results are discussed in Chapter 13. Recommendations for further research are made in Chapter 14.

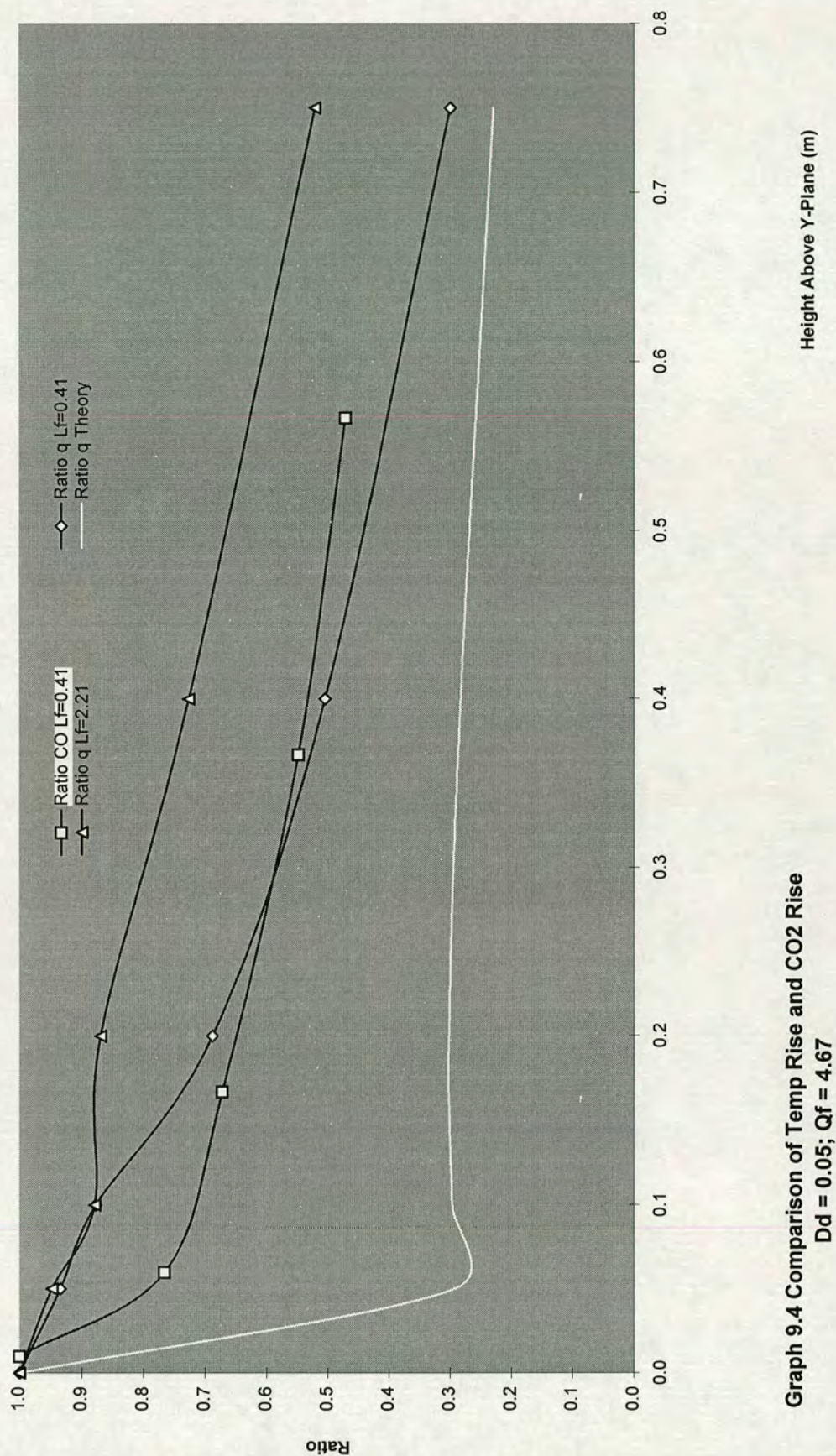


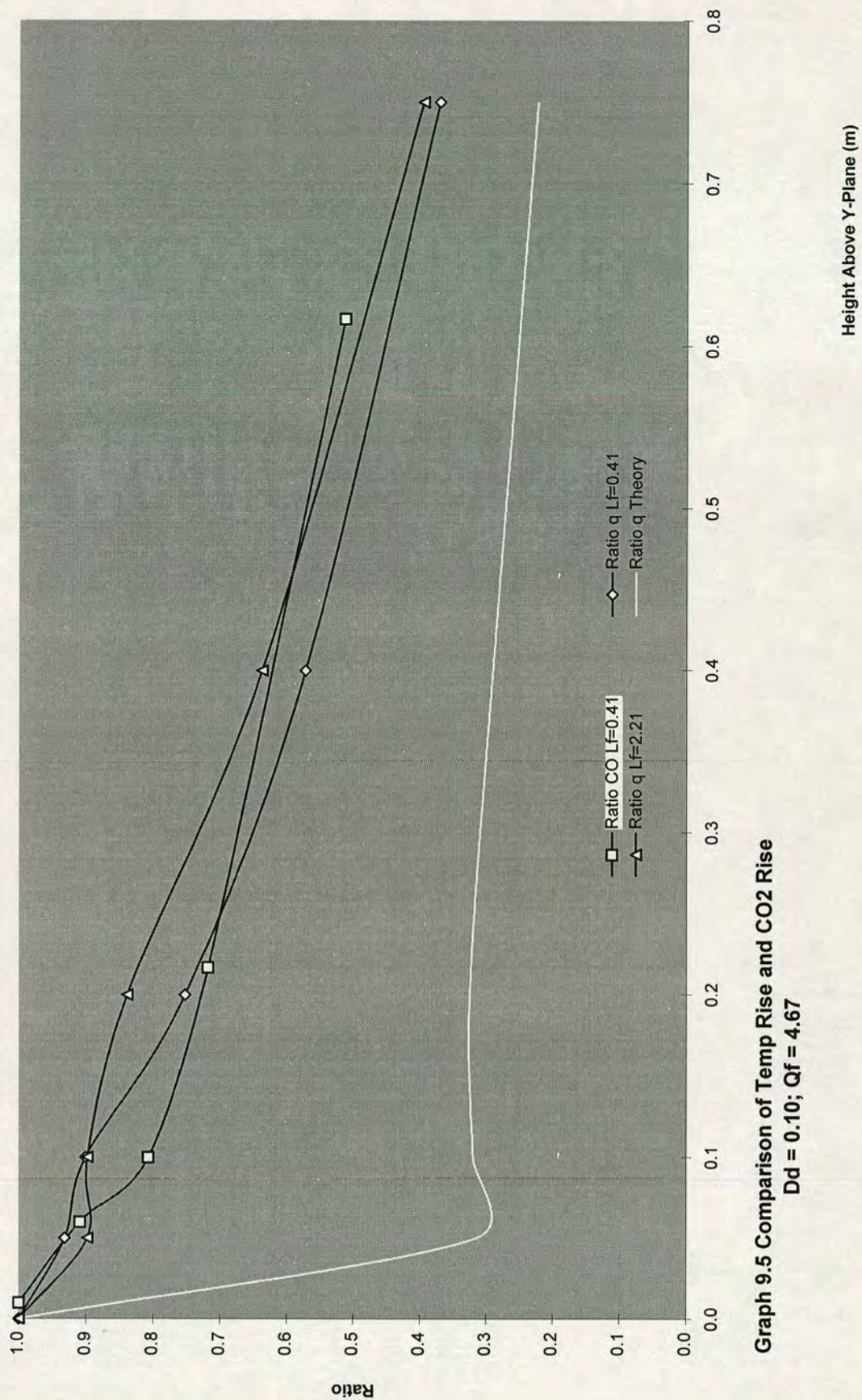
Graph 9.1 Maximum Temperature Rise Ratios
 $(\theta z/\theta_y) Q_f=4.67; z(\text{res})=0.75$

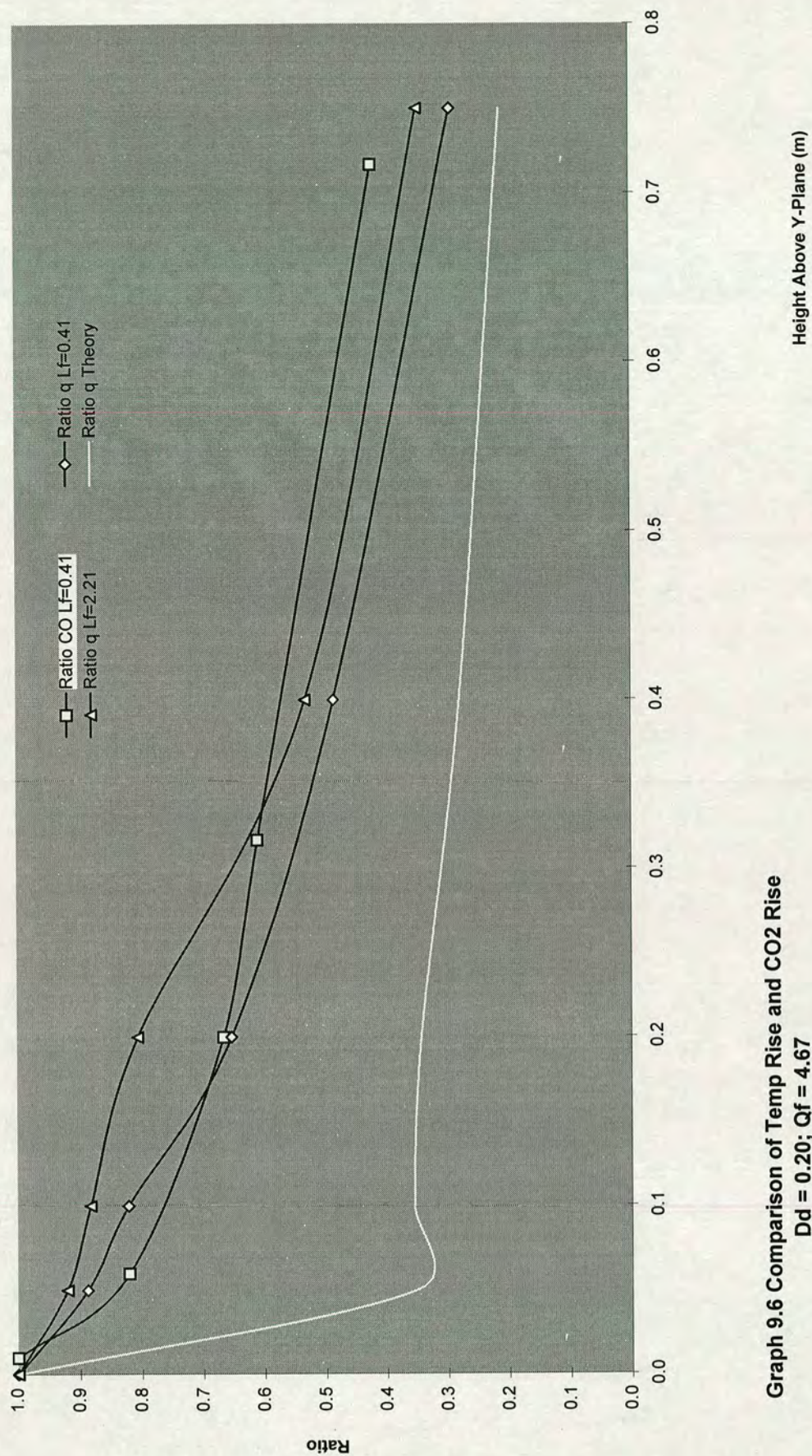




Graph 9.3 Comparison of Temp Rise and CO2 Rise
 $D_d = 0.00$; $Q_f = 4.67$







Part 3 Smoke Control Systems

Chapter 10 The Fire Safety Life Cycle

Chapter 11 Smoke Control Questionnaire

Chapter 12 Examples of System Failure

Chapter 10 The Fire Safety Life Cycle

10.1 General

In Chapter 3, it was demonstrated that the potential for success of a smoke control system is the result of two variables:

- the variation of the fire environment (examined in Chapters 4 to 9).
- the variation of the performance of the smoke control system,.

In this chapter the causes of variation in the performance of smoke control systems are examined, and a methodology is developed to determine what level of performance is being achieved

A series of events (such as design intention, errors, variations to requirements and the deterioration of the materials used in the installation) determine this performance of a smoke control installation during its life-cycle. These need to be identified to improve system performance and to assess the risk of failure. They also provide a basis for the classification of failure mode types.

10.2 Fundamental Causes of System Variation

10.2.1 A System

A system consists of three related sets (Aslaksen and Belcher, 1992):

- elements
- interactions between elements
- boundary conditions (interactions to elements outside the subsystem).

The performance of a system is defined by these sets. These have their performance affected in many ways, but there are fundamental causes of all of these (Aslaksen and Belcher, 1992, Smith 1993 and System Safety Analysis Handbook, 1993):

- natural variability of the elements' (components') performance
- knowledge uncertainty and system effect
- human error

10.2.2 Variability of the Performance of Elements

All components exhibit changes in strength and quality leading to variation. A component can fail due to manufacturing faults creating populations of substandard items owing to microscopic flaws in welds, joints and cracks and the inclusion of impurities dislocations and cracks. They can also wear out due to, corrosion, oxidation, friction wear, fatigue and so on. Failure can also be caused by transient periods of excess stress (Smith 1993).

These fault causes collectively form the 'bath-tub' curve, which shows varying reliability over the life of a component, see Figure 10.1 (Smith 1993). This can be applied to most components.

The reliability and the variability of the life of a component depend on the effectiveness of quality control procedures. Risk assessment is often limited to simply analysing component reliability, omitting other aspects of system performance.

System performance can also be affected by component compatibility. This is particularly problematic for control systems and electrical items.

10.2.3 Knowledge Uncertainty

When designing a system, there is always a level of uncertainty regarding the exact the performance of the system. Even without the effects human error and component faults, it is difficult to exactly model a system's performance. This is referred to as 'system effect' in some publications (ASHRAE PAPER). This is due to knowledge uncertainty and the effect of components and component interfaces upon the system. In HVAC systems it can occasionally cause major reductions in volume flow rates, from predicted values, sometimes up to 20 %.

10.2.4 Human Error

People are the most unreliable part of any large engineering system (Wolfram 1991). Human error analysis has developed from reliability and risk studies of large nuclear installations and large chemical engineering plants. Many of the analytical methods examine the effects operatives have on plant operations, particularly with hazardous processes. For example Human Error Analysis identifies the points of human and machine in a design interaction to ensure that methods of 'error control' are introduced (Safety Systems Handbook 1993). Human Reliability Analysis assesses the impact that human reliability has on processes, and can be developed into an event tree to calculate the overall reliability of 'human' factors in a process industry (Safety Systems Handbook 1993). These methods do not consider design errors that exist in a system.

Groner and Chubb (1995) state that in fire safety engineering systems, human error prior to a fire scenario may have greater consequences than the errors immediately prior to and during a fire. They distinguish between latent and active errors. Active errors are committed by the people at the onset of and during an emergency, having immediate affect, causing and aggravating an emergency. Latent errors have a delay between the error and its consequence. 'A single latent error is unlikely to cause a large disaster, instead they combine in largely unpredictable and insidious ways.'

Groner and Chubb (1995) state there are three types of errors:

- skills-based - e.g. forgetting a procedure, recording a wrong value
- rules-based - e.g. misuse of a model
- knowledge-based - e.g. error with a unique problem

These classifications can be applied to latent or active errors. Skill based errors are relatively easy to detect, by careful quality control measures. Rule and knowledge based errors are harder to detect. Every action and decision can cause error.

The affect of human error on design is being studied in more depth in other engineering disciplines. Rackwitz (1986) reports that 90 % of serious structural failures can be traced back to human error of some form. In structural engineering, much research is being conducted to analyse and quantify, by probability methods, the effect of human error on the potential strength of structures. These studies have revealed the importance of understanding the sensitivity of an engineered system to human error. Stubbs (1986) has examined the affect of human error on the probability of failure of a simple structural frame in a hurricane. He has proposed a method of estimating the magnitude of the increase in probability of failure of a structure due to human error has been proposed. The method consists of the following stages:

1. list all possible scenarios of human error occurrences.
2. determine the frequency of occurrence of the scenarios.
3. compute the frequency in the increase in the probability of failure from the error-free state for a given scenario.
4. Develop risk curves of the probability of failure.
5. Compute the risk of frame failure.

He demonstrated that for high frequencies of failure, the probability of failure due to human error might be several orders of magnitude greater than the error free probability of failure.

Human error would play an important part in the failure of smoke control and fire engineering. It is not possible to show, here, the whole range of possible causes of human error that could effect a smoke control system, merely to demonstrate that smoke control system failures are more likely to be attributed to human failure, rather than unexpected system or component faults.

10.2.5 Life-cycle of a System

The nature of systems has been briefly described and the three causes of variation in performance have been introduced. These can be variations can be initiated at any stage in a system's life-cycle. The cause of system failures needs to be examined at each stage of the life-cycle.

In structural engineering the frequency of errors during the life of a building have been examined. Ellingwood (1986) reports the frequency of errors for structures in buildings, shown in Table 10.1.

These frequencies demonstrate the importance of identifying the source of errors in design, and how usage and maintenance could have a limited effect on failure. The figures could not be directly applied to smoke control systems. The failures during maintenance could be higher with smoke control systems, because these are dynamic systems that may require higher levels of maintenance.

Survey	Planning and Design (%)	Construction (%)	Usage and Maintenance (%)	Other (%) ^a
CEB 157	50 ^e	40 ^e	8	-
Mastousek	45 ^d	49	6	-
Taylor	36 ^e	12 ^f	-	-
Yamamoto	36	43	21	-
Rackwitz	46	30	23	-
AEPIC	67	33	-	-
Melcher	55	24	21	-
Fraczek	55	53	-	-
Allen	55	49	-	-
Hadipriono	49	27	33	20
Hauser	67	35	5	23
Gonzales	29	59	-	13

a - not attributed to only one factor

c - materials 15 %, execution 25 %

e - design only

g - multiple errors for single failure

b - planning 25 %, design 25 %

d - planning 11 %, design 34 %

f - construction and usage

Table 10.1 Incidences of Error in Building Process by Phase (Ellingwood 1987)

10.3 The Life-cycle of a Smoke Control System

10.3.1 General

Variations to the performance of an integrated fire-safety engineering system can be caused at any stage of a building's life. These can be due to the variability of the performance of the components, system effects or human error.

10.3.2 The Potential for Error

Expertise in fire safety and smoke control may be present at various stages throughout the life-cycle of a smoke control system, such as at the early design stage, when producing a smoke control strategy. Fire safety engineers may make a range of errors in their design, but should have the experience to detect them. Few are experts in all areas of fire safety engineering and may not have the necessary expertise to design smoke control systems. The optimal design solution may not always be chosen. They may fail to appreciate how people interact with the hardware design and compromise its performance (Groner 1995).

After the initial system design, other people become involved in the process of implementing a fire safety design (including the smoke control design). Decisions can be made by anyone involved, directly or indirectly, with the system (for example architects, cost engineers, HVAC engineers and contractors, maintenance engineers), who may not understand enough about fire and smoke, to be able to develop and carry through the objectives for a smoke control system. They might not recognise the consequences of their actions on fire-safety (Groner 1995), unaware of how 'building-systems' can form a part of the fire safety system, so its performance may be compromised.

Even if a fire strategy, and its smoke control requirements, are clearly defined, it could still be compromised by other systems within a building. All activities involved in the life of a building, especially during construction, involves people with specialist skills, such as architectural design, financial control or fire engineering. Each person aims to solve specific sub-problems (MacPherson, Kelly

and Webb 1993), while attempting to work as a team to complete various parts of the life-cycle process. As a result, communication and co-ordination problems occur and the fire safety concept can be lost, because the people making and implementing decisions become remote from its origins.

There may be no expert fire safety engineering advice on some projects, even complex ones. Clients can be reluctant to employ fire safety engineers, to save on consultancy fees. If fire safety engineers are employed, it is often for a limited scope of work, so their advice is not available for the totality of the design. The result is that the full benefit of a fire engineers advice is not available so that the most effective decisions are not made. Advice may be sought from other parties, such as manufacturers of fire-safety equipment to design parts of the system, who may not provide unbiased advice.

10.3.3 Feedback Information

To reduce knowledge based uncertainty and variations in performance, feedback on the performance and effectiveness of smoke control designs is needed. It is rarely obtained. The performance of the system is not tested as a whole, but as a series of components. Very few buildings in the UK have full scale fire tests, so this complete system performance testing is rare. Many fire safety practitioners would argue that this is unnecessary, for an individual building, and that full-scale fire tests are only necessary to develop and validate smoke flow models. Occasionally organisations make more detailed tests of a buildings smoke control system. In other engineering systems (such as HVAC or electrical) testing and daily use, provide feedback on system performance to designers.

A few examples exist of this occurring, Dillon (1994) found that the plume diameter, in a fire test in a stadium only had one half of the expected diameter and one half of the mass flow rate predicted by plume models. The smoke extract capacity was twice that needed for efficient smoke control. However, problems occurred in the pedestrian concourse, where smoke bypassed extract grills and proceeded to flow up

stairways. Demonstrating that the smoke control design should not be limited to examining the characteristics of a simple plume, but extended to peripheral areas, where smoke logging could occur.

10.3.4 The Life-cycle of Smoke Control Systems

During design, construction, and maintenance, events (errors, faults in materials and so on) affecting the performance of smoke control systems will occur. The effect of these events will not become apparent until a building is operational. Suitable design reviews prior to construction, followed by rigorous commissioning and testing of the smoke control procedures, are required to discover any deficiencies within a system. Marchant has demonstrated the importance of identifying the stages in the life cycle of fire safety systems (Marchant 1976) and smoke control systems (Marchant, 1993 and Paveley and Marchant 1995), and that a conscious effort needs to be made to ensure that these systems are developed and maintained effectively.

A complex interaction of activities occurs, within the life-cycle of a building (Marchant 1993). The major stages are:

1. Design
2. Manufacture
3. Construction
4. Commissioning
5. Occupation
6. Fire Scenario
7. Demolition

Any smoke control system and its performance represents the result of all of the activities (and errors committed) during these stages. Figure 10.2 shows the life of a system and how major events can affect its performance. This example, would be for a reasonably well designed and constructed system, with a typical maintenance procedure. If greater design or construction errors occurred, then there would have been a greater performance range, possibly complete system failure.

Poorly performing smoke control systems are too common, for example an investigation of pressurisation systems, by Shipp (1980) revealed that 11 out of 12 systems failed to reach the recommended overpressures. This was due to design and construction errors. Most of these systems were not commissioned on completion, and this investigation was the first inspection and performance measurement that had been made with them.

The following section examine the events that can occur and problems that can be encountered during the life of a smoke control system, and their potential effect on performance.

10.4 Events During Design

10.4.1. General

The process of defining the needs and techniques of a particular smoke control system runs parallel with other parts of the fire safety system. According to standard engineering design methods, a 'top down' design procedure (Aslasken and Belcher, 1992) is used ideally, in which the specification of particular solutions is avoided until, the whole fire safety concept is developed. The process (involving client, design team and building control team), derived from Klote (1992), can be defined in its ideal form as:

Identify:	OBJECTIVES
Develop:	STRATEGY
Model:	TACTICS
Define:	TECHNOLOGY

Few building design processes follow this pattern strictly. The 'culture' of the design process splits the work into various commercial and professional groups so that parts of a design may be well advanced, while others are still yet to be identified. Often fire engineers are brought into projects at a late stage, so it is difficult to effectively incorporate fire engineering strategies. The architect, project manager and client (Stollard 1986) must identify the need for early involvement, but these people may not have sufficient knowledge of fire problems to be concerned. Fire engineers' need to ensure that a co-ordinated approach is used for fire safety design, otherwise major design requirements may be missed (Dwyer 1989).

A performance based (integrated fire-safety engineering) approach would aim to use a 'top-down' pattern. A code based design is a 'bottom up' approach, in which aspects of the tactics are pre-determined and the technology specified accordingly.

10.4.2 Design Objectives

The design objectives of smoke control systems were defined in Chapter 2 as:

1. Minimise the exposure of the occupants of a building to the hazards of smoke
2. Minimise damage to property, by limiting the spread of smoke.
3. Minimise disruption to organisational activities, by limiting the spread of smoke.
4. Aid fire-fighters activities, by providing smoke free routes to reach the fire
5. To purge the smoke from buildings after a fire

The primary objective is usually to enhance life-safety standards. The level of life-safety can determine the major features of the system and often whether one is installed or not.

It is difficult to determine an acceptable level of risk, especially for life-safety. These levels are set externally to the design process and to the organisation for whom the building is being built, although the client may wish to increase the level of risk reduction. There are no standard figures for these levels of risk, mainly because they

are difficult to generate. In identifying the levels of risk, it is also necessary to identify the fire scenarios that are to be controlled.

As objectives change, so does design emphasis. For example:

- a system primarily for life-safety could run for a short period, half an hour, as time to escape could be within the fire growth period.
- a system for property protection to prevent ingress of smoke to a sensitive computer centre, for example, might need to remove all smoke in surrounding zones; have pressurisation for six hours to exceed the duration of most fires; or high levels of separation from surrounding compartments.
- a system solely for smoke purging may allow smoke logging of certain areas, so the extract rate could be low, only being equal to 40% of the peak rate.

The elements of an integrated fire safety system may have the same objectives, although elements may have a more direct benefit to one particular objective. For example, sprinklers are often associated with property protection, but they are also an important factor in smoke control system design, controlling the fire size.

The brief must have the correct and sufficient detail for the development of a suitable fire-safety concept for the emerging building design, otherwise the system objectives and resultant design will be inappropriate. The client may not understand 'buildings', so the brief needs to be reviewed during the design process, because the emerging building form will give them clues about potential needs and problems. Without this fundamental changes, after completion of the project, may be required to ensure that fire-safety objectives are met.

10.4.3 Design Strategy

A coherent methodology is developed to achieve the objectives. A balance must be made of the requirements for means of escape, passive measures, and active systems must be made, otherwise the smoke control strategy will not match that for the other fire safety systems, in concept or detail.

The method of control must be identified: containment or extraction, and passive or active. Smoke free areas, and the acceptable height of the clear layer in other areas, should be identified. These decisions should be subject to review as the design evolves. Reviews should discover any concepts that are fundamentally flawed or incorporate high risk, radical and/or expensive technologies.

A range of factors influence the choice, such as the form of evacuation; provision of refuge areas; zones for compartmentation; suppression system requirements (zones and time to control the fire) and detection (time to respond).

The influences on smoke control requirements can be complex, for example the type of alarm will influence when people will initiate escape, and therefore the time to complete escape, so the system requirements will change (such as time to operate and time to fill the smoke reservoir).

The strategy must be prepared thoroughly and reliance on 'quick' solutions must be avoided. An example is an automatic postal sorting building, over 12000m² in area. The local code officials classed the building as being 'office' space, according to the planned activity of 'sorting paper'. The building was closer to 'Light Industrial' in many ways, due to the building form, machinery and processes. If the 'office' classification had been used, the smoke vents would have been designed for a steady 2 MW (16m²) fire. Careful examination of the fire loads revealed that a steady 9 MW (36m²) fire would be more appropriate. This building would have been deficient if designed to building code classifications.

10.4.4 Design Tactics

10.4.4.1 General

At this stage, models, data and input from other systems are used to identify and quantify the problem; solutions are found with the development of hardware and control systems.

10.4.4.2 Models, Data and Input from Other Systems

The scenario and quantities derived by a building designer are unlikely to match that of specialist researchers, working with the same models. Models used by less able people, away from the controlled research environment, will lead to more errors. Training, education and experience will determine the ability of the user to understand and manipulate a model. If knowledge of the model is below a reasonable level, serious errors could occur. Support by experts or more experienced people is not always possible.

Anecdotal evidence suggests that incorrect models are often used, for example some environmental CFD modellers (for HVAC design) have used their systems to design smoke control systems, resulting in poor data. Errors and deviations from standard practice include the wrong detail in grids, poor input data and heat transfer modelling.

Organisational demands on time and cost will reduce the potential for effective design. General data available and information specific to the building from other design team members about the building, are unlikely to be exact. Assumptions will be needed throughout the process.

Economics factors ultimately determine the choice of model, whether consciously or not, a designer will decide what the value of risk reduction using a more complex model is, compared to the added cost of using that model. If a 'better' (but more expensive) model cannot demonstrate improvements in predictions, then it is unlikely to be used.

10.4.4.3 Hardware and Control Systems Interaction

This includes the development of active and passive schematics and performance specifications, for ductwork, screens, vents, fan locations and loads, and computer control system layouts and hierarchies. The influence of these on fire and smoke

must be assessed. The smoke control strategy must be reviewed after these calculations.

Common problems are that the resultant scheme design may have no continuity for the air flow or inappropriate paths for smoke, such as inlet louvers within the smoke reservoir; or the scheme design might be incorrectly co-ordinated with other parts of the building system. To illustrate this are the following two examples:

Example 10.1: Figure 10.3

This problem was identified in a design review. The system had an extract volume of 120 m³/s of smoke, 60 m³/s from each end of the mall within the building. The smoke would have to cross the atrium void, but because it is buoyant, it would rise up into the upper reaches of the atrium, smoke logging escape routes at upper levels. The designer had not fully considered this aspect (Marchant 1993).

Example 10.2: Figure 10.4

During the design review, it was realised that external air would be drawn in through the open gable ends. This would mix with the smoke, increasing its volume, causing it to descend to below an acceptable level. A more thorough examination of the potential flow of smoke and the entrainment of air would have revealed this problem. A solution was to install high level gable ends to prevent the entry of external air (Marchant 1993).

The other systems that form a part of the integrated smoke control system need to be correctly interfaced with the smoke control system. The system as a whole needs to be correctly interfaced with other systems within the building. For example detection systems should not be sited so that ventilation air flow will prevent smoke from reaching the detectors (Pennycook 1995).

The controls for the smoke control system must be carefully detailed. The controls specialist will not know all of the operation sequence requirements for smoke control systems. If not correctly planned, unexpected operational sequences can occur (Marchant, R, 1992).

10.4.5 Design Technology

10.4.5.1 General

The schematic performance designs, from the tactical stage, represent an ideal. Specifiers need to identify the technologies (components) to produce that ideal. This specification and interface detailing, will involve a series of compromises and errors, altering a system's potential performance. Some common technology errors occur for smoke control systems, due to reasons discussed in section 10.4.2.

Specification and detailing is done by a variety of people, depending on contractual arrangements; consultants, contractors or specialist manufacturers, having differing skills, each advantageous to the project, but few with the full range of knowledge and information to choose the best solution for the system. Resources and technology are always limited, so the optimal set of components cannot usually be chosen. Specifications can be changed, so inferior products have been specified, to replace more expensive, but more reliable components. This was found in one project where 'quality exhaust ventilator's had been re-specified to an inferior alternative of glazed windows with automatic openers (Record, Building Services 1995), even though they would not strictly comply with British Standards.

In HVAC and electrical engineering, where much of the 'culture' of smoke control system design originates, many details are knowingly left unresolved in the design office, in the belief that they will be resolved on site (MacPherson et al, 1993).

10.4.5.2 Typical Technology Problems:

Some examples include:

Component Problems:

Fire, smoke and combined dampers are often used in the wrong situation, due to misunderstandings or misinterpretations of their technical performances and sometimes due to misapplication of the building regulations.

Dampers solely operated by fusible links are often specified (cheapest dampers). Their operational characteristics may not meet the requirements of the system. Dampers controlled by detector operated building management systems, with fail safe closure or opening methods, can offer earlier and more reliable response to fire and smoke threat, preventing recirculation of smoke or encouraging the safe extract of smoke.

Varying types of roof ventilator are available, and continuing research, demonstrates that each type would have different wind pressure coefficient values across them at similar roof locations (Gosh, 1993). Pressure coefficients can also vary, due to the roof layout and influence of surrounding buildings (Marchant 1984). These factors will cause variations in the performance of a natural ventilation system (and some difference to extract systems).

Reliability comparisons, between various components and systems, can omit important factors, such as stating the ambient environment. They can also include irrelevant failure modes for certain components in a particular situation. How a product fails, is as important as how often it fails.

Some components are not designed to meet the conditions that the system will experience. These are not necessarily those associated with the smoke environment, which can be little different from the ambient environment, but, for example, corrosive local conditions (Mecker and Hamada 1995).

Confusion about the meaning of various types of certification exists. 'If a component is listed by an agency such as the Underwriters Laboratory, then this may be based on safety alone, not functional reliability'. This certification has often been misinterpreted, to mean that a component has the reliability needed for a fire protection. So a motor that was designed to open and close curtains, has been found to have been specified for fire safety systems (Campbell and Longhitano 1984).

Component Interfaces:

A component is only as good as the construction into which it is built, for example smoke sealed doors may give very low leakage rates during standard testing, but the surrounding door jamb details may give a notably higher air flow rate.

Sealing of services' penetrations, through fire compartment walls, can often be detailed by technicians unaware of the requirements or practicalities of such methods.

10.5 Manufacture

10.5.1.General

Many manufacturing problems can exist. This section provides a general list of those that can cause further variation to the system performance.

10.5.2 Variability

As shown in Section 10.2.1, there is a natural variability in the performance of the components that form a smoke control system, due to 'burn-in' faults, random failures and component wear and tear.

The specification of different components can affect the performance of a system. Products made to the same standard, can vary. For example, smoke-seal doors, vary by a factor of 200 in their air-leakage rates, when a standard air pressure differential

is applied across them (Gross 1981). Some suppliers provide technical literature and advice with their products, but not all aspects of a component's performance are stated or known.

In specialist work, such as fire engineering, many configurations of components are unique, so that previous experience may not have revealed all potential problems that could occur with the buildings intended use.

Manufacturing faults always occur, so do variations in the performance of individual components, supplied to a project. The reliability of these products depends on the efficiency of factory and site based testing.

10.5.3 Limited Product Range

There is a technical and economic limit to the range of products available, especially with specialist items, such as smoke control fans and louvre types. The choice during specification is limited and it will not always be possible to match the product to the system requirements and the main reason for choosing a product can be other factors, such as cost, space availability, power supply and ease of maintenance instead.

10.5.4 Specialists

Most of the fire safety manufacturers exist as separate organisations, only a few are involved in several parts of fire safety engineering (Xiao, Marchant and Griffith 1993/4), and few have the range of products or understanding suitable for ease of integrated design. Incompatibility and complex interfacing of products can result, especially with power and communications. The sales team or suppliers are not always aware of any incompatibility. Component design standards need to be flexible in their application, so issues of compatibility are not always addressed.

10.5.5 Dubious Claims

Manufacturers of smoke control components have different areas of knowledge. Some give good advice; others may not, due commercial pressure or lack of experience. Many building designers may be tempted to rely upon them for advice.

In one case, manufacturers claimed a double-door set was 1/2 hour fire-rated. The local fire inspector asked for certification, and found that they had only been tested as single leaf units. Tested as a double-door set, they failed after only 11 minutes (Lake 1995).

Product literature often says “tested to British Standard 476”, without stating the nature of the test, the results and whether the test is relevant to that product anyway (Lake 1995).

10.6 Construction

10.6.1 General

‘Smoke control’ is one of many systems installed within a building. Key elements of a smoke control systems, such as the walls to the smoke reservoir, are often formed by other systems. Most contractors aim to install all of the design systems within a building to the correct standard, but there is often a conflict of interests during construction. The requirements of one system may be compromised by another. This can be due to time and cost constraints and conflicts of interest, which can adversely influence the construction process, reducing the quality of work, through errors, omissions and variations to a design.

Efficiently organised contractors can construct a good system correctly, but a poorly organised design will become worse during this stage, as many contractual conflicts come from these technical issues (Tyler 1994). Contractors can have great difficulty resolving serious design problems during construction, due to contractual, economic and time restrictions. For example, during the refurbishment of a shopping mall in the UK, “the specification for the smoke control system only consisted of a number

of air changes to the malls and shopping units". A tight building programme had commenced, "without submissions to the regulating authorities". The system was rejected, delaying work by three months and tripling the cost of smoke control (Dwyer 1989).

Many forms of contractual and organisational relationships exist. Discussion of these is beyond the scope of this paper, but the fire engineer's input and responsibilities will vary greatly as a result. Uncertainty of these in a project could leave the design input as insufficient or too late and the engineer overburdened. The final design, as installed on site, could be unacceptable.

10.6.2 Some Problem Areas Causing Compromises To System Performance

10.6.2.1 Subcontractors, Skills, Traditions and Supervision

Co-ordination of the many subcontractors on site can be an immense problem and conflicts can arise. Within this atmosphere, elements of the system may not be built to the correct standard.

The traditional groupings of skills on construction sites do not cover 'smoke control' sufficiently. Certain elements of the system may need to be installed to a higher standard than the industry norm. Any design that differs from standard practice and requiring special abilities for installation, if not clearly identified, will create problems during construction.

Smoke control fan and vent manufacturers may train and approve companies to act as installation teams for their products, but this will only ensure that a particular element functions correctly. The interfacing of the other system components may not be appropriate and components can even be damaged. Often, without suitable supervision subcontractors can assume that a required function is being carried out by another subcontractor, such as when fire alarm and building management system contractors are responsible for parts of the smoke control system communications and controls (Brown 1990).

Supervision and inspection of the work is essential, but there may not be sufficient resources available to ensure this. Many site staff do not have a suitable knowledge of fire to understand all aspects of the system.

A common result of this is that penetrations through fire compartment walls are not sealed properly, allowing smoke to travel throughout a building. One of many examples occurred at a nursing home fire in Fort Worth, Texas, USA (Fire Prevention 1994). Smoke barriers in roof voids had many services passing through them, no sealing had been fitted around these. During a fire, the building became smoke logged.

10.6.2.2 Procurement, Variations and On-Site Detailing

During the procurement process, due to economic reasons or availability, the contractor may choose materials and equipment that do not match the full requirements of the specification. This often occurs if the specification documents do not give clear performance criteria.

Variations and on-site detailing are required for all construction work, occur because no design is ever complete prior to or during construction. If the smoke control designer is not aware of these 'alterations', then variations in the system performance cannot be evaluated.

10.6.3.3 Communication

The concept of smoke control is not understood by all involved, and is not always stated clearly to people involved in installing elements of the system. If not clearly communicated (documentation, written or verbal instruction), then construction errors are very likely.

Many layers of communication exist, so that the installation of many elements is carried out by people remote from the designer, so that the concept can be lost amongst a mass of other information.

Example 10.3 Metropolitan House (Marchant 1993)

In this 12-storey office building, design errors were worsened by construction errors. A stairwell pressurisation system, a concrete duct, was to have had motorised dampers on each floor, supplying air to the corridors and stairwell. The motorised dampers would not fit into the duct, due to the installation of a dry riser in the duct space. Therefore simple air transfer grills were fitted instead. As a result the pressure differentials varied. The upper floors were over-pressurised and the lower floors under-pressurised.

A fire occurred in a lift lobby and pushed smoke into the staircase. Levels 7 to 9 were smoke logged. Smoke was also seen at the top of the staircase, as it re-entered the building through the duct inlet fan. A pressurisation fan located at the top of this stairwell did not operate. Smoke was detected entering through the fan and actuated dampers on the inlet, so switching off the fan.

10.7 Commissioning

10.7.1 Introduction

Testing on completion is essential, to reveal faults in a system, which may otherwise have been unnoticed. This is often neglected. It should be conducted with a disciplined engineering approach, which comprehensively examines the performance of a smoke control system, and testing requirements should be incorporated into the design process (Tyler 1994). This testing should aim to prove that a system has been installed and set to work to specification. The measurements compare the performance of the system against the specified requirements.

When commissioning is limited to testing the final installation, it can be demonstrated that the installation meets specified requirements, but does not prove that the design conditions and calculations for the smoke control system are correct.

Acceptance testing, in which the system installation is examined and performance may be measured, is a part of the commissioning process.

The commissioning process has varying definitions. In this section it is the process of achieving, verifying and documenting a concept through design, construction and a minimum of one year of operation after official handover to owner, in accordance with design intent (Tyler, 1994, reporting ASHRAE draft proposals, 1993).

This definition extends the responsibility of 'verification', to all parties involved in the design and construction process. This should be reviewed by a commissioning team (either an independent party (Tyler, 1994) or a representatives of the project team (ASHRAE Guideline 5, 1994). The fundamental requirement is to prove that the concept and design will work at all stages of the system procurement process, otherwise there may be many expensive problems to solve prior to handover. It is within this framework that effective acceptance testing should be performed.

10.7.2 Acceptance Testing Methods

Testing smoke control systems is problematic, because the correct environment is needed to test the system. Few people want fire and smoke introduced into their building and simulating the fire regime is difficult.

Many methods of testing are used, usually most systems have this done using ambient conditions, running the system without smoke, and taking ambient measurements, such as fan rates, pressure differentials, and checking the controls sequencing (BS 5588 Part 10). Acceptance of natural vents is by checking that there is the correct opening areas and inspection of certificates stating the aerodynamic coefficients, found in independent product tests (BS 5588 Part 10). Cold smoke (or

smoke bomb) tests (Klote and Milke 1992) are occasionally used in with these tests. Air movement and the rate of clearance of non-buoyant cold smoke can be found. This can identify some system and component faults, but without buoyant smoke, the true performance of a smoke control system is not measured (Marchant, R 1992).

Small hot smoke tests in which smoke bombs and a small 10kW heat source (Klote and Milke 1992) create small quantities of buoyant smoke, demonstrate limited buoyancy effects (Marchant, R 1992), as the mass flow rate is small. There may not be enough smoke to 'challenge' parts of the system.

Large smoke tests, using controlled fires, such as alcohol pan fires (around 0.4 to 5 MW) are closer to real fire and smoke environments, giving a better indication of a system's ability to control buoyant smoke (Marchant 1992). It can identify problems such as, high smoke leakage rates; obstructions blocking 'smoke' routes, and control system errors.

Hot smoke tests can confirm that the system can deal with a certain fire size, in a certain location, and can be the most successful in discovering system errors. It can demonstrate whether the system as a whole operates efficiently, but unfortunately does not prove conclusively that the system will work for most reasonably sized fire. The fire is a managed event and is only as good as the test methods and the people conducting them (Marchant, R, 1992). A system's true performance is related to its 'flexibility' to cope with a variety of reasonable fire sizes in differing locations. Other aspects of the fire engineering system (such as sprinklers) need to be working correctly. Also ambient conditions can be variable, tests may not demonstrate the extreme conditions a smoke control system may have to overcome. Conversely conditions may help smoke ejection from the building, for example is the stack effect evident during cold periods (MacMunn, Knowles and Morgan 1991).

The test in a stadium, (Dillon, 1992) described in Section 10.3.3, demonstrates the benefits of hot smoke testing. Despite these results, that highlight a potential failure

of the system in the concourse, Dillon (1992) concludes that little was gained from the tests, beyond what is written in the ASHRAE Guideline 5 (1994) and the use of 'appropriate calculations'.

Hot smoke tests obviously cause building owners concern, worried about damage during the tests. One early attempt at this in the UK (MacMunns et al, 1991) was carried out before the building finishes had been completed. Although the ventilation system was demonstrated to work reasonably well, smoke was observed to bypass channels and issue through gaps in blockwork, from the fire compartment. It is probable that these flows would not have occurred if the plasterwork had been applied. The results in the completed building would be different.

Example 10.4 The Myer Centre; Adelaide (Marchant, R, 1991)

Atkinson and Marchant (< biblio >) have demonstrated the hot smoke test's effectiveness in many tests in South Australia. The Myer Centre tests were for a smoke exhaust system, consisting of an extraction system in the atrium of a 5-storey department store and another in the atrium of an adjoining mall. The following problems were discovered in the system:

1. As smoke detectors at the edge of the atrium activated, logic errors in the Building Management System stopped fans from operating.
2. In one location an exhaust fan was to start and dampers to a grill to open at the same time, the negative pressure of the fan became too large to allow the dampers to open. No extraction occurred.
3. A variation to the exhaust grills to the extraction system reduced the free area by 50%, greatly increasing the pressure drop.
4. A fire lit in the carpark caused the store above to become smoke logged. The lift (elevator) shaft connecting the two areas acted as a smoke shaft. This air leakage problem had not been considered during the design stage. 'Cold testing' may have found some of these problems, but not the design concept errors, which included the lift shaft leakage and alarm problem.

10.8 Occupation

10.8.1 General

Once a building is handed over to the owner, few of the design team have further involvement with the building. The building users may receive little information about the design of the fire safety systems. The result of this remoteness from design can be inadequate maintenance and poor measurement of a system's ability, as occupancy changes.

The main factors influencing the fire and smoke regime and smoke system performance are the activities, alterations and maintenance.

10.8.2 Activities

As the activities change, so can factors in the system change, such as fire loads, numbers of occupants, potential ignition sources and ambient conditions. The basic elements of the design can change significantly, even the objectives and strategy can change. This can cause great variations to the performance of a system relative to the fire environment.

10.8.3 Alterations

Alterations to the building fabric can have large impact on a smoke control system. If systems are not reviewed, as these changes occur, then new deficiencies could be missed.

10.8.4 Maintenance

Flaws, fatigue and wear, and extreme loads, cause degradation of components over time reducing a system's performance, ultimately causing complete failure.

Component failure can either be sudden and random, or after a period of degradation, where the strength finally falls below the applied stress and, to a limited degree, is predictable (for well tested components). Thus a system can stop working suddenly or demonstrate reduced performance. Maintenance procedures should identify those

items performing below a certain level, due to degradation, but it can be difficult to identify those likely to fail suddenly (Smith 1993). Surprise modes of failure can occur, usually due to the component experiencing conditions different to those used for manufacturer's testing.

The problems in the maintenance of smoke control systems are outlined in the following paragraphs:

10.8.4.1. Reliability Data

Little data is available for components, but manufacturers have difficulty making predictions about performance (Mecker and Hamada, 1995 and Wong, K, 1995). Not all data may be suitable for specialist situations, such as smoke control.

There can be great difficulty calculating reliability from basic data on components, methods and data can differ, resulting in large variations in values. In a study of a particular type of circuit board (Wong, K, 1995), a failure rate of 0.5% to 3713% per year was calculated, using the same method, but with data from different, well known sources.

10.8.4.2. Planning

Various professional and manufacturing bodies have published guidelines on the maintenance of building services in general (CIBSE Technical Memorandum 1994). Some publications exist to provide detailed guidance on the maintenance of other fire safety systems, such as detection systems (Pike and Pennycook, 1992). Some limited guidance is available in BS 5588 Part 10 (1990) on the maintenance of shopping mall smoke control systems. An integrated approach is needed; detailing maintenance schedules, for the fire safety engineering system as a whole. Suppression, detection and other systems need to be correctly maintained to ensure the efficiency of the integrated fire safety engineering system.

The organisation and planning of the maintenance procedures should start during the design process, so that at handover, a detailed maintenance programme is in place. If not testing periods, might be set by organisations without a strong 'fire-safety' emphasis. By conducting this exercise, the system can be reviewed, possibly leading to major redesign: a system could be discovered to be prohibitively expensive. This also ensures that the organisation responsible for maintaining the systems has the expertise available to conduct procedures to the standard required (Tyler 1994).

The frequency of these tests and examinations should be assessed individually. For most systems, standard test periods could be used, but factors such as risk to occupants, the complexity of the system, the use of sensitive or unproved technologies, could alter this. If the testing simply finds whether a component operates, rather than measurement of values (such as flow rates for a fan), a component performing below acceptable standards could be undetected. If a real fire occurs, complete testing and examination of all components is necessary, otherwise a serious damage to the system could be missed.

Responsibilities must be clearly identified, otherwise parts of the system will be missed. For example in a hospital building (Tyler, 1994), some of the 'interface' items between electrical and mechanical engineers, such as air-conditioning actuators, were never examined; each group thinking that the other was responsible. These items were also overloaded, they drifted from their 'set points'. This failure was undetected.

In the same building cleaners had not been instructed to clean air diffuser grills, thinking it was the HVAC engineers' responsibility, who in turn thought it was the cleaners responsibility. Dirt built up and air flow across these was greatly reduced.

10.8.4.3. Understanding the system

The maintenance team are remote from original design team, who might not provide sufficient 'communication' (documentation, training and briefing) about the system.

They may not clearly understand the system and the consequences of particular maintenance regimes. As a result the performance of as system will decline.

This 'communication' should include the aims of the system, to ensure understanding of how the 'whole' should perform. Some manufacturers offer long term maintenance, this ensures that some components of the system perform to a reasonable standard, but the maintenance engineers need to examine the performance as a whole, similar to 'cold' testing (without smoke) at commissioning.

At first, a building may have an excellent maintenance routine, but as the owners, occupants and maintenance teams are changed, aspects of the system's objectives are forgotten. The maintenance documents can be lost (Tyler, 1994) and a less efficient routine may be initiated. A problem of 'remoteness from the design' (Groner 1995).

Economic factors and little understanding of the system, can lead to a reduced, even zero, maintenance schedule. Many building's are run with tight budgets, in designing a system and planning its maintenance the costs and the technical performance of potential maintenance organisations should be examined to ensure that the maintenance requirements will not exceed resources (Chapman, 1996). Target figures for such expenditure is scarce and often the figures are developed by crude comparisons of unrelated building types, with similar occupancies. These resources may be cut, regarded as non-productive expenditure.

Example 10.5 IMF Building, Washington DC, USA (Lathrop, 1979)

This building had a smoke ventilation system to purge smoke from a central atrium. Four out of six of the springs to the automatic roof vents had perished. The maintenance teams had not noticed that these items were defective. Smoke vents had to be opened by hand by fire fighters, at an early stage in the fire. The system was unable to deal with the volumes of smoke produced, as insufficient replacement air was provided. The Fire Department's portable smoke extract fans could not fit on to the roof openings.

10.9 Fire

10.9.1 General

Occupants cannot be relied upon to operate a system in a certain way, during a fire, otherwise it will be dependant upon the action of individuals under severe stress. Research has shown that human error rates of 10^{-2} to 10^{-4} exist for each operation required for a system in normal circumstances (Thomson 1987). The error rate is dependent on the skills of the operator and the complexity of the system. In emergency situations the error rate increases to 16 %, in air crashes, or 25 % in nuclear power stations (Thomson 1987). This error rates for well trained personnel. Other research suggests that the error rate can reach 55 % when the person is totally unfamiliar with operation, acting under extreme stress and has no idea of the outcome (Smith 1993). This represents the situation with security personnel, who might be the first people to encounter a serious fire.

Even so, decisions about the operation of the smoke control system need to be made during a fire, to prevent an adverse condition developing or to improve performance in some aspect. These would be conducted by fire fighters. Without training and examination of an individual building's fire control capabilities; fire fighters may not fully understand its capabilities, so use it inefficiently (Groner 1995). In the IMF fire in Los Angeles, the fire service were not completely familiar with the building. An HVAC engineer was only available long after they had arrived, to explain the vent system's purge capabilities (Lathrop 1979).

Without training, maintenance engineers will only have an limited understanding of the system, having only been interested in a small part of the system (Groner 1995). During a fire they may attempt to alter the operation of the system, to reduce the hazards from the fire. This could be on the basis of a misconceived idea, prior to the fire services arrival.

Groner (1995) states that occupiers and fire fighters should be provided with "a simplified understanding how their actions relate to system performance."

Control systems need to ensure that the correct zone in a smoke control system is operated. Longhatino and Campbell (1984) identified a problem in a nursing care facility, which had four pressurisation zones. The control system was activated by manual alarms. People escaping are not likely to activate these alarms in the fire zone, they may do this at the final exit door, away from the fire, in the wrong zone. Incorrect zones could be pressurised; pressurising the fire compartment. Smoke would be forced out into escape zones.

10.10 Conclusion

10.10.1 General

The performance of a system can vary greatly, failure occurs when this is outside certain acceptable limits. Figure 10.2 shows a typical system having varying potential performance over its lifetime.

The events that occur during the life-cycle of a smoke control system have a major affect on the performance of a smoke control system. The examples provided in the previous section provide evidence that the design, implementation and operation of smoke control systems is not a smooth transition from theory to practice.

It could be thought, after this demonstration of the events during a system life-cycle, that smoke control systems are bound to fail. There are many reports of inspections of smoke control systems that have serious errors, but there have been few cases where this has lead to smoke control failure during a fire. This could be due to a variety of factors:

- the number of seriously deficient systems is not significant.
- smoke control systems have a very conservative design to accommodate many errors in design.
- few fires occur in buildings that have smoke control systems, because these are well managed.
- the performance of smoke control systems during a fire is not commented on or investigated, during post fire investigations.

The process of smoke control system design and installation in building needs to be investigated, to show who designs, builds, tests and maintains them and who ensures this is done properly. The guidance that is available and used needs to be identified. This can be shown with examination of the experiences of designers and operators.

10.10.2 Questionnaire and Case Studies

A questionnaire was developed to investigate the procurement process and the performance of smoke control systems. This attempted to gain a overview of the information that designers of smoke control systems use, the depth of experience that they have, how they commission the systems and the problems they have encountered. This is presented in Chapter 11.

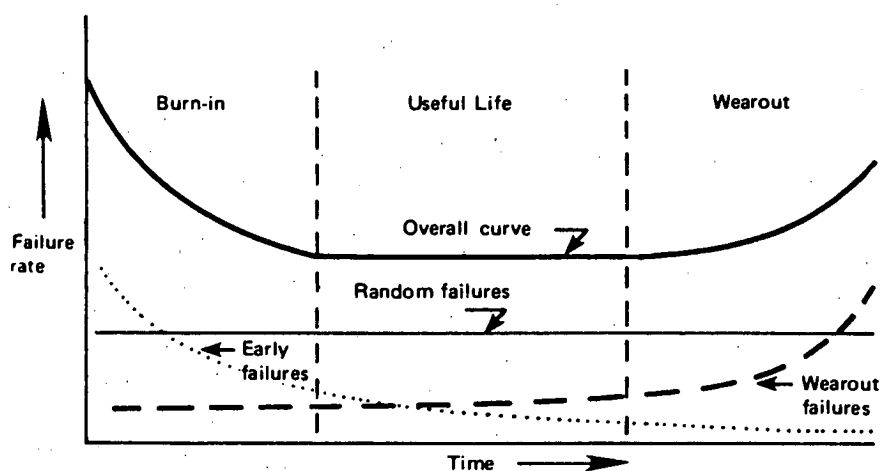
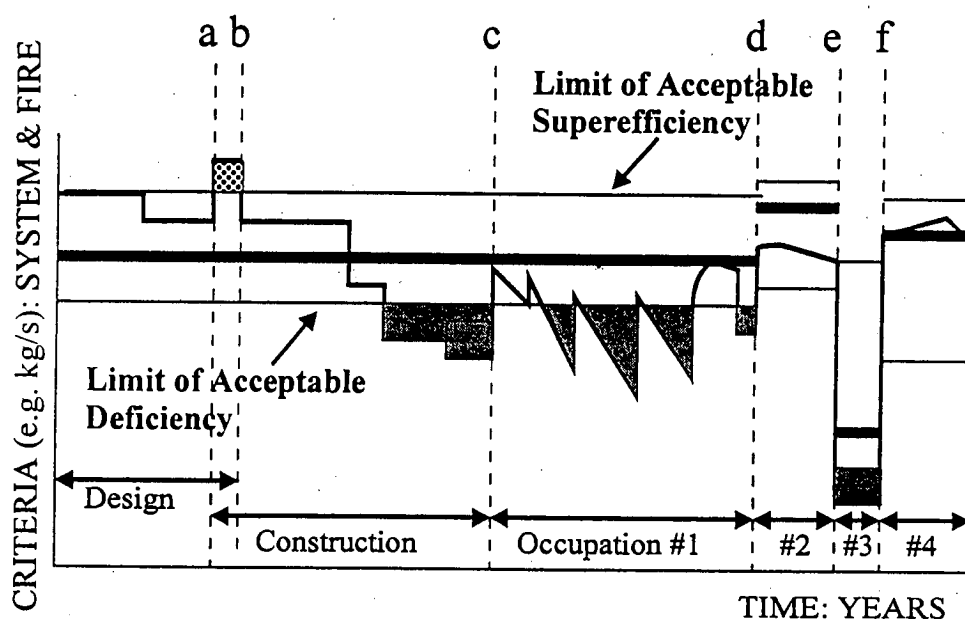


Figure 10.1 Bathtub Curve (from Smith 1993)



Events in the life Cycle

- a - Design finalised
- b - Design review
- c - Commissioning
- d - Change in use, lower fire load
- e - Change in use, higher fire load
- f - System upgrade

Figure 10.2 Smoke Control System Performance During its Life-cycle

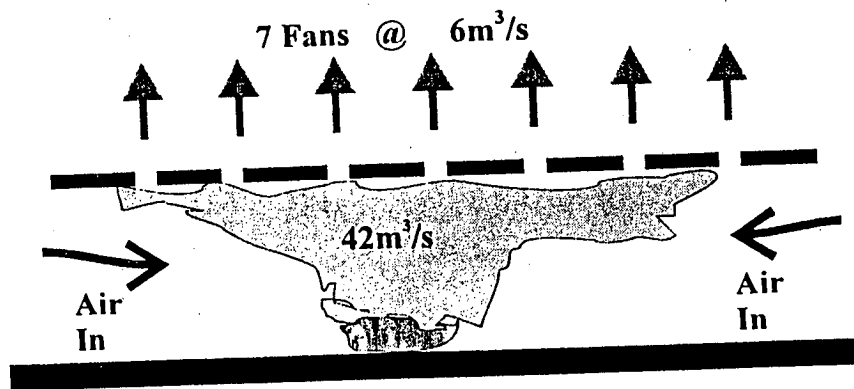


Figure 10.3 Single Storey Mall

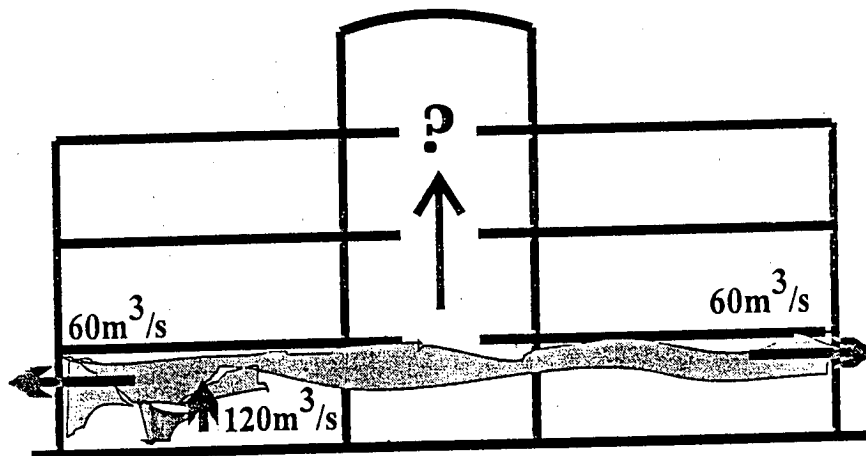


Figure 10.4 Atrium Smoke Control System

Chapter 11 Smoke Control Questionnaire

11.1 Introduction

Chapter 10 demonstrated how events during the life-cycle of a smoke control system have an effect on the performance of a smoke control system.

A questionnaire was developed to investigate the design, manufacture, construction, and maintenance processes of smoke control systems and the resultant performance of smoke control systems. This attempted to gain an overview of the following:

- depth of experience of those responsible for design, manufacture, construction and maintenance and the methods of smoke control that they had experience with.
- the information and sources of advice that are used to design smoke control systems
- problems encountered with the systems
- testing methods

Respondents would also be able to provide information for case studies. This with the results from the survey and case studies would provide information for the development of a framework for the analysis of the cause of smoke control system performance variation and failure modes.

11.2 Questionnaire Strategy

This was a pilot questionnaire, to provide an indication of the range of problems with smoke control, and the level of involvement and interest that exist within the Building Services profession. The results of the survey would indicate the potential for success of a further more detailed survey or whether an alternative method would be needed to generate data about smoke control system performance.

This survey was not intended to generate reliability data, for calculations of the probability of system failure, because it would be a difficult to receive a comprehensive set of replies. One reason for this is that there might be a reluctance to participate in a survey that asks for experience of system failure, for which respondents may have been responsible, due to professional pride. There could also be a low level of interest in the subject.

The questionnaire was originally targeted at Building Services Engineers, as they can often find themselves in a situation where they need to design smoke control systems or recommending that a fire safety consultant be employed to design the system.

11.3 Questionnaire Method

It was decided that at early stage, that in order to gain a broad view of the experiences of Building Services Engineers a large target group would need to be contacted, to find enough people with smoke control experience to provide enough data for system design. Directly posting the questionnaire to companies would only reach a limited number of people. The best way of reaching a large number of people would be to include the questionnaire in a well distributed journal, such as the Journal of the Chartered Institute of Building Services Engineers.

The questionnaire would be included as a loose leaf insert in the journal. It would be printed on a A3 sheet, folded to form 4 pages of questions on A4 paper.

The number of questions and the level of cross referencing originally intended in the questionnaire, meant that the questionnaire would be extremely complex. There was potentially a large number of replies that could be sent back. An experienced survey team would be needed to provide advice on the basic approach, to compile the questionnaire and provide administrative support, collating and logging the data. The questionnaire was developed with the help of the Centre for Educational Sociology (CES), at Edinburgh University, a group set up to conduct surveys of the high standard required for statistical analysis in Social Sciences.

Surveys conducted by the CES Team Experience usually receive a 25 to 35 % reply rate, when sent directly to the target group. This rises to 60 % to 70 % if the group are prompted to reply, with two letters requesting that the questionnaire be returned. It estimated that for this survey, the response would be less than 25 %, closer to 10 %. A survey conducted in Fire Prevention Magazine regarding readers views on fire protection, received a response rate of 6 %.

The response rate depends in part on the level of interest in the survey subject. A suitable preamble to the questionnaire was developed to encourage people to reply, emphasising that there was no commercial interest in the survey, confidentiality and that the results would be passed back to the readers. The CES team developed the questionnaire format to ensure a better response rate. The questionnaire could be returned free post, to further encourage response.

The questionnaire was worded so that people who had no experience of smoke control systems would reply, to increase the number of responses. Everyone who received a questionnaire would be able to respond.

One thousand questionnaires were sent out in the CIBSE Journal. The resultant response rate was low, so another two hundred were sent out in the Institute of Fire Safety Journal. The replies are readily differentiated, because all of the CIBSE replies were from Building Services Engineers or related professions such as mechanical or electrical engineers. The IFS replies were from fire safety consultants, or related professions.

11.4 The Questions

11.4.1 General

The questionnaire was developed after several draft formats were presented to the CES for comment. The CES developed the questions to minimise ambiguity and eliminate conflicts between questions. A final draft, prepared by the CES was read

through by colleagues in the Department of Civil Engineering, and two smoke control professionals for comment, particularly regarding the ease with which it could be completed.

The questions were developed to ensure that everyone could provide an answer, with the appropriate box. The questionnaire layout was arranged to allow it to be easily answered. It was felt that the questionnaire would be completed in approximately 7 minutes. The questions in their basic form were:

1. To identify the respondent's professional role.
2. To identify the experience of the respondent with different methods of smoke control, at different stages during the life-cycle.
3. To identify the frequency of design and specification experience, with different smoke control methods.
4. To identify the sources of information used.
5. To identify organisations that have provided advice for smoke control systems.
6. To identify if people have had problems with smoke control systems.
7. To identify the problems that people have had with different smoke control methods, and the source of the problem, at different levels within the system:
 - components faults
 - system faults, for example, due to system design errors.
 - faults in associated systems, such as detection, control systems and so on.
8. To identify the methods used for acceptance testing.

The questionnaire is presented in Appendix 11.

11.5 Results

11.5.1 Sample

11.5.1.1 CIBSE Journal

The CIBSE Journal has a net circulation of approximately 16,600. The largest proportion of CIBSE readers (41 %) are building services engineers, a large proportion are involved in contracting (19 %) and government related work (20 %).

The questionnaire was sent to 1000 readers. The distribution was random, therefore it is most probable that 410 building services engineers received a copy, contractors 190 copies, and government professionals 200 copies.

11.5.1.2 IFS Journal

Details are not available of the IFS Journal distribution. It is sent to all members of the Institute of Fire Safety Engineering, libraries and so on. Two hundred copies were sent out directly in members copies. Membership of the IFS is made up of people in several engineering professions, but all working in the field of fire safety engineering. Some members were trained as fire safety engineers.

11.5.1.3 Smoke Vent Association

Twenty copies of the questionnaire were posted directly to fan and vent manufacturers, all members of the Smoke Ventilation Association. This association represents the interests of the manufacturers of smoke control fans and vents. It produces publications for guidance on smoke control specification and design.

11.5.1.4 Other Copies Distributed

Eight copies of the questionnaire were sent to smoke control researchers outside the UK. These were not intended to form part of the analytical results, but for information only and to provide a contact for case study material.

11.5.2 Response Rate

There were 49 replies to the questionnaire, a combined response rate of 4.0 %.

Four respondents were unable or unwilling to fill in the questionnaire, due to 'conflict of interests' as one respondent wrote. Two of these were involved with fire safety research and felt that they would give answers biased towards results, but provided information for case studies. These 4 respondents have been eliminated from the analysis of the results.

The responses from each distribution of the questionnaire are as follows:

CIBSE Journal:	24	2.4 %
IFS Journal:	18	9.0 %
Fan manufacturers	7	35.0 %

Two questionnaires from researchers outside the UK were returned. One respondent sent a letter was sent instead of the questionnaire, declining to respond, but providing comments on smoke control failure.

11.5.3 Replies to the Questions

The following shows a basic analysis of the replies to the questions. In order to simplify the analysis respondents that have no experience of smoke control have been eliminated from the analysis. The proportion of building services engineers', who replied and have no smoke control experience, does not represent the true proportion with no smoke control experience. It is possible that many of those not replying had no or limited experience of smoke control systems.

For the purposes of comparative analyses, the reply from the mechanical engineer has been combined with the building services engineers'; and from one fire prevention officer has been combined with the fire engineers. Numbers in each group are shown below:

Building Services Engineers:	17
Fire Safety Engineers:	13
Manufacturers (SVA members):	7

The results are shown in the tables below, with the relative frequency (as a percentage) for each reply. Details are shown in the Appendix.

As the building services engineers with no experience of smoke control systems have been eliminated from the results,

11.5.4 Experience of Different Smoke Control Methods

	Fire Safety Engineers	Building Services Consultant	Manufacturers
Natural Ventilation: Shed	100.0	58.8	57.1
Nat. Ventilation: Mall / Atria	100.0	76.5	57.1
Stairwell Pressurisation	92.3	82.4	85.7
Corridor Pressurisation	53.8	58.8	71.4
Zoned Pressurisation	38.5	35.3	57.1
Depressurisation	30.7	35.3	28.6
Passive Containment	84.6	38.5	28.6
Mechanical Extraction	76.9	64.7	71.4

Table 11.1 Percentage of Respondents with Experience of Different Smoke Control Methods

Table 11.1 shows the range of experience with different methods of smoke control, for respondents who have had some experience of smoke control systems. Those who have had no experience of smoke control at all have been eliminated from the analysis.

Fire safety engineers have had more experience of the different smoke control systems than the other groups. This is not surprising, as building service engineers are involved a wider variety of technical issues within buildings. The SVA manufacturers show a similar range of experience as building services engineers.

This is reflected in the mean number of methods of smoke control that have been experienced by the different groups are:

building services engineers	-	3.8
fire safety engineers	-	5.8
manufacturers	-	4.1

This shows that fire engineers have a broader range of smoke control experience, but not the depth of experience.

11.5.4 Experience of Different Stages of the Life Cycle

The frequency at which each group has had experience of a smoke control system at different stages of the life-cycle is shown in the Tables 11.2 to 11.4 below.

The percentages are for the relative frequency for which each group has had at different stages of the life cycle for a particular method of smoke control. So for example if everyone who has had corridor pressurisation experience, has had experience at the design stage then this is a relative frequency of 100 %.

Table 11.2 shows that in the main fire engineers are involved at the design stage, and approximately one third of these not becoming involved with the specification of smoke control systems. There is only limited involvement in the later stages of the life cycle, especially with installation and maintenance.

Higher levels of involvement occur during acceptance testing, possibly due to the need for tests to be witnessed.

A higher level of involvement occurs during the operational stage, possibly due to system problems, requiring a fire engineering assessment.

	Design	Spec	Install	Mainten	Oper't'n	Coms'n
Natural Ventilation: Simple Shed	100.0	61.5	7.7	7.7	23.1	15.4
Natural Ventilation: Mall / Atria	84.6	69.2	7.7	7.7	15.4	15.4
Stairwell Pressurisation	83.3	58.3	8.3	8.3	16.7	16.7
Corridor Pressurisation	100.0	71.4	14.3	14.3	28.6	14.3
Zoned Pressurisation	100.0	60.0	0.0	20.0	20.0	20.0
Depressurisation	75.0	50.0	0.0	0.0	0.0	25.0
Passive Containment	90.9	72.7	9.1	9.1	18.2	18.2
Mechanical Extraction	90.0	60.0	10.0	10.0	30.0	20.0

Note: No experience of any method at the manufacture and supply stage.

Table 11.2 Fire Safety Engineers with Experience of Smoke Control Methods at Different Stages of the Life Cycle

	Design	Spec	Install	Mainten	Oper't'n	Coms'n
Natural Ventilation: Simple Shed	90.0	80.0	30.0	20.0	10.0	0.0
Natural Ventilation: Mall / Atria	84.6	69.2	23.1	15.4	15.4	0.0
Stairwell Pressurisation	85.7	92.9	14.3	14.3	14.3	7.1
Corridor Pressurisation	90.0	80.0	10.0	20.0	10.0	10.0
Zoned Pressurisation	83.3	83.3	16.7	16.7	16.7	0.0
Depressurisation	50.0	50.0	16.7	16.7	16.7	0.0
Passive Containment	60.0	60.0	0.0	0.0	0.0	0.0
Mechanical Extraction	63.6	72.7	36.4	18.2	0.0	9.1

Note: Limited experience of any method at the manufacture and supply stage.

Table 11.3 Building Services Engineers' Experience of Smoke Control Methods at Different Stages of the Life Cycle

Building services engineers have similar levels of involvement at the design stage, but unlike fire engineers maintain their involvement during the specification of smoke control systems. This would be expected with the nature of their role in the

construction process. There is a drop in the level of involvement during the construction stage.

The respondents to the questionnaire have limited post installation involvement. The figures for commissioning could be low, because this item was not an option in the questionnaire and was only volunteered as an 'other' item.

	Design	Spec	Manu	Supply	Install	Maint	Oper'n
Natural Ventilation: Simple Shed	75.0	50.0	100.0	75.0	50.0	50.0	50.0
Natural Ventilation: Mall / Atria	75.0	50.0	100.0	75.0	50.0	50.0	50.0
Stairwell Pressurisation	66.7	50.0	100.0	83.3	33.3	33.3	16.7
Corridor Pressurisation	60.0	40.0	100.0	80.0	40.0	40.0	20.0
Zoned Pressurisation	50.0	50.0	100.0	100.0	50.0	50.0	25.0
Depressurisation	50.0	50.0	100.0	100.0	50.0	50.0	50.0
Passive Containment	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Mechanical Extraction	40.0	40.0	80.0	80.0	40.0	40.0	40.0

Table 11.4 Manufacturers' Experience of Smoke Control Methods at Different Stages of the Life Cycle

Manufacturer's involvement during the life cycle process remains high at most stages. This could be due to being involved in providing design and specification advice, as well as supplying, installing and maintaining the hardware.

11.5.5 Frequency of Experience During Design

Full details are in the Appendix.

	Often	Occasional	Seldom	Never
Natural Ventilation: Simple Shed	30.8	46.2	30.8	0.0
Natural Ventilation: Mall / Atria	23.1	46.2	23.1	7.7
Stairwell Pressurisation	30.8	30.8	23.1	15.4
Corridor Pressurisation	7.7	38.5	7.7	46.2
Zoned Pressurisation	30.8	7.7	0.0	61.5
Depressurisation	15.4	7.7	0.0	76.9
Passive Containment	46.2	30.8	0.0	23.1
Mechanical Extraction	15.4	53.8	7.7	23.1

Table 11.5 Frequency of Fire Safety Engineers' Design Experience with Different Methods of Smoke Control

Except of corridor, zoned and depressurisation systems, fire safety engineers often or occasionally become involved in the design of smoke control systems. Passive containment is the most commonly designed system.

	Often	Occasional	Seldom	Never
Natural Ventilation: Simple Shed	11.8	29.4	11.8	35.3
Natural Ventilation: Mall / Atria	5.9	41.2	5.9	23.5
Stairwell Pressurisation	0.0	47.1	29.4	23.5
Corridor Pressurisation	0.0	35.3	17.6	47.1
Zoned Pressurisation	0.0	17.6	11.8	70.6
Depressurisation	0.0	5.9	23.5	70.6
Passive Containment	0.0	5.9	23.5	70.6
Mechanical Extraction	5.9	41.2	23.5	29.4

Table 11.6 Frequency of Building Services Engineers' Design Experience with Different Methods of Smoke Control

Building services engineers become involved with smoke control system design less often than fire safety engineers. For those who have experience in designing particular methods of smoke control, most engineers have 'seldom' had experience of this method.

	Often	Occasional	Seldom	Never
Natural Ventilation: Simple Shed	28.6	28.6	0.0	42.9
Natural Ventilation: Mall / Atria	14.3	28.6	14.3	42.9
Stairwell Pressurisation	14.3	14.3	28.6	42.9
Corridor Pressurisation	14.3	0.0	28.6	57.1
Zoned Pressurisation	0.0	14.3	14.3	71.4
Depressurisation	0.0	0.0	14.3	85.7
Passive Containment	14.3	0.0	0.0	85.7
Mechanical Extraction	14.3	0.0	14.3	71.4

Table 11.9 Frequency of Manufacturers' Design Experience with Different Methods of Smoke Control

Manufacturers have higher levels of involvement with ventilation systems, than pressurisation systems and extraction systems.

11.5.6 Sources of Information and Advice

The main sources of information (the Building Regulations and British Standards) are used by all of the respondents. Surprisingly only 66 % of fire engineers and 53 % of building services engineers use FRS guidance. These usually provide the main sources for smoke control design. Even if not used, these would need to be referred to when dealing with local authorities to explain why FRS design guides are not being used.

Source of Information	Fire Engineers	Building Services Engineers
Approved Doc B (or equiv)	100	100
British Standards	100	100
FRS	66	53
LPC	46	27
SVA	36	40
CIBSE	27	93
ASHRAE	46	20
SFPE	27	0
IFS	18	0
IFE	18	13
Journals	90	33

Other sources state but not included in table.

Full details are in the Appendix.

Table 11.10 Sources of Information

Fire engineers make more use of guidance and information from specialist fire safety and fire protection organisations, such as the Loss Prevention Council (LPC) and the Society for Fire Protection Engineering (SFPE). Fire engineers have more specialist requirements, so refer to science and engineering journals more frequently.

The building services engineers, unsurprisingly refer to CIBSE information more.

Source of Information	Fire Engineers	Build' Services Engs
Fire Authority	36	93
FRS	36	47
FPA	18	0
Manufacturers	82	93
Fire Safety Consultant	46	20
NIST	46	0
Trade	55	27
NFPA	9	0

Table 11.11 Sources of Advice

Building services engineers use the fire service as a source of advice, to a high degree, much more than fire service engineers. This could be because the fire service can act as a 'free' source for services engineers. Manufacturers are used as a source

of specialist advice by both types of engineers. Fire safety engineers use the specialist organisations for advice much more.

11.5.7 Smoke Control Failures

11.5.7.1 General Response

46.2 % of fire engineers and 64.7 % building services engineers answered that they have had no experience of a smoke control system performing so badly that it would not achieve its objectives.

Only 3 manufacturers filled in this section of the questionnaire. Only one reported any poor performance, due to calculation errors by others.

11.5.7.2 Frequency of Experience of Faults

The number of respondents experienced with a particular method of smoke control, and the number of those who have, at any time, experienced poor performance is shown in Table 11.12 below.

	Building Services Engineers		Fire Safety Consultants	
Method	Frequency of Experience with Method	Frequency of Experience Poor Performance	Frequency of Experience with Method	Frequency of Experience Poor Performance
Natural Ventilation: Simple Shed	10	2	13	3
Natural Ventilation: Mall / Atria	13	1	13	2
Stairwell Pressurisation	14	3	12	4
Corridor Pressurisation	10	2	7	3
Zoned Pressurisation	6	0	5	4
Depressurisation	6	2	4	3
Passive Containment	5	0	11	2
Mechanical Extraction	11	1	10	3

Table 11.12 Frequency of Respondents who have Experienced Poor Performance with Smoke Control Systems

These figures are combined in Table 11.13, to show the percentage of all building services engineers and fire safety engineers who have experienced poor system performance.

Method	Frequency of Experience with Method	Frequency of Experience Poor Performance
Natural Ventil'n: Simple Shed	23	21.7 %
Natural Ventilation: Mall / Atria	26	11.5 %
Stairwell Pressurisation	26	26.9 %
Corridor Pressurisation	17	29.4 %
Zoned Pressurisation	11	36.4 %
Depressurisation	10	50.0 %
Passive Containment	16	12.5 %
Mechanical Extraction	21	19.0 %

Table 11.13 Percentage of Poorly Performing Smoke Control Systems

It should be noted that these figures include respondents with a varying degree of experience with smoke control. However, though not shown in the results above, examination of individual questionnaire returns did not suggest any link between the degree of experience and the frequency of failure.

The percentage of respondents who have experienced smoke control problems could be exaggerated. People who have had experience of poor smoke control systems would feel more inclined to respond to the questionnaire than those who had never encountered any difficulties.

11.5.7.3 Smoke Control System Faults

The number of respondents with experience of particular failure types is limited so that only a broad analysis of the results will be made. Question 8 (selecting the most common cause of failure) was rarely answered. The results are shown in Tables A11.10 in the Appendix.

Component Faults

Smoke removal (ventilation and extraction systems) have been experienced with ventilators, fans, curtains, screens, doors and dampers. There has been limited experience of component interfacing problems.

With pressurisation methods, respondents have experienced a greater level of component faults. Approximately 50 % of the respondents who have experienced poor performance of pressurisation systems have experienced fan faults and component interfacing faults. A limited number have experienced faults with doors and dampers.

Passive containment systems have had their performance reduced by dampers and doors and other unspecified faults.

System Faults

With smoke removal methods one respondent reported that the system performed to expectations but was oversized. None reported having undersized systems. An unspecified subsystem fault was reported.

With pressurisation methods, respondents have experienced a greater level of system faults. Approximately 50 % of the experience with poorly performing stairwell and zoned pressurisation systems has been due to systems being oversized. With corridor pressurisation systems, 50 % of the poorly performing systems are undersized. Two stairwell pressurisation systems suffered from excessive air leakage. Another failed to achieve the correct pressures due to dampers not operating correctly.

No system faults were been reported for passive containment.

Associated Systems

It is with this aspect of smoke control that a large number of faults have been experienced. With most methods of smoke control, approximately 50 % of the respondents who have experienced significant faults have had these occur with detection, and power systems. The exceptions are depressurisation systems and passive containment, where no faults are reported.

11.5.8 Smoke Control System Testing

Method of Testing	Fire Safety Engineer		Building Services Engineer	
	Usual	Preferred(3)	Usual	Preferred (4)
Sequence of Operations	83.3	40.0	100.0	87.5
Air Flow Measurements	75.0	60.0	70.6	87.5
Pressure Measurements	50.0	50.0	52.9	87.5
Cold Smoke	50.0	10.0	35.3	75.0
Small Heat Source (1)	8.3	0.0	5.9	62.5
Small Heat Source (2)	8.3	20.0	0.0	87.5
Large Heat Source	16.6	30.0	0.0	62.5

(1) 10 kW with no heat measurements (2) 10 kW with heat measurements
(3) 10 respondents replied to Question 10 (4) Only 13 respondents replied to Question 10

Table 11.14 Smoke Control Testing Methods at Commissioning

A variety of methods are used to test smoke control systems. Most engineers use 'standard' ventilation commissioning techniques, to test system performance. Most fire engineers examine sequence of operations during testing, although this could have a significant effect on smoke control performance.

Air flow and pressure provide a basic measurement of system performance, and should be made along with checking the sequence of operations. A significant number of respondents do not make these measurements.

Cold smoke measurements can provide an indication of the direction of air flow, during ambient testing. It does not act like buoyant smoke. No pressure differentials are created to effect system performance. There would be no indication of the effectiveness of the passive smoke containment measures that exist for all smoke

control measures. It is used by half of the fire engineers and, to a lesser extent, by building services engineers.

Hot smoke testing is carried out more rarely. Only one building services respondent has used hot smoke testing. Four fire engineers have used it in some form.

Fewer respondents answered question 10 on the preferred method of testing, and a few may have answered to indicate the additional tests, rather than all of the tests that they would use if resources were available.

It is significant that many more respondents would use hot smoke testing if resources were available. In particular, many building services engineers would like to tests their systems with 'smoke' form large heat sources. This possibly reflects less confidence in the effectiveness of the basis for smoke control design.

Method of Testing	Fire Safety Engineer	Building Services Engineer
Sequence of Operations	83.3	93.8
Air Flow Measurements	41.7	25.0
Pressure Measurements	33.3	18.8
Cold Smoke	16.7	0.0
Small Heat Source (1)	8.3	6.3

(1) 10 kW with no heat measurements

Table 11.15 Usual Smoke Control Testing Methods during Maintenance

During maintenance, the over half of the respondents check the system by testing the sequence of operations. Fire engineers tend to use more methods to maintenance tests. These may be 'one-off' examinations of existing installations, whereas building services engineers may be involved in more regular maintenance checks. The latter would be simplified to minimise cost and effort.

The researchers involved experience with most types of smoke control systems. Testing has been conducted with all types of systems. The preferred method of testing is checking the sequence operation and airflow and pressure measurements,

with a smoke test using a large heat source. One researcher stated that cold smoke testing is of little value, because it proves little about a systems performance.

One researcher stated that tests found 95 % Integrated Systems had faults prior to commissioning. Component interfaces and all associated fire engineering systems have faults.

11.6 Conclusions

11.6.1 General

This questionnaire has been a useful attempt to develop an understanding of the state of the art of smoke control installations. There was a limited response to the questionnaire. This could be due to the method of distributing the questionnaire and the attitude of the people receiving it.

The data produced cannot be used for quantified reliability analysis, but does provide an indication of the level of involvement of the respondents with smoke control.

The low response could also indicate that few of the people who received the questionnaires, have experienced any difficulties with smoke control systems.

11.6.2 Life-cycle

Building services engineers and fire safety engineers mainly restrict their involvement with smoke control systems to the design stage. Fire engineers have less involvement in the design stage.

11.6.3 Failure Modes

A range of failure modes has been experienced with most forms of smoke control. Pressurisation systems are generally the least reliable systems. Between 25 % and 50 % of respondents, with experience of these systems found problems.

Component faults occur, particularly with fans. System faults appear to be common, occurring for a variety of reasons.

Controls and other associated systems seem to cause smoke control systems to perform poorly most often. Over 50 % of respondents who have experienced poor system performance, have experienced difficulties with controls.

The results have confirmed a general system engineering principle that, as a system becomes more complex, failure is more likely to occur.

There were no respondents who experienced a poorly performing smoke control system, whose poor performance was caused by deficiencies in smoke movement models and smoke movement processes.

11.6.4 Testing

Ranges of testing methods are used. Building services engineers conduct fewer different tests, but are more keen on hot smoke testing. This could be due to building services engineers having less experience of smoke control systems, so feeling less confident about their successful operation, so believing that a more onerous testing methods, than simple velocity measures are required. Building services also have more specification and commissioning experience in general, so may be strongly aware that a smoke control could be subject to many variations to their performance

11.6.5 Case Studies

Some material for case studies was gathered from this survey (see Chapter 12). Also contacts were made for any future research into smoke control system performance.

11.6.6 Development

If research into the performance of smoke control systems was continued, then a more detailed examination of the causes and effects of faults is needed. Also a better response is needed. This could be achieved with the following methods:

1. A better response to questionnaires may better response if they are sent directly to various target groups.
2. As an alternative to questionnaires, volunteers for short detailed interviews could be found. Groups with an interest in an honest assessment of smoke control system performance would need to be approached. Target groups include:
 - fire safety engineers
 - building services engineers
 - building control officials
 - fire officers
 - commissioning engineers
 - facilities managers
3. The performance of a number of existing systems could be examined in detail, to provide an objective assessment of smoke control system performance.

Chapter 12: Examples of System Failure

12.1 Introduction

12.1.1 General

The survey could only reveal a general industry wide experience with smoke control systems. This Chapter presents examples of problems that have occurred with smoke control systems. These will not provide a comprehensive range of faults that can cause variations in the performance of some specific smoke control systems, but can demonstrate some typical scenarios.

The case studies are of smoke control systems, with which difficulties have been experienced at any stage of the life-cycle process. It should be emphasised here that an extensive search for published reports was made. Many people involved with smoke control systems were contacted, in an attempt to gather information for case studies. Some interesting material has been uncovered. Not all of it can be included within this thesis, because some has been the subject of litigation. Other people were not willing to provide information for case studies.

12.1.2 Sources of Information

The case studies have drawn from three sources:

1. Examples from the survey
2. Fire reports
3. Published reports on smoke control systems

12.2 Case Studies from the Survey

12.2.1 General

Some short case histories were obtained as a result of the survey. These do not represent a conclusive range of smoke control system faults, but are illustrative of typical difficulties encountered.

12.2.2 Void Extract System

12.2.2.1 Structure

This is a large masonry structure. The walls are 3 m thick at lower level. Figures 12.1 and 12.2 show the layout of the building.

It has been converted to a mixed occupancy space. The building is expected to attract a large throughput of people, who are unfamiliar with the building. Floors are being added inside of the structure, as shown in the plans.

12.2.2.2 Use

- The building has craft production processes on Levels 1 and 2. There are displays on Level 2. Activities on Level 1 can be viewed through open voids.
- Levels 3 and 4 are retail spaces. Level 5 has a restaurant and an exhibition room.

12.2.2.3 Fire Safety Issues

The Local Authorities have approved the proposed change of use, but there are outstanding problems in relation to the design and proposed design changes:

- This building has voids through all of the floors. A fire at lower level would create large volumes of smoke at high level, allowing a rapidly deepening smoke layer to develop. A fire at Level 1 would cause the void to smoke log rapidly.
- There will probably be a large number of occupants on Levels 3, 4 and 5. In Level 5 there could be a peak occupancy of 250 people in the restaurant.
- It is possible that rapid smoke logging of Level 5 could subject the occupants to hazardous conditions before escape could be completed.

A smoke control system was designed to overcome life safety within the space. The designer was a competent building services engineer, but inexperienced with smoke control design. As with many building projects, this was the only large development with which the client had been involved. The client did not have the level of knowledge of fire safety of a more experienced developer. There was a tight budget and the developer wished to avoid 'unnecessary' expenses.

12.2.2.4 Original Smoke Control Design

The smoke control system was designed with a steady state 5 MW fire, occurring at Level 2 and a 3 m clear layer being maintained above Level 3.

The restaurant at Level 5 was to have been separated by fire resistant construction. Level 1 and Level 2 were also to have been separated by fire resistant construction.

An extraction system was to remove smoke at $24 \text{ m}^3/\text{s}$, from the main void through fans located on the roof, see Figure 12.1. Additional fans were to remove smoke at $14 \text{ m}^3/\text{s}$ from the restaurant. The two systems were to operate simultaneously. There appeared to be no clear design basis for the restaurant smoke control system, for example it is uncertain what clear layer height that it was intended to achieve or the fire size selected for the design of the smoke control system.

Replacement air for the void extract system was through a 6.3 m^2 opening, formed in the side of the masonry walls, at Level 2. The louvre was to open automatically upon detection of smoke in the space.

Replacement air for the restaurant smoke control system would to be through the restaurant doors. These would not open automatically upon detection of smoke.

12.2.2.5 Effectiveness of Original Design

The smoke control system, for the original design condition would not achieve its objectives, for the following reasons:

- The 5 MW fire size (based on a convective heat release rate of 500 kW/m^2) used is for sprinklered fires in retail premises, but this building will not be sprinklered. The building will not be sprinklered, therefore there could be few restrictions to fire growth. It is likely that a fire could grow to flashover, to involve the whole of Level 2, and even the whole building. A fire involving all of Level 2 could exceed 50 MW, although this is dependent on the ventilation conditions.
- The smoke control system is undersized for a 5 MW steady state fire. To maintain a clear layer 3 m above Level 3, for a 5 MW fire size, an extract capacity of $120 \text{ m}^3/\text{s}$ is needed. The system could cope with a steady state fire size of approximately 190 kW (assuming a convective heat output of 500 kW/m^2).
- The restaurant smoke extract system would not be needed within the restaurant and would not provide any additional extract capacity to the void area. There would be inadequate provision of inlet air to the restaurant, because the entrance doors could remain closed. The space would become depressurised and as a result air would be drawn through all available leakage routes. Smoke could be drawn from the void space into the restaurant through unsealed penetrations and cracks in the construction. If there are sufficient areas for smoke leakage, then the restaurant could become smoke logged due to the extract system.

All volumes of smoke calculated using the method in the Appendix of BR258, see Appendix 5 of this thesis.

It should be noted that the building complied with the building regulations, and occupants could escape away from the void areas. However, the regulation that requires the spread of smoke to be limited is not likely to be fully met. A smoke extract system may not have been needed. The time for hazardous conditions to develop on Level 3 could be over 6 minutes from ignition. This level may be clear of occupants by this time, depending on the method of detection and alarm.

12.2.2.6 Design Changes

The design of the building was changed. The voids in the floor of Level 2 were added. The fire resistant construction between Level 5 and the upper section of the void was omitted. The extract capacity, above the whole of the void was 38 m³/s.

In this situation the smoke control system would need to protect the occupants of the restaurant, by maintaining a clear layer of 2.5 m above Level 5. This is the minimum clear layer height recommended in BR 186 and BR 258. There would be additional entrainment into the plume, due to the increased height of rise of the plume, therefore increasing the mass flow rate.

The fire locations that would create the most hazardous conditions in the building:

- the weaving area Level 1
- the shop Level 2

The fire sizes discussed below are based on a convective heat output of 500 kW/m².

12.2.2.7 Fire Level 1

In steady state conditions, the smoke control system could cope with a fire size of 220 kW. The smoke at this level would only be 6 °C above ambient. It would be weakly buoyant. It is probable that the smoke layer would not stratify, but mix with the ambient air in the void. This would form smoke of low hazard. However, as the fire would continue to grow above this size. The smoke would become more buoyant, forming a stable hot layer in the reservoir. The smoke would rapidly build down in the atrium, smoke logging the void.

A smoke control system with a capacity in excess of 180 m³/s would be needed to ensure that a clear layer above Level 5 was maintained for 5 minutes. It is assumed there could be a medium growth fire (see Appendix 12) in Level 1, due to the low fire loads that would be present.

12.2.2.8 Fire Level 2

The effective height of rise at this level is less, than from Level 1 (9.4 m rather than 11.8 m), but the width of the opening would be much greater (18 m rather than 9 m). The effective height of rise and width of the line plume are great enough to cause excessive dilution.

A smoke control system with a capacity in excess of 200 m³/s would be needed to ensure that a clear layer above Level 5 was maintained for 5 minutes. It is assumed there could be a fast growth fire (see Chapter 4) in this shop. This extraction volume is not practicable, because:

- This extract rate would depressurise the building. Occupants would find it very difficult to open doors with the large pressures applied to across them.
- Replacement air would be need to enter through the inlet at 27 m/s. This is close to an exit door, therefore escape will be impeded by crosswinds. Air would also be drawn through escape routes at high velocity, as people opened exit doors. The windows could be altered to provide extra intake air, but may provide insufficient replacement air.
- An extraction system with a capacity of 200 m³/s would require 65 fans, operating at 3.1 m³/s each to maintain a clear layer of 2.5 m above Level 5.
- Smoke fogging will cause problems to people on Level 3.

Calculations for the smoke arriving at 3 m above Level 5 show that the temperature would be less than 1 °C above ambient. It is most probable that the smoke layer would either stratify or completely mix with air at lower levels.

12.2.2.9 Discussion

An initial examination of the smoke control system revealed that it is undersized, for the original design concept and severely undersized for the revised form. This occurred due to:

- The smoke control system designer was inexperienced, and did not know what the appropriate calculations were to quantify the smoke volumes. Some approximate calculations were needed to examine the system performance for this example, because some of the geometries were outside the standard compartment layout for FRS calculation procedures.
- The wrong fire sizes were selected during design. Additionally, little design information is available for reasonably accurate fire sizes, for this situation. The effects of fire growth and the potential for flashover were ignored.
- The design was altered, making the original design condition redundant.
- There would be little time to escape from the restaurant area and the floors. Escape needs to commence as soon as possible. The people in the restaurant may be reluctant to leave their meals. Thus it is possible in this situation that the time to complete evacuation is well in excess of 5 minutes. Also, certain areas do not appear to have adequate escape routes. For example, the only access to a conference room on Level 4 is via a lift.

12.2.2.10 Some Solutions

Certain design measures were suggested to improve the fire safety in the building:

- Installing sprinklers to reduce the fire sizes.
- Separate Levels 1 and 2 with fire resistant construction.
- Separate the restaurant from the rest of the void area, with fire resistant glazing, such as toughened glazed screen.
- Install fire resistant glazing (toughened glass) screen to shop on Level 2, to separate it from the void area.
- Increase the inlet area. The vent area is limited, due to the expense and restrictions on cutting through the external walls.

12.2.3 Extraction System

Two respondents reported extraction systems to atria that had very low extract volumes, because the inlet area for replacement air was much smaller than required.

12.2.4 Air Leakage in Stairwell Pressurisation System

A respondent reported difficulties with a stairwell pressurisation system, which failed to achieve the required pressure differences. This was due to high rates of air leakage, through a lift shaft. It was known that air leakage through the lift shaft, would prevent the correct pressure differentials from developing. The air leakage across the lift shaft doors was not specified, consequently standard doors were installed and the pressurisation system failed to work.

One respondent reported that unsealed penetrations through the walls to the stairwells of one pressurisation system prevented it from achieving the required pressures.

12.2.5 Control Panel Errors

A control board in a block of flats was faulty. The alarms and stairwell pressurisation system were continually activated. The maintenance team disconnected the fans to prevent further system activation. The pressurisation system was no longer operational. If a fire occurred, the stairs could become smoke logged.

A similar fault was revealed in a shopping mall. When testing a ventilation system, the control room panel indicated that the system had operated. Visual inspection of the vents revealed that they remained shut. Investigations revealed that the system had been disconnected, due to a malfunction that caused the vents to open without any fire threat being present.

Two other respondents reported that errors with the zoning of detectors and controls, which caused smoke control systems to operate in the wrong sequence.

In response to the questionnaire, one researcher stated that 95 % of integrated fire safety systems had faults prior to commissioning. There were also faults with component interfaces and all associated fire engineering systems have faults.

12.2.6 Klote Examples

In response to the questionnaire Klote (1996) composed a letter providing the following examples of pressurisation system faults, found during field tests. All of these systems had had an acceptance test.

1. A fan not connected to the electricity supply.
2. A fan wired incorrectly, so that it ran in reverse.
3. A fan that operated, but created no pressure.
4. Automatically closing doors that failed to close.
5. Control dampers that failed to operate.
6. Overcomplex design, that aimed to provide various degrees of pressurisation, in stairs, lobbies, and other areas. The control dampers and resultant pressures were in a constant state of flux.
7. Stairwells and external walls with excessive leakage rates, making pressurisation impossible.
8. Pressurisation controls that did not have the correct operation sequence.
9. A pressurisation system that pressurised the floors either side of the fire floor, forcing smoke into the smoke duct. The buoyancy pressures of the smoke in the duct above the fire floor, was greater than the pressures generated by the supply air. Smoke could be forced into floors above the fire. See Figure 12.3.

12.2.7 Library, North America (Boehemer 1996)

On inspection of a pressurisation system in a library, the following faults were found:

1. A damper was wired into the wrong zone, reducing the pressure differences, between zones.
2. A exhaust fan shut down during a smoke bomb test, because smoke was detected in the return air duct. The system should have continued to run, with smoke in the return air duct.

12.3 Smoke Control and Fires

12.3.1 Introduction

Fire reports can provide information on the performance of smoke control systems in fires. These reports can provide an assessment of the range of factors that contribute to system failure.

There are a limited number of engineered smoke control system failures reported. Dillon (1991) states that major fires involving smoke control system failure are rare. Fires in commercial buildings, built to modern codes and equipped with functioning sprinklers have an outstanding record of providing adequate occupant safety without smoke control.

In this section fires involving engineered smoke control systems are examined. Although fires in buildings which would require engineered systems or controls are also examined.

After a fire incident, there can be a thorough examination of a system's performance, often more detailed than during acceptance testing.

12.3.2 First Interstate Bank, L.A., (Isner 1990)

This 62-storey office block constructed in the 1960's. A fire occurred on the 12th floor, and eventually spread to include three floors above.

Many factors contributed to the fire and smoke spread, particularly, the cladding and air shafts. The aluminium mullions of the curtain wall deformed due to inadequate fire-stopping at the edges of floor slabs. A 100mm gap (at ambient) normally closed with fire-stopping, opened up, let flames and smoke spread to the floor above. Eventually, the main source of floor-to-floor flame spread, was external flames breaking windows.

A return air shaft, running from the 12th to 31st floor, was built of 16 mm plasterboard on metal studs. The excessive heat from the fire on the 12th floor caused the plasterboard to fail on the 12th, 13th and 14th floors. From the 13th to 31st Floor, the dampers to distribution ducts, extending from the air shaft, failed to shut, as fusible links were on the wrong side. Smoke was able to spread throughout these floors.

Smoke also spread up through pipe chases, lift shafts, services ducts and stairways. There was smoke damage on all floors above the fire floor.

Here the performance requirements for all of the elements of a building, that will affect the integrated fire safety performance had not been identified, so the potential problems with detailing the air shaft and the fire stopping were missed.

Fire safety elements in the building were being upgraded at the time of the fire, but the cladding and air shaft details were not part of this improvement.

12.3.3 Fire in Private Club, Indianapolis (Isner)

This is a nine storey building was constructed in 1922, for use as a private hotel and leisure club. The building had a fire resistant construction, but penetrations in the compartmentation, the use of combustible finishes and large undivided concealed spaces allowed rapid fire spread.

During the fire, the HVAC system continued to operate, spreading toxic smoke around the building. This exposed occupants remote from the fire to toxic smoke and caused smoke damage throughout the whole building. Although not an engineered smoke control system, the building lacked a basic smoke control function: the shutdown of air distribution systems. The air conditioning system had been upgraded prior to the fire, at a time when new systems were required to shutdown upon detection of smoke.

12.3.4 Metropolitan House (Marchant, 1993)

This nineteen storey office building had a stairwell and corridor pressurisation system. Air was supplied to the stairwell via a single point top injection of air through an independent dedicated fan that drew pressurising air from roof level.

Air was supplied to the corridors via a concrete duct. Motorised dampers were to control the airflow from the duct the corridors on each floor. During construction it was found that the motorised dampers would not fit into the duct, so fixed louvre air transfer grilles were fitted instead. Pressure losses were significant down the duct, and as a result the pressure differentials across the grilles at each floor varied. Higher volumes of air were supplied air to the upper floors, than the lower floors. The upper floors became over-pressurised and the lower floors under-pressurised.

A fire occurred in a lift shaft and lift lobby on the eighth floor. Pressurisation of the corridors was inadequate, and could not contain the smoke in the lift lobbies. As a result the staircase from Levels 7 to 9 became smoke logged.

Smoke was also seen at the top of the staircase (Levels 12 to 19). The fan at head of this stairwell did not operate during the fire. Smoke had been detected entering through the intake ducts, actuating the dampers on the inlet and switching off the fan.

This building suffered design errors, such as the poor stairwell pressurisation design, made worse by construction errors, such as the change in grille specification.

12.3.5 Spanish Disco

A fire occurred at Ground floor in a nightclub in Zaragosa, Spain (Fire Prevention, October 1990). The fire was not large and was extinguished in 20 minutes by the fire brigade, but the HVAC system continued to run, during the fire, pumping smoke into a nightclub in the basement. The escape doors and stairs met the requirements of local building codes, but the occupants were very quickly incapacitated by highly

toxic smoke, and were unable to travel the short distance to safety. Forty-one people died in the basement.

There were many factors contributing factors to the high number of fatalities in the fire in Frankfurt airport. One factor, is that the HVAC system continued to operate during the fire, rapidly spreading hot, toxic gases around the concourse area (New Civil Engineer 1996). Full details of this fire are not yet available. It is also thought that control systems for the smoke control system did not operate correctly.

12.3.6 Fires Atria Buildings with Smoke Control systems

A fire occurred in a nightclub, on the First Floor of the Hyatt Regency Hotel, (Cresci 1975). The hotel had an atrium, which rose from the 1st to the 10th floor. This rapidly smoke logged. Some occupants had to escape along atrium balconies through smoke. The smoke control system failed to operate, because it had been switched off by maintenance staff.

The International Monetary Fund building is a 13 storey office block, with a full height atrium. A fire occurred on the tenth floor (Lathrop, 1979). It remained confined to a 3m by 5 m office.

This building had a smoke ventilation system to purge smoke from a central atrium. Four out of six of the springs to the automatic roof vents had perished, and had not been replaced during maintenance. During the fire, the vents had to be opened by hand by some maintenance workers early in the fire. Even with the vents open, the smoke filled part of the atrium down to the ground floor. The system design had was deficient too, as there was little replacement air, providing no throughflow ventilation. The HVAC system had smoke removal capability, but was not used, because it did not operate automatically and no engineering staff were on hand to advise the Fire Department on how to operate the system.

Portable smoke extract fans would not fit on to the roof openings, so had to be used at the Ground Floor entrance of the atrium, in an attempt to push the smoke out of the ventilators. The portable fans, in effect, diluted the smoke. It took 3 hours to remove the smoke.

12.4 Fire Tests

12.4.1 General

As described in Chapter 10, and borne out by responses stated in Chapter 11, hot smoke tests, using controlled fires, such as alcohol pan fires (around 0.4 to 5 MW) are rarely carried out, but give a better indication of a system's ability to deal with buoyant smoke (Marchant 1992). These tests have revealed faults with smoke control systems.

12.4.2 Test in Stadium

A test in a stadium, (Dillon, 1992) found that the plume diameter only had one half of the expected mass flow rate predicted by plume models. The smoke extract capacity was twice that needed for efficient smoke control. However, problems occurred in the pedestrian concourse, where smoke bypassed extract grilles and proceeded to flow up stairways. The calculation method used overestimated the extract rate through the grilles.

12.4.3 The Myer Centre; Adelaide (Marchant, R, 1991)

The Myer Centre, South Australia has a smoke exhaust system serving an atrium in a 5-storey department store and another serving the atrium of an adjoining mall. In hot smoke tests, Atkinson and Marchant (Marchant, R, 1991) found the following faults:

- As smoke detectors at the edge of the atrium activated, logic errors in the Building Management System stopped fans from operating.
- In one location an exhaust fan was to start and dampers to a grill to open at the same time, the negative pressure of the fan became too large to allow the dampers to open. No extraction occurred.
- A variation to the exhaust grills to the extraction system reduced the free area by 50%, greatly increasing the pressure drop.
- A test fire in the carpark caused the store above to become smoke logged. The lift (elevator) shaft connecting the two areas acted as a smoke shaft. This air leakage problem had not been considered during the design stage.

12.4.4 Brussels Airport Hot Smoke Test

The FRS carried out a hot smoke test to assess the performance of the new terminal building at Brussels Airport (Morgan, Williams, Harrison and Shipp, 1995).

The building had shops opening onto a concourse. The concourse was equivalent to a shopping mall. A natural smoke ventilation system was installed in the concourse.

Two tests were carried out, both using a 2 MW fire in a heat resistant fire compartment built inside a shop unit. The following effects were found:

1. The smoke layer depth in the concourse was less than expected. The predicted smoke reservoir depth was 4.5 m, the resultant experimental smoke depth was 3.8 m. It is possible that a 2 m/s wind across the roof, creating areas of negative pressure, may have aided smoke ventilation.
2. Openings in builders work ducts, allowing rapid transport of smoke throughout the building were identified.
3. The air conditioning ductwork also allowed rapid transport of smoke. Dampers had not been installed to prevent this.

Tests have also been conducted by Tamura, Klote and others, specifically to improve design information for pressurisation systems. Issues arising from these are included in the next chapter.

12.5 Other Published Case Studies

An investigation of pressurisation systems, by Shipp (1980) revealed that 11 out of 12 systems failed to reach the recommended overpressures. Typical faults included:

- pressure losses being higher than anticipated, due to extra bends in ductwork, undersized ductwork or extra louvers added.
- many systems had air leakage greater than anticipated. In some cases the stairwells had doors opening directly to outside or to toilet areas, with extraction systems. Many stairs had poorly sealed ducts and shafts.
- in some well-sealed, air-conditioned buildings, air leakage was too low, so the recommended levels of overpressure could not be achieved.

Some systems were fundamentally deficient, examples include:

- a system that had supplementary extraction on each floor to increase the pressure differentials across the doorways. The rate of extraction was in excess of the supply volume to the staircase. During testing, additional air was drawn through the ground floor. Smoke would have filled the staircase, in the event of a ground floor fire.
- a system that had a fan, but with no ductwork connecting it to the stairwell. The stairwell would not have become pressurised.
- a system that had smoke detection in the stairwell only, so that smoke would have needed to enter the staircase before the system could activate.
- a fire risk (tea-room) was not separated from one stairwell. Smoke would have filled the stair and would have been injected into adjoining compartments.

Some of the problems noted here, were due in part to inadequate information at the time of the system's design. They also revealed a limited understanding of the

requirements for pressurisation. This investigation, by Shipp (1980) carried out in 1975-78, provided the basis for recommendations in later building codes and research. Systems are still being designed that would fail to achieve their objectives. For example, a design review of a pressurisation system, for a stairwell in a residential development, revealed that the air supply duct was inadequate. The pressure loss down the duct had not been taken into account. Adjustable grills were required, to control the air supply at each floor level. This is a basic mistake, showing that suitable design information is either not being used or not being understood.

The systems examined by Klote (1996), the Carlyle Condominium (Taylor 1975, see Chapter 3) and Metropolitan House (see Section 12.3.4) had similar problems with a poorly balanced pressure distribution in a stairwell and corridor pressurisation system.

12.6 Discussion of Examples

12.6 Typical Causes Smoke Control Failure

These examples show that a variety of faults can occur with smoke control systems. The faults have been caused at different stages in the life-cycle process. The faults have varying degrees of effect on the performance of smoke control systems.

In some instances, there is complete system failure, in others partial failure. In these particular examples, control system faults often cause complete system failure.

These examples also reveal problems with the passive elements of smoke control systems.

All of the examples given demonstrate hardware faults. Most are due to human factors (inexperienced designers developing unsuitable designs, poor maintenance and so on) rather than due to fire and smoke dynamics.

No instances of poor system performance, due to unexpected variations in the fire and smoke environment, were found. In a few instances phenomena occurred that would not have been modelled with standard zone model techniques. For instance smoke from the atrium smoke reservoir, in the IMF fire, descended below the office, reaching Ground Floor for a period. This would not have been predicted by most zone models used for atrium smoke control design.

12.6.2 Smoke Threat

These examples also show that smoke can be the major threat to life-safety and property in fires. In many cases smoke spread for a long distance from the seat of the fire, causing extensive smoke damage. Much of the damage in the IMF Building fire was caused by the smoke in the atrium (Lathrop, 1979). In a recent fire in a commercial research and development building, fire damage was limited to £50,000, but smoke damage exceeded £5 million pounds, including the cost of lost research.

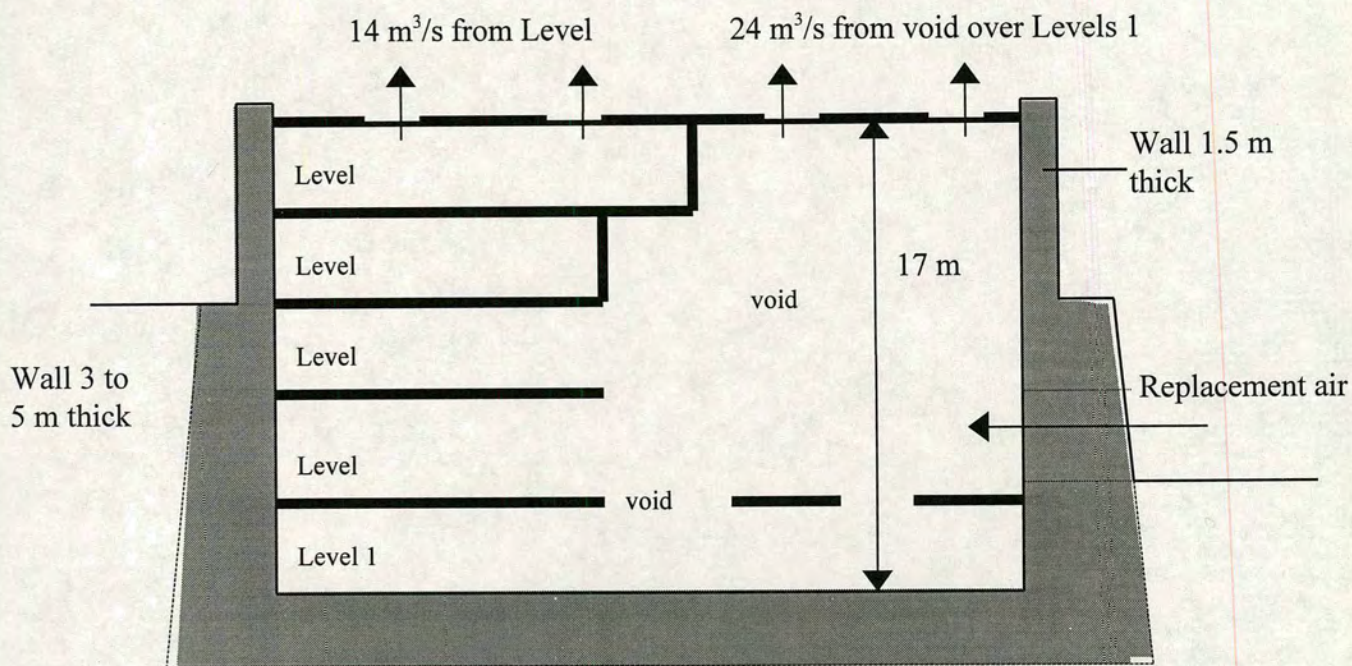
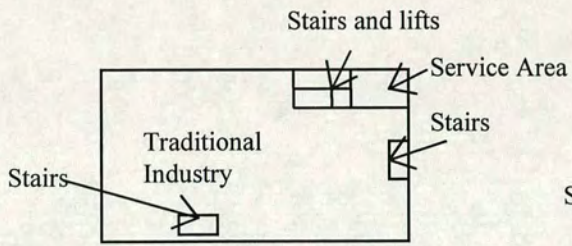
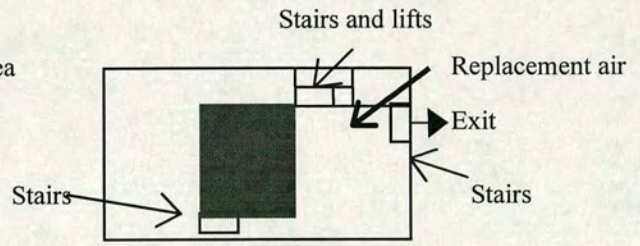


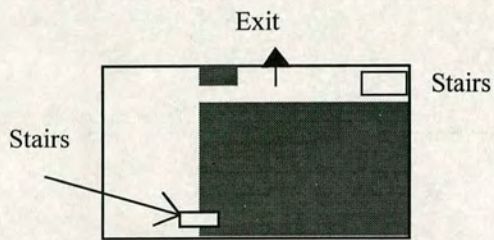
Figure 12.1 Section Through the Building



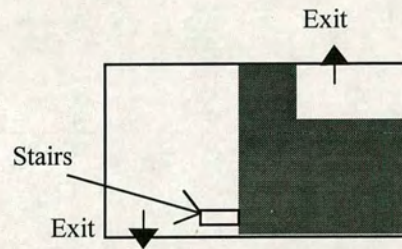
LEVEL 1



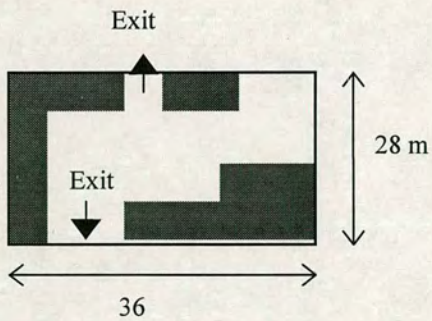
LEVEL 2



LEVEL 3



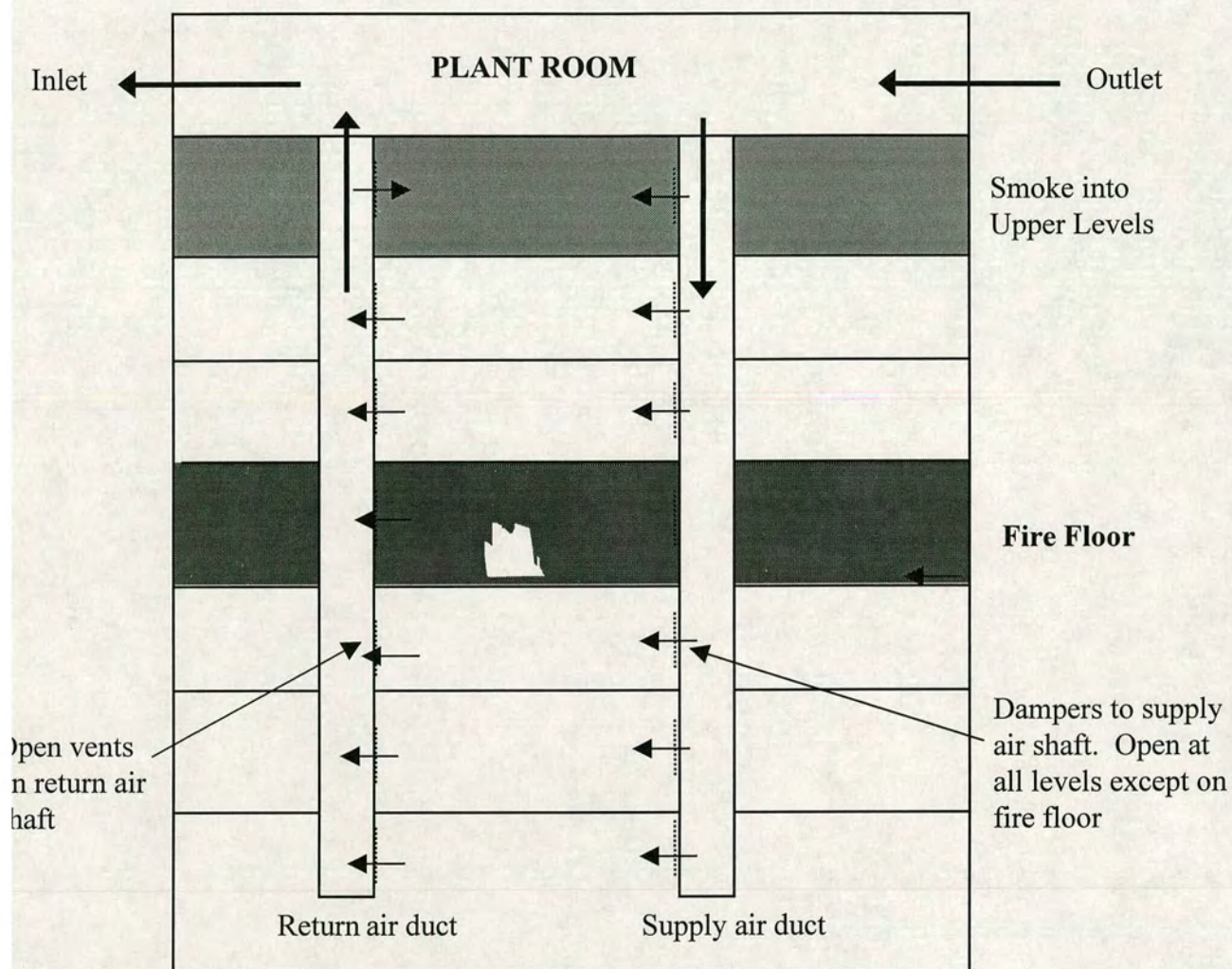
LEVEL 4



LEVEL 5

■ Void in floor

Figure 12.2 Plans of Each Level



Fire floor: Return air duct. All vents permanently open.

Supply air duct. Dampers to fire floor open. Supply air shut.

Figure 12.3 Fundamentally Flawed Smoke Control System (Klote 1996)

Part 4 Concluding Chapters

Chapter 13 Smoke Control Failure Modes

Chapter 14 Conclusion

Chapter 13 Smoke Control Failure Modes

13.1 Introduction

13.1.1 General

In previous chapters it has been shown how variations to the performance of smoke control systems can occur. These two basic causes of the variations are:

1. Variations in fire environment, from the predicted performance due to natural (stochastic) variations and knowledge deficiency.
2. Variations in hardware performance, due to component, subsystem and system deficiencies.

Associated systems, such as sprinklers, passive measures (such as compartmentation), and the means of escape affect the overall performance of fire engineering system. This in turn affects how the performance of the smoke control system is judged.

In this Chapter, an exhaustive list of failure modes cannot be presented, however the main modes of failure are outlined. Issues relating to extract systems are examined in more detail, in order to provide a more detailed analysis of smoke control failure and to draw together the results of the experimental work. A limited number of examples of failure modes of containment failures are provided. No hybrid systems are examined.

In Sections 13.2 and 13.3, the conditions for smoke removal and smoke containment systems failure are examined.

In Sections 13.4 to 13.11 various forms of system failure are described, and their effects assessed.

13.2 Failure Modes of Smoke Removal Systems

13.2.1 General

In Chapter 3, it was stated that when smoke enters (or could enter) areas that the smoke removal system was designed to keep clear, then failure has occurred:

1. Smoke forms a layer at a level below acceptable limits.
2. Smoke flows into adjoining compartments.
3. Smoke drawn down perimeter of compartment, below reservoir.
4. Smoke collects at low level.

The hazard to the occupants may increase beyond acceptable levels, although the smoke may be at the correct design height. The smoke removal system has failed if the smoke has excessive:

1. Temperature
2. Toxicity
3. Obscuration (i.e. very poor visibility)

The smoke removal system can adversely affect other activities in the building. Incoming air velocity can hinder escape, affect the fire or other aspects of fire safety. It can also adversely affect the general performance of routine activities in a building during testing, due to vibration, noise or air movement.

13.3 Containment Systems

13.3.1 General

In Chapter 4, it was stated that when smoke enters (or could enter) areas that the smoke containment system was designed to keep clear, then failure has occurred:

The hazard to the occupants may increase beyond acceptable levels system has failed if the smoke has excessive:

1. Temperature
2. Toxicity
3. Obscuration (i.e. very poor visibility)

The smoke removal system can adversely affect other activities in the building. Incoming air velocity can hinder escape, affect the fire or other aspects of fire safety. It can also adversely affect the general performance of routine activities in a building during testing, due to vibration, noise or air movement.

13.4 Component Faults

13.4.1 General

The components that form part of a smoke control system can include fans, vents, dampers, curtains, smoke seal doors and other items. Many of these items are multi-functional.

The individual components can fail separately or in any combination, during the life-cycle of the system, as discussed in Chapter 10. The following sections provide examples of typical modes of failure that can occur as a part of their function as smoke control components.

13.4.2 Fans

13.4.2.1 Failure

Smoke extraction fans need to keep running at elevated temperatures. BS 7346 (1990) details a method of testing fans. The fans are graded according to the maximum temperature at which they can keep operating. If fans are exposed to excessive temperatures, then their performance starts to decline until they fail.

Courtier and Wild 1991 have described the effect of temperature on fan performance. Excessive temperatures and stress can cause fan blades and casings of extract fans to fail, so the structural material of fans needs to be chosen carefully. Aluminium is unsuitable at temperatures above 400 °C. Mild steel starts to become unserviceable above 500 °C. Lubricants can fail at elevated temperatures. Specialist lubricants are available for temperatures between 400 °C and 450 °C. These can continue to operate at these temperatures for the period of time required for most smoke control applications smoke control. There is a limited life for lubricants above 450 °C.

Some smoke control fans use aluminium blades. These blades expand more than the steel casings. If a fan is to be used at high temperatures, then a larger gap between the blade tip and the casing is provided to allow for the aluminium blade expansion. Fan stalling can occur if this gap is too large. A fan may be designed to operate at temperatures from ambient to a maximum temperature of 400 °C. It will be detailed to allow for the expansion of the aluminium blades at these temperatures. However at much lower temperatures, the fan will not operate efficiently and may even stall, due to the gap between blade tip and casing being excessive.

The life of a fan at elevated temperatures can vary considerably. Courtier and Wild (1991) have found that fans of similar rating, tested at 400 °C can vary $\pm 50\%$. The fans ran for a minimum of 3 hours though. This is long enough to provide life safety, and property protection in most situations. The decline in performance of the fans during the tests is not reported. Courtier and Wild (1991) add that if a fan has been in service for some time, then failure could occur more quickly.

A fan could be subject to excessive temperatures because the smoke temperature is underestimated or because an inappropriate fan is used for extraction.

Smoke control fans can suffer all of the range of faults that occur with HVAC systems. For example systems can have fans that operate, but create no pressure (Klote 1996). Fans may be wired incorrectly, so that they run in reverse or may not

be connected at all to the electricity supply (Shipp 1980 and Klote 1996). These faults should be discovered during basic acceptance testing procedures. Smoke control fans can be installed without due regard to the potential pressure losses that could occur in extract ductwork, resulting in greatly reduced flow rates.

Smoke control systems with fans are dependant on a continuous power supply, see Section 13.7 below.

13.4.2.2 Effect

The effect of fan failure depends on the nature of the fault. Most smoke control systems have back-up fans, for example this is recommended for smoke control systems in shopping centres (BS 5588 Part 10). These operate if a fan fails, however fan failure may be caused by a common fault (common mode failure).

If common mode failure occurs, for example due to excessive temperatures affecting all of the fans, then total failure of the smoke control system could occur. Back-up fans would provide little additional benefit in this instant, because these could fail due to the same fault.

Reduced performance of a smoke control system could occur, if many of the fans had deficient performance, due to poor installation or maintenance.

13.4.3 Ventilators

13.4.3.1 Failure

Smoke ventilators are relatively simple components (in comparison to fans). However ventilator failure can occur.

Two common faults are that the ventilator area and the coefficient of discharge (used to calculate the aerodynamic area) are wrong. It is possible that the vents may not have been tested, to measure the vent aerodynamic coefficients and vents can be incorrectly specified. In one ventilation system high quality exhaust ventilator's had

been re-specified to an inferior alternative (Record, Building Services, June 1995), even though they would not strictly comply with British Standards.

The performance of ventilators varies with the wind. Research has shown that each type of ventilator has different wind pressure coefficient values across them at similar roof locations (Gosh 1993). These factors will cause variations in the aerodynamic efficiency of the ventilators, so effecting the rate of smoke flow through them. As discussed previously, wind pressures can be great enough prevent smoke flowing from ventilators.

To provide effective life safety benefit, the ventilators need to fail-safe to the 'open' position. Thus if power is lost the ventilators can open. This is an advantage over powered extract systems which cannot have such fail-safe measures. Ventilators that are solely operated by fusible links may not meet the requirements of the smoke control system. They may only operate close to the fire, providing a limited area of smoke ventilation. They will respond slowly to a growing fire too (Hinkley 1992). The first vent may not open until the space that they are required to protect is completely smoke logged.

Correct acceptance procedures, such as those stated in BS 5588 Part 10 should uncover any of the faults listed above.

13.4.3.2 Effect

If these can fail safe open, are not operated solely by fusible links and if selected for suitable roof location (one where it will not be adversely effected by the wind), then total failure of natural ventilation systems, due to ventilator failure is unlikely. However reduced efficiency is possible due to inadequate ventilator areas or aerodynamic efficiency.

13.4.4 Dampers

13.4.4.1 Failure

Dampers can seal off different parts of a building, preventing smoke flow through ductwork. They can also form an active part of smoke control, for example in pressurisation systems, directing air to the correct locations.

Fire dampers do not perform the same function as smoke dampers. Fire dampers prevent the spread flame along a duct, and need to remain intact for one hour or more at temperatures in excess of 1000 °C. They are not intended to be air tight.

Smoke dampers need to prevent the spread of smoke. They need to have much lower air leakage rates than fire dampers. Most smoke dampers are not fire resistant. If fire resistance is needed too, combined fire and smoke dampers should be used. Often fire dampers are specified as a cheap form of smoke damper. These have air leakage characteristics that are inferior to those of smoke dampers (McCabe 1984).

All of the damper components need to have the same level of fire resistance. For example, if a damper is to open for smoke control, to allow the supply of external air into a space, it could be rated for ambient temperatures. However, the risk of exposure to high temperatures outside the duct needs to be assessed. Often damper motors and actuators are sited outside the ductwork. These often have limited fire resistance, despite the recommendations of codes (such as BS 7346). They are unreliable above 140 °C.

Dampers need to be operated centrally. Those that are operated solely by a fusible link, fail to operate, because the link is protected by the damper blades from direct heat (Isner 1990). Dampers controlled by detector operated building management systems, with fail safe closure or opening methods, can offer earlier and more reliable response to fire and smoke threat, preventing recirculation of smoke or encouraging the safe extract of smoke.

Some dampers can fail to close properly, so only partially reduce the airflow through a duct (Tamura and McGuire 1984).

If dampers are not closed before fans are fully energised, then ductwork pressures can prevent closure (Marchant R 1991).

13.4.4.2 Effect

The effect of damper failure or partial failure is dependent on their function, and no general conclusions can be made. If the dampers are required to shut down an HVAC system, then smoke spread between compartments may occur. The amount of smoke spread is dependent on the number of dampers that fail to perform correctly.

If part of a pressurisation system, then low pressure differentials will develop. The effect needs to be examined individually.

13.4.5 Other Active Systems

Other components that form part of active smoke control systems include air inlets, automatically closing or opening doors and smoke curtains. As with fans, vents and dampers, there are codes of practice to ensure that an adequate standard of component is achieved. For each the effect of failure can vary, depending on the use for which the system is required.

If smoke curtains fail to descend, then smoke can spread under ceilings to other zones, smoke logging areas well away from the fire compartment. Failure will allow line plumes (see Chapter 5) to develop excessive widths, forming large quantities of cooler smoke, overwhelming smoke removal systems.

13.4.6 Smoke Barriers for Containment

13.4.6.1 Failure

Walls, ceilings and floors form barriers to smoke, however careful detailing is needed to provide a complete smoke barrier at the edge of smoke control zones. No standards or recommendations are specifically produced in relation to building construction specifically for smoke control, however good construction practice minimises potential smoke leakage. Some special elements for smoke control purposes are available though such as smoke seal doors. They have standards and testing methods that are applicable to them, however their performance can vary.

Air leakage through smoke seal doors can vary by a factor of 200, when the same pressure difference is applied across them (Gross 1981). Later research by Gross (1991) has attempted to quantify the airflow rates through gaps around doors, based on the width, number of bends and additional features such as brush seals, reducing uncertainty in performance of smoke seal doors. Lift shaft doors can have similar smoke seal requirements.

Shipp (1980) found many pressurisation systems could not achieve the design pressures, due the air leakage being greater than anticipated. The stairwells had doors opening directly to outside or to toilet areas, with extraction systems. Many stairs had poorly sealed ducts and shafts. In one case the fan installed to generate pressure was not connected to the stairwell.

In many buildings, there are concealed spaces. If measures are not taken, smoke can spread through these into other parts of a building. Poor fire stopping of voids has been responsible for extensive smoke spread in many fires (c.f. Silcock 1975). Approved Document B (1992) of the Building Regulations makes specific recommendations for the sealing of cavities in buildings to prevent this.

All gaps in buildings can provide routes for smoke spread. The general recommendations for protecting openings in compartment walls, in Approved

Document B, can be used to reduce the risk of smoke spread. Recommendations on the size of gaps between smoke curtains are given in BS 7436. However even minor gaps in construction allow the spread of smoke.

If ceiling voids are to form separate smoke zones, then the edges of ceiling tiles can form routes for smoke. Tile joints in suspended ceilings have allowed large volumes of smoke to pass through them (Silcock 1975).

A common form of damage to smoke barriers is by services penetrations. Investigations of 12 fires in schools of dry-wall construction (Silcock 1975), found that smoke spread through penetrations through smoke barriers, for building services, occurred in all cases. Smoke can even spread up through pipe chases (Isner 1990).

13.4.6.2 Effect

The effect of excessive leakage through smoke barriers is that containment systems cannot achieve the correct level of pressurisation. Leakage may be so high that pressurisation is impossible. For example high rates of air leakage, through lift shafts will prevent the correct pressure differentials from being achieved, it can even result in them acting as smoke shafts (Marchant, R, 1991).

Some designs rely on a degree of air leakage. In some well-sealed, air-conditioned buildings, air leakage is too low, so that the recommended levels of overpressure cannot be achieved (Shipp 1980). Smoke would be able to flow from the fire compartment to the protected compartment.

Smoke removal systems rely on smoke being contained at high level in reservoirs. The amount of smoke that could spread to adjoining zones is dependent on the leakage area and the pressure differences developed by the smoke. The system is unlikely to suffer total failure.

13.4.7 Component Interfaces

The detailing of component interfaces may not be adequate, so that when expansion due to heat occurs, gaps can open in the smoke barriers to allow fire and smoke spread (cf. Isner 1990). Other examples of poor component interfacing include fans that are connected to ductwork, with flexible connectors that do not have adequate temperature rating (Courtier and Wild 1991 and Questionnaires).

The effect of component interface failure is dependent on the functions of the components involved. It could result in partial failure, for example additional air leakage, or total failure due to common mode failure. For example, if non-fire rated flexible connections are used to connect all of the ducts and fans in a smoke control system, then total system failure could occur. The smoke temperature in all of the ducts could be high enough to cause degradation of the connector material.

13.5 Subsystem Faults

13.5.1 Ductwork

13.5.1.1 Failure Mode

A key part of pressurisation and extraction systems is the ductwork. This can experience faults common to HVAC ductwork.

The extract or pressurisation ductwork have excessive pressure losses or air leakage, due to extra bends in ductwork, undersized ductwork or extra louvers added (Klote 1996, Milewski 1985 and Shipp 1980).

Static pressures of 500 to 1500 Pa, in a duct, can cause it to collapse. This has occurred at ambient conditions during testing (Milewski 1985). There have been instances of this occurring after acceptance testing.

Complex ductwork designs can suffer 'system effect' (Bevirt 1992). This is common in HVAC systems, where the volume flow rates can be up to 25 % below predicted values. Bevirt states that high pressure losses occur due to unexpected air flow

patterns developing in the ductwork. These are caused by inlets, bends and fans. Dedicated smoke control ductwork is generally less complex, but system effect could occur if inlets, bends and fans are close to each other.

13.5.1.2 Effect

If this occurs with a smoke removal systems, then the flow rate from a smoke reservoir will be lower, reducing the clear layer height required for a steady state design or reducing the time for hazardous conditions to develop for time based smoke dispersion systems (see Chapter 2).

If this occurs with a pressurisation system, the pressure differences that can be achieved in a space can be greatly reduced. If reduced to below 20 Pa, then smoke could enter the stairwell.

13.5.2 HVAC Systems for Smoke Control

13.5.2.1 Failure Mode

Using HVAC systems for smoke control can be difficult. The components may not be suited to the conditions generated by a fire. For example the controls may have plastic pneumatic components, which could fail in a fire (Milewski 1985).

HVAC systems are becoming increasingly complex, and may not have suitable capacity for smoke control. For example variable air volume systems have fans within ceiling voids. Often the main ducts are sized with a limited number of these fans running, due to air conditioning loads varying within different locations in a building, during the day. The system may not work correctly with the system operating at full capacity. This has been found during routine testing, where operating at full capacity has caused damage to the system, even caused glazing to implode (Milewski 1985).

Some HVAC systems have fail safe requirements that are the opposite of that required for smoke control. For example the fail-safe mode for dampers to outside air for HVAC systems is usually 'shut', for smoke control it is likely to be 'open'.

13.5.2.2 Effect

If an HVAC system is used for smoke control, without upgrading it to meet the requirements of smoke control, the system may only operate for a limited period. Total system failure could occur and could even result in worse conditions than when no smoke control function was provided, due to smoke being forced into protected spaces (Milewski 1985).

13.5.3 Ceiling Extraction

When smoke is to be extracted through false ceilings, a minimum 25 % free area is required in the ceiling. If less than 25 % is provided limited amounts of smoke will be drawn into the ceiling layer. As the free area is reduced, more smoke will flow under a ceiling and into adjoining spaces. More research is needed to develop the experimental work by Spratt and Heselden (1974) to investigate the performance of varying the free area in ceilings.

13.6 System Faults

13.6.1 Fire Size

13.6.1.1 Failure Mode

The smoke control system design could be based on an inappropriate steady state fire size. The more suitable design fire size could be significantly larger. This means that there would be a greater probability of fire sizes exceeding the design fire size. As a result there is a greater probability that there will be larger volumes of smoke and higher temperatures than predicted.

If the smoke control system is based on a growing fire, an inappropriate growth rate could be used. This could underestimate the resultant volumes of smoke and

temperatures. The probability of flashover would increase and would be likely to occur more quickly.

In some smoke control designs in unsprinklered buildings, the possibility, and the effects of flashover are not considered. Flashover causes greater volumes of smoke at much higher temperatures to be produced.

Another aspect of fire size that could effect smoke control design are the values used for the burning rates. These can vary from 85 kW/m² for stacked chipboard, to 630 kW/m² for cardboard cartons (Milke and Klotz 1992). Retail fires are based on a worst case value of 500 kW/m² and office fires on 62.5 kW/m² for sprinklered offices (Hansell and Morgan 1994). These are all convective values of heat produced from a fire. The choice of the burning rate can effect the plume temperature and density, therefore the buoyancy and volume of the smoke.

13.6.1.2 Effect

With unsuitably small steady state fire sizes, smoke removal systems could be undersized (either low extract rates or low ventilator areas). This would increase the probability of the clear layer heights being lower than expected and temperatures higher than expected.

If a system design is based on a growing fire, then selection of too low a growth rate for a smoke removal system design will result in hazardous conditions developing more rapidly.

If the flashover can occur within a fire, then aside from other fire safety issues, the smoke removal system would be greatly undersized, result in hazardous conditions developing more rapidly.

The choice of the burning rate can effect the plume temperature and density, therefore the buoyancy and volume of the smoke. As a result, if the burning rate is

underestimated, then there will be an increased probability that the plume temperature will be underestimated. This could result in an undersized smoke removal system.

If the burning rate is overestimated, then there will be an increased probability that the plume temperature will be overestimated. This could result in an increased probability that smoke could stratify at high level.

The discussions of the effects of the selection of the fire size have centred on smoke removal systems and smoke dispersion. Other smoke containment systems do not require the fire size to be determined for the system design.

13.6.2 Smoke Flow Modelling

13.6.2.1 Failure

During design many mistakes can be made in modelling smoke. Inappropriate design models can be used. Incorrect input parameters can also be used. This was discussed in Chapter 10.

Examples can include the wrong dimensions being used in calculations or the components of the smoke control system not forming the dimensions in the calculations.

For example smoke barriers (curtains, screens and so on) may not be provided to limit line plume widths to the dimensions in the spill plume calculations.

13.6. 2.2 Effect

It is impossible to generalise on the effect of inaccurate and inappropriate forms of plume modelling. Beard (1994) in examining the reliability of computer models, states that it is impossible to quantify the effects of such errors.

Examples include the case study of the void extract system in Chapter 12 (Section 12.2.2). Other examples include the common practice to size smoke control systems based on floor area (typically providing vents areas equivalent to 2.5 % of the floor area) and in America, to base extract capacity on 6 air changes per hour (ACH). These ignore the height of rise of a plume, fire size and many other variable discussed in Chapters 5 to 9 of this thesis.

13.6.3 Smoke Reservoir

13.6.3.1 Failure Mode

The design of smoke reservoirs is an important part of smoke extract design. Various conditions in the design need to be met:

1. The depth of smoke flowing under a ceiling or roof in a shop and at high level in malls or atria could be greater than the intended reservoir depth. This would result in a reduced clear layer height. Typically this is assumed to be a minimum of 2.5 m, with the smoke at 200 °C (BR 186). It is acceptable to use a smaller clear layer height only if the smoke temperature is significantly less than 200 °C.
2. Plugholing (see Chapter 2) can occur with natural ventilation and powered extract systems. If it occurs a ambient air will be drawn through the ventilators or fans, along with the smoke. Then there will effectively be a reduced extract (or venting) rate of the smoke. This will result in the smoke layer descending to a lower level, until the effective extract rate equals the mass flow rate of the plume entering the smoke layer.
3. Smoke reservoir areas can be excessive, so that heat loss is excessive and the smoke undergoes excessive cooling. If cooling reduces the temperature to below 20 °C above ambient, then it the smoke may have insufficient buoyancy to produce a stable layer (BR 258). The smoke could mix downwards into the ambient air (see Chapter 5). A long established general rule is that reservoir areas should not exceed 2000 m² for natural ventilation systems and 2600 m² for powered extract systems.
4. In the final design or installation smoke curtains, screens or other measures may not be provided to ensure that smoke reservoir sizes are not excessive.

5. The building structure and construction may have openings with routes to the outside, that are below the neutral pressure plane (see Appendix 13), that would allow ambient air to be drawn directly into the smoke reservoir. Then there will effectively be a reduced extract (or venting) rate of the smoke. This will result in the smoke layer descending to a lower level, until there is the mass flow rate of smoke entering the plume matches the effective extract rate. Example 10.2 (Marchant 1993), from Chapter 10.
6. There could be openings above the neutral pressure plane (see Appendix 13), that would allow smoke to enter adjoining occupancies.
7. The smoke temperature could exceed the temperature rating of the glazing or other elements forming the reservoir envelope. This would then lead to much high probability of failure of part of the envelope.
8. Zones need to be clearly identified, otherwise smoke may not flow along the intended routes to smoke extract points (see Example 10.1 (Marchant 1993), from Chapter 10).
9. In atrium smoke extraction systems and other removal systems that have large heights of rise, the potential and effect of choked flow (Milke 1990) needs to be considered. This occurs when a rising plume widens such that it may contact all of the bounding walls, before reaching the ceiling, see Figure 13.1. Entrainment will be limited above this height, but the atrium should be considered to be smoke logged above this point. This forms the effective reservoir depth. It is impossible to have a clear layer above this point, along the length of the plume, because the full atrium width would be smoke logged.

13.6.3.2 Effect

The effects of failures of elements of the smoke reservoir envelope are included in the discussion above. As a general result of these reservoir deficiencies three developments could occur with the smoke layer.

1. The layer could deepen, reducing the clear layer height.
2. The layer could mix down into the clear layer below, smoke logging lower levels.
3. Smoke could spread into adjoining spaces.

13.6.4 Replacement Air

13.6.4.1 Failure

Insufficient inlet area could be provided for replacement air. This can result in excessive air inlet velocities that would hinder escape. Generally the inlet velocity is limited to 5 m/s (BR 186 and BR 258).

If the inlet is close to the smoke layer, then the replacement air could mix directly into the smoke layer. The Smoke Ventilation Association Guide (REF) provides recommendations to minimise this. If the velocity is above 1 m/s, then smoke layer should be kept 2 m above the top of the inlet. If the velocity is below 1 m/s, then the smoke layer need only be 500 mm above the top of the inlet. Often it is difficult to meet these conditions.

Sufficient area for replacement air is occasionally omitted (Lathrop 1979 and Questionnaires). If it is not provided the smoke removal system will have a greatly reduced extract rate.

13.6.4.2 Effect

If there is insufficient inlet air provided, then the extract (or ventilation) rate of the smoke removal system will be greatly reduced. The clear layer will become smoke logged.

If mixing occurs at the inlets, escape routes can become smoke logged and the clear layer could become heavily smoke fogged, even smoke logged. The smoke layer depth could increase as the additional entrainment into the smoke layer produces more smoke.

13.6.5 The Wind and Smoke Removal

13.6.5.1 Failure Mode

Wind pressures could adversely affect natural smoke ventilation. Marchant (1984) showed that the onset of positive pressures above vents will reduce the efficiency of the vents. Eventually these positive pressures will be great enough to prevent the flow of smoke out of the vents. It is possible to calculate, for different wind speeds and wind directions, the reduction in flow through a vent. Using meteorological data, the probability of complete failure and probabilities of partial failure of a natural ventilation system can be calculated (Morgan and Marchant 1975), and the optimal vent locations selected according to the probability of vent failure and reduced efficiency.

During the course of the smoke flow experiments conducted as a part of this thesis, it was found that powered extract systems could also be adversely affected by wind pressures. If the extract system has low velocities and generates low static pressure differences, then the outlets could be subject to positive pressures, preventing smoke extraction.

13.6.5.2 Effect

The wind can aid smoke extraction, but more importantly it can reduce the flow rate through ventilators and powered extract systems with low design static pressures. The wind can cause the reservoir smoke layer to deepen, possibly reducing the clear layer height to below a critical value.

Natural ventilators can suffer total failure if the wind can prevent smoke flowing from all of the ventilators.

13.6.6 Wind Effects on Pressurisation Systems

13.6.6.1 Failure Modes

Wind pressures can adversely affect pressurisation systems. Marchant (1984) showed that the wind pressures that could be generated across the face of a building could reduce the pressure differences across the doors between a stairwell and fire compartment.

Hong and Marchant (1990) demonstrated the effect of the wind on roof level intakes. Stairwell pressurisation systems, to the requirements of BS 5588 Part 4, are designed to achieve a 50 Pa pressure difference across doors. If the wind develops negative pressures greater than 35 Pa across the intake to pressurised shafts, then it could reduce the pressure difference across a doorway to below 15 Pa (the minimum pressure difference to prevent smoke from entering the stairwell). The wind speed for this condition would typically be above 6.8 m/s. The probability of failure of the pressurisation system would vary geographically. If positive pressures are generated at the inlet, then the shaft pressure would be increased. This would have no adverse affect on a well designed system, because the pressure relief system should operate. For both positive and negative pressures at the intake, there exists the possibility that smoke from the building could flow back through the inlet. This is dependent on wind speed.

13.6.6.2 Effect

The wind could intermittently reduce the pressure differentials to below the levels required to prevent smoke flow across doorways. Smoke will flow into stairwells. The frequency at which this can happen is dependent on the pressures generated by within the fire compartment, the geometry of the roof and air inlet and the wind environment at the building location.

13.6.7 Other Pressurisation System Failures

13.6.7.1 Failure Modes

There are instances of stairwell and corridor pressurisation systems not being designed with correct account being made of pressure losses down the stairwell. This includes the stair and corridor systems described in Chapter 3 (Taylor 1975), the system at Metropolitan House (Marchant 1993).

Where air is supplied via ductwork to provide a balance pressure distribution in the duct, the other failures have occurred. In Metropolitan House (Marchant 1993), air was supplied to the corridors via a concrete duct fixed louver air transfer grilles. The upper floors became over-pressurised and the lower floors under-pressurised.

Other system failures have included pressurisation systems with fans, but no ductwork connecting it to the stairwell (Shipp 1980).

The number of open doors in stairwell, reduces the effectiveness of a pressurisation system. Research by Tamura (1992) has shown that systems designed to standards similar in principle to BS 5588 Part 4, will be effected as follows:

1. If more than two doors are opened, then the stairwell becomes contaminated with smoke.
2. Increasing velocities at stair doorways can pressurise the fire floors, pushing smoke into adjoining spaces.

If pressurisation is operated in combination with mechanical venting of the fire floor, up to four doors on the stair can be opened (Tamura 1992). If extraction is made on all floors adjoining the stairwell, then the total rate of extraction could exceed the supply volume to the staircase. Additional air could be drawn through the adjoining accommodation. If air is drawn through the fire compartment, then smoke will fill the staircase Shipp (1980).

Pressurisation fans at the bottom of a stairwell are preferable to fans at the top of the stairwell, because the power supply to the fan is more easily protected, fan start-up is assisted by stack action and there is less chance of smoke from the fire being drawn into the smoke control system.

13.6.7.2 Effect

The failures described can have a varying effect on smoke control. During the course of a fire smoke may periodically enter the stairwell and protected zones. The degree of smoke logging in the stairwell depends on the frequency and amount of smoke allowed to enter the stairwell and the location of the fire compartment in relation to areas of high and low pressurisation in the stairwells.

Total system failure can occur if the pressure differences are too low, pressurise the wrong space or basic faults, such as fans not being connected to stairwell ductwork.

13.6.8 Controls for Smoke Control Systems

13.6.8.1 Failure Modes

There are many examples of smoke control system failure. These appear to be a dominant cause of smoke control failure. Examples include:

- Vents, fans, dampers, smoke curtains and inlets that do not operate upon detection or operate incorrectly. (Questionnaire)
- Some controls do not function. For example a ventilation system control panel indicated that the system had operated, but visual inspection showed that they remained shut. The system had been disconnected, due to a malfunction that caused the vents to keep opening (Questionnaire). Another stairwell pressurisation system was disconnected, because the detection system suffered many false alarms. The maintenance team had disconnected the fans to prevent further 'false system activation', so the pressurisation system was no longer operational. (Questionnaire). A smoke control system in a fire at the Hyatt Regency Hotel, (Cresci 1975) failed to operate because it had been switched off by maintenance staff.

- The controls may have unintentional operation sequences. Control structures (even for 'stand alone' controllers) can have serious flaws, where rigid programmes cannot cope with scenarios outside designers expectations. Errors with the zoning of detectors and controls has caused smoke control systems to in the wrong sequence. (Questionnaire). In the Myer Store tests (Marchant, R, 1992) some detector activation patterns caused the control unit to shut fans down. Smoke control elements can be incorrectly connected to the controls, in one case a damper was wired into the wrong zone, reducing the pressure differences, between zones. (Questionnaire).
- If an integrated building management system is being used, other systems such as HVAC may take priority(Brown 1990). NFPA 92A states that smoke control operation should take priority, although this is not always clearly specified by smoke control designers (Brown 1990). Some smoke control systems and building management system controls can be (electronically) incompatible (Brown 1990).
- The zoning of the detection, sprinkler and smoke control systems may be incompatible (Brown 1990).
- With integrated systems, if the central processing unit fails and there is no stand alone capability included for fire safety systems, then only very basic (manual) control of the smoke control systems will be possible (Marchant, R, 1992).
- Overcomplex pressurisation designs can prove difficult to control. The control dampers and resultant pressures can be in a constant state of flux (Klote 1996).
- An exhaust fan for a zoned pressurisation system would not run correctly, because if smoke was detected in the return air duct, the system would be switched.. (Questionnaire). In Metropolitan House (Marchant 1993), a fan at head of a stairwell did not operate during a fire. Smoke entering through intake ducts activated the dampers on the inlet and switched fans off.
- In fires in Dusseldorf Airport (New Civil Engineer 1996) and a nightclub in Zaragosa, Spain (Fire Prevention, October 1990) the HVAC systems were not shut down upon fire detection. The HVAC system continued to operate during the fires. Smoke was rapidly transported around the buildings.

- One pressurisation system had smoke detection in the stairwell only, so that smoke would need to enter the staircase before the system could activate (Shipp 1980).
- If a control system can be activated by manual alarms, then people leaving the building are not likely to activate these alarms in the fire zone, but instead at the final exit door, away from the fire, in the wrong zone. Incorrect zones could be pressurised. Smoke could be forced out into escape zones (Longhatino and Campbell, 1984).
- Power needs to be maintained to building management systems. In one case emergency power was provided to fans and dampers, but those also under the control of the building management system (BMS) did not operate properly. This was because the memory of the BMS was lost when primary power was lost.
- Having no emergency control (with a fireman's switch) may cause difficulties for fire-fighting use of complex air-handling systems (Zivney 1985).

13.6.8.2 Effect

Only a general description of the effect of smoke control system faults on smoke control system operation, the effects can be so varied. The faults can cause reduce efficiency of a system, even induce complete failure. Some control faults can actively cause hazardous conditions to develop rapidly.

13.7 Associated System Faults

13.7.1 Introduction

As discussed in earlier Chapters, smoke control systems should form part of an integrated fire safety system. Smoke control systems rely on the performance of these other fire safety systems. It can also affect the performance of other systems. Some of these are outlined in the Sections below:

13.7.2 Sprinklers

13.7.2.1 Failure

Sprinklers reduce the probability of a fire becoming large (Morgan 1992). Most smoke control system designs are for buildings with sprinklers, for which design fire sizes are available. The sprinklers could fail or could have a deficient performance. A fire in the building could exceed the design size; unsprinklered fires can grow to many times the size of sprinklered fires. For example the design fire size for sprinklered offices is 16 m², whereas for unsprinklered offices it is 47 m² (BR 258). As discussed in Chapter 3, investigations have shown that the failure rate of sprinklers is low.

In their experiments on the effect of smoke automatic sprinkler protection on smoke control systems, Tamura and Mawhinney (1994) found that sprinklers were very effective in controlling the fires, reducing the smoke and fire hazard to near negligible levels. However, when there was sprinkler shielding, the fire continued to burn at a reduced burning rate (from the unsprinklered condition). The risk of shielding, means that the installation of a sprinkler system does not eliminate the possibility of a fire producing large volumes of smoke. As a result of this research, allowing sprinkler systems to be treated as a form of smoke control in their own right (the Canadian Building Control Code), is to be re-examined. Additional smoke control measures may be required in the code.

13.7.2.2 Effect

Sprinkler failure could lead to large fire sizes and excessive smoke volumes and temperatures. These would rapidly overwhelm the smoke removal systems, causing smoke logging of protected spaces.

Spaces protected by pressurisation systems are more likely to become contaminated by smoke if sprinkler protection is not available (Tamura 1992).

13.7.4 Detector Failures

A suitable standard of detection is needed to ensure that smoke control measures can be activated at an early stage. Delay in the operation of detectors will allow hazardous conditions to develop more rapidly.

13.7.5 Power Supply

Standby power with fire-rated cables needs to be provided to maintain the electrical supply. Generators may not be adequately sized to deal with the start-up power required for smoke control fans (Brown 1990).

Plastic isolators have been used, adjacent to fan casing, on a fan intended to operate for 2 hours at 400 °C. Clearly the isolator would fail very quickly (Brooks 1996).

13.7.6 Smoke Barriers and Walls

These are briefly discussed in the Components Section (13.4).

13.7.7 Means of Escape

Full examination of means of escape issues is beyond the scope of this thesis. However development of the analysis of the interrelation of escape and the development of hazardous conditions in a building is a key feature of fire safety engineering.

If smoke starts to enter an escape route, then escape can be hindered, increase the time for people can clear a building.

Emergency lighting produces minimal amounts of light to aid escape. Smoke at high level may obscure the lights, reducing the illumination levels to below a satisfactory amount required for escape. This could also increase the time for people to escape from a building.

13.7.8 Other Building Systems

Smoke control and other integrated fire safety systems can affect, and be affected by other building systems, such as air conditioning, or building geometry. One aspect of the affect of building geometry on fire safety systems has been examined. This is the affect of building geometry on smoke movement and entrainment.

Other issues have been the subject of other research projects. For example Pennycook (1995) has examined the affect of air handling systems on detection systems.

13.8 Fire Environment Variations

13.8.1 General

The variations in the environment, that can cause it to differ from that predicted during design is discussed in Chapter 4. These are variations are due to lack of knowledge in areas of fire and smoke behaviour and due to natural variations in fire and smoke behaviour.

It would be impossible to examine the full range of variations and their effects, so the results of the experiment are used to provide an example. A limited examination is also made of some other areas of uncertainty.

13.8.2 Fire

13.8.2.1 Variations

A large range in natural variations with fire sizes can occur. Most smoke control designs use steady state fire sizes. As discussed in Chapter 4 and 10, the design fire sizes for compartments with sprinklers are conservative estimates. Research suggests that these estimates may be too large. At present, if an appropriate fire size is chosen for a smoke control system, then there is a low probability that an excessive fire size could develop to overwhelm the smoke control system.

There are attempts to refine the information for fire sizes for smoke control system design, particularly with sprinkler controlled fires (REF). This includes creating a wider range of steady state fire sizes and fire growth models applicable for different forms of occupancy. It could allow the capacity of smoke control systems for some occupancies to be reduced.

There are many CFD based research attempts to model fire sizes and (REF). Different compartment geometry, construction, layouts, contents, locations for ignition are examined and resultant fire scenarios quantified. These are used for studying fire growth, in post fire reconstruction. These are not available for design use at present, as they are still being validated. They would have limited design use due to the large number of scenarios and sensitivity analyses that would be needed to quantify fire growth in a particular compartment.

13.8.2.2 Effect

Large variations in fire size from predicted values will occur. If a fire is larger than predicted occurred, then the effect will be as follows:

Smoke Removal Larger volumes of smoke will be produced. The removal system will not have adequate capacity. The smoke layer will descend below the design clear layer. Smoke of a volume filling will occur more rapidly.

The smoke may also be hotter, so the structure containing the smoke and removal system may fail, due to excessive temperatures.

Smoke Containment The larger volumes of smoke will cause the fire compartment and adjoining unprotected spaces to fill with smoke more rapidly.

The smoke may also be hotter, so the structure containing the smoke and removal system may fail, due to excessive temperatures.

13.8.3 Effect of Sprinklers on Smoke

13.8.3.1 Variations

The effect of sprinkler cooling on smoke is difficult to model. At present there is much research to model the sprinkler spray droplets, and their interaction with smoke (Morgan 1992). These models are improving, but are not suitable for smoke control design yet.

There is also much controversy with regard to the interaction of sprinklers and smoke ventilation. Factory Mutual, an American research organisation have believed that vents have an adverse effect on sprinkler operation, delaying their operation, thereby encouraging fires to grow larger (Battrick 1986). Other research organisations, particularly the Fire Research Station believe that there is insignificant adverse effect on sprinkler operation caused by vent operation. Both organisations have conducted tests to assess the effect of ventilation on sprinkler operation.

Morgan (1992) has produced a set of interim guidelines, based research work described by Hinkley (1992a). The main recommendations concern the downdrag of smoke by sprinkler spray. Downdrag is caused by high velocity of water jets from sprinkler heads entraining smoke and air. A smoke layer can be completely destabilised and forced to mix into the ambient air below, creating large volumes of cool smoke. Downdrag only occurs where there is a high water flow rate, that occurs with Extra High Hazard occupancies. This would include warehouses storing highly flammable goods.

In other less hazardous occupancies, that use sprinklers with lower flow rates, downdrag is insignificant. Limited downdrag of smoke occurs with sprinklers that are close to walls or vents. It is suggested by Morgan that this is unlikely to block escape routes.

Sprinkler spray can adversely effect ventilators that are close to sprinkler heads, however as only one vent is likely to be effected, then only one vent should be

discounted. Ventilators that are not close to sprinkler heads are unaffected by sprinkler spray Hinkley (1992a).

One issue raised in the experimental work by Tamura and Mawhinney (1994), is that smoke from sprinkler controlled fires, generally has low buoyancy, due to much cooling by the sprinkler spray. This smoke will not generate pressures nor rise within building spaces, as hot smoke would be expected to. In atrium smoke control systems, a fundamental design assumption, is that the smoke will rise, albeit to a limited height, aiding extraction and ventilation. This is in disagreement with the work by Hinkley (1992a).

Hinkley (1992a), Tamura and Mawhinney (1994) and others have also found that concentrations of CO₂ and CO rise are much higher in shielded sprinklered fires, than in unsprinklered and unshielded sprinklered fires.

13.8.3.2 Effect

Sprinklers will have little effect on smoke, except for cooling the smoke, in most situations. This excludes high hazard sprinkler applications. The degree of cooling could affect smoke significantly, if it is cooled as low as suggested by Tamura and Mawhinney (1994), whereby it has little buoyancy. Even if cooling is not that extreme, then cooling could mean that where smoke has a high height of rise, additional entrainment will produce very cool smoke and stratification could occur.

13.8.4 Smoke

13.8.4.1 Variations

The spill plume experiments described in Chapters 5 to 9 demonstrate the variations that can occur with the flow of smoke from a compartment.

Other research into smoke movement is continuing to refine the understanding of smoke flow. However stochastic variations in the behaviour of smoke can still produce a wide range of variations to smoke characteristics.

It is impossible to present here a full range of variations that can occur. Chapter 5 discusses those in relation to the flow of smoke out of compartments and in atria and malls in some detail. A detailed of the results of the experiment is presented in Section 13.9, as an example of the variability of smoke flow.

13.8.5 Wind Effects

Marchant (1984) and Hong and Marchant (1990) identified possible failure modes of smoke control systems due to the wind. The potential for failure is dependent on the wind direction and wind speed.

Ingason and Persson (1995) have studied wind effects on venting and concluded that more investigations of the combined affect of the fire and the wind needs to be studied. The wind can cause serious problems with the stability of the smoke reservoir. The pattern of smoke flow within the reservoir can have significant affects on the efficiency of flow through vents.

13.8.6 Glass Breakage

The glass to a compartment breaking during a fire can increase the heat release rate of a fire and increase entrainment into the smoke. This results in larger volumes of smoke. The smoke temperature may not necessarily be higher.

Predictions on the time at which glass may break can vary greatly. This is dependent on the temperature of the glass and to a lesser extent on the pressures generated.

Usually, in smoke control design, low values are used for the temperature at which glass breaks. BR 258 recommends that in calculations, it should be assumed that float glass will fail at 70 °C and laminated glass will fail at 200 °C. These are pessimistic estimates of the temperature at which glass can fail, for the purpose of atrium (and mall) smoke control design. This effects smoke control design in a number of ways. If an atrium smoke control system is to prevent glass failure, then

the height of rise of the plume is raised until entrainment into the plume reduces its temperature to below that at which the glass may fail.

A review of the temperatures at which glass fails has been conducted by Shields (1996). This has found that failure occurs at much higher temperatures, therefore glass breakage will be limited and smoke will be contained by glass for periods longer than expected. This will result in increased filling times of atria. It will also result in reduced line plume widths, so create less smoke (but of a higher temperature).

13.9 Variations in Smoke Flow in Atria

13.9.1 General

The experiments conducted as a part of this thesis have some significant implications for smoke control system design. If these results were confirmed by a wider set of spill plume experiments, then smoke control applications would be affected in the following manner:

13.9.2 Fan and Vent Sizes

Smoke extract systems designed to BR 258 would have capacities 10 % greater than these results suggest, if a downstand is present. The systems would be 10 % smaller than these results suggest, if no downstand is present.

13.9.3 Temperature Rating of Atria Enclosure

The temperatures in the experiment were significantly different from predictions. This could be in part due to differences in heat loss. However, a large degree of difference is caused by limited entrainment into the smoke.

The experiments indicate that there is not a large amount of entrainment occurring in the rotation region. This means that smoke temperatures in the atrium are higher

than predicted. Components that are rated for the lower temperatures could fail, as a result of the temperatures being higher.

For example, float glass can fail at temperatures above 70 °C. Using the calculation methods in BR258, it could be shown that plume temperatures will not exceed this value, in a particular building design. If the float glass meets other design criteria, it should be acceptable to use it to separate the atrium from adjoining spaces, preventing smoke spread. The experiments in this thesis show that smoke temperatures could be much higher, causing the float glass to fail. Smoke would be able to spread into adjoining spaces.

Variations in entrainment occur with building geometries. Some of these are quantified in BR 186 and BR 258.

The experiments have investigated the effect of other variations in geometry, such as increasing the fire compartment length. The results of the experiment were not conclusive for variations in the entrainment into smoke to be predicted.

13.9.4 Margins for Error

As discussed in earlier Chapters, most design advice for smoke systems is generally conservative, so that there is probably a reasonable margin of safety in most designs.

For example, the design fire sizes used in many smoke control designs could be much larger than could actually occur. Unpublished research, currently being conducted at the Fire Research Station, is finding that sprinklered fires in typical offices are significantly smaller than the design fire sizes for offices. The potential for failure is reduced by these margins of safety.

13.9 Summary

Smoke control systems can fail due to many reasons, but these can be classified into a limited number of types. These are stated below:

13.9.1 Smoke Removal Systems

There can be inadequate areas of ventilation or extract rates and provision for inlet for effective smoke removal.

There may not be continuous paths for smoke and air movement, preventing effective smoke removal. There can be inappropriate leakage areas for given locations at the component interfaces and joints. Smoke buoyancy, wind, stack effect or fans can create pressures that are excessive or too low.

There are other criteria that will influence the performance of containment systems, such as temperature, sequencing of actions and external environmental factors.

13.9.2 Smoke Containment Systems

There can be inappropriate leakage areas in components, at component interfaces and joints. Smoke buoyancy, wind, stack effect or fans can create pressures that are excessive or too low. There may not be a continuous path for air movement, which to provide a barrier to smoke.

There are other criteria that will influence the performance of containment systems, such as temperature, sequencing of actions and external environmental factors.

13.9.3 Life Cycle Effects

Few smoke control systems are due to unavoidable natural variations in the system. Many of the failure modes described in this chapter are avoidable. Human error during design, construction and other stages of the life cycle process. The life cycle of smoke control systems needs to be carefully controlled to avoid unnecessary faults being incorporated into smoke control system designs.

13.9.4 Variations in Performance

These two sets of variations can be summarised in Figure 13.2. This shows the performance of a simple extract system varying during the life of a fire. If reasonably well managed system throughout its life-cycle, it will have a potential range of performance, measured by the extract rate.

As a life-safety system, the system will be judged by the time available for escape. In this example escape must occur before the mass of smoke produced from a fire exceeds the extract rate. It should be noted that in reality there will be a period during which the smoke base will descend to a certain level, after which escape will be increasingly hazardous.

The design smoke curve represents the volumes of smoke modelled for a particular fire regime. Stochastic variations and variations in knowledge can occur, resulting in variations to the modelled volumes of smoke. There would be upper and lower limits to the variations of the modelled volumes of smoke that could be produced. The upper limit could be the maximum volume of smoke for 90 percent of possible variations and the lower limit, the maximum volume for 10 percent of variations.

The system curve represents the extract rate of the smoke extraction system. The range of potential performance for a system, due to life-time events and periodic variations (daily, weekly and so on) is represented by the upper and lower limits to the system performance. The range represents the variations that could reasonably be expected to occur for a well designed, installed and maintained system, therefore excludes gross errors that could cause a system to fail completely. The upper limit is the maximum volume extract rate for 90 percent of possible variations. The lower limit represents the maximum volume extract rate for 10 percent of variations.

The two sets of variations will result in greatly varying escape times. Time D represents the most likely outcome. Time C represents a less likely outcome, in

which the performance of the system is at its lower limit, with the smoke volumes as predicted. Time C, represents the escape time reduced by 40 percent. Times A and B represent the effect of greater volumes of smoke being produced. The escape time is obviously less for A, due to the rapid growth in smoke volumes, and low extract rate of the system. The extra time available for escape is lost, even with the upper range of system performance, if rapid growth of smoke volumes occurs, as shown with time B.

These are hypothetical curves, so definitive conclusions cannot be drawn, but the importance of system variations is demonstrated. This could be developed into an analytical tool, for all system types, to assess probable outcomes for fire scenarios during the life of a building. Further research would be needed to quantify the effect of these variations. This needs to provide data for fire and smoke models and system performance.

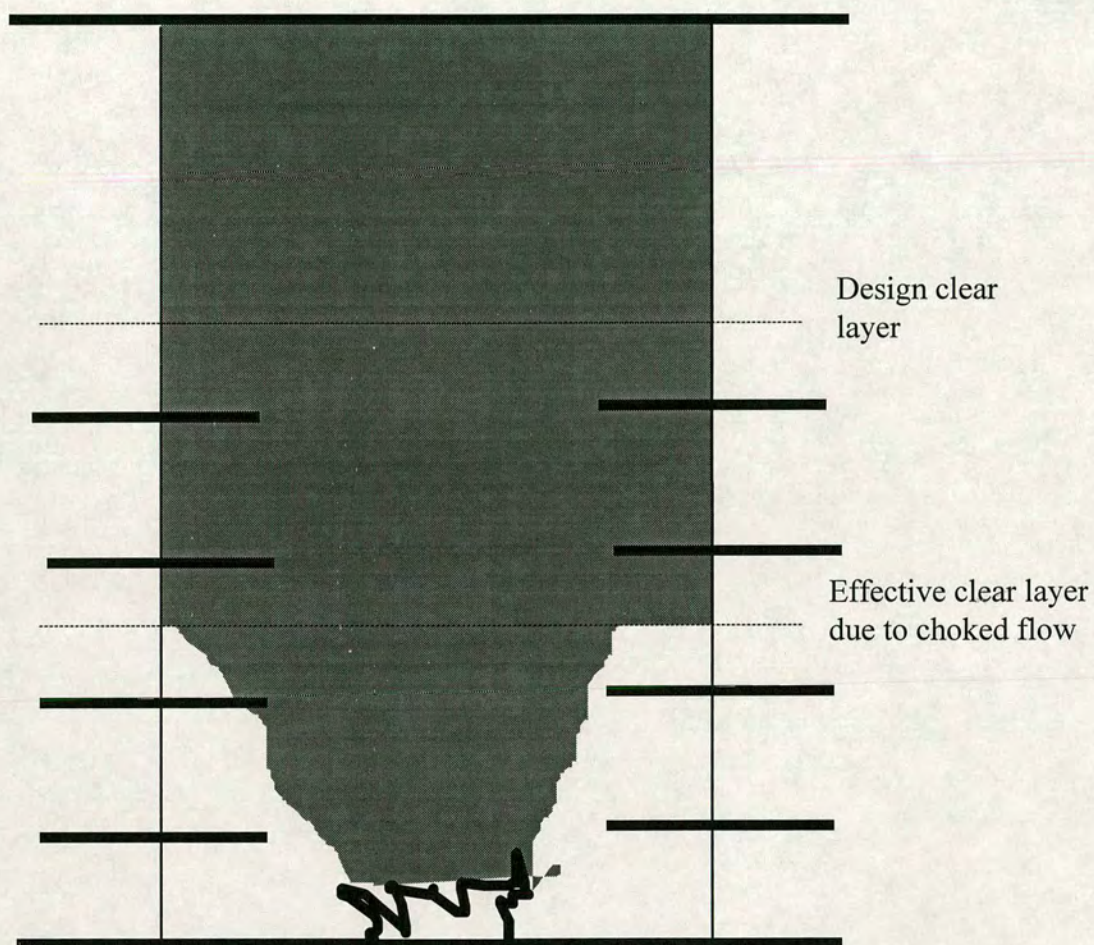
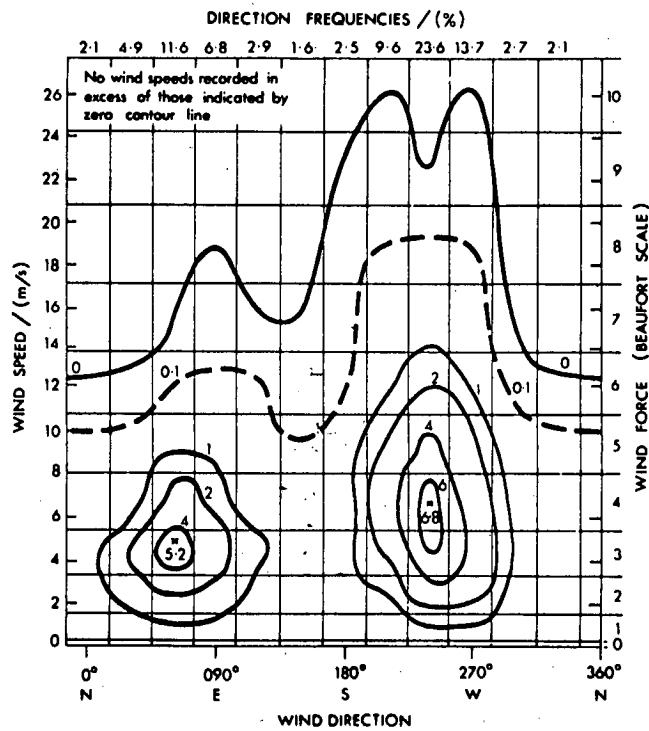


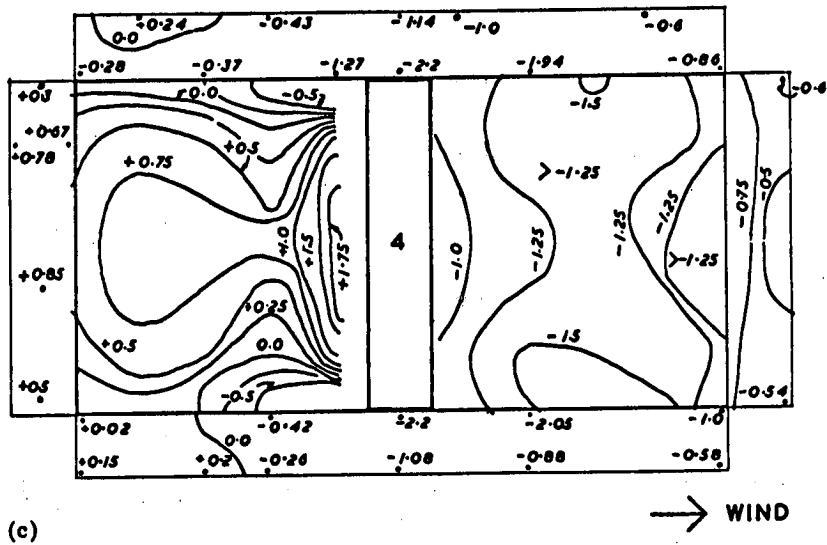
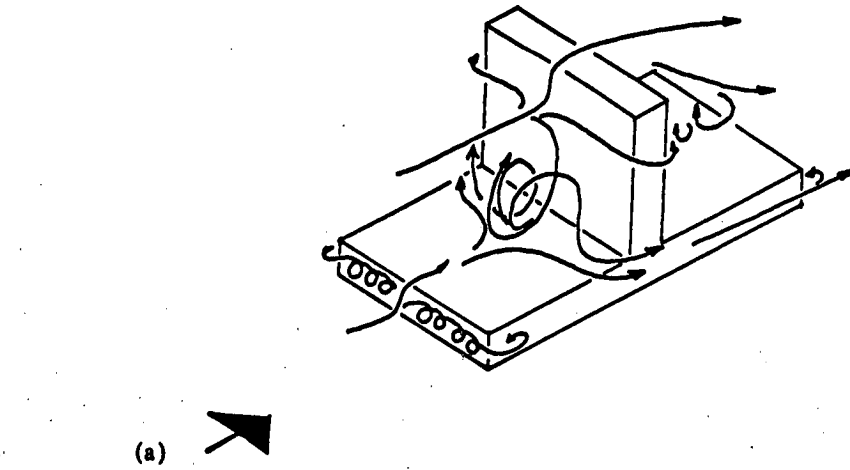
Figure 13.1 Choked Flow in an Atrium



On 15.9% of hours speed was ≤ 0.3 m/s (calm)
 On 20.7% of hours speed was ≤ 1.6 m/s

(d) Edinburgh (Turnhouse Airport). Period 1957-66.
 Effective height 10 m.

Figure 13.2 Wind Frequencies at Edinburgh (CIBSE Guide Volume A 1986)



X - Location of vent in analysis

Figure 13.3 Airflow Patterns and over a Simple Building (Marchant 1984)

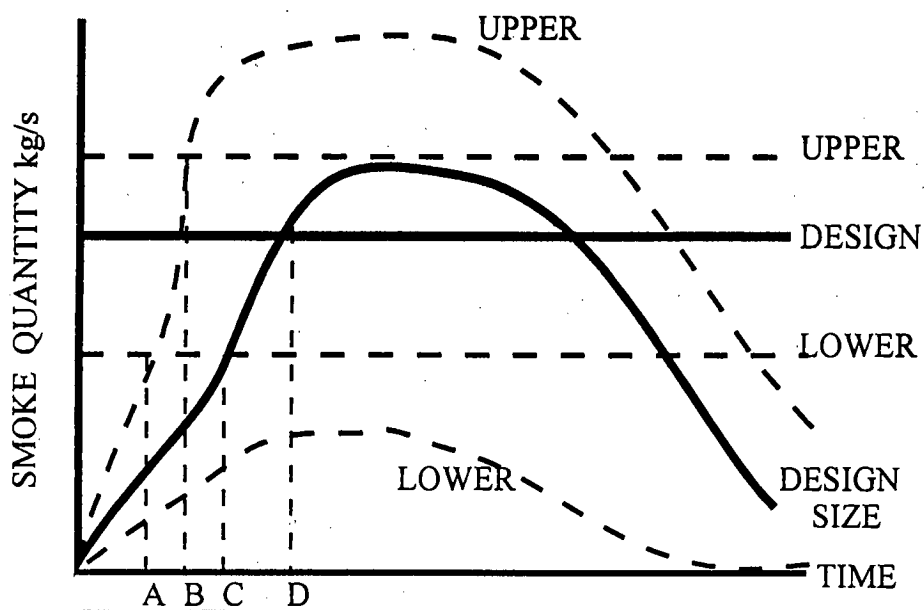


Figure 13.4 Result of Variations in Smoke Quantities and System Performance

Chapter 14: Conclusion

Smoke control system performance varies due to variations in the fire environment and due to variations in system performance. The cause and effect of these variations has been examined.

14.1 Experimental Results

The variations to the design quantities predicted by fire and smoke models was examined in detail for one particular model, the Fire Research Station spill plume calculations. Variations to the predictions for adhered plumes were found to be as follows:

1. The depth of a downstand has a limited effect on the flow from a compartment.
The coefficient of discharge (C_d) is approximately constant for an adhered plume.
2. Good agreement is made with the form of Law's formula (1995), which was developed from Yokoi's (1960) data correlation. The coefficient for the formula differs due to the experiment using an adhered plume.
3. Using the data from the duct measurements, the formula for adhered spill plumes (with free ends) has been correlated as:

$$M_z = 0.19(Q_f L^2)^{1/3} (z + 0.25(Dd + h)) \quad \text{kgs}^{-1}$$

The constant is 0.11 using PIV plume data.

4. There is a slight reduction in the mass flow rate, at the z-plane, due to increasing compartment length.
5. There is no large scale entrainment into the smoke in the rotation zone. Net entrainment in the rotation zone is limited to approximately 5 %. In some configurations there may be mass loss, because some smoke passing the w-plane is stripped from the main flow and re-enters the fire compartment.
6. Entrainment in the line plume close to the y-plane (up to 1.5 m above the y-plane full-scale) is higher than predicted by spill plume theory.

7. Additional entrainment to the mass flow rate of 20 to 50 %, may be occurring in the smoke reservoir.

14.1.1 Experimental Method

The measurements have been able to provide information on the characteristics of smoke flow from compartments into atria. A wider range of experimental configurations, geometry and fire size, need to be used to show that these results hold for a wide range of conditions. To minimise uncertainty about the results and the effect of scaling errors, a series of full-scale tests, providing measurements at the locations used in the experiments would be needed.

There was not, nor could there be, enough variation to the compartment geometry or fire sizes to allow a full range of data to be gathered to develop an alternative spill plume theory. This data has demonstrated the limitations of one theory and has identified areas requiring further research.

14.1.2 PIV

The experiments have demonstrated the benefit of using PIV measurement techniques. It has provided accurate instantaneous velocity data, in locations in the flow that were previously difficult to measure. Visualisation of the flow has allowed a more detailed and clearer understanding of the quantitative results than could otherwise be practicable.

There were limitations with the technique, with respect to the results that were required from this experiment. The technique is time consuming. A large amount of processing time required and many images are required for a representative range of data for time averaged values. Technical developments may improve this.

Regions of the flow that are dominantly two-dimensional do not provide accurate results. Large velocity ranges can be difficult to accommodate.

14.1.3 Recommendations for Further Research

As a result of this experiment two areas of research development have been identified:

1. Spill plumes
2. PIV in smoke and fire experiments

14.1.3.1 Spill Plumes

These experiments indicate that although the net result of the Fire Research Station spill plume calculations are correct, the quantities derived from intermediate calculations are subject to large errors. Further research is needed, particularly to determine:

- the effect of reservoir entrainment
- entrainment into the rotation region
- variations with the fire compartment geometry

There should be full-scale tests to provide benchmark values for a range of reduced scale experiments and possibly CFD analysis.

14.1.3.2 PIV

The use of PIV could be extended to be used for other reduced scale smoke flow and fire dynamics experiments.

14.2 Overview of the State of Smoke Control System Design

14.2.1 General

Events during the life-cycle of a smoke control system have a major affect on the performance of a smoke control system. The examples provided in the previous chapters provide evidence that the design, implementation and operation of smoke control systems is not always effectively conducted.

There are many reports of inspections of smoke control systems that have serious errors, but there have been few cases where this has led to smoke control failure during a fire. This could be due few systems being significantly deficient; systems having conservative designs; few fires occurring in buildings with these systems; and few post-fire investigations being made about the performance of these systems.

14.2.2 Questionnaire

A questionnaire attempted to determine the process of smoke control system design and installation.

It was found that building services engineers and fire safety engineers mainly restrict their involvement with smoke control systems to the design stage. Fire engineers have less involvement in the design stage.

Ranges of acceptance testing methods are used, but few hot smoke tests are conducted.

The results have confirmed a general systems engineering principle, that, as a system becomes more complex, failure is more likely to occur. Pressurisation systems are generally the least reliable systems.

A range of failure modes have been experienced with most forms of smoke control. Component faults occur, particularly with fans. System faults are common; controls and other associated systems are a common cause of poor smoke control system performance.

There were no respondents who experienced a system with poor performance that was caused by deficiencies in smoke movement models and smoke movement processes.

14.2.3 Examples of Smoke Control System Failure

Examples are provided of a wide range of forms of failure and performance variation. Although some are due to natural events, such as material degradation, many of are due to human error. On very large complex projects a discipline, Human Factors Analysis, has developed to ensure efficient interaction between project team members, at all stages. Part of this technique involves understanding the engineering disciplines and the degree of error that can be introduced into a system, and the consequences of these errors. From this reliability analysis is made to compare the potential for success of different engineering options (Pidgeon and Turner, 1986).

14.2.4 Development

Continued research into the performance of smoke control systems will require a more detailed examination of the causes and effects of faults, by direct contact with various target groups and conducting short interviews. Also the performance of a number of existing systems could be examined in detail, to provide an objective assessment of smoke control system performance.

14.3 Risk Assessment of Smoke Control System Performance

As discussed, there is, and nor is it likely to be possible to develop suitable data for quantitative analysis of smoke control system reliability. However, by developing a comprehensive taxonomy of failure modes, it would be possible, using expert judgement to identify the potential for failure.

An effective methodology for qualitative assessment of the reliability of particular smoke control systems is 'Failure Modes, Effects and Criticality Analysis.

The major components, sub-systems and related fire engineering systems and importance to the smoke control system needs to be identified. The potential for failure needs to be judged as Frequent, Probable, Occasional, Remote or Improbable.

The potential for human error factors must be included in this analysis. The consequences can be judged to be Catastrophic, Severe, Serious, Minor and Negligible. This provides the basis for a 'pilot' format.

The reliability of a smoke control system needs to be judged against the purpose for which it is provided. Life safety systems require very high (near absolute) reliability, property protection systems require a high reliability (the level of which would be determined by a cost benefit analysis) and fire fighters' smoke clearance systems require the lowest level of reliability.

14.4 Application of this Work to Other Areas of Fire Safety

The format for this analysis could be extended for other fire safety systems, to form an extended analysis of integrated fire safety systems.

It could be used in the analysis of fire safety and smoke control in applications other than buildings, such as tunnels, mines and ships.

In all situations, where fire safety systems may be required, the reliability of the system needs to be known. This allows the benefits of fire safety options to be judged clearly, and form part of the selection process. Ideally this should be quantified. However, it is difficult to develop reliable data. Qualitative assessment provides a comprehensive method of assessing potential failure.

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APPENDIX

There are no Appendices to Chapters 1 to 4.

APPENDIX 5

The calculation method for the mass flow rate of adhered and free plumes, taken from BR 258, Appendix B is shown in this section.

Outline of procedure

The calculation proceeds in discrete stages:

- 1 The designer must know:
 - (a) the internal geometry of his building, including relevant channel widths, and
 - (b) at least two of the key parameters of the approach flow. Useful pairs are:
 - mass flow/heat flux
 - mass flow/mean layer temperature
 - mass flow/ceiling temperature
 - heat flux/mean layer temperature
 - heat flux/ceiling temperature
 - heat flux/layer depth
 - layer depth/mean layer temperature
 - layer depth/ceiling temperature
- 2 Using the known parameters for the approach flow, calculate the remaining parameters of the flow.
- 3 Using the results from the preceding stage, calculate the entrainment into the flow as it rotates around the void edge, ie as the smoky gases change from a horizontally-moving flow to a vertically-moving flow. By the end of this stage the key parameters of the vertically-moving gases will be known at the horizontal plane passing through the ceiling/void edge. These parameters are the heat flux, the vertically-moving mass flux, and the kinetic energy of the gases (this last is based only on the vertical component of velocity).
- 4 The plume at greater heights behaves as if it rises from an infinitely wide source located in the horizontal plane passing through the ceiling/void edge, where that source has horizontal profiles of

both buoyancy and (the vertical component of) velocity which can be described by Gaussian functions. This source is, of course, virtual. We have followed Lee and Emmons⁵⁰ in using this source, and indeed in the method of calculating the plume above the source. We follow Lee and Emmons in calling this source an 'Equivalent Gaussian source'.

Calculate the key parameters of the Equivalent Gaussian source by ensuring that the three key parameters from Stage 3 above keep the same values.

- 5 Knowing the height above the ceiling/void edge (for example, this is likely to be chosen to be equal to the smoke layer base in the reservoir above the void), calculate the entrainment into the spill plume. This calculation treats the plume as a perfect two-dimensional plume having a length equal to the width of the channel of the approach flow.
- 6 Calculate the additional entrainment into the free ends of the plume. This assumes that the bulk of the plume is relatively unaffected by these end effects — reasonable for plume heights typically smaller than or comparable to the plume length³⁶.

Detailed procedure

Stage 1

Complete all necessary pre-calculations to derive the key parameters of the approach flow described in 1b on this page.

Stage 2

Select from the following equations¹⁷ to determine the remaining parameters for the approach flow from the initial known parameters:

Calculate the mean layer temperature ($\bar{\Theta}_w$)

$$\bar{\Theta}_w = \frac{Q_w}{M_w c} \quad \dots(B1)$$

Calculate the mass flow rate (M_w) at the opening given by³⁰:

$$M_w = \frac{2}{3} C_d^{3/2} (2g \Theta_{cw} T_o)^{1/2} \frac{W \rho_o}{T_{cw}} d_w^{3/2} K_M \quad \dots(B2)$$

where $\rho_o = 1.22 \text{ kgm}^{-3}$ for an ambient temperature T_o of 288 K

$C_d = 0.6$ for opening with a deep downstand
or 1.0 for no downstand

$g = 9.81 \text{ ms}^{-2}$

$K_M = 1.3$ for most typical flowing layers

The depth of the layer (d_w) at the opening is then given by³⁰:

$$d_w = \left[\frac{3M_w T_{cw}}{2C_d^{3/2} K_M W \rho_o (2g \Theta_{cw} T_o)^{1/2}} \right]^{2/3} \dots(B3)$$

The mass-weighted average temperature $\bar{\Theta}_w$ of the gas layer is³⁰:

$$\bar{\Theta}_w = \frac{K_Q}{K_M} \Theta_{cw} \dots(B4)$$

where $K_Q = 0.95$ for most typical flowing layers.

Note the importance of knowing whether there is a downstand running along the edge of the void (and thus at right angles to the direction of the flow), because this changes the value of C_d .

Greater accuracy can be achieved by calculating the values of the profile correction factor K_M and K_Q using the temperature dependent formulae in Reference 30, although this is usually unnecessary for most practical designs.

The layer's characteristic velocity (v) is given by¹⁷:

$$v = 0.96 \frac{C_d K_M}{K_Q^{1/3}} \left[\frac{g Q_w T_{cw}}{c \rho_o W T_o^2} \right]^{1/3} \dots(B5)$$

For a deep downstand, where $C_d = 0.6$, this becomes:

$$v = 0.76 \left[\frac{g Q_w T_{cw}}{c \rho_o W T_o^2} \right]^{1/3} \dots(B6)$$

With no downstand at the opening, $C_d = 1.0$, and:

$$v = 1.27 \left[\frac{g Q_w T_{cw}}{c \rho_o W T_o^2} \right]^{1/3} \dots(B7)$$

Calculate the horizontal flux (B) of vertical buoyant potential energy^{17,36} (relative to the void edge):

$$B = \frac{\rho_o}{2} \frac{\Theta_{cw}}{T_{cw}} g v d_w^2 \dots(B8)$$

Stage 3

Calculate the mass flux (M_y) rising past the void edge¹⁷:

$$M_y = \frac{2}{3} \rho_o W \alpha' \left[2g \frac{\Theta_c}{T_o} \right]^{1/2} d_w^{3/2} + M_w \dots(B9)$$

where the entrainment constant (α') = 1.1

If the line plume is single-sided, go to Stage 7 of this procedure, after completion of Stage 3.

Stage 4

Calculate the Equivalent Gaussian Source:

First convert Q and M_y into the corresponding parameters per unit length of plume (ie divide by the channel width (W) to give Q_o and A).

Then solve the following equations³⁶:

$$\xi = \left[A + \frac{Q_o}{T_o c} \right] \frac{1}{\sqrt{\pi} \rho_o} \quad \dots(B10)$$

$$\left[\frac{\Theta}{T} \right]_G = \frac{Q_o \sqrt{1 + \lambda^2}}{T_o c \lambda \left[A + \frac{Q_o}{T_o c} \right]} \quad \dots(B11)$$

where the empirical thermal constant⁵⁰ (λ) = 0.9

$$\zeta = \frac{2B}{\sqrt{\pi} \rho_o \left[\frac{1}{\sqrt{3}} - \left[\frac{\Theta}{T} \right]_G \frac{\lambda}{\sqrt{1 + 3\lambda^2}} \right]} \quad \dots(B12)$$

$$u_G = \sqrt{\frac{\zeta}{\xi}} \quad \dots(B13)$$

and:

$$b_G = \frac{\xi}{u_G} \quad \dots(B14)$$

where $\left[\frac{\Theta}{T} \right]_G$, u_G and b_G are parameters of the Equivalent Gaussian Source.

Stage 5

Calculate the entrainment into the rising plume.

The Source Froude number (F) for the line plume is³⁶:

$$F = \left[\frac{2}{\pi} \right]^{1/4} \left[\frac{\alpha}{\lambda \left[\frac{\Theta}{T} \right]_G} \right]^{1/2} \frac{u_G}{(g b_G)^{1/2}} \quad \dots(B15)$$

where $\alpha = 0.16$ for double-sided⁵⁰ and 0.077 for single-sided line plumes³⁷. Calculate the transformed parameter (v_G) for the Equivalent Gaussian Source:

$$v_G = \frac{1}{(1 - F^2)^{1/3}} \quad \dots(B16)$$

Determine the value of $I_1(v_G)$ by using the following procedure or an alternative method set out in later in this appendix on page 53.

v_G represents a value on the vertical axis of Figure B1. Look across to the middle solid curve and find the corresponding value of $I_1(v_G)$ on the other axis.

Calculate the transformed height parameter of x' corresponding to the desired plume height (x):

$$x' = \frac{2}{\sqrt{\pi}} \alpha \frac{x}{b_G} \quad \dots(B17)$$

Next calculate $\Delta I_1(v)$:

$$\Delta I_1(v) = \frac{x'}{\left[F^2 (1 - F^2) \right]^{1/3}} \quad \dots(B18)$$

$$\text{and} \quad I_1(v) = I_1(v_G) + \Delta I_1(v) \quad \dots(B19)$$

Determine values of b' , p' and u' corresponding to the calculated value of $I_1(v)$ using the following procedure or the alternative method on page 53.

$I_1(v)$ represents a value on the horizontal axis of Figure B1. Using this value find the corresponding values (from all three curves) for u'' , p'' and b'' . Then use the following equations to determine u' , p' and b' ,

where:

$$u' = u'' F^{1/3} \quad \dots(B20)$$

$$p' = \frac{1}{(1 - F^2)^{1/3} p''} \quad \dots(B21)$$

$$b' = b'' \left[F^2 (1 - F^2) \right]^{1/3} \quad \dots(B22)$$

Next determine the characteristic half-width (b) of the line plume³⁶ at height x :

$$b = b' b_G \quad \dots(B23)$$

Then calculate the axial vertical velocity component (u) of the gases at height x :

$$u = \frac{u' u_G}{F} \quad \dots(B24)$$

Calculate the mass flow per unit plume length (m_r) passing the chosen height³⁶ x :

$$m_r = \sqrt{\pi} \rho_0 u b \left[1 - p' \left[\frac{\Theta}{T} \right]_G \frac{\lambda}{(1 + \lambda^2)^{1/2}} \right] \quad \dots(\text{B25})$$

Convert to the total mass flow in line plume (ignoring end effects) by multiplying Equation B25 by the channel width (ie $m_r W$).

Stage 6

Calculate³⁸ the entrainment δM_r into the free ends of the line plume. The width of the line plume (and also its axial velocity) can be taken as being approximately constant for most of its height as a first order approximation, and equal to the mean of the values at the Equivalent Gaussian Source and at the chosen height (x).

The entrainment δM_r into both ends of the line plume is then³⁸:

$$\delta M_r = 4 \bar{h} \bar{u} \alpha x \rho_0 \quad \dots(\text{B26})$$

where:

$$\bar{h} = (h_G + b) / 2 \quad \dots(\text{B27})$$

$$\bar{u} = (u_G + u) / 2 \quad \dots(\text{B28})$$

Add this to the plume entrainment result from Stage 5 to obtain the total mass flow M_r of smoky gases rising past the specified height (x).

$$\text{ie:} \quad M_r = m_r W + \delta M_r \quad \dots(\text{B29})$$

It should be noted that where both ends of a plume are bounded by side walls (eg, as in a shaft) then $\delta M_r = 0$.

Stage 7

Modifications to the above procedure for single-sided^{17,37,51} (or adhered) line plumes.

Convert both the Equivalent Gaussian Source and the plume into a composite of a real and an imaginary half, so that the centre line of the composite lies along the vertical wall to which the plume is adhering. This is done by doubling values for B , M_v (and hence A), and Q from Stage 3 before returning to Stages 4 to 6 above. Note that experiments³⁷ show that the value of α needed in Stages 4 to 6 should change from 0.16 (valid for a free or double-sided plume) to 0.077 for the adhered plume.

On completing Stage 6, halve the final value of mass flow M_r rising past the desired plume height (x).

Alternative method for determination of $I_1(v_G)$

If v_G is greater than 1.549 then $I_1(v_G) = (v_G - 0.75)/0.9607$

If v_G is less than or equal to 1.549 and v_G is greater than 1.242 then $I_1(v_G) = (v_G - 0.843)/0.8594$

If v_G is less than or equal to 1.242 and v_G is greater than 1.059 then $I_1(v_G) = (v_G - 0.9429)/0.6243$

If v_G is less than 1.069 then $I_1(v_G) = (v_G - 1.0)/0.3714$

Alternative method for calculating value of b' , p' and u'

(a) Determination of u''

If $I_1(v)$ is greater than 1.896 then $u'' = 1.0$

If $I_1(v)$ is greater than 0.786 and $I_1(v)$ is less than or equal to 1.896 then $u'' = 0.0908 I_1(v) + 0.821$.

If $I_1(v)$ is less than or equal to 0.786 then $u'' = I_1(v)^{0.35}$

(b) Determination of p''

If $I_1(v)$ is greater than 0.832 then $p'' = 0.9607 I_1(v) + 0.75$

If $I_1(v)$ is greater than 0.464 and less than or equal to 0.832 then $p'' = 0.8594 I_1(v) + 0.8429$

If $I_1(v)$ is greater than 0.186 and $I_1(v)$ is less than or equal to 0.464 then $p'' = 0.6243 I_1(v) + 0.9429$

If $I_1(v)$ is less than or equal to 0.186 then $p'' = 0.3714 I_1(v) + 1.0$

(c) Determination of b''

If $I_1(v)$ is greater than 2.161 then $b'' = 0.938 I_1(v) + 0.82$

If $I_1(v)$ is less than or equal to 2.161 and $I_1(v)$ is greater than 1.296 then $b'' = 0.89 I_1(v) + 0.95$.

If $I_1(v)$ is less than or equal to 1.296 and $I_1(v)$ is greater than 0.896 then $b'' = 0.81 I_1(v) + 1.071$.

If $I_1(v)$ is less than or equal to 0.896 and $I_1(v)$ is greater than 0.65 then $b'' = 0.619 I_1(v) + 1.214$.

If $I_1(v)$ is less than or equal to 0.65 and $I_1(v)$ is greater than 0.543 then $b'' = 0.331 I_1(v) + 1.414$.

If $I_1(v)$ is less than or equal to 0.543 and $I_1(v)$ is greater than 0.421 then $b'' = 0.0627 I_1(v) + 1.55$.

If $I_1(v)$ is less than or equal to 0.421 and $I_1(v)$ is greater than 0.348 then $b'' = 1.821 - 0.6 I_1(v)$

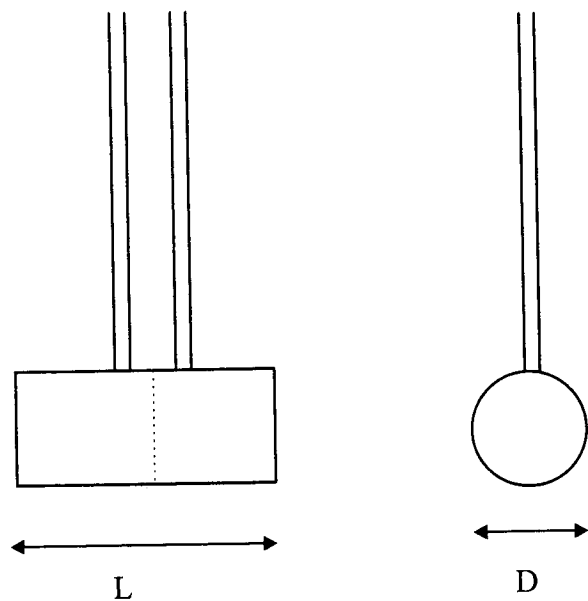
If $I_1(v)$ is less than or equal to 0.348 then $b'' = I_1(v)^{-0.4}$

Now calculate u' , p' and b' from Equations B20, B21 and B22 in Stage 5.

APPENDIX 6

A 6.1 Bi-directional Probe

The probe shown in Figure A6.1 (McCaffrey and Heskestad) consists of a short piece of stainless steel tubing ($L/D = 2$) with a diaphragm in the centre and two taps drilled close to, and on either side of the diaphragm. The tube axis is aligned with the flow, the upstream tap sensing the stagnation pressure, the downstream tap sensing slightly less than static. The small tubes used to carry the signals also serve as mountings for the probe.



Typically $D = 25\text{ mm}$, but probes down to 10 mm diameter are commonly used.

Figure A6.1 Bi-Directional Probe

A6.3 Cross Correlation Velocimetry (CCV)

The fundamentals of CCV are described by Motevalli et al (1992). In turbulent flow, eddy structures retain their shape and characteristics over a time period and space. If the turbulent level is low, then the development of eddies is 'frozen' during a short time period. If these eddy structures can be traced and identified, then the most probable mean velocity of the flow can be estimated as the weighted average of the velocities with which the eddies are moving. This weighing is inherent in CCV since the larger eddies have a more profound effect on the correlation results.

Research has shown that the best correlation obtained for a sensor signal is:

$$\Delta t = \Delta x / u \quad \quad \quad s \quad \quad \text{Eq. A6.1}$$

Which demonstrates that the mean flow velocity can be found by measuring the time for an eddy structure to move between two points, at a set spacing.

The eddy structure is most easily traced in hot gas flows, over short distances, by measuring temperature. Therefore, two sensors, aligned in the direction of the flow, can be used to measure the movement of eddy structures.

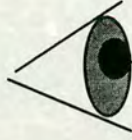
Highly sensitive thermocouples are needed to respond to rapid temperature changes. A typical choice is Type E (chromel-constantan) thermocouple, 0.0254 mm diameter.

The distance between thermocouples needs to be carefully controlled, especially in reduced-scale experiments. It needs to be smaller than the eddy structure, i.e. less than ceiling jet thickness. It also needs to be large enough to allow a time shift between pairs of thermocouples to be detected. Special data processing methods are needed to compare the temperature readings of a pair of thermocouples.

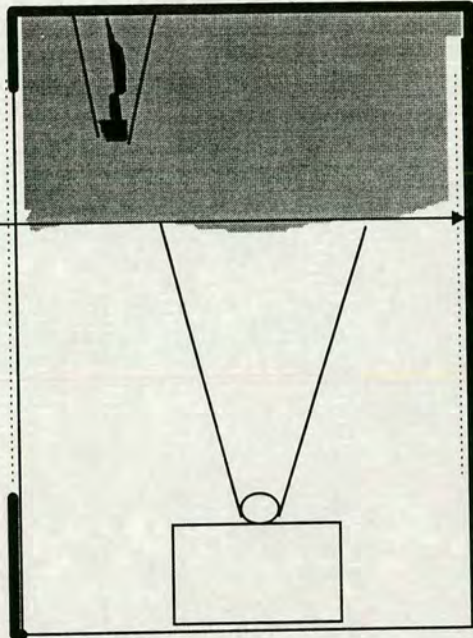
If thermocouple junction beads vary in size then errors can occur, due to differing time responses.

A6.4 Visualising the Flow, and Measuring

Smouldering fibreboard, suspended in wire cage, at high level in the atrium to provide tracer smoke.



Scales marked on the glass and on the rear wall of the atrium to provide level line of sight to measure depth of smoke



Slide projector to illuminate the flow

A6.5 Log Linear Rule

Daly (1992) describes a method of measuring the air velocity in ducts. The standard instrument to use is the pitot-static tube. The tube needs to be aligned parallel with the duct axis. The radii at which measurements are taken have been selected by the 'log-linear rule', being off-centre by an amount which takes account of the most probable velocity distribution across the element area. The mean velocity can be found from these.

A6.6 Alternative Heat Sources

A6.6.1 Electric heaters

These can be a relatively convenient, clean and safe form of heat source, but could not be used because they cannot generate the required heat output per area, so tend to produce laminar plumes (Marshall 1994) or flow regimes more similar to Ventilation Controlled fires (Hansell 1993). They also require a much longer period to reach steady state.

A6.6.2 Wood cribs

Small wood cribs can be constructed to use as a fuel source. It can be quite a convenient method to use, but do not give a steady heat output, which is also hard to quantify. The mass loss rate can be measured, but the heat release rate needs to be estimated, as the combustion of wood occurs with varying degrees of efficiency, depending on the ventilation conditions and other factors.

A6.6.3 Gas

Gas can give a controlled steady heat output. The area of fire can be varied for a particular heat output. The fire can be safely controlled. Butane is commonly used for fire safety experiments, as it produces little soot and carbon monoxide.

No gas supply was available and the limited carbon monoxide production may have had health and safety implications, restricting the experiment.

A.6.7 Safety Procedures

The following safety procedure was developed to avoid accidental spillage and to control the fumes from the methanol:

A6.7.1 Prior to the Experiment

Only one Winchester bottle of methanol to be in laboratory at any time. None to be left in laboratory overnight.

Inspect Reservoir, supply lines and burning tray to ensure no spillage or leaks could occur.

Check that on/off valves below the reservoir are off, and that the drainage valve is sealed shut.

Check flow meter control valve is off.

Check laser that the laser start up has been initiated and ready to use.

Start fans to laboratory and fans from model atrium.

Place ice packs around reservoir and transfer methanol from Winchester bottle into reservoir.

Fit lid to reservoir for duration of experiment. Keep vent pipes closed.

A6.7.2 During Experiment

Turn on reservoir valve.

Turn on control valve and set flow to correct flow rate and ignite methanol.

Open vent pipe.

Monitor flow rate and flame regularly. Inspect at all times to ensure that no leaks or spillage develop.

A6.7.3 After Experiment

Turn off valve at reservoir and at control valve; let excess methanol on burning surface burn off. Close vent pipe to reservoir.

Drain off excess methanol from reservoir into Winchester. Return this to Fire Safety Laboratory.

Keep atrium fans running for a minimum of 10 minutes. Keep laboratory fans on until all work in laboratory complete.

Inspect equipment for any faults.

Clean burning plate.

A6.7.4 Accidental Spillage

Turn off valves.

Cover burning plate with fibrous material.

Inform others to keep away.

Mop up with water: dilute greatly.

Ventilate area. Keep fans running.

Large spillage: contain with sand. Soak up with towels.

Appendix 7 Results

Lf (m)	Dd (m)	Qf (kW)	z (m)	$\theta (^{\circ}\text{C})$	$\rho(\text{kg/m}^3)$	$v \text{ (m/s)}$	$V \text{ (m}^3\text{/s)}$	$m \text{ (kg/s)}$
0.41	0.00	6.09	0.75	36.5	1.134	3.273	0.213	0.242
0.41	0.00	4.67	0.75	35.0	1.140	2.833	0.185	0.210
0.41	0.00	4.67	0.55	38.5	1.127	2.116	0.138	0.155
0.41	0.05	6.09	0.75	38.0	1.129	2.682	0.175	0.197
0.41	0.05	4.67	0.75	37.0	1.133	2.321	0.151	0.171
0.41	0.05	4.67	0.55	40.5	1.120	1.800	0.117	0.131
0.41	0.10	6.09	0.75	40.5	1.120	2.239	0.146	0.163
0.41	0.10	4.67	0.75	41.0	1.118	1.994	0.130	0.145
0.41	0.10	4.67	0.55	44.0	1.108	1.698	0.111	0.123
0.41	0.20	6.09	0.75	43.0	1.111	1.751	0.114	0.127
0.41	0.20	4.67	0.75	41.0	1.118	1.689	0.110	0.123
0.41	0.20	4.67	0.55	43.5	1.109	1.463	0.095	0.106
1.01	0.00	4.67	0.75	33.0	1.147	2.564	0.167	0.192
1.01	0.00	4.67	0.55	40.0	1.122	2.045	0.133	0.149
1.01	0.05	4.67	0.75	38.0	1.129	2.119	0.138	0.156
1.01	0.05	4.67	0.55	40.0	1.122	1.789	0.117	0.131
1.01	0.10	4.67	0.75	33.5	1.146	1.940	0.126	0.145
1.01	0.10	4.67	0.55	35.5	1.138	1.558	0.102	0.116
1.01	0.20	4.67	0.75	38.0	1.129	1.625	0.106	0.120
1.01	0.20	4.67	0.55	40.0	1.122	1.399	0.091	0.102
1.61	0.00	4.67	0.75	34.0	1.144	2.401	0.156	0.179
1.61	0.00	4.67	0.55	38.5	1.127	2.040	0.133	0.150
1.61	0.05	4.67	0.75	34.5	1.142	2.440	0.159	0.182
1.61	0.05	4.67	0.55	38.5	1.127	1.826	0.119	0.134
1.61	0.10	4.67	0.75	35.0	1.140	1.972	0.128	0.146
1.61	0.10	4.67	0.55	36.0	1.136	1.596	0.104	0.118
1.61	0.20	4.67	0.75	34.0	1.144	1.769	0.115	0.132
1.61	0.20	4.67	0.55	39.0	1.125	1.379	0.090	0.101
2.21	0.00	6.09	0.75	33.5	1.146	2.211	0.144	0.165
2.21	0.00	4.67	0.75	32.0	1.151	2.229	0.145	0.167
2.21	0.00	4.67	0.55	36.5	1.134	1.724	0.112	0.127
2.21	0.05	6.09	0.75	36.0	1.136	2.100	0.137	0.155
2.21	0.05	4.67	0.75	34.0	1.144	2.166	0.141	0.161
2.21	0.05	4.67	0.55	40.0	1.122	1.593	0.104	0.116
2.21	0.10	6.09	0.75	37.5	1.131	1.855	0.121	0.137
2.21	0.10	4.67	0.75	34.0	1.144	1.806	0.118	0.135
2.21	0.10	4.67	0.55	40.5	1.120	1.380	0.090	0.101
2.21	0.20	6.09	0.75	38.0	1.129	1.831	0.119	0.135
2.21	0.20	4.67	0.75	34.5	1.142	1.774	0.116	0.132
2.21	0.20	4.67	0.55	37.0	1.133	1.316	0.086	0.097

Table A7.1 Calculations for Mass Flow Rates in the Extract Duct sumvel02

A7.2 Ratio of Maximum to Mean Streamwise Flow (Umean/Umax)

Umean/Umax m/s		Dd= 0.00	Dd= 0.05	Dd= 0.10	Dd= 0.20
Lf = 0.41	w-plane	0.589	0.643	0.736	0.527
Lf = 2.21	w-plane	0.508	n/a	n/a	0.557
Lf = 0.41	y-plane	0.758	0.733	0.579	0.598
Lf = 2.21	y-plane	0.633	n/a	n/a	0.722
Lf = 0.41	z 0.75	0.667	0.725	0.477	0.565
Lf = 2.21	z 0.75	0.650	n/a	n/a	0.753

Table A7.2 Ratio of Maximum to Mean Streamwise Flow (Umean/Umax

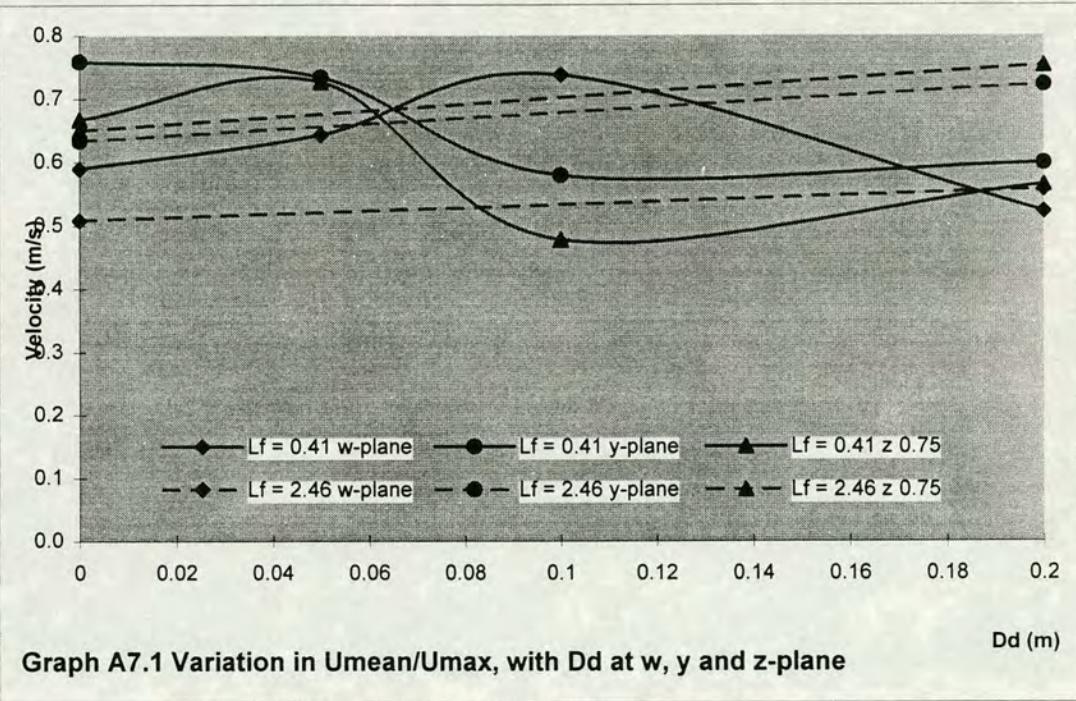


Table A7.4 Summary of W-Plane Data
PIV Velocity Data; Velocities at Interrogation Cell Centres (m/s)

Dd = 0	Lc = 660	Dd = 0	Lc = 2460
rzceiling	m/s	rzwall	m/s
0	0	0	0
6.92	0.666031	15.7	0.793456
24.2	0.59038	33	0.587054
41.48	0.467009	50.2	0.472938
58.76	0.425969	67.5	0.240088
76.04	0.342232	104	0
93.32	0.269348		
128	0		
Dd = 50	Lc = 660	Dd = 50	Lc = 2460
rzceiling	m/s	rzwall	m/s
0	0		
12.9	0.444165	No data	
33.6	0.468442		
54.2	0.474787		
74.9	0.46742		
95.6	0.229912		
156	0		
Dd = 100	Lc = 660	Dd = 100	Lc = 2460
rzceiling	m/s	rzwall	m/s
0	0		
14.5	0.558114	No data	
32.4	0.56844		
50.3	0.421074		
68.1	0.374796		
86	0.354738		
107	0		
Dd = 200	Lc = 660	Dd = 200	Lc = 2460
rzceiling	m/s	rzwall	m/s
0.0	0.00000	0	0
15.0	0.66070	16.2	0.660354
34.200	0.47333	35.4	0.446306
53.400	0.41948	54.6	0.415958
72.600	0.30972	73.8	0.389984
91.800	0.32134		0
111.000	0.15033		
130.200	0.00000		
158.000	0.00000		

rzceiling = distance below ceiling (mm) Lc = length of compartment
 Supplementary appendix shows velocity data for the grids.

PIV Velocity Data for W-Plane;**Interpolated Velocities at Thermocouple Centres (m/s)**

rzceiling mm	Lc = 660 d = 0	Lc = 660 d = 50	Lc = 660 d = 100	Lc = 660 d = 200	Lc = 2460 d = 0	Lc = 2460 d = 200
0	0.000	0.000	0.000	0.000	0.000	0.000
10	0.687	0.393	0.437	0.510	0.583	0.510
20	0.621	0.477	0.593	0.675	0.807	0.675
30	0.551	0.469	0.577	0.528	0.643	0.528
45	0.453	0.470	0.472	0.421	0.510	0.421
60	0.421	0.479	0.390	0.419	0.330	0.419
75	0.345	0.462	0.383	0.382	0.181	0.382
90	0.300	0.269	0.313	0.292	0.086	0.292
105	0.182	0.179	0.765	0.179	0.000	0.179
120	0.055	0.124	0.000	0.070	0.000	0.070
180	0.000	0.000	0.000	0.000	0.000	0.000
240	0.000	0.000	0.000	0.000	0.000	0.000

Thermocouple Data for W-Plane**Temperature Rise Interpolated at 15 mm Centres (C)**

rzceiling mm	Lc = 660 d = 0	Lc = 660 d = 50	Lc = 660 d = 100	Lc = 660 d = 200	Lc = 2460 d = 0	Lc = 2460 d = 200
0	71.9	82.8	96.9	128.5	65.7	97.8
10	71.9	82.8	96.9	128.5	65.7	97.8
20	65.9	76.3	94.7	127.5	67.0	99.5
30	59.7	70.7	91.3	120.3	67.2	95.1
45	51.7	64.0	84.5	85.6	62.6	70.9
60	44.2	52.1	75.2	51.8	55.2	46.6
75	39.3	45.6	62.8	35.0	35.9	31.2
90	35.1	39.9	48.7	25.0	24.4	20.7
105	27.9	28.3	30.8	17.3	14.0	13.3
120	22.3	20.8	18.4	13.2	8.9	9.7
180	10.6	8.7	9.7	10.1	4.6	5.9
240	5.9	6.4	6.9	9.1	4.1	5.6

Mass Flux at W-Plane (kg/s)

rzceiling	Lc = 660	Lc = 660	Lc = 660	Lc = 660	Lc = 2460	Lc = 2460
mm	d = 0	d = 50	d = 100	d = 200	d = 0	d = 200
0	0.000	0.000	0.000	0.000	0.000	0.000
10	0.660	0.367	0.392	0.451	0.569	0.298
20	0.607	0.454	0.536	0.552	0.785	0.335
30	0.548	0.452	0.526	0.440	0.625	0.241
45	0.461	0.462	0.438	0.417	0.502	0.192
60	0.438	0.487	0.371	0.338	0.332	0.148
75	0.364	0.479	0.377	0.342	0.192	0.125
90	0.320	0.284	0.321	0.343	0.094	0.110
105	0.199	0.195	0.083	0.210	0.000	0.042
120	0.061	0.139	0.000	0.000	0.000	0.000
180	0.000	0.000	0.000	0.000	0.000	0.000
240	0.000	0.000	0.000	0.000	0.000	0.000

Heat Flux at W-Plane (kW)

rzceiling	Lc = 660	Lc = 660	Lc = 660	Lc = 660	Lc = 2460	Lc = 2460
mm	d = 0	d = 50	d = 100	d = 200	d = 0	d = 200
0	0.00	0.00	0.00	0.00	0.00	0.00
10	47.69	30.58	38.22	58.22	37.56	44.94
20	40.17	34.82	50.99	70.75	52.88	60.25
30	32.87	32.15	48.27	53.23	42.19	45.56
45	23.93	29.70	37.22	35.91	31.56	28.87
60	19.46	25.52	28.02	17.61	18.39	20.24
75	14.38	21.95	23.80	12.00	6.94	12.94
90	11.29	11.40	15.73	8.62	2.31	6.77
105	5.57	5.56	2.56	3.64	0.00	2.73
120	1.37	2.89	0.00	0.00	0.00	0.78
180	0.00	0.00	0.00	0.00	0.00	0.00
240	0.00	0.00	0.00	0.00	0.00	0.00

Summary of Flow Characteristics at W-Plane

		Lc = 660	Lc = 660	Lc = 660	Lc = 660	Lc = 2460	Lc = 2460
	Dd =	0	50	100	200	0	200
Umax	m/s	0.666	0.475	0.568	0.661	0.793	0.660
Umean	m/s	0.393	0.305	0.419	0.345	0.403	0.368
Umean/Umax		0.589	0.643	0.736	0.522	0.508	0.557
Du=0	mm	128.0	156.0	107.0	133.0	104.0	130.0
Dw(u)	mm	98.0	109.0	87.0	96.0	74.5	97.0
amb	C	20.5	20.0	21.0	20.0	21.0	21.0
Tmax	C	71.9	82.8	96.9	128.5	67.2	99.5
Tmean	C	52.7	56.5	78.7	79.8	60.9	62.7
T240	C	5.9	6.4	6.9	9.1	4.1	5.6
Dw(T)	mm	107.0	105.0	101.5	75.0	90.0	70.0
Dw#(T)	mm	100.0	95.5	88.0	70.5	87.0	66.0
Du/DT		0.92	1.04	0.86	1.47	0.83	1.39
Du/DT#		0.98	1.10	0.99	1.06	0.86	1.47
Re		2424	2207	1927	1881	1978	2054
m	kg/s	0.0440	0.0412	0.0365	0.0372	0.0359	0.0407
Q	kW	2.330	2.340	2.884	2.986	2.194	2.562

Table A7.5 Summary of Y-Plane Data

PIV Velocity Data; Velocities at Interrogation Cell Centres (m/s)

Im1-8 Dd = 0 Lc = 660 rzwall m/s 0.0 0.000 8.2 0.366 25.5 0.541 42.8 0.537 60.0 0.577 77.3 0.523 94.6 0.561 111.9 0.244 128.0 0.000	Im 9-16 Dd = 0 Lc = 660 rzwall m/s 0.0 0.000 3.0 0.071 24.6 0.620 46.2 0.742 67.8 0.699 89.4 0.481 111.0 0.312 132.6 0.120 144.0 0.000	Im95-105 Dd = 0 Lc =2460 rzwall m/s 0.0 0.000 5.4 0.258 22.7 0.411 40.0 0.510 57.3 0.516 121.0 0.000	
Im25-32 Dd = 5 Lc = 660 rzwall m/s 0.0 0.000 5.2 0.269 25.8 0.659 46.5 0.596 67.2 0.310 87.8 0.221 108.5 0.081 118.0 0.000	Im33-40 Dd = 5 Lc = 660 rzwall m/s 0.0 0.000 10.7 0.207 31.4 0.587 52.0 0.687 72.7 0.595 93.4 0.490 114.0 0.044 121.0 0.000	Dd = 5 Lc =2460 rzwall m/s No Data	
Im49-56 Dd=10 Lc = 660 rzwall m/s 0.0 0.000 14.6 0.594 32.4 0.786 50.3 0.534 68.1 0.274 86.0 0.130 134.0 0.000	Im57-64 Dd=10 Lc = 660 rzwall m/s 0.0 0.000 14.2 0.634 35.8 0.685 57.4 0.632 79.0 0.361 100.6 0.063 108.0 0.000	Dd=10 Lc =2460 rzwall m/s No Data	
Im73-80 Dd=20 Lc = 660 rzwall m/s 0.0 0.000 16.2 0.379 35.4 0.388 54.6 0.316 96.0 0.000	Im81-88 Dd=20 Lc = 660 rzwall m/s 0.0 0.000 14.4 0.481 33.6 0.527 52.8 0.514 72.0 0.289 91.2 0.099 93.0 0.000	Im121-128 Dd=20 Lc =2460 rzwall m/s 0.0 0.000 8.4 0.449 27.6 0.622 46.8 0.552 66.0 0.400 103.0 0.000	Im129-136 Dd=20 Lc =2460 rzwall m/s 0.0 0.000 21.5 0.662 46.4 0.667 71.4 0.636 96.4 0.043 100.0 0.000

PIV Velocity Data for Y-Plane;

Velocities at Thermocouple Centres (m/s)

	Image 1-8	Image 9-16	Image 25-32	Image 33-40	Image 49-56	Image 57-64	Image 73-80	Image 81-88	Image 95-105	Image 121-8	Image 129-36
rzwall	L660	L660	L660	L660	L660	L660	L660	L660	L2460	L2460	L2460
mm	d=0	d=0	d=50	d=50	d=100	d=100	d=200	d=200	d=0	d=200	d=200
0	0.000	0.000	0	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.400	0.698	0.386	0.193	0.445	0.560	0.267	0.378	0.314	0.479	0.352
20	0.505	0.734	0.584	0.393	0.691	0.718	0.401	0.516	0.391	0.586	0.582
30	0.549	0.746	0.677	0.564	0.784	0.672	0.398	0.523	0.459	0.624	0.697
45	0.541	0.702	0.601	0.673	0.616	0.526	0.347	0.534	0.525	0.555	0.667
60	0.574	0.560	0.397	0.664	0.382	0.322	0.275	0.441	0.496	0.453	0.678
75	0.522	0.419	0.263	0.581	0.188	0.061	0.156	0.252	0.376	0.298	0.567
90	0.572	0.302	0.204	0.523	0.113	0.016	0.045	0.111	0.257	0.139	0.179
105	0.369	0.164	0.099	0.254	0.069	0.000	0.000	0.000	0.130	0.000	0.000
120	0.114	0.065	0.000	0.000	0.032	0.000	0.000	0.000	0.003	0.000	0.000
180	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
240	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
300	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Thermocouple Data for Y-Plane

Temperature Rises Interpolated at 15 mm Centres (C)

	L660	L660	L660	L660	L2460	L2460
mm	d=0	d=50	d=100	d=200	d=0	d=200
0	77.14	84.00	95.10	125.8	48.70	90.00
10	77.14	84.00	95.10	125.8	48.70	90.00
20	73.92	82.54	96.10	127.1	58.60	95.89
30	70.70	78.68	94.80	123.5	65.24	96.80
45	67.60	67.50	86.67	97.2	67.60	80.00
60	58.07	55.66	76.44	70.36	66.07	61.56
75	52.22	42.69	59.86	35.40	57.80	36.88
90	38.78	29.97	44.52	18.78	47.98	18.07
105	30.6	20.89	29.93	11.35	30.39	10.78
120	25.19	14.66	21.78	10.49	18.79	8.71
180	7.78	2.04	7.03	7.66	5.82	6.23
240	5.66	7.20	8.50	9.04	5.41	6.64
300	4.55	6.49	7.42	8.11	5.27	6.17

Mass Flux at Y-Plane (kg/s)

	Image 1-8	Image 9-16	Image 25-32	Image 33-40	Image 49-56	Image 57-64	Image 73-80	Image 81-88	Image 95-105	Image 121-8	Image 129-36
rzwall	L660	L660	L660	L660	L660	L660	L660	L660	L2460	L2460	L2460
mm	d=0	d=0	d=50	d=50	d=100	d=100	d=200	d=200	d=0	d=200	d=200
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.380	0.664	0.361	0.181	0.404	0.508	0.225	0.318	0.324	0.441	0.323
20	0.485	0.704	0.549	0.369	0.626	0.649	0.337	0.434	0.391	0.530	0.526
30	0.531	0.722	0.642	0.536	0.712	0.610	0.337	0.443	0.451	0.564	0.629
45	0.528	0.685	0.589	0.659	0.571	0.488	0.314	0.483	0.513	0.524	0.629
60	0.575	0.561	0.402	0.672	0.363	0.307	0.267	0.429	0.486	0.449	0.673
75	0.532	0.427	0.276	0.611	0.187	0.061	0.168	0.271	0.377	0.318	0.605
90	0.606	0.320	0.223	0.572	0.118	0.016	0.051	0.125	0.265	0.157	0.202
105	0.401	0.179	0.111	0.286	0.075	0.000	0.000	0.000	0.142	0.000	0.000
120	0.126	0.072	0.000	0.000	0.036	0.000	0.000	0.000	0.003	0.000	0.000
180	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Heat Flux at Y-Plane (kW)

	Image 1-8	Image 9-16	Image 25-32	Image 33-40	Image 49-56	Image 57-64	Image 73-80	Image 81-88	Image 95-105	Image 121-8	Image 129-36
rzwall	L660	L660	L660	L660	L660	L660	L660	L660	L2460	L2460	L2460
mm	d=0	d=0	d=50	d=50	d=100	d=100	d=200	d=200	d=0	d=200	d=200
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	29.48	51.47	30.52	15.24	38.61	48.50	28.42	40.27	15.85	39.85	29.24
20	36.01	52.28	45.53	30.60	60.41	62.71	43.04	55.40	23.03	51.12	50.72
30	37.73	51.29	50.80	42.36	67.83	58.08	41.89	55.02	29.56	54.83	61.21
45	35.85	46.54	39.93	44.72	49.71	42.49	30.69	47.24	34.82	42.09	50.57
60	33.55	32.76	22.48	37.58	27.92	23.56	18.90	30.31	32.29	27.80	41.63
75	27.93	22.39	11.86	26.20	11.27	3.66	5.97	9.63	21.90	11.77	22.43
90	23.63	12.48	6.72	17.22	5.26	0.73	0.97	2.36	12.77	2.85	3.67
105	12.34	5.494	2.33	6.00	2.25	0.00	0.00	0.00	4.33	0.00	0.00
120	3.194	1.822	0.00	0.00	0.78	0.00	0.00	0.00	0.07	0.00	0.00
180	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Summary of Y-Plane Characteristics

		Image 1-8	Image 9-16	Image 25-32	Image 33-40	Image 49-56	Image 57-64	Image 73-80	Image 81-88	Image 95-105	Image 121-8	Image 129-36
rzwall		L660	L660	L660	L660	L660	L660	L660	L660	L2460	L2460	L2460
mm	Dd	0	0	50	50	100	100	200	200	0	200	200
Umax	m/s	0.577	0.742	0.659	0.567	0.786	0.685	0.388	0.527	0.510	0.622	0.667
Umea	m/s	0.446	0.552	0.443	0.450	0.431	0.417	0.223	0.328	0.323	0.438	0.493
Umean/Umax		0.772	0.744	0.672	0.794	0.549	0.609	0.575	0.622	0.633	0.705	0.739
byu=0	mm	128.0	144.0	118.0	121.0	134.0	108.0	96.0	93.0	121.0	103.0	100.0
by(u)	mm	113.5	93.0	83.5	104.5	83.5	72.5	89.0	91.0	107.5	82.0	88.0
amb	C	21.00	21.00	20.00	20.00	21.00	21.00	20.00	20.00	21.00	21.00	21.00
Tmax	C	77.14	77.14	84.00	84.00	96.10	96.10	127.1	127.1	65.24	96.80	96.80
Tmean	C	56.25	62.66	64.97	55.27	83.76	89.70	97.32	92.59	58.97	73.73	69.38
T300	C	4.55	4.55	5.42	5.42	7.42	7.42	8.11	8.11	5.27	6.17	6.17
dpmea	kg/m3	0.190	0.208	0.214	0.187	0.262	0.277	0.294	0.283	0.198	0.237	0.226
by(T)	mm	111.0	111.0	90.0	90.0	131.0	131.0	70.0	70.0	111.5	70.0	70.0
by#(T)	mm	105.0	105.0	88.5	88.5	125	125	62	62	108	77.0	77.0
bu/bT		1.023	0.838	0.928	1.161	0.637	0.553	1.271	1.300	0.964	1.171	1.257
bu/bT#		1.081	0.886	0.944	1.181	0.668	0.58	1.435	1.468	0.995	1.065	1.143
Re		2836	2878	2067	2004	1999	1679	1099	1653	1941	2004	2418
m	kg/s	0.051	0.052	0.037	0.048	0.036	0.030	0.020	0.030	0.035	0.036	0.044
Q	kW	2.908	3.287	2.448	2.649	3.05	2.75	1.95	2.79	2.09	2.69	3.06

Table A7.6 Summary of Z(750) - Plane Data
PIV Velocity Data; Velocities at Interrogation Cell Centres (m/s)

Dd = 0	Lc = 660	Dd = 0	Lc = 2460
rzwall	m/s	rzwall	m/s
0.0	0.000	0.0	0.000
15.0	0.755	15.7	0.920
33.4	0.898	33.5	0.791
51.8	0.837	51.4	0.719
70.2	0.877	69.2	0.583
88.6	0.635	87.1	0.517
107.0	0.531	135.0	0.000
125.4	0.510		
199.0	0.000		

Dd = 50	Lc = 660	Dd = 50	Lc = 2460
rzwall	m/s	rzwall	m/s
0.0	0.000	No Data	
7.6	0.747		
26.0	0.864		
44.4	0.857		
62.8	0.822		
81.2	0.611		
99.6	0.412		
118.0	0.255		
136.4	0.203		
156.0	0.000		

Dd = 100	Lc = 660	Dd = 100	Lc = 2460
rzwall	m/s	rzwall	m/s
0.0	0.000	No Data	
17.8	1.050		
36.2	0.952		
54.6	0.685		
73.0	0.633		
91.4	0.326		
109.8	0.224		
128.2	0.068		
161.0	0.000		

Dd = 200	Lc = 660	Dd = 200	Lc = 2460
rzwall	m/s	rzwall	m/s
0.0	0.000	0.0	0.000
17.8	1.243	14.0	1.124
36.2	1.069	32.5	1.029
54.6	1.111	51.1	0.981
73.0	0.753	69.6	0.759
91.4	0.509	88.2	0.750
109.8	0.363	106.8	0.625
128.2	0.255	131.0	0.000
146.6	0.139		
162.0	0.000		

PIV Velocity Data for Z(750)-Plane;**Velocities at Thermocouple Centres (m/s)**

rzwall mm	Lc =0.66 Dd = 0	Lc =0.66 Dd = 50	Lc =0.66 Dd = 100	Lc =0.66 Dd = 200	Lc =2.46 Dd = 0	Lc =2.46 Dd = 200
0	0.000	0.000	0.000	0.000	0.000	0.000
10	0.561	0.817	0.683	0.765	0.675	0.867
20	0.835	0.875	1.072	1.267	0.707	1.145
30	0.891	0.905	0.999	1.139	0.826	1.040
45	0.894	0.890	0.777	1.115	0.736	1.004
60	0.858	0.875	0.660	1.040	0.648	0.874
75	0.788	0.720	0.602	0.800	0.683	0.742
90	0.625	0.527	0.333	0.520	0.485	0.742
105	0.619	0.394	0.251	0.391	0.345	0.648
120	0.531	0.258	0.067	0.298	0.164	0.335
150	0.339	0.064	0.021	0.111	0.000	0.000
180	0.134	0.000	0.000	0.000	0.000	0.000
240	0.000	0.000	0.000	0.000	0.000	0.000

Thermocouple Data for Z(750)-Plane**Temperature Rise Interpolated at 15 mm Centres (C)**

rzwall mm	Lc =0.66 Dd = 0	Lc =0.66 Dd = 50	Lc =0.66 Dd = 100	Lc =0.66 Dd = 200	Lc =2.46 Dd = 0	Lc =2.46 Dd = 200
0	23.4	24.8	35.9	37.5	35.0	33.8
10	23.4	24.8	35.9	37.5	35.0	33.8
30	20.7	22.7	34.1	35.4	31.9	30.4
60	18.8	19.8	29.5	29.2	26.5	26.5
90	14.8	15.8	24.2	22.6	20.5	20.4
120	13.6	14.4	21.2	19.0	17.3	17.5
150	9.6	12.8	17.2	13.5	15.8	16.5
180	9.6	11.0	15.8	13.5	11.6	13.2
240	6.9	9.3	12.0	11.7	7.9	11.7
300	6.1	9.0	11.5	11.4	7.0	11.1

Mass Flux at Z(750)-Plane (kg/s)

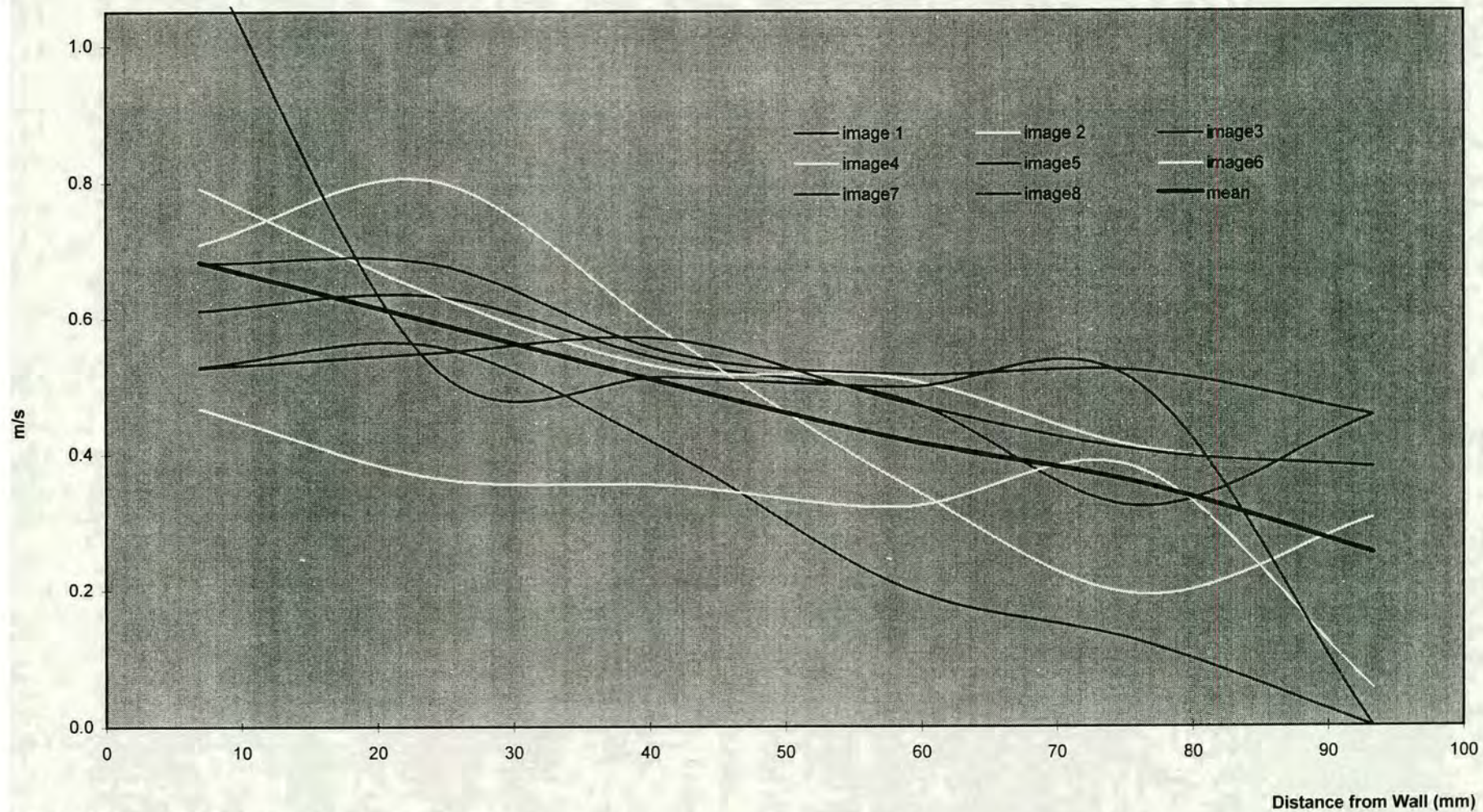
rzwall mm	Lc =0.66 Dd = 0	Lc =0.66 Dd = 50	Lc =0.66 Dd = 100	Lc =0.66 Dd = 200	Lc =2.46 Dd = 0	Lc =2.46 Dd = 200
0	0.000	0.000	0.000	0.000	0.000	0.000
10	0.622	0.904	0.727	0.813	0.722	0.930
20	0.930	0.969	1.145	1.355	0.759	1.234
30	0.996	1.009	1.069	1.218	0.891	1.127
45	1.002	0.993	0.838	1.205	0.794	1.094
60	0.965	0.984	0.716	1.133	0.711	0.958
75	0.892	0.812	0.660	0.882	0.758	0.822
90	0.712	0.600	0.367	0.578	0.542	0.830
105	0.707	0.449	0.279	0.438	0.387	0.726
120	0.608	0.295	0.074	0.335	0.185	0.378
150	0.390	0.074	0.024	0.126	0.000	0.000
180	0.156	0.000	0.000	0.000	0.000	0.000
240	0.000	0.000	0.000	0.000	0.000	0.000

Heat Flux at Z(750)-Plane (kW)

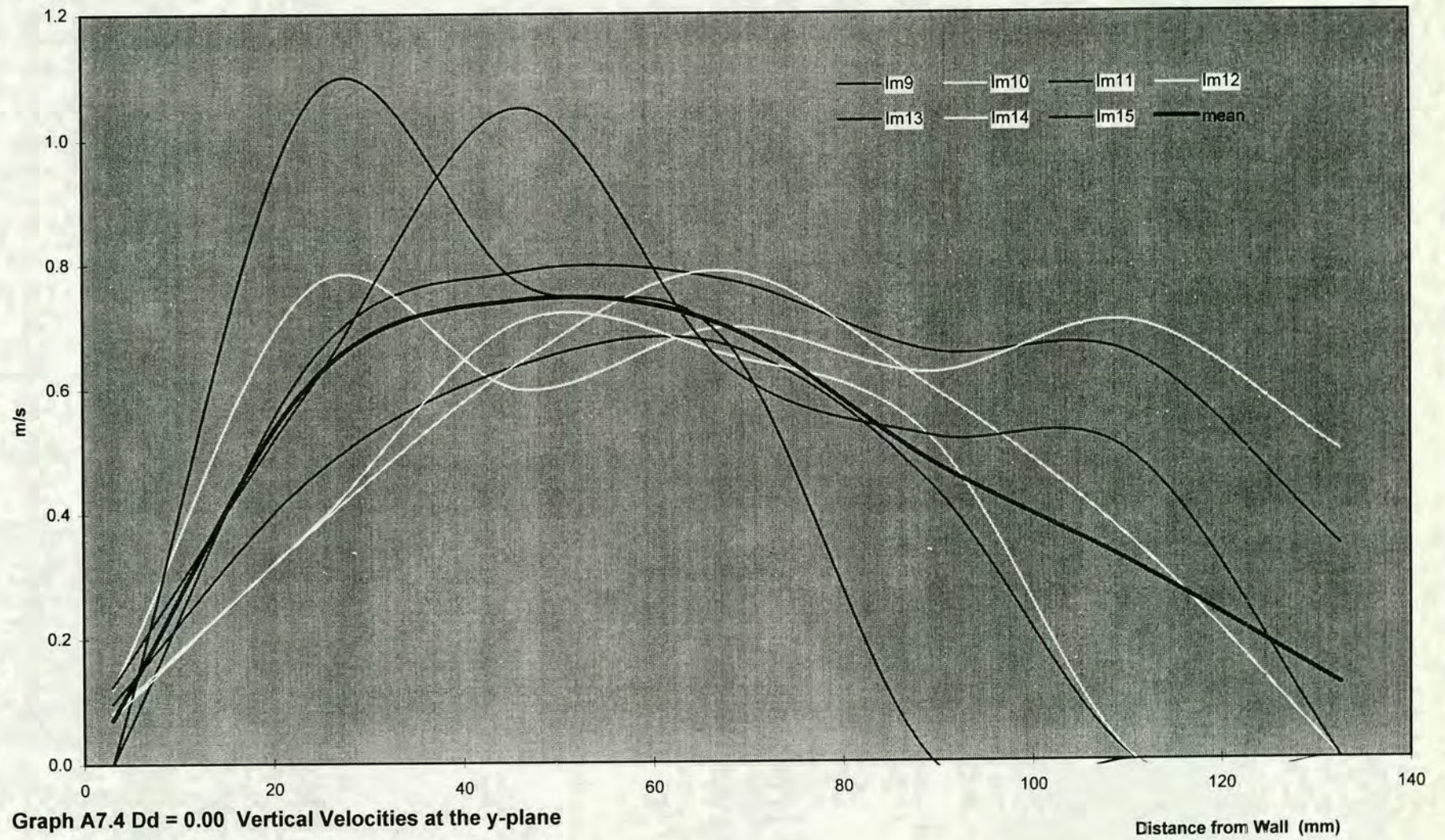
rzwall mm	Lc =0.66 Dd = 0	Lc =0.66 Dd = 50	Lc =0.66 Dd = 100	Lc =0.66 Dd = 200	Lc =2.46 Dd = 0	Lc =2.46 Dd = 200
0	0.000	0.000	0.000	0.000	0.000	0.000
10	14.611	22.490	26.244	30.609	25.394	31.598
20	20.461	23.973	40.141	48.121	25.400	39.842
30	20.750	22.988	36.586	43.273	28.533	34.427
45	19.841	22.121	26.551	38.885	25.403	31.634
60	18.235	19.548	21.228	33.243	18.910	25.565
75	14.979	15.227	17.327	22.525	17.466	19.205
90	10.564	9.504	8.920	13.123	11.151	16.985
105	9.956	7.009	6.257	9.064	7.331	14.614
120	8.304	4.253	1.582	6.403	3.215	6.649
150	4.519	0.965	0.434	2.017	0.000	0.000
180	1.498	0.000	0.000	0.000	0.000	0.000
240	0.000	0.000	0.000	0.000	0.000	0.000

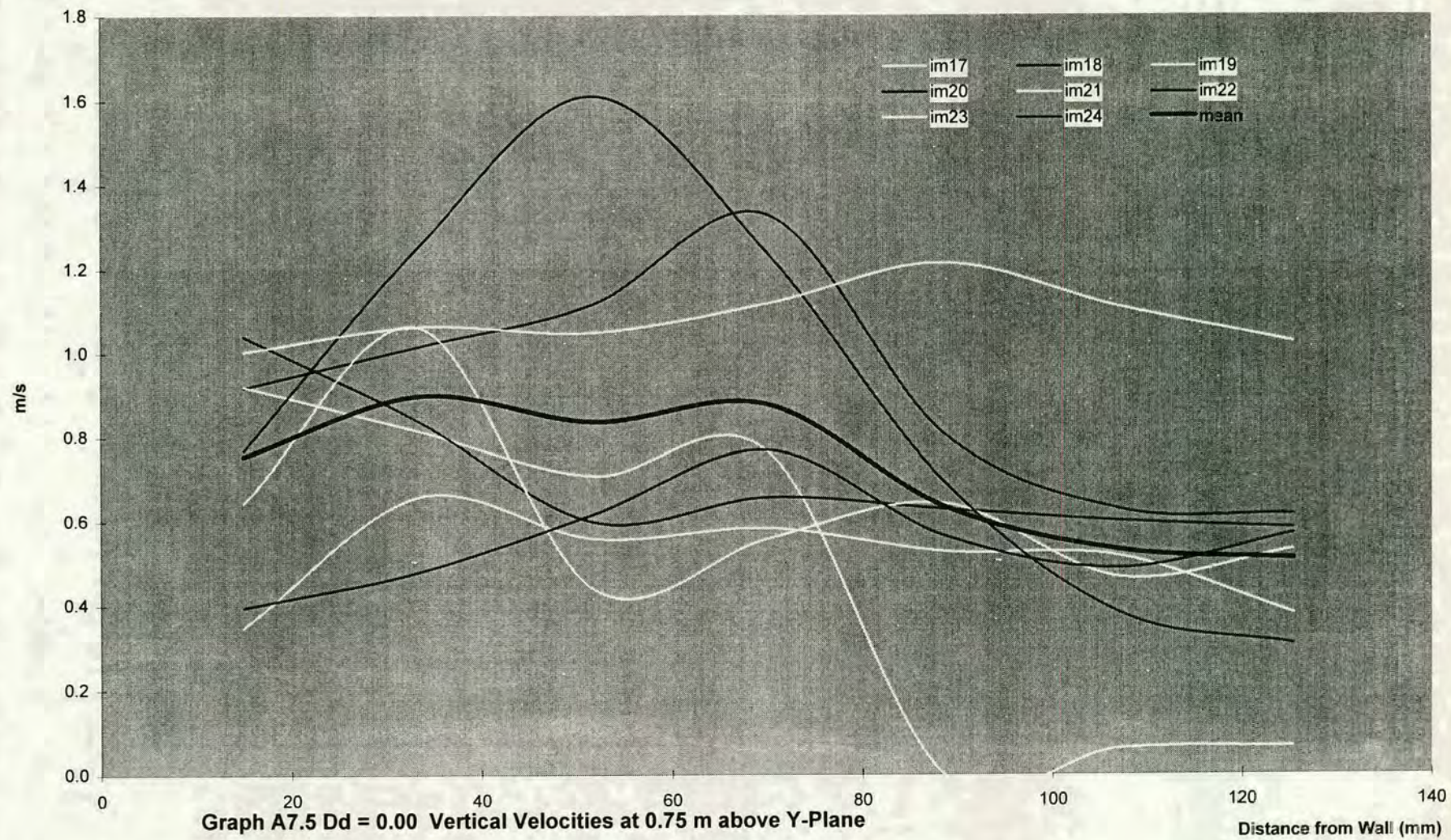
Summary of Flow Characteristics at Z(750)-Plane

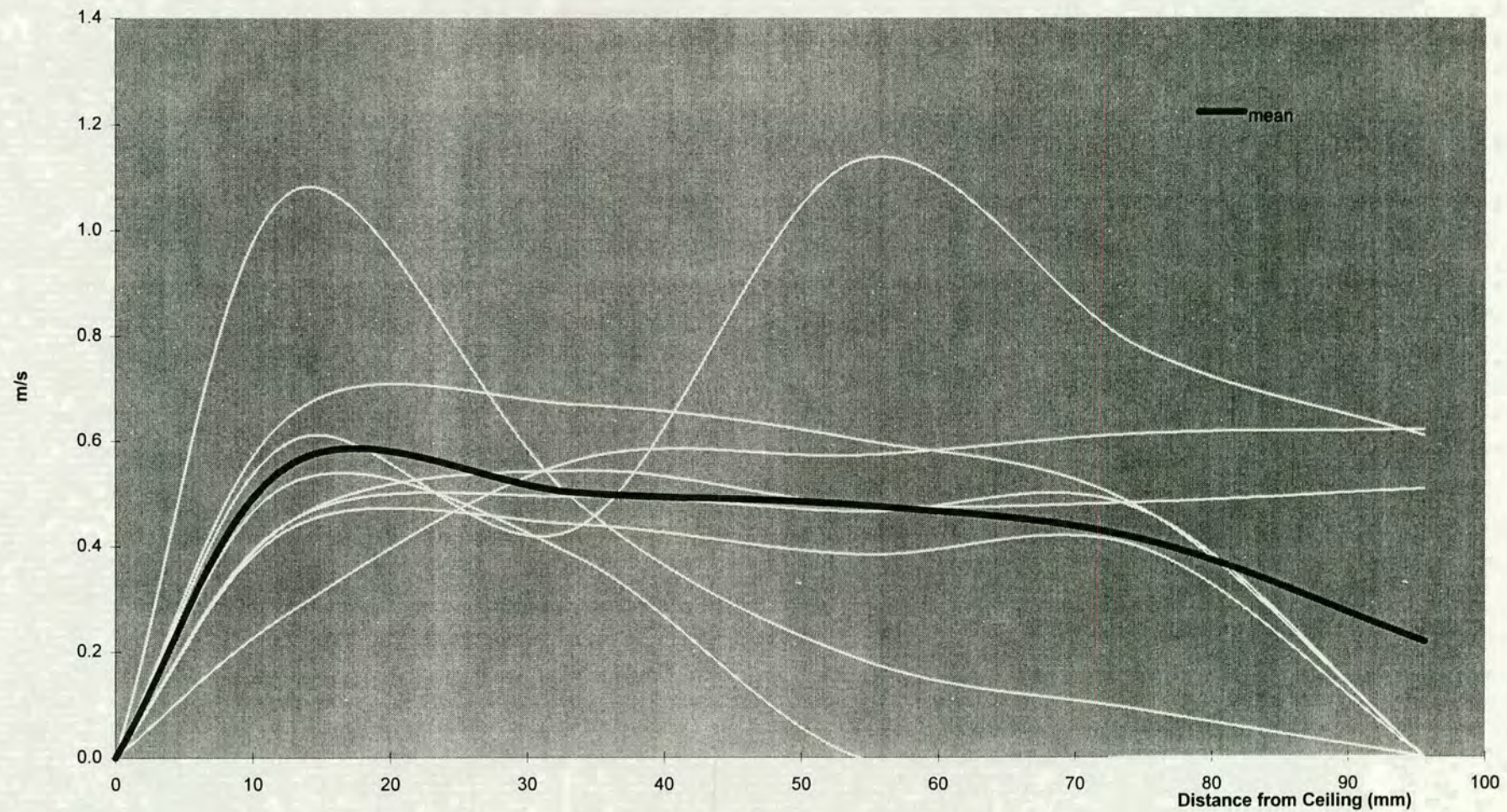
rzwall	Lc =0.66	Lc =0.66	Lc =0.66	Lc =0.66	Lc =2.46	Lc =2.46	
mm	Dd = 0	Dd = 50	Dd = 100	Dd = 200	Dd = 0	Dd = 200	
Character	units	0	50	100	200	0	200
Umax	m/s	0.898	0.864	1.050	1.243	0.920	1.124
Umean	m/s	0.599	0.626	0.501	0.702	0.598	0.846
Umean/Umax		0.667	0.725	0.477	0.565	0.650	0.753
Du=0	mm	199.0	156.0	161.0	162.0	135.0	131.0
by(u) wall	mm	118.6	112.2	88.3	97.1	104.0	117.7
amb	C	20.5	19.5	21.0	20.0	20.5	20.5
Tmax	C	23.4	24.8	35.9	37.5	35.0	33.8
Tmean	C	17.16	20.40	30.81	29.66	27.64	26.73
T300	C	6.1	9.0	11.5	11.4	7.0	11.1
dpmean	kg/m3	0.041	0.042	0.068	0.064	0.074	0.056
bz(T) wall	mm	198.0	144.8	213.7	175.8	180.3	203.5
bz#(T) wa	mm	127.6	103.1	126.1	102.8	120.0	96.8
bu/bT		0.599	0.775	0.413	0.552	0.577	0.578
bu/bT#		0.929	1.088	0.700	0.945	0.867	1.216
Re		6734	5463	4367	6175	4408	6074
Fr		2.23	2.60	1.58	2.27	1.98	3.29
m	kg/s	0.1163	0.0943	0.0754	0.1066	0.0761	0.1049
Q	kW	2.005	1.934	2.335	3.179	2.115	2.817



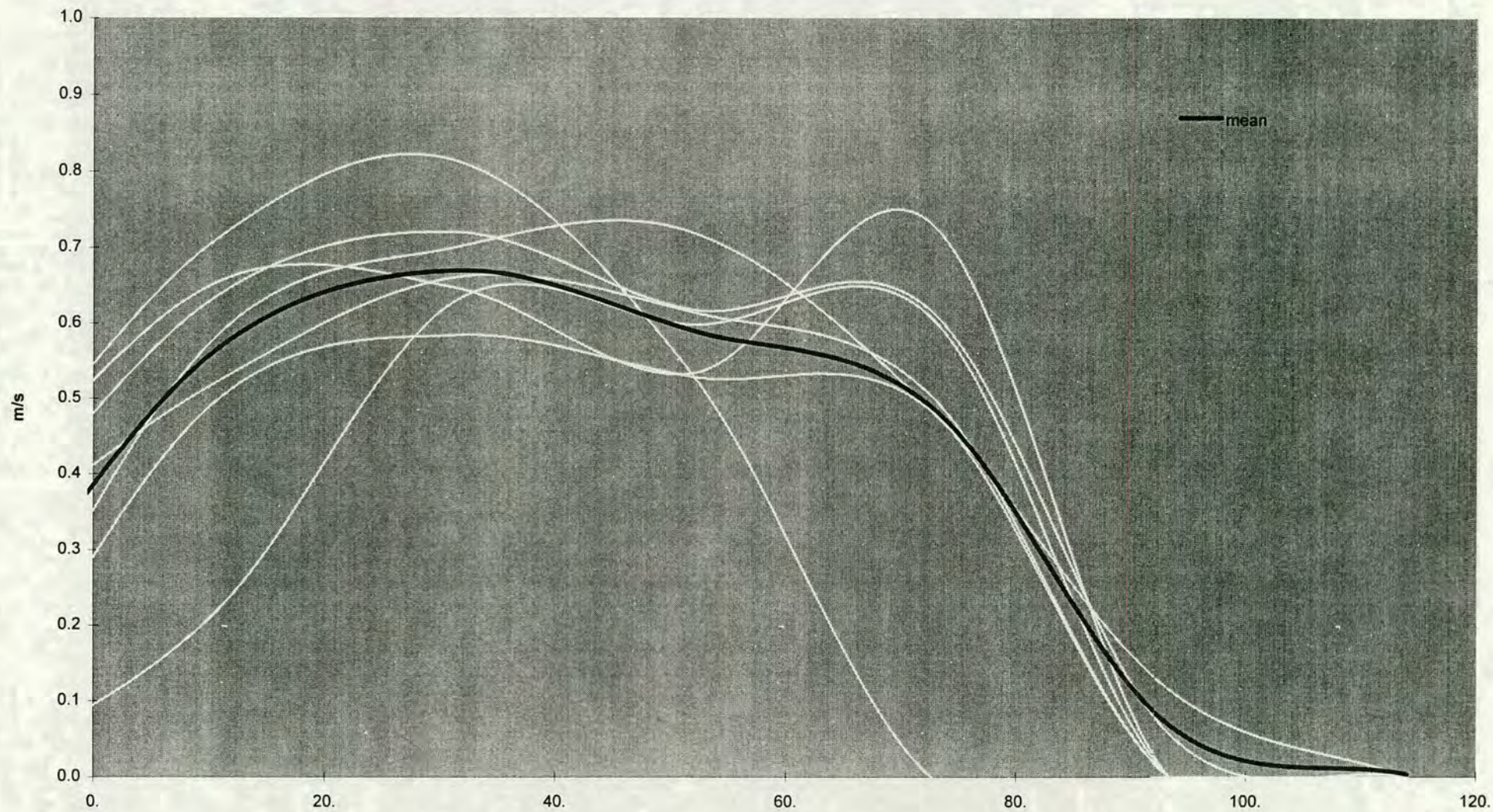
Graph A7.3 Dd=0.00; Horizontal velocity at w-plane





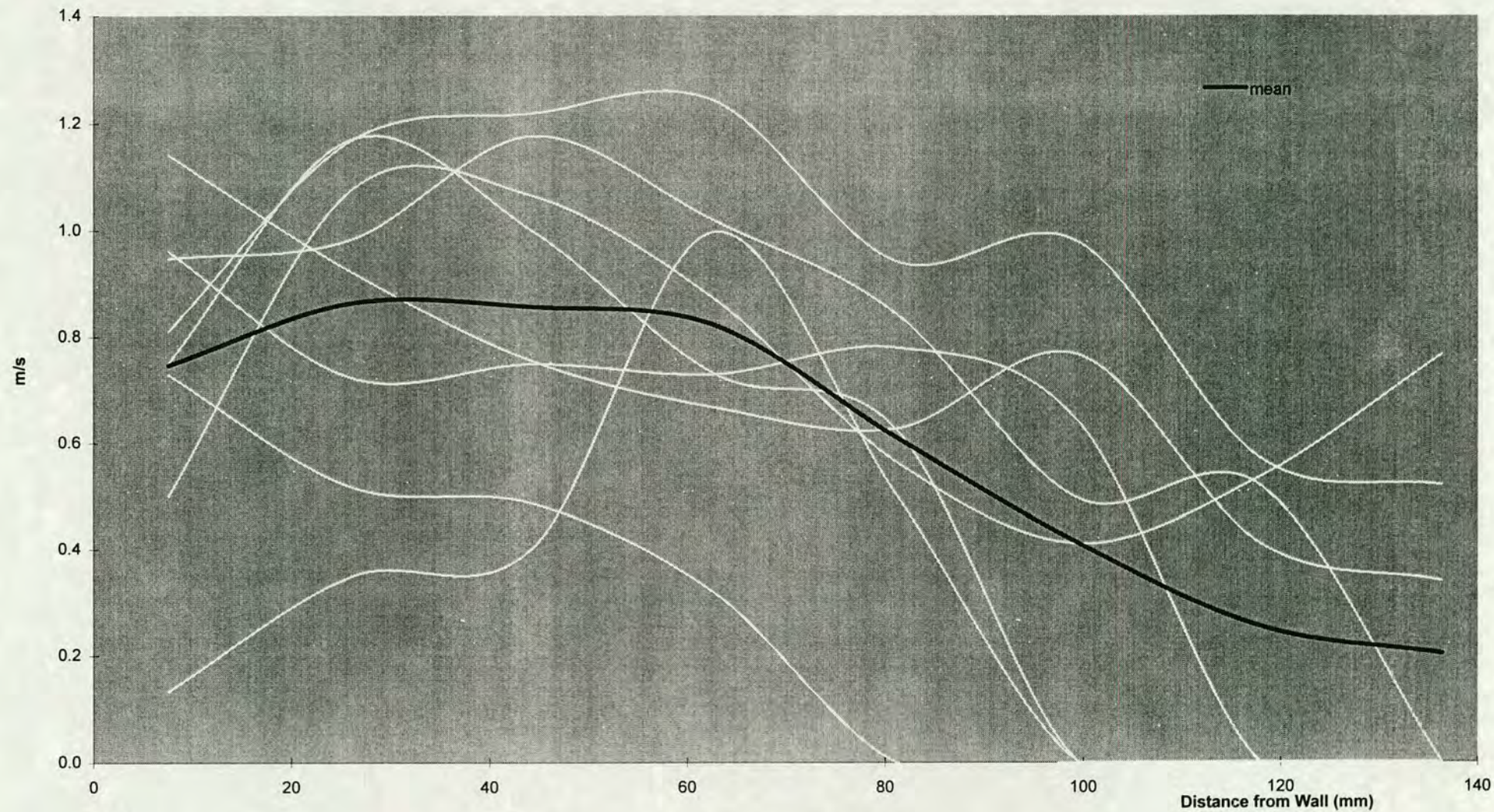


Graph A7.6 $Dd = 0.05$ Horizontal velocity at w-plane

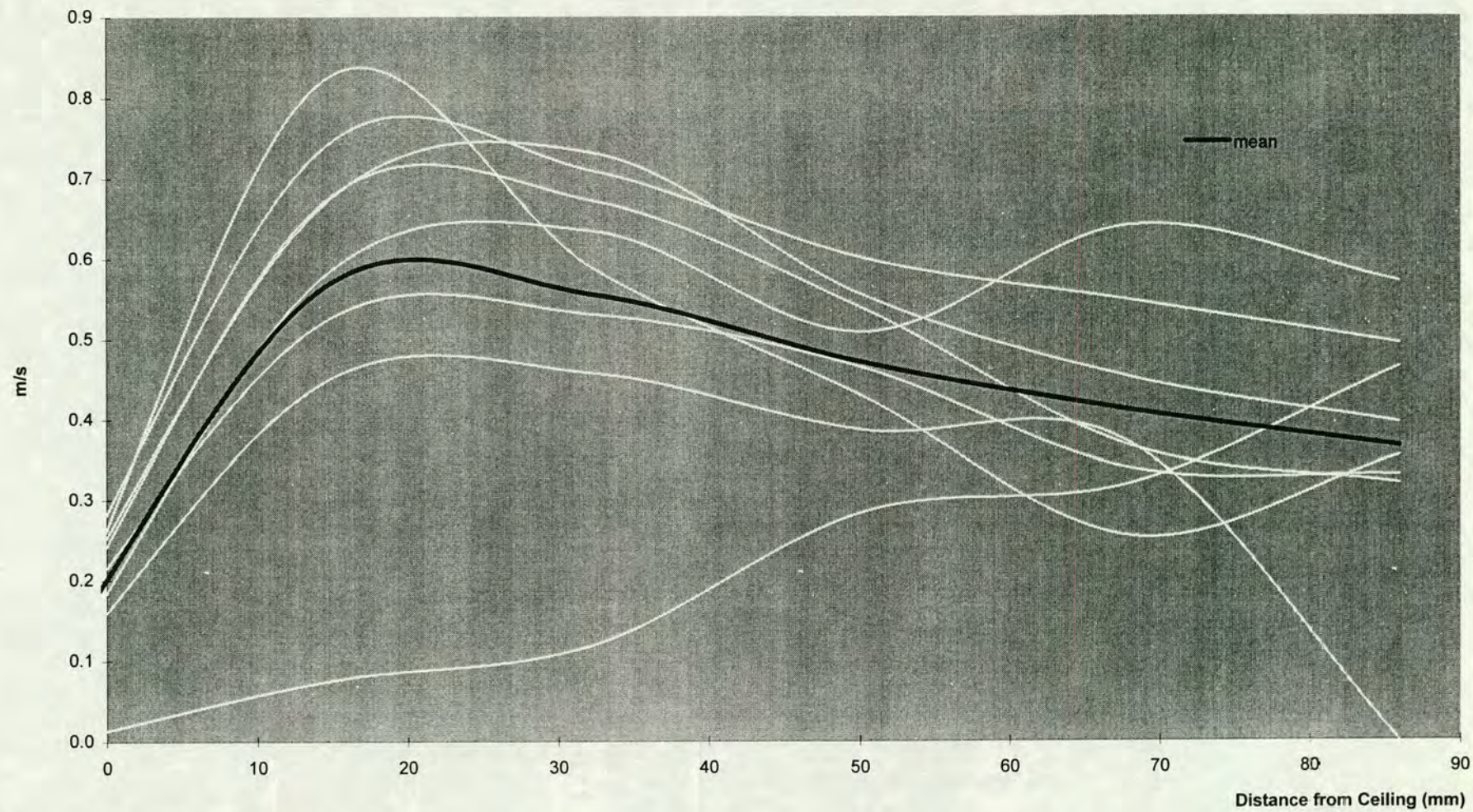


Graph A7.7 $Dd = 0.05$ Vertical velocities at y-plane

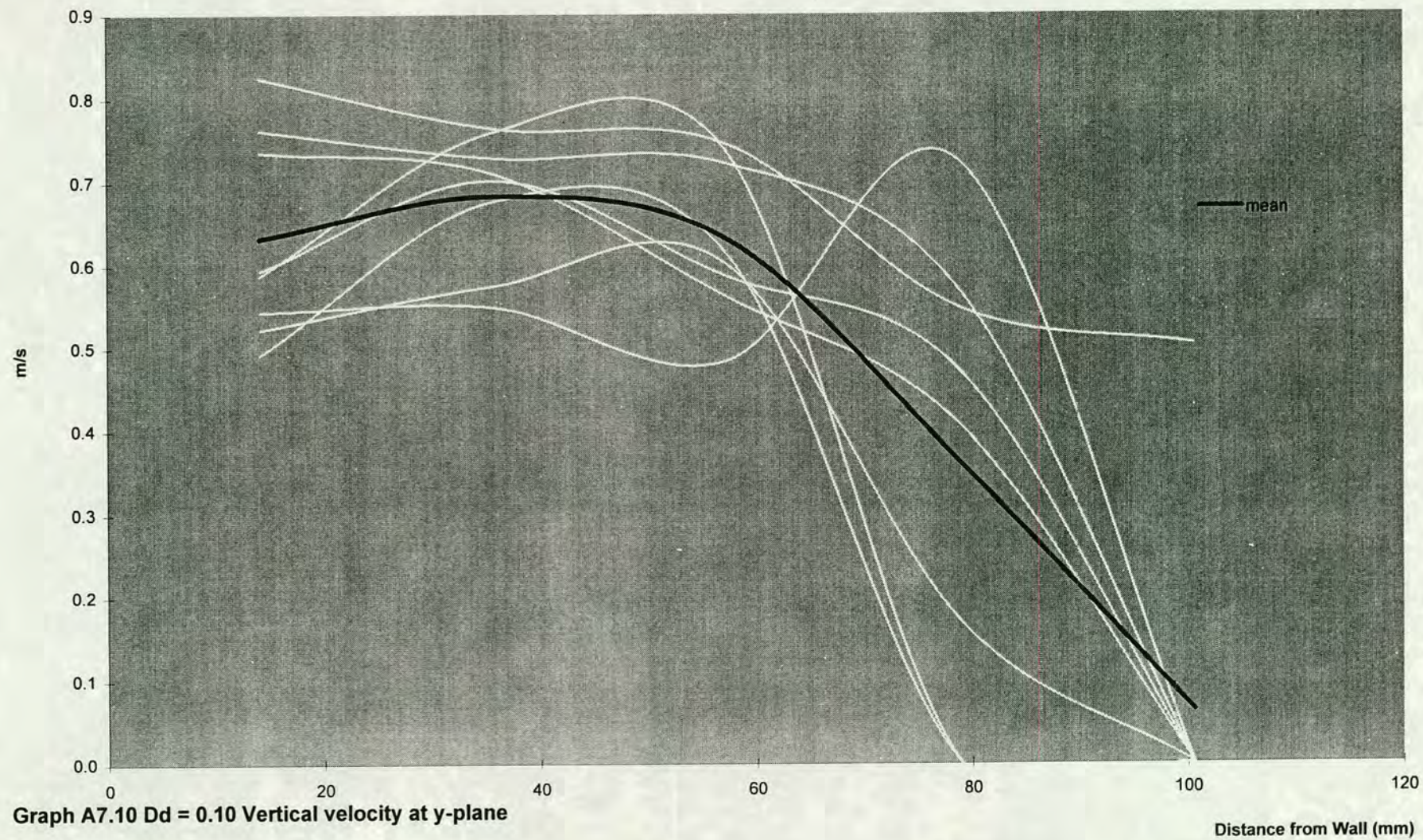
Distance from Wall (mm)



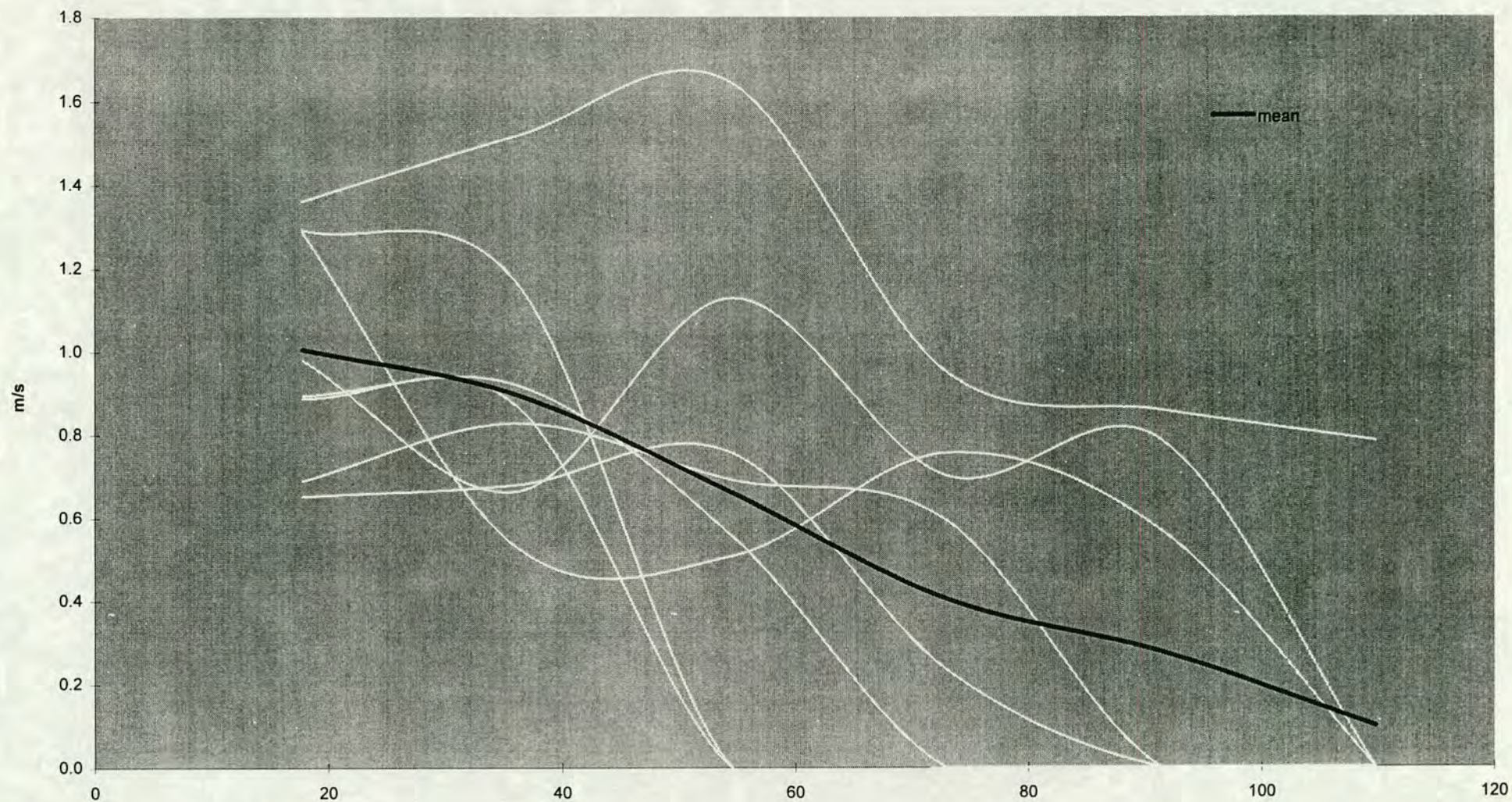
Graph A7.8 $Dd = 0.05$ Vertical velocity at 0.75 m above y-plane



Graph A.7.9 Horizontal velocity at w-plane

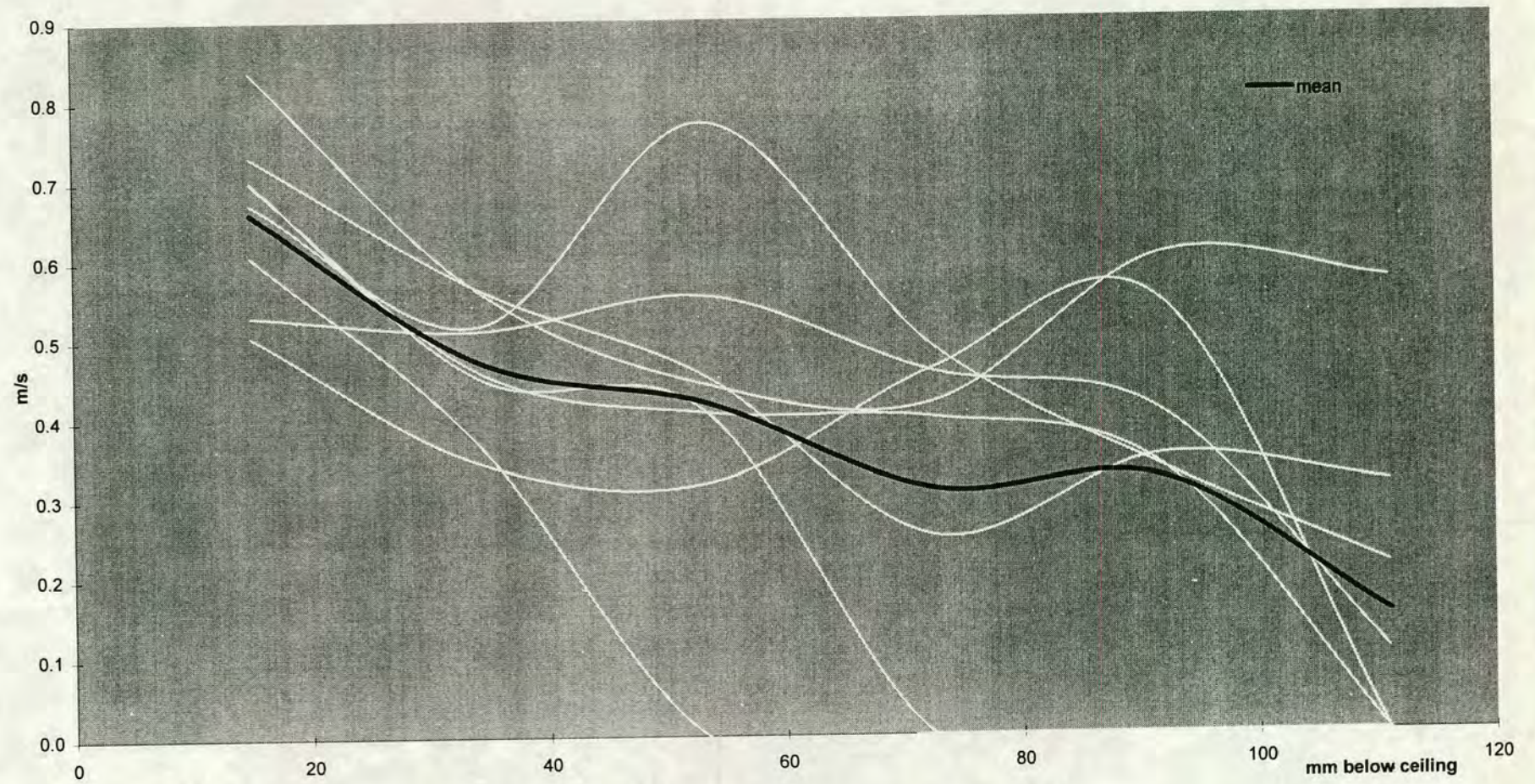


Graph A7.10 $Dd = 0.10$ Vertical velocity at y-plane

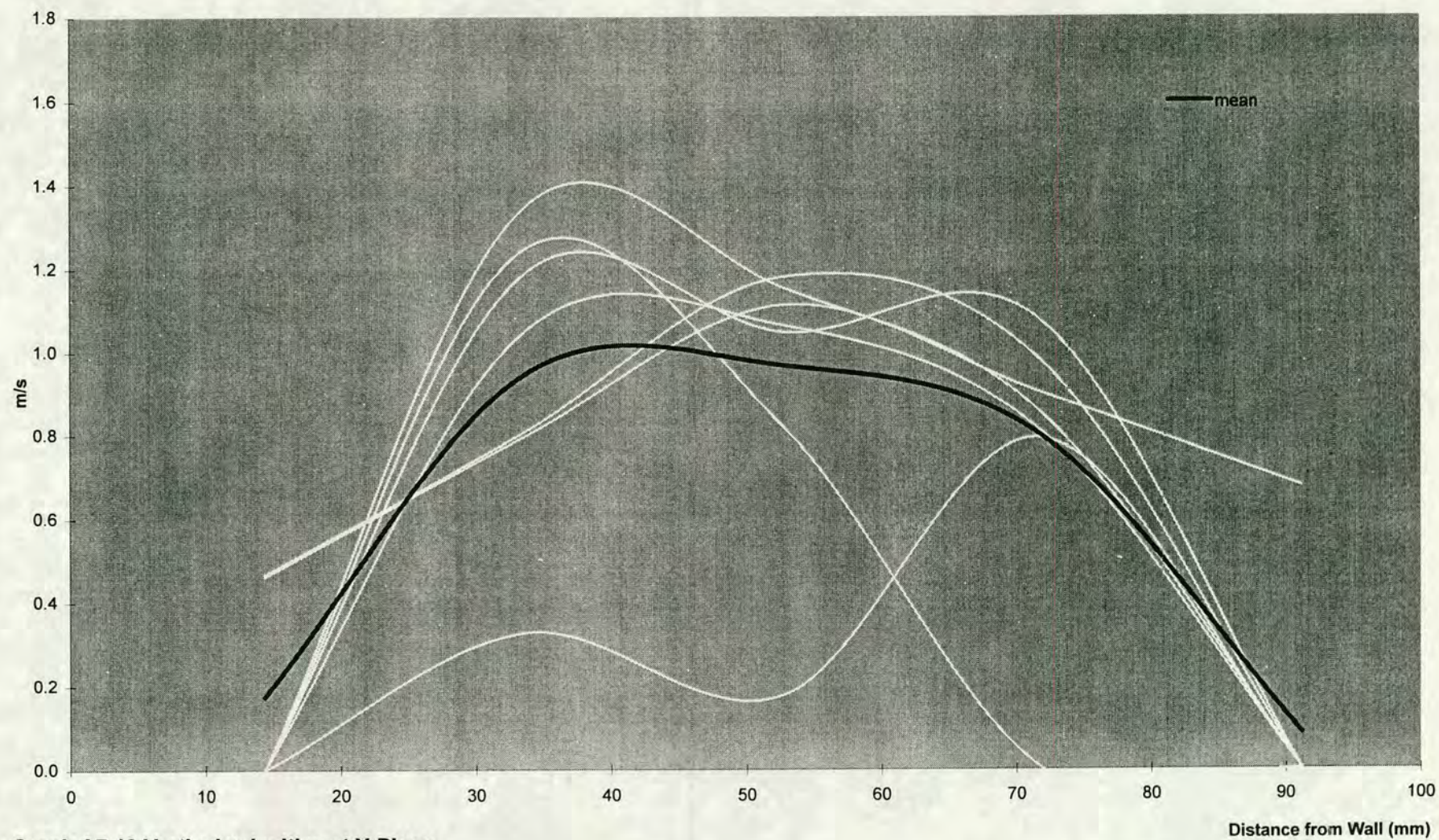


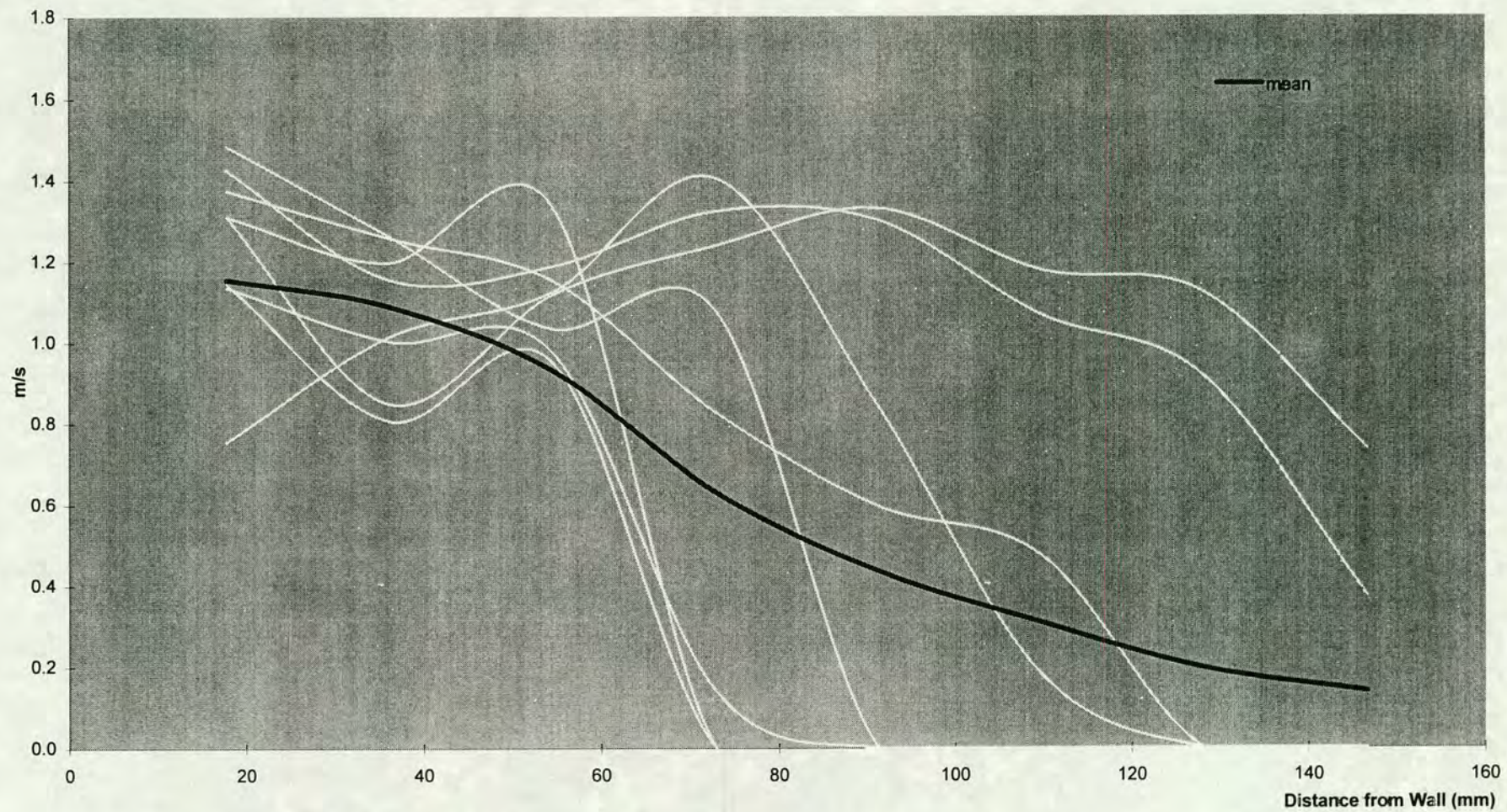
Graph A7.11 Vertical Velocities at 0.75 m above y-plane

Distance from Wall (mm)

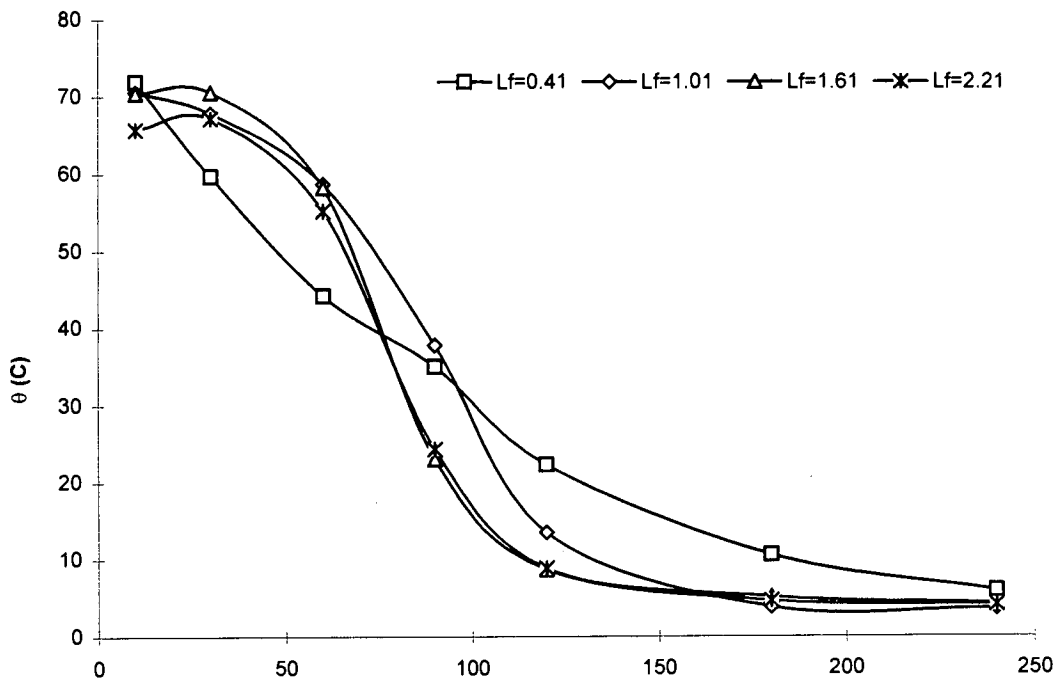


Graph A7.12 Horizontal velocity at W-Plane
 $D_d = 0.2$ m, $L_f = 0.41$ m

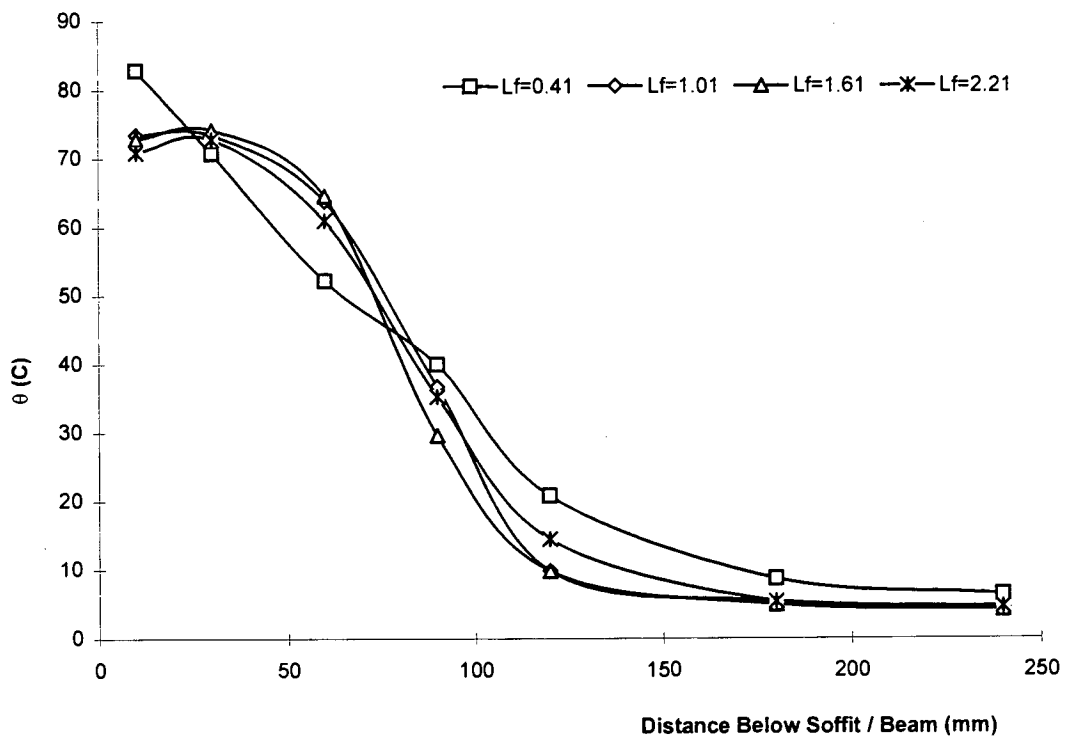




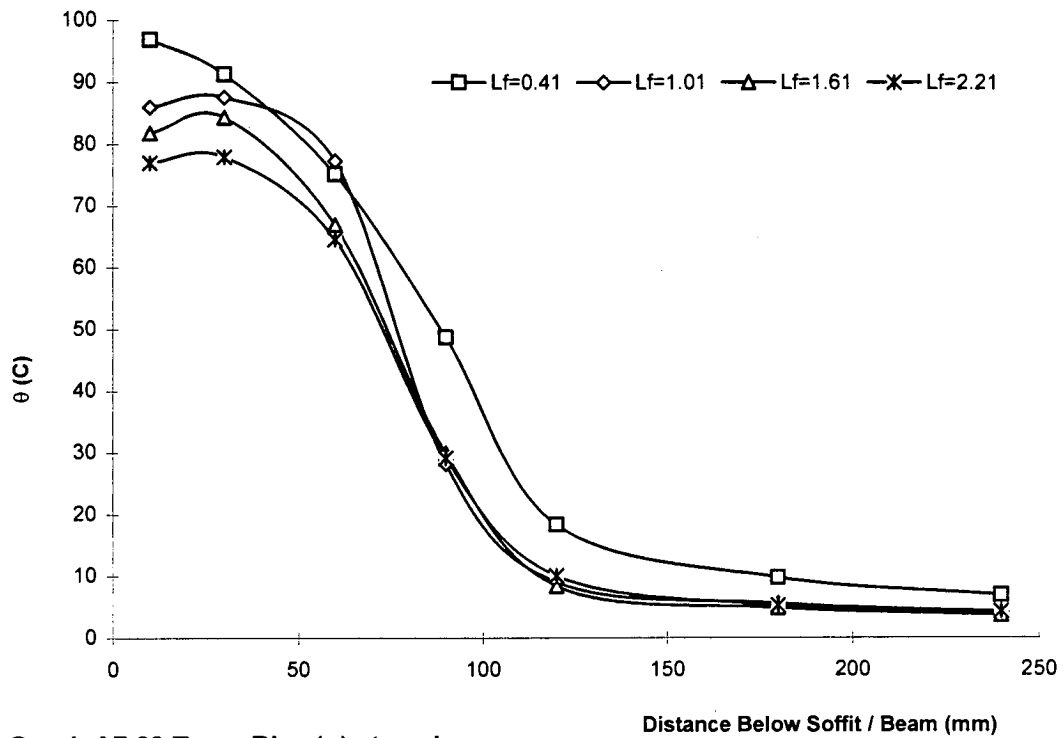
Graph A7.14 Vertical Velocities at 0.75 m Above Y-Plane



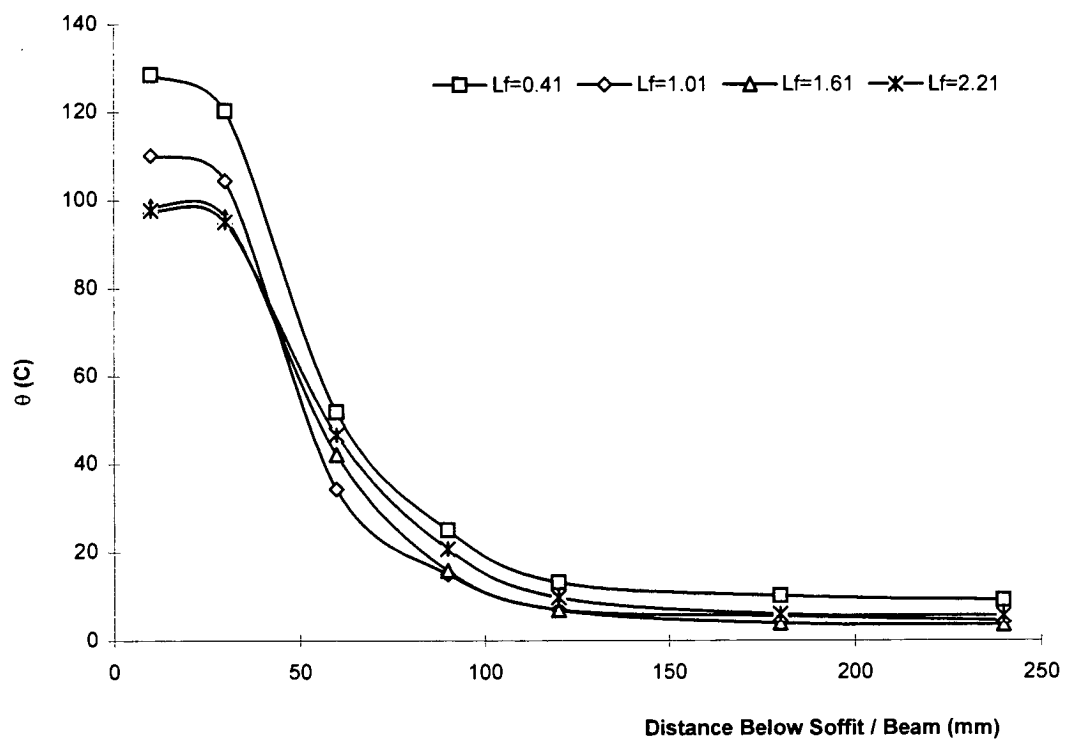
Graph A7.21 Temp Rise (q) at w-plane
Dd = 0.00; Qf = 4.67



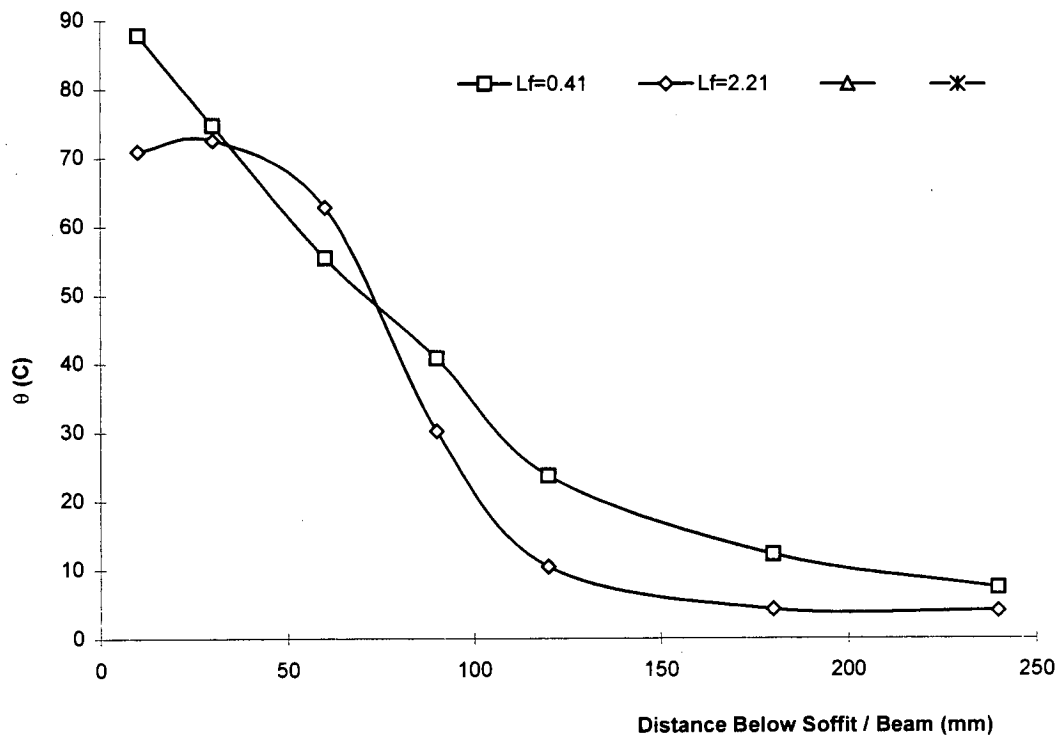
Graph A7.22 Temp Rise (q) at w-plane
Dd = 0.05; Qf = 4.67



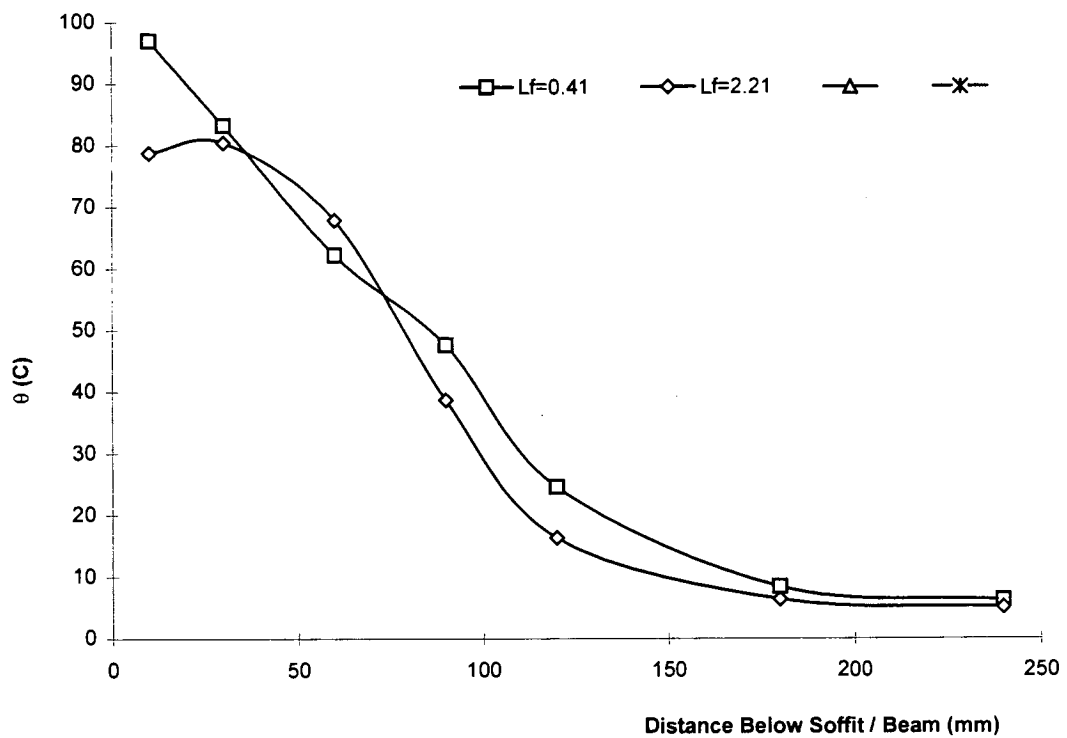
Graph A7.23 Temp Rise (q) at w-plane
Dd = 0.10; Qf = 4.67



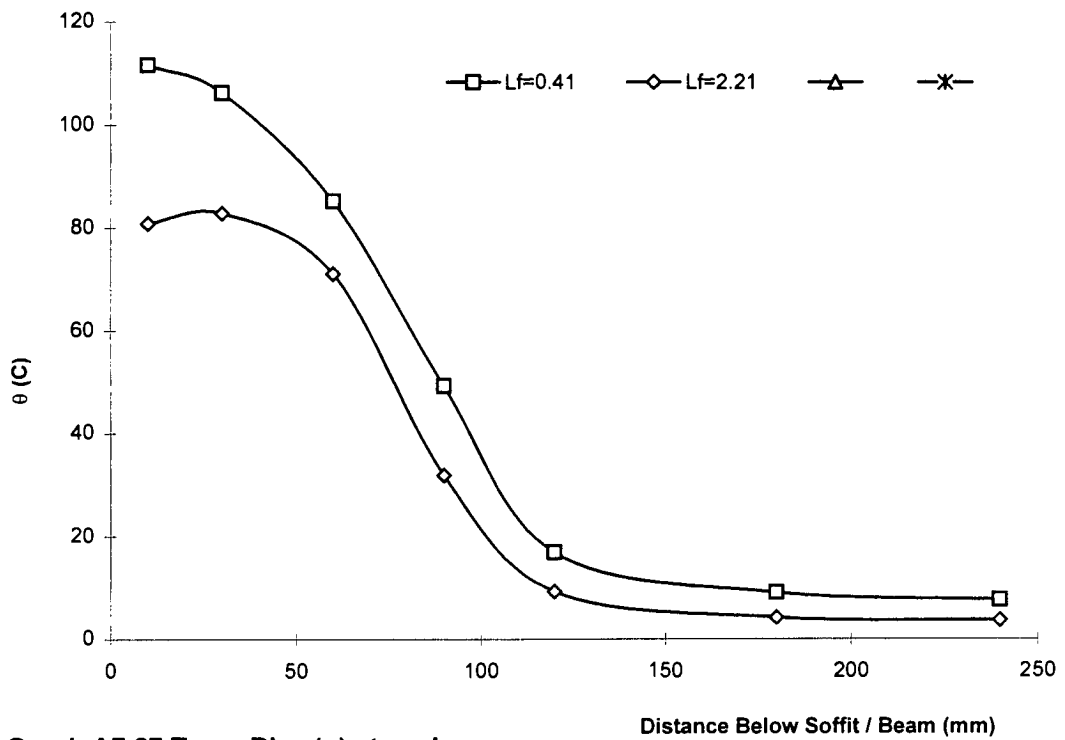
Graph A7.24 Temp Rise (q) at w-plane
Dd = 0.20; Qf = 4.67



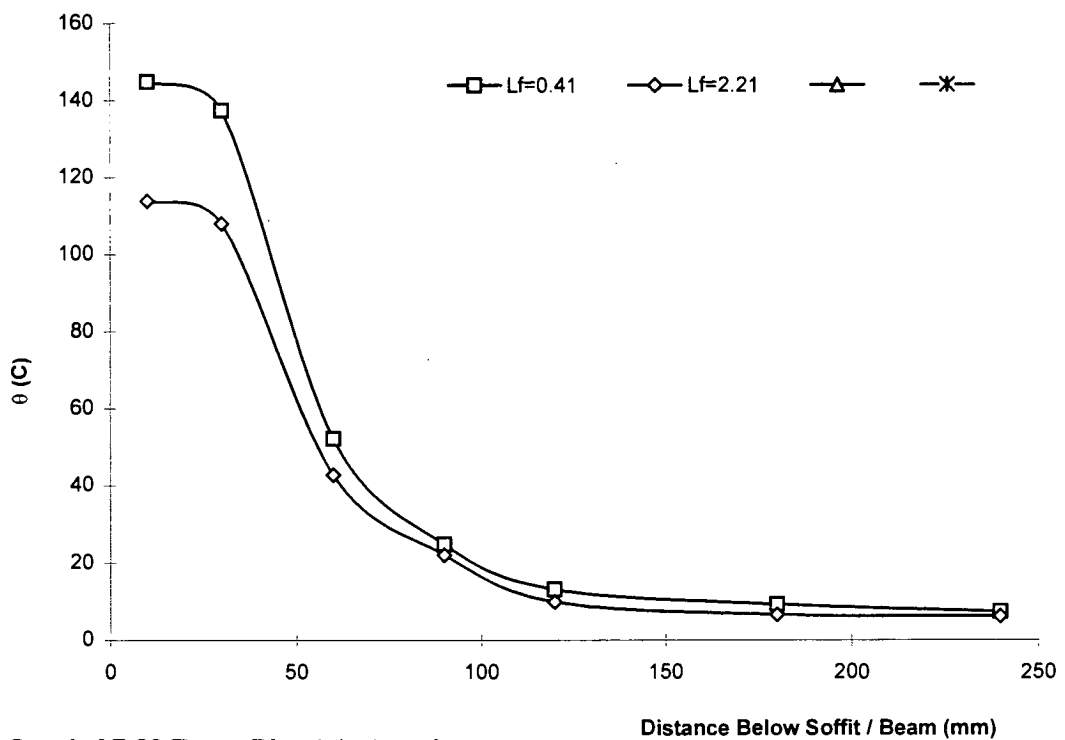
Graph A7.25 Temp Rise (θ) at w-plane
Dd = 0.00; Qf = 6.09 kW



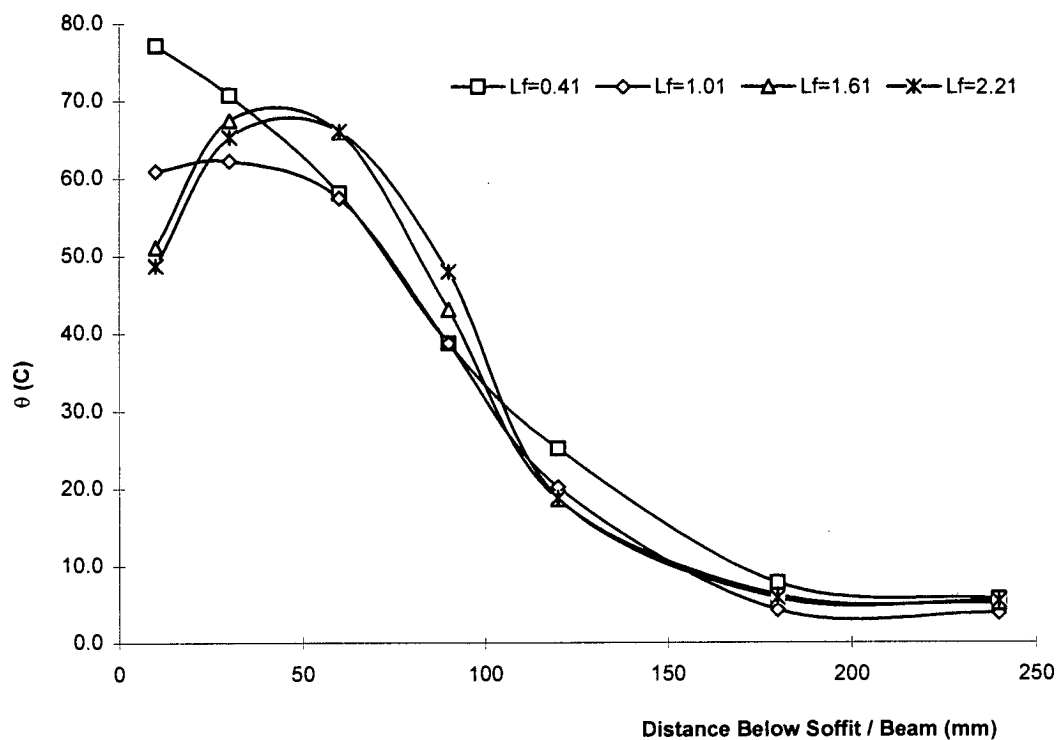
Graph A7.26 Temp Rise (q) at w-plane
Dd = 0.05; Qf = 6.09 kW



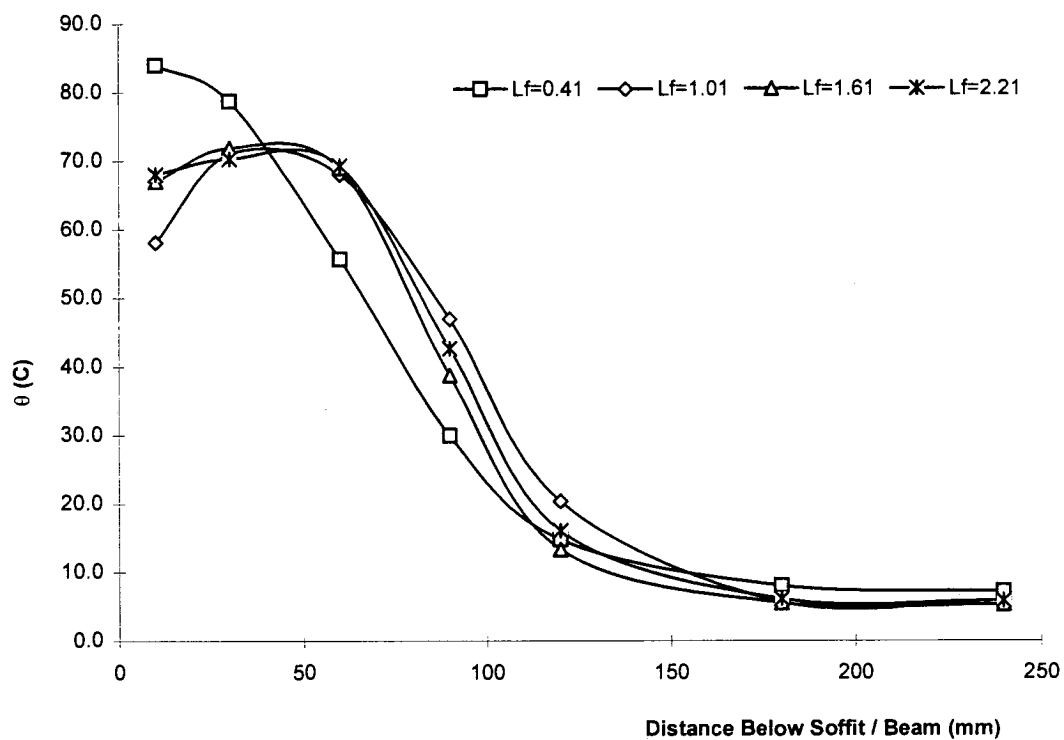
Graph A7.27 Temp Rise (q) at w-plane
Dd = 0.10; Qf = 6.09 kW



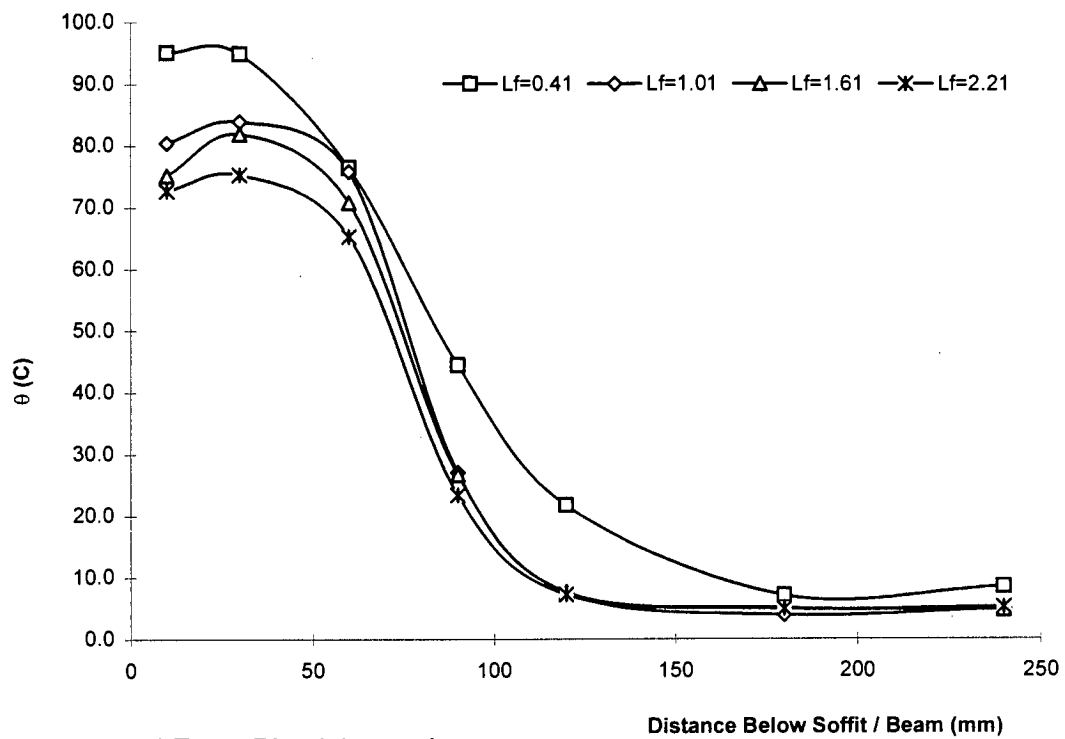
Graph A7.28 Temp Rise (q) at w-plane
Dd = 0.20; Qf = 6.09 kW



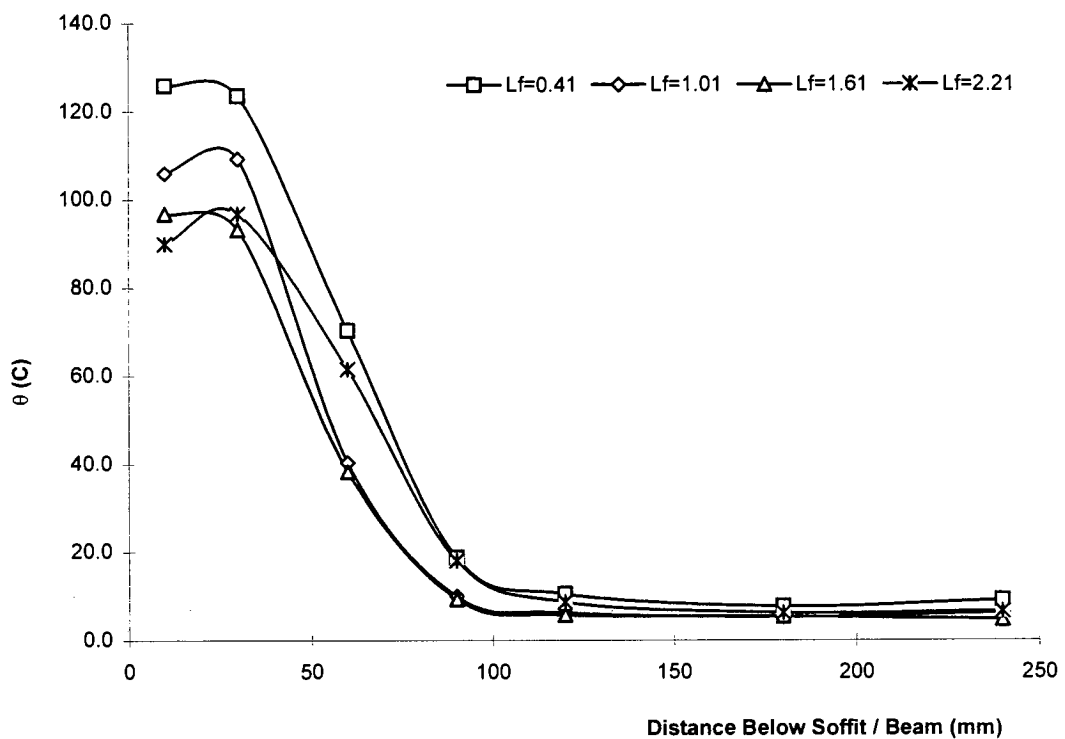
Graph A7.29 Temp Rise (θ) at y-plane
 $D_d = 0.00$; $Q_f = 4.67$



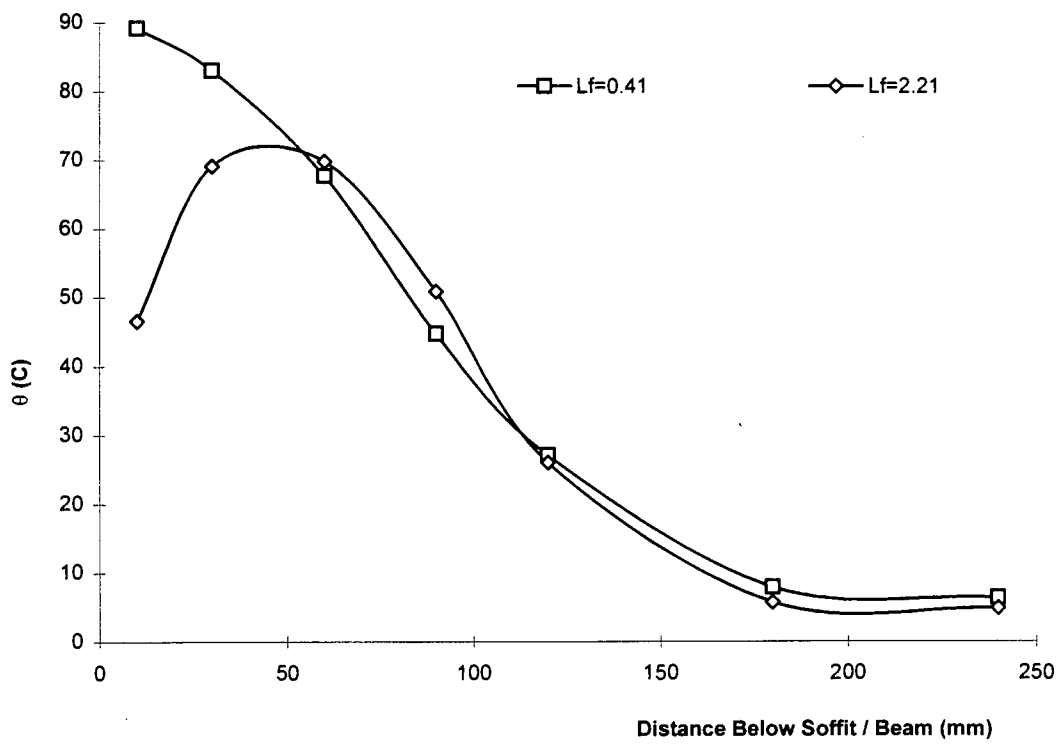
Graph A7.30 Temp Rise (q) at y-plane
 $D_d = 0.05$; $Q_f = 4.67$



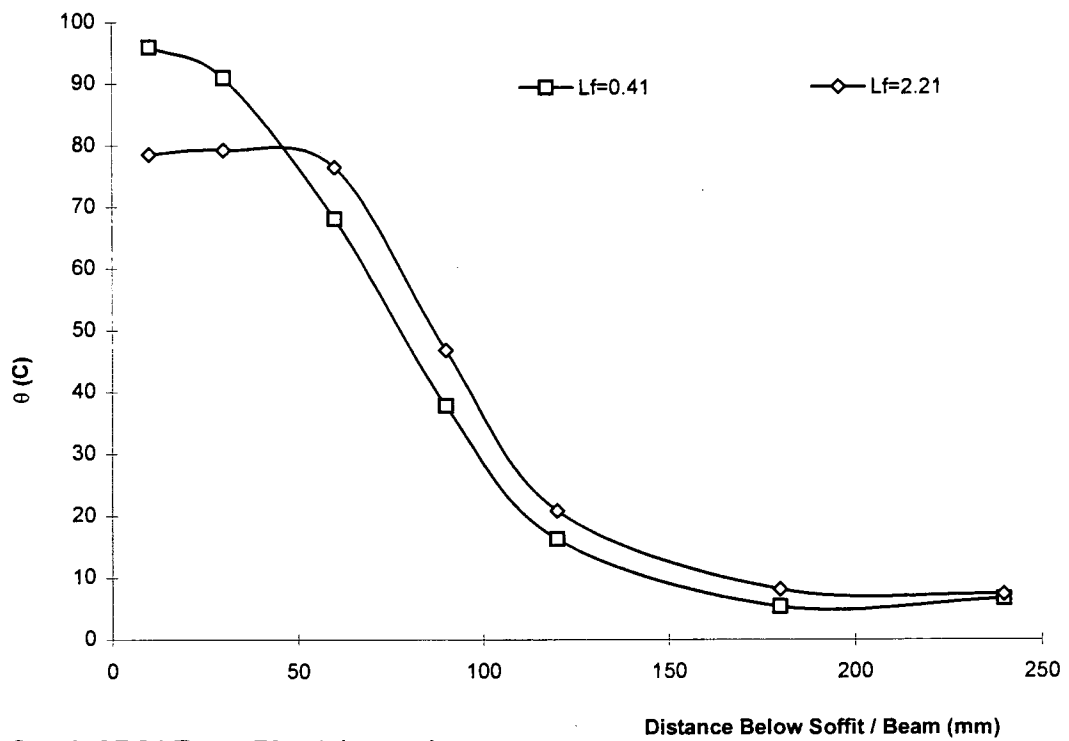
Graph A7.31 Temp Rise (q) at y-plane
Dd = 0.10; Qf = 4.67



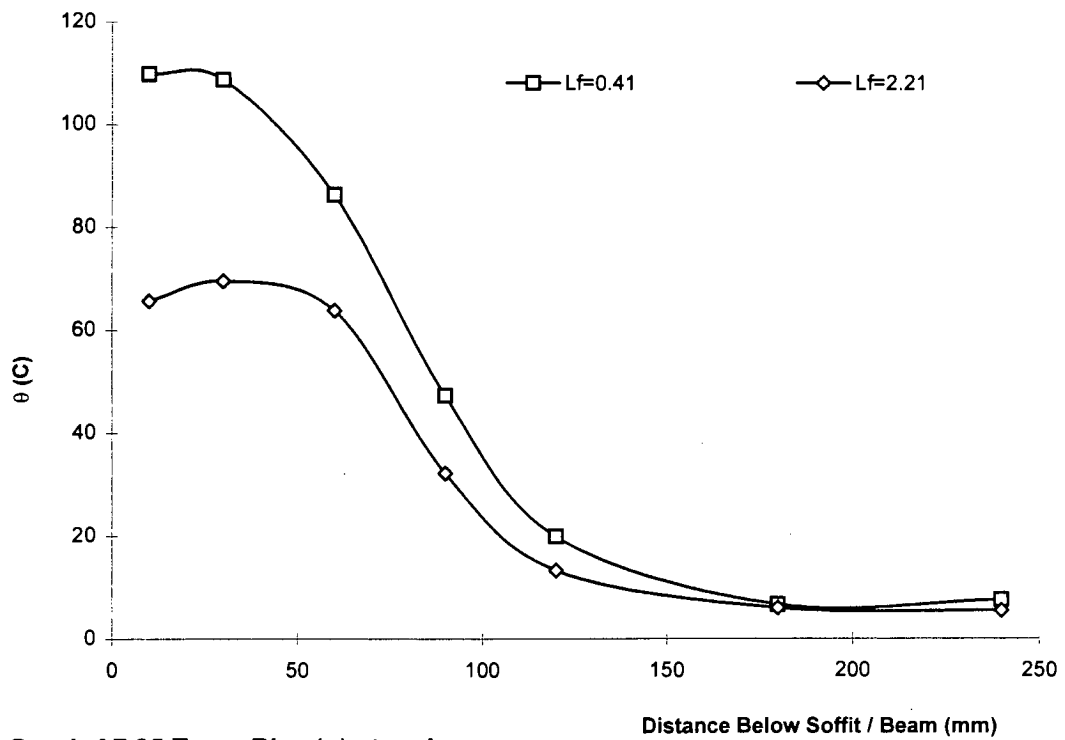
Graph A7.32 Temp Rise (q) at y-plane
Dd = 0.20; Qf = 4.67



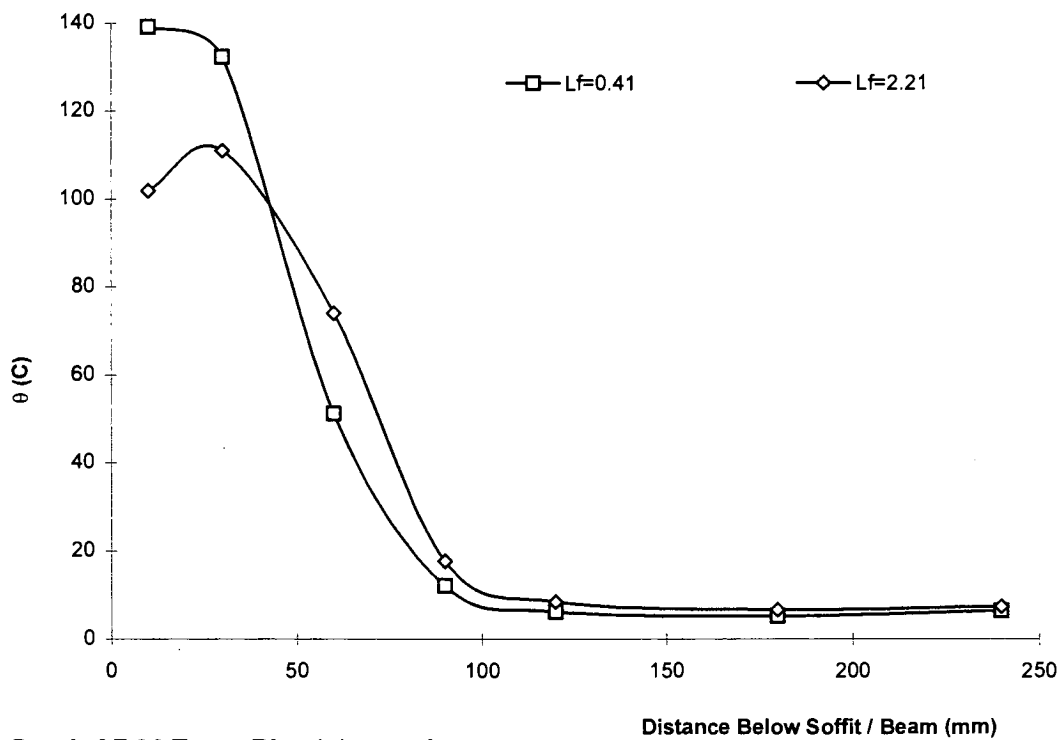
Graph A7.33 Temp Rise (θ) at y-plane
 $D_d = 0.00$; $Q_f = 6.09$



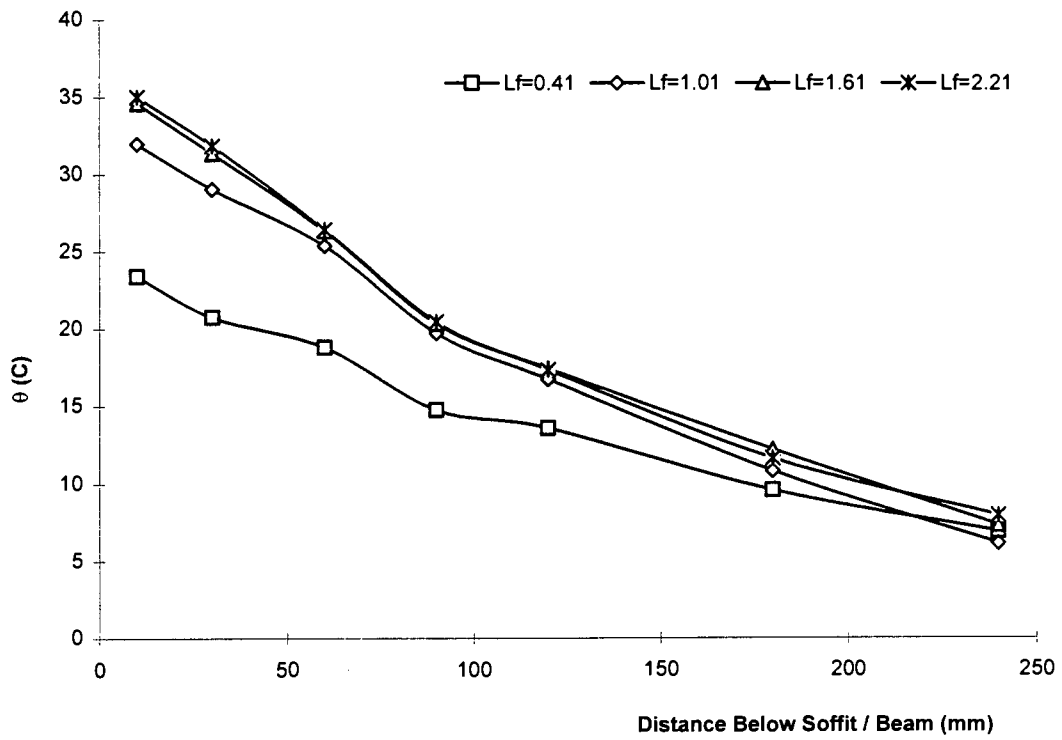
Graph A7.34 Temp Rise (q) at y-plane
 $D_d = 0.05$; $Q_f = 6.09$



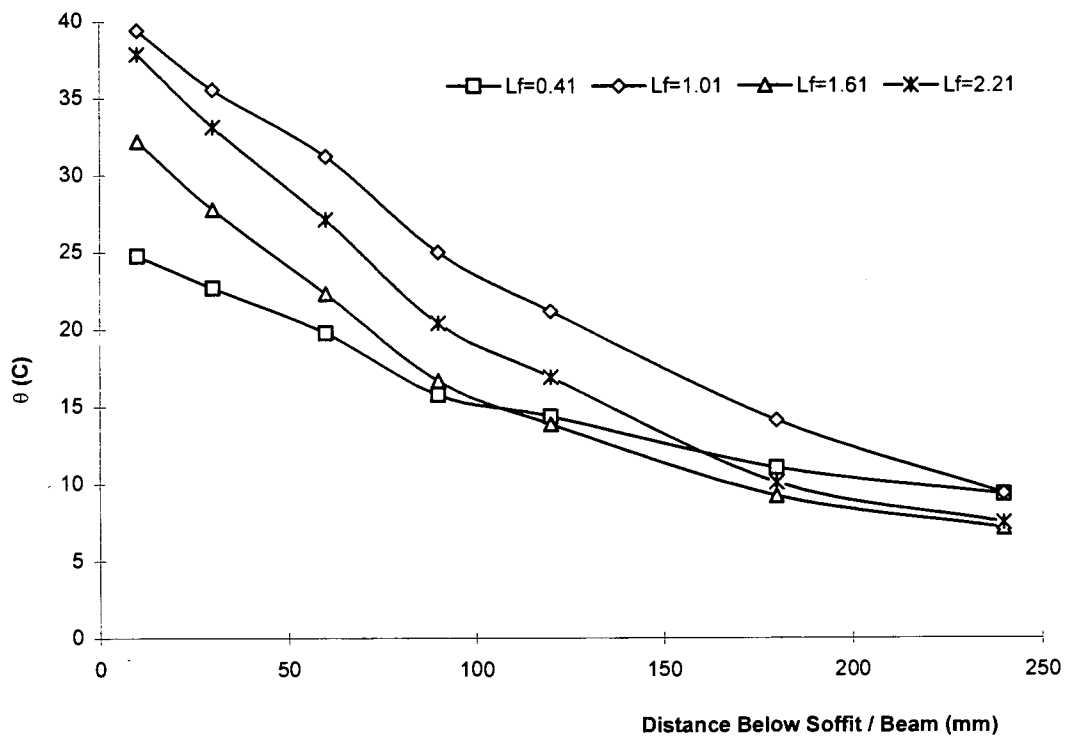
Graph A7.35 Temp Rise (q) at y-plane
Dd = 0.10; Qf = 6.09



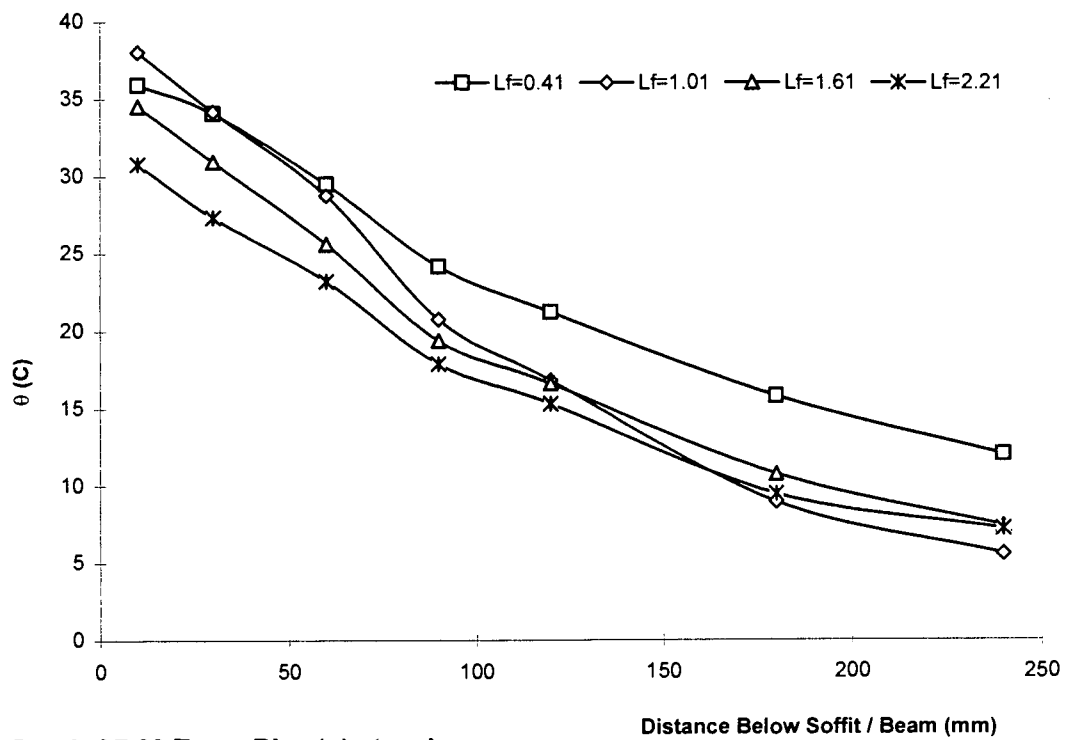
Graph A7.36 Temp Rise (q) at y-plane
Dd = 0.20; Qf = 6.09



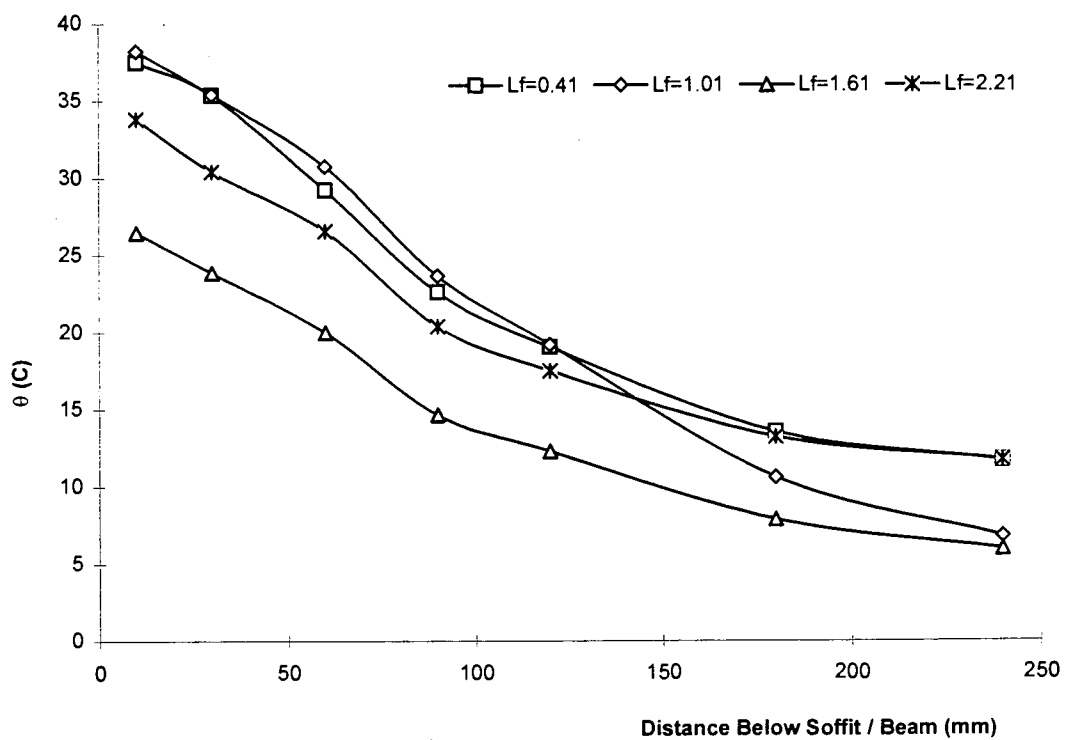
Graph A7.37 Temp Rise (θ) at z-plane
Dd = 0.00; Qf = 4.67



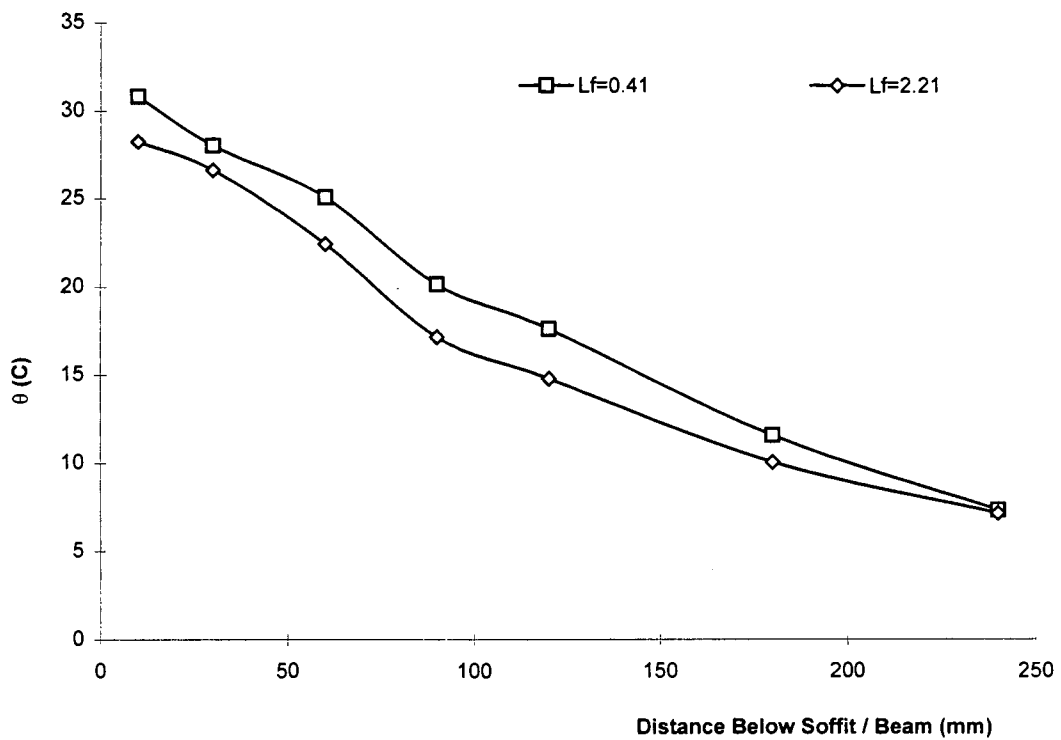
Graph A7.38 Temp Rise (q) at z-plane
Dd = 0.05; Qf = 4.67



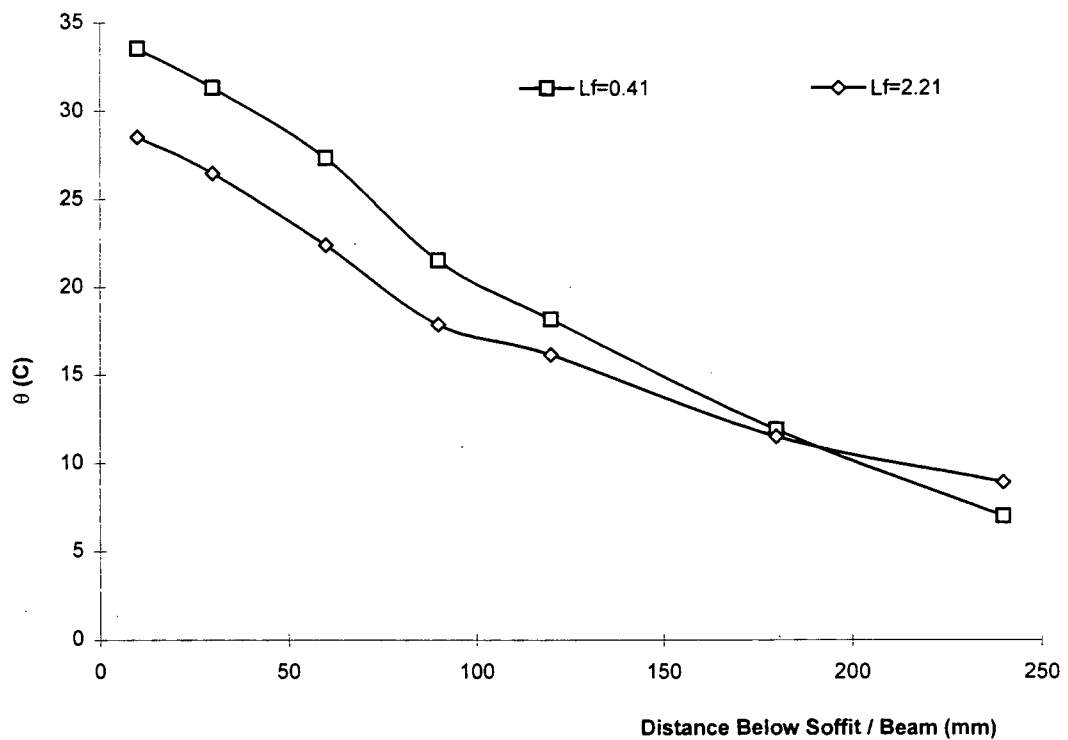
Graph A7.39 Temp Rise (q) at z-plane
Dd = 0.10; Qf = 4.67



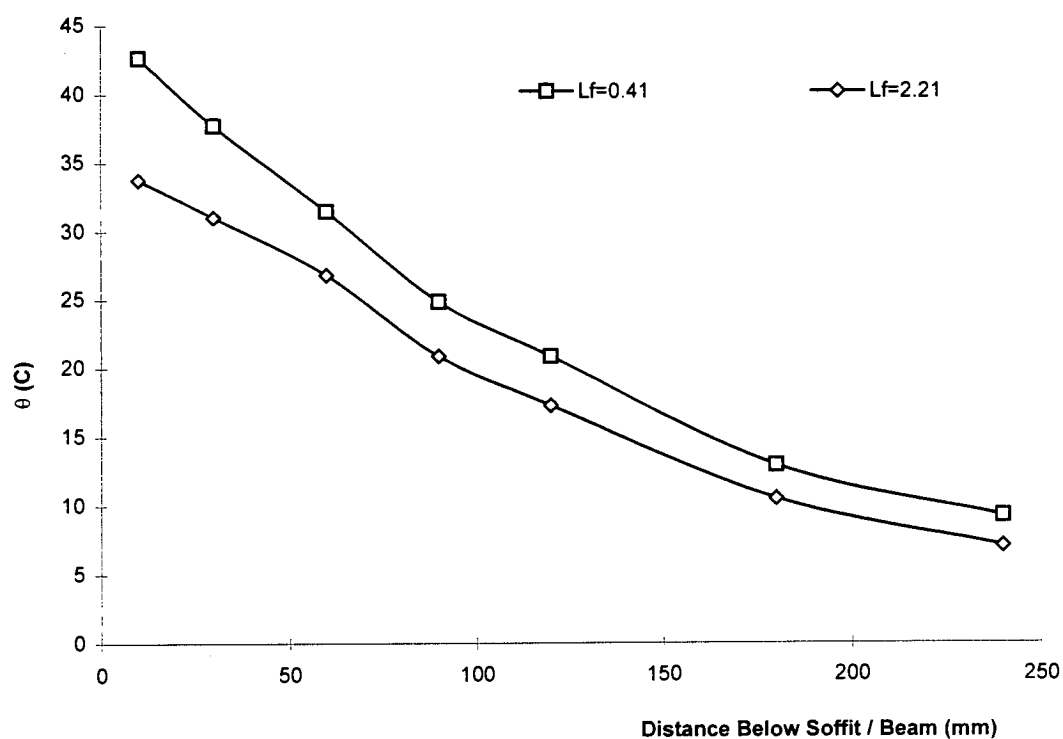
Graph A7.40 Temp Rise (q) at z-plane
Dd = 0.20; Qf = 4.67



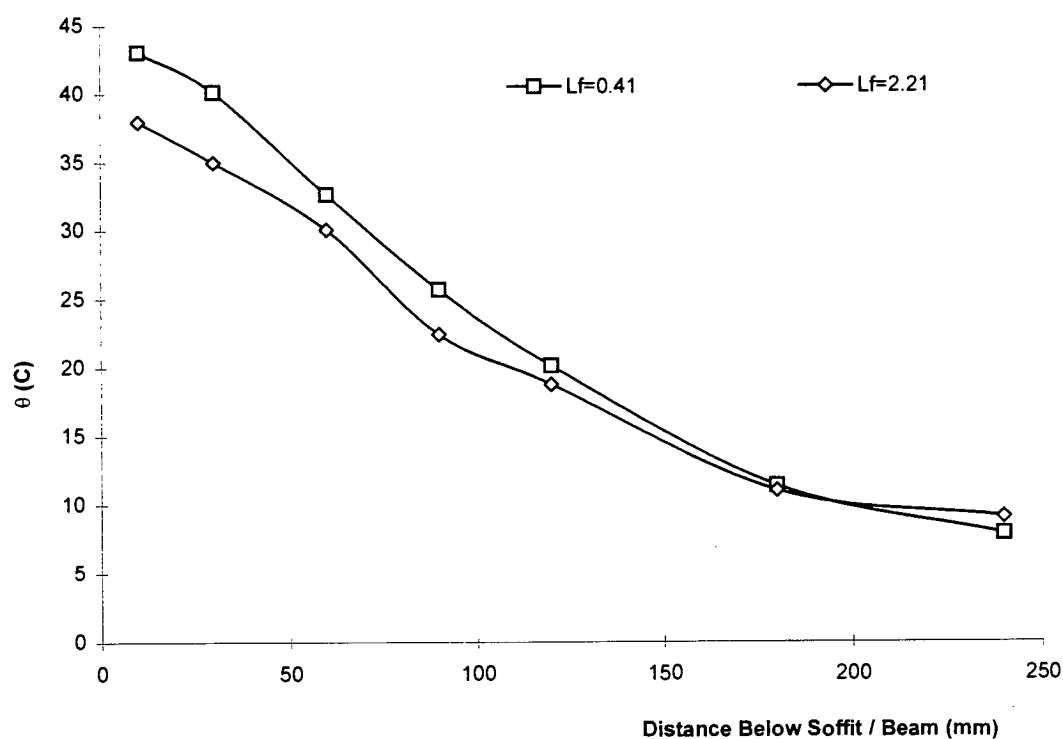
Graph A7.41 Temp Rise (θ) at z-plane
Dd = 0.00; Qf = 6.09



Graph A7.42 Temp Rise (q) at z-plane
Dd = 0.05; Qf = 6.09



Graph A7.43 Temp Rise (q) at z-plane
 $Dd = 0.05$; $Qf = 6.09$



Graph A7.44 Temp Rise (q) at z-plane
 $Dd = 0.20$; $Qf = 6.09$

	Offset from Centreline of Compartment Wd (m)				
D (m)	0	0.1	0.2	0.3	0.4
0.010	77.0	74.1	70.3	72.9	68.8
0.025	71.3	70.4	69.0	68.8	69.3
0.050	45.2	48.5	54.4	50.3	67.3
0.080	33.7	35.5	40.9	38.5	66.9
0.120	20.3	18.8	19.0	17.5	54.3
0.150	6.8	7.1	6.7	6.6	13.3
0.340	5.2	4.8	4.0	4.1	4.0

Dd = 0.00

	Offset from Centreline of Compartment Wd (m)				
D (m)	0	0.1	0.2	0.3	0.4
0.010	113.2	121.0	118.0	115.8	118.5
0.025	100.2	106.4	107.0	105.8	97.9
0.050	112.5	110.8	104.3	109.2	113.7
0.080	101.1	93.7	83.1	92.2	106.0
0.120	47.5	46.7	39.0	46.1	75.5
0.150	13.0	15.7	18.8	20.1	23.0
0.340	7.6	5.9	8.1	7.9	6.3

Dd = 0.20

Table A7.7 Temperature Rise Profiles at Offsets from the Compartment

Centreline, at w-plane; Qf=4.67 kW; Lf=0.41

		centreline of compartment	0.05 m from side wall	difference %
w-plane	Dd=0.1	1.10	1.15	4.5
w-plane	Dd=0.2	1.55	1.42	8.4
y-plane	Dd=0.1	0.79	0.70	11.4
y-plane	Dd=0.2	0.95	0.82	15.9

Table A7.8 Maximum CO₂ Measurements

	θ	ρ	v	V	m
Measurement	C	kg/m ³	m/s	m ³ /s	kg/s
Set 1	35.0	1.140	2.833	0.185	0.210
Set 2	36	1.136	3.132	0.204	0.232
Variation %	+ 2.9	- 0.3	+ 10.5	+ 17.2	+ 16.9

$L_f = 0.41$ m; $D_d = 0.00$ m

Measurement	θ	ρ	v	V	m
Set 1	37.0	1.133	2.321	0.151	0.171
Set 2	36	1.136	2.297	0.150	0.170
Variation %	- 2.7	+ 0.3	- 1.0	- 0.1	+ 0.2

$L_f = 0.41$ m; $D_d = 0.05$ m

Measurement	θ	ρ	v	V	m
Set 1	41.0	1.118	1.994	0.130	0.145
Set 2	41.0	1.118	2.202	0.143	0.160
Variation %	0 %	0 %	+ 10.4 %	+ 19.5 %	+ 19.5 %

$L_f = 0.41$ m; $D_d = 0.10$ m

Measurement	θ	ρ	v	V	m
Set 1	41.0	1.118	1.689	0.110	0.123
Set 2	41.5	1.116	1.817	0.118	0.132
Variation %	+ 1.2	- 0.2	+ 7.6	+ 2.8	+ 2.6

$L_f = 0.41$ m; $D_d = 0.20$ m

Measurement	θ	ρ	v	V	m
Set 1	32.0	1.151	2.229	0.145	0.167
Set 2	32.5	1.149	2.189	0.143	0.164
Variation %	+ 1.6	+ 0.2	+ 1.8	- 7.6	- 6.8

$L_f = 2.21$ m; $D_d = 0.00$ m

Measurement	θ	ρ	v	V	m
Set 1	34.5	1.142	1.774	0.116	0.132
Set 2	35	1.140	1.581	0.103	0.117
Variation %	+1.4	- 0.1	- 10.9	- 16.7	- 16.8

$L_f = 2.21$ m; $D_d = 0.20$ m

Table A7.9 Mass Flow Rate in Duct Comparison of Repeated Measurement;

$$Q_f = 4.67 \text{ kW}; \quad z = 0.75 \text{ m}$$

Lf	D = 0.01	D = 0.03	D = 0.06	D = 0.09	D = 0.12	D = 0.18
0.41	0.978	0.960	0.961	0.975	0.925	0.895
1.01	0.978	1.022	1.075	1.114	1.020	1.052
1.61	0.972	1.032	1.044	0.999	1.054	0.973
2.21	1.032	1.010	1.089	1.119	1.077	1.060
mean	0.990	1.006	1.042	1.052	1.019	0.995

Dd = 0.00 m

Qf = 4.67 kW

Lf	D = 0.01	D = 0.03	D = 0.06	D = 0.09	D = 0.12	D = 0.18
0.41	1.024	1.031	1.051	1.108	0.987	1.061
1.01	1.050	0.998	0.978	1.066	1.161	0.921
1.61	0.966	1.074	1.050	0.907	0.953	0.976
2.21	0.992	0.987	1.068	0.907	1.047	1.103
	1.008	1.023	1.037	0.997	1.037	1.015

Dd = 0.05 m

Qf = 4.67 kW

Lf	D = 0.01	D = 0.03	D = 0.06	D = 0.09	D = 0.12	D = 0.18
0.41	1.022	1.018	1.051	1.072	1.151	1.016
1.01	0.982	0.979	0.956	0.936	0.959	0.950
1.61	0.984	0.969	1.127	1.154	1.164	0.935
2.21	0.970	1.000	1.091	1.170	1.078	1.029
mean	0.990	0.991	1.056	1.083	1.088	0.982

Dd = 0.10 m

Qf = 4.67 kW

Lf	D = 0.01	D = 0.03	D = 0.06	D = 0.09	D = 0.12	D = 0.18
0.41	1.014	1.021	1.201	1.093	1.153	1.045
1.01	1.041	1.042	1.167	1.178	1.176	0.937
1.61	1.005	1.028	0.937	0.994	1.035	1.095
2.21	0.985	1.002	1.022	1.000	1.033	1.017
mean	1.011	1.023	1.082	1.066	1.099	1.023

Dd = 0.20 m

Qf = 4.67 kW

Table A7.10 Temperature Variations in W-Plane; $Q_f = 4.67$ kW; $z = 0.75$ m

Mean Temperature Rise

These have been calculated as follows:

$$\theta_{\text{mean}} = Q_c / m \quad {}^{\circ}\text{C} \quad \text{Eq.A7.1}$$

where: θ_{mean} - mean temperature ${}^{\circ}\text{C}$
 Q_c - heat flux at plane of interest kW (see Section 7.3.5)
 m - mass flow rate (kg/s)

		d = 0.00	d = 0.05	d = 0.10	d = 0.20
Theory	w-plane	53.0	66.3	73.8	97.3
Lf = 0.41	w-plane	52.7	56.5	78.7	79.8
Lf = 2.21	w-plane	60.9	no data	no data	62.7

Theory	y-plane	40.3	36.2	43.3	63.2
Lf = 0.41	y-plane	59.5	60.1	86.7	95.0
Lf = 2.21	y-plane	59.0	no data	no data	71.6

Theory	z = 0.75	26.4	25.0	28.0	33.6
Lf = 0.41	z = 0.75	17.2	20.4	30.8	29.7
Lf = 2.21	z = 0.75	27.6	no data	no data	26.7

Table A7.11 Mean Temperature Rise (θ_{mean} ; ${}^{\circ}\text{C}$)

Appendix 9

A9.1 Thomas Line Plume Theory Mass Flow Rates

Thomas's line plume theory was developed for double sided line plumes, not adhered plumes. By using the ratio of the entrainment constant for free plumes and adhered plumes $0.077 / 0.16$, as a factor in the calculation, then the mass flow rate can be calculated. The results are shown in Tables A9.1 to A9.3 below.

	Thomas Line Plume Theory	Duct Measurement			
Dd (m)		Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	0.171	0.210	0.192	0.179	0.167
0.05	0.167	0.171	0.156	0.183	0.161
0.10	0.163	0.145	0.145	0.146	0.135
0.20	0.156	0.123	0.120	0.132	0.132

Table A9.1 Comparison of Thomas Line Plume Theory to Experimental Mass Flow Rates Measured in Extract Duct.

Heat Release Rate: $Q_f = 4.67$ kW; Height of Rise: $z = 0.750$ m

	Thomas Line Plume Theory	Duct Measurement			
Dd (m)		Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	0.129	0.155	0.149	0.150	0.127
0.05	0.125	0.131	0.131	0.134	0.116
0.10	0.122	0.123	0.116	0.118	0.101
0.20	0.115	0.106	0.102	0.101	0.097

Table A9.2 Comparison of Thomas Line Plume Theory to Experimental Mass Flow Rates Measured in Extract Duct.

Heat Release Rate: $Q_f = 4.67$ kW; Height of Rise: $z = 0.550$ m

	Thomas Line Plume Theory	Duct Measurement			
Dd (m)		Lf = 0.41	Lf = 1.01	Lf = 1.61	Lf = 2.21
0.00	0.186	0.242	no data	no data	0.165
0.05	0.182	0.197	no data	no data	0.155
0.10	0.178	0.163	no data	no data	0.137
0.20	0.170	0.127	no data	no data	0.135

Table A9.3 Comparison of Thomas Line Plume Theory to Experimental Mass Flow Rates Measured in Extract Duct.

Heat Release Rate: $Q_f = 6.09$ kW; Height of Rise: $z = 0.750$ m

The ratio of mass flow rate when $D_d = 0.00$ m to when $D_d = 0.05, 0.10$ and 0.20 m, as derived in Thomas's line plume theory are significantly different from the values shown in Table 9.1. The ratios are shown below:

	Duct Measurement		
	$Q_f = 4.67$	$Q_f = 4.67$	$Q_f = 6.09$
Dd (m)	$z = 0.75$	$z = 0.55$	$z = 0.75$
0.00	1.00	1.00	1.00
0.05	0.978	0.973	0.978
0.10	0.956	0.947	0.956
0.20	0.913	0.895	0.913

Table A9.4 Ratios of Mass Flow rates for Different Fire Size and Height of Rise

The ratios for the deeper downstands are much higher than found experimentally.

A9.2 Heat Flux in the Duct and the Plume at the Z-Plane

From Section 9.5.

Lf = 0.41 m				
	d = 0.00	d = 0.05	d = 0.10	d = 0.20
Duct	3.07	3.01	2.92	2.60
PIV at z = 0.75	2.01	1.93	2.34	3.18

Table A9.5 Heat Flux at W, Y and Z-Planes (kW); Lf = 0.41 m

Lf = 2.21 m		
	d = 0.00	d = 0.20
Duct	2.52	2.24
PIV at z = 0.75	2.12	2.82

Table A9.6 Heat Flux at W, Y and Z-Planes (kW); Lf = 2.21 m

A9.3 Entrainment into the Adhered Plume

Ratios of the temperature rise at the y-plane to the temperature rise at a height above the y-plane. Refer to Section 9.6.

	Height Above Y-Plane (m)					
	0.00	0.05	0.10	0.20	0.40	0.75
Lf=0.41	1.00	0.85	0.75	0.62	0.49	0.30
Lf=2.21	1.00	1.00	0.93	0.79	0.65	0.53
Theory	1.00	0.91	0.92	0.94	0.87	0.68

Dd=0.00

Lf=0.41	1.00	0.92	0.87	0.68	0.45	0.30
Lf=2.21	1.00	0.98	0.91	0.90	0.75	0.54
Theory	1.00	0.91	0.93	0.94	0.88	0.72

Dd=0.05

Lf=0.41	1.00	0.95	0.92	0.77	0.58	0.38
Lf=2.21	1.00	0.93	0.93	0.87	0.66	0.41
Theory	1.00	0.92	0.93	0.94	0.84	0.65

Dd=0.10

Lf=0.41	1.00	0.91	0.84	0.67	0.50	0.30
Lf=2.21	1.00	0.93	0.89	0.81	0.54	0.35
Theory	1.00	0.92	0.93	0.90	0.73	0.55

Dd=0.20

Table A9.7 Ratio of $\theta_{\max}$ at Y-Plane to $\theta_{\max}$ at Z-Plane (θ_z / θ_y);

Qf = 4.67 kW; z = 0.75 m

	Height Above Y-Plane (m)					
	0.00	0.05	0.10	0.20	0.40	0.75
Lf=0.41	1.00	0.86	0.76	0.62	0.48	0.35
Theory	1.00	0.39	0.39	0.40	0.37	0.30

Dd=0.00

Lf=0.41	1.00	0.91	0.83	0.67	0.47	0.29
Theory	1.00	0.28	0.28	0.28	0.27	0.22

Dd=0.05

Lf=0.41	1.00	0.94	0.88	0.72	0.53	0.26
Theory	1.00	0.30	0.30	0.30	0.28	0.22

Dd=0.10

Lf=0.41	1.00	0.91	0.83	0.69	0.51	0.30
Theory	1.00	0.33	0.34	0.34	0.27	0.21

Dd=0.20

Table A9.8 Ratio of $\theta_{\max}$ at Y-Plane to $\theta_{\max}$ at Z-Plane (θ_z / θ_y);
 $Q_f = 6.09 \text{ kW}; \quad z = 0.75 \text{ m}$

Appendix 11

Question 1. What is Your Main Professional Role?

The figures below show the total reply to the questionnaire (including those eliminated from the analysis).

Building Services Engineer	38.6 %
Electrical Engineer	2.3 %
Mechanical Engineer	2.3 %
Fire Engineer	20.5 %
Fire Prevention Officer	2.3 %
Building Control Surveyor	2.3 %
Manufacturer	18.2 %
Component Supplier	2.3 %
Researcher	9.1 %
Student	2.3 %

Question 2. If you have ever had experience of any of the following methods of smoke control, at which stages were you involved

Key to Tables	a	-	Natural Ventilation: Simple Shed
	b	-	Natural Ventilation: Mall / Atria
	c	-	Stairwell Pressurisation
	d	-	Corridor Pressurisation
	e	-	Zoned Pressurisation
	e	-	Depressurisation
	f	-	Passive Containment
	g	-	Mechanical Extraction
	n	-	Never
	d	-	Design
	sp	-	Specification
	man	-	Manufacture
	sp	-	Supply Only
	sup	-	Installation
	man	-	Maintenance
	op	-	Operation
	comm	-	Commissioning

	n	d	sp	man	sup	in	main	op	comm
a	7	9	8	1	2	3	2	1	0
b	4	11	9	1	1	3	2	2	0
c	3	12	13	1	2	2	2	2	1
d	7	9	8	1	2	1	2	1	1
e	11	5	5	1	1	1	1	1	0
f	11	3	3	1	1	1	1	1	0
g	12	3	3	1	0	0	0	0	0
h	6	7	8	1	1	4	2	0	1

Table A11.1 Frequency of Responses to Question 2: Building Services Engineers

	n	d	sp	in	main	op	comm
a	0	13	8	1	1	3	2
b	0	11	9	1	1	2	2
c	1	10	7	1	1	2	2
d	6	7	5	1	1	2	1
e	8	5	3	0	1	1	1
f	9	3	2	0	0	0	1
g	2	10	8	1	1	2	2
h	3	9	6	1	1	3	2

Table A11.2 Frequency of Responses to Question 2: Fire Safety Engineers

	n	d	sp	man	sup	in	main	op
a	3	3	2	4	3	2	2	2
b	3	3	2	4	3	2	2	2
c	1	4	3	6	5	2	2	1
d	2	3	2	5	4	2	2	1
e	3	2	2	4	4	2	2	1
f	5	1	1	2	2	1	1	1
g	5	1	1	1	1	1	1	1
h	2	2	2	4	4	2	2	2

Table A11.3 Frequency of Responses to Question 2: SVA Manufacturers

Number of Methods Experienced With	Fire Safety Engineer	Building Services Engineer	Manufacturer
1	0	0	1
2	2	4	1
3	0	4	1
4	0	4	1
5	3	3	1
6	3	0	0
7	2	2	1
8	3	0	1
Mean Number	5.8	3.8	4.1

Table A11.4 Number of Smoke Control Methods Experienced by Each Respondent

	often	occasional	seldom	never
a	4	6	3	0
b	3	6	3	1
c	4	4	3	2
d	1	5	1	6
e	4	1	0	8
f	2	1	0	10
g	6	4	0	3
h	2	7	1	3

Table A11.5 Frequency of Involvement During Design: Fire Engineers

	often	occasional	seldom	never
a	2	5	4	6
b	1	7	5	4
c	0	8	5	4
d	0	6	3	8
e	0	3	2	12
f	0	1	4	12
g	0	1	4	12
h	1	7	4	5

Table A11.6 Frequency of Involvement During Design: Services Engineers

	often	occasional	seldom	never
a	2	2	0	3
b	1	2	1	3
c	1	1	2	3
d	1	0	2	4
e	0	1	1	5
f	0	0	1	6
g	1	0	0	6
h	1	0	1	5

Table A11.7 Frequency of Involvement During Design: Manufacturers

Source of Information	Fire Engineers	Building Services Engineers	Manufacturers
Sample Size	11	15	n/a
Approved Doc B	11	15	
British Standards	11	15	
FRS	7	8	
LPC	5	4	No
SVA	4	6	reliable
CIBSE	3	14	data
ASHRAE	5	3	given
SFPE	3	0	
IFS	2	0	
IFE	2	2	
Journals	10	6	

Other sources state but not included in table.

No manufacturers completed this section correctly, if at all.

Two fire safety engineers and two building services engineers failed to complete this question.

Table A11.8 Sources of Information

Source of Information	Fire Engineers	Building Services Engs	Manufacture
Fire Authority	4	14	
FRS	4	7	
FPA	2	0	No
Manufacturers	9	14	reliable
Fire Safety Consult't	5	3	data
NIST	5	0	given
Trade	6	4	
NFPA	1	0	

Table A11.9 Sources of Information

Smoke Control in Buildings Questionnaire



Fire safety is a universal responsibility. In many buildings, special systems for the control of smoke movement are essential safety features.

This questionnaire is about the possible failure modes of smoke control systems. This forms part of a research project which aims to generate a taxonomy of potential system failures. Your help is needed to enhance the outcome of what is an unsponsored project, and your participation will be appreciated. If colleagues wish to participate in this survey, photocopies of this questionnaire would be acceptable. The results will be available to respondents on request by July 1996 and a paper will be offered to the CIBSE Journal.

Research into various aspects of fire safety, especially smoke control in buildings, has been pursued for twenty-eight years at the University of Edinburgh. This questionnaire has been compiled by Joe Paveley and Eric Marchant of the Department of Civil and Environmental Engineering.

The survey is being conducted by the CES Survey Team at the University of Edinburgh. Your answers will be treated in strict confidence and no one will be able to identify you in the results. The contents of this study will not be used commercially.

January 1996

1. What is your main professional role?

tick one box

☐ 1 Architect	☐ 8 Manufacturer	☐ 15 Specialist Sub-contractor (fire)
☐ 2 Building Services Engineer	☐ 9 Component Supplier	☐ 16 Commissioning Engineer
☐ 3 Electrical Engineer	☐ 10 General Contractor	☐ 17 Maintenance Engineer
☐ 4 Mechanical Engineer	☐ 11 Building Services Contractor	☐ 18 Researcher
☐ 5 Fire Engineer	☐ 12 Electrical Contractor	☐ 19 Student
☐ 6 Fire Prevention Officer	☐ 13 Mechanical Contractor	☐ 20 Other (please specify)
☐ 7 Building Control Surveyor	☐ 14 Controls Engineer	

2. If you have ever had experience of any of the following methods of smoke control, at which stage(s) were you involved?

tick all that apply for each method

Stage of Involvement

Method	Never	Design	Specification	Manufacture	Supply only	Installation	Maintenance	Operation	Other
Natural Ventilation: simple 'shed'	☐	☐	☐	☐	☐	☐	☐	☐	☐
Natural Ventilation: complex mall/atria	☐	☐	☐	☐	☐	☐	☐	☐	☐
Stairwell Pressurisation	☐	☐	☐	☐	☐	☐	☐	☐	☐
Corridor Pressurisation	☐	☐	☐	☐	☐	☐	☐	☐	☐
Zoned Pressurisation	☐	☐	☐	☐	☐	☐	☐	☐	☐
Depressurisation	☐	☐	☐	☐	☐	☐	☐	☐	☐
Passive Containment	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other (please specify)	☐	☐	☐	☐	☐	☐	☐	☐	☐

IF YOU HAVE NEVER HAD ANY EXPERIENCE WITH SMOKE CONTROL, PLEASE STOP HERE AND RETURN THE QUESTIONNAIRE TO THE FREEPOST ADDRESS ON THE LAST PAGE. THANK YOU FOR YOUR ASSISTANCE.

3. If you have had design and/or specification experience with smoke control systems, please specify how often for the methods listed below.

tick one box for each method, first for design experience, then for specification experience

Method	Design Experience				Specification Experience			
	Often	Occasionally	Seldom	Never	Often	Occasionally	Seldom	Never
Natural Ventilation: simple 'shed'	☐ 1	☐ 2	☐ 3	☐ 4	☐ 1	☐ 2	☐ 3	☐ 4
Natural Ventilation: complex mall/atria	☐ 1	☐ 2	☐ 3	☐ 4	☐ 1	☐ 2	☐ 3	☐ 4
Stairwell Pressurisation	☐ 1	☐ 2	☐ 3	☐ 4	☐ 1	☐ 2	☐ 3	☐ 4
Corridor Pressurisation	☐ 1	☐ 2	☐ 3	☐ 4	☐ 1	☐ 2	☐ 3	☐ 4
Zoned Pressurisation	☐ 1	☐ 2	☐ 3	☐ 4	☐ 1	☐ 2	☐ 3	☐ 4
Depressurisation	☐ 1	☐ 2	☐ 3	☐ 4	☐ 1	☐ 2	☐ 3	☐ 4
Passive Containment	☐ 1	☐ 2	☐ 3	☐ 4	☐ 1	☐ 2	☐ 3	☐ 4
Other (please specify)	☐ 1	☐ 2	☐ 3	☐ 4	☐ 1	☐ 2	☐ 3	☐ 4

4. Have you ever consulted any of the following sources of information to help you with your work with smoke control systems?

tick all that apply

☐ Building Regulations Approved Document B (England & Wales)	☐ CIBSE
☐ Building Regulations Technical Standards (Scotland)	☐ ASHRAE
☐ Building Regulations (Northern Ireland)	☐ Society of Fire Prevention Engineers
☐ British Standards	☐ Institute of Fire Safety
☐ Fire Research Station	☐ Institute of Fire Engineers
☐ Loss Prevention Council	☐ Science or Engineering Journals
☐ Smoke Ventilation Association	☐ Other (please specify)

5. Have you ever sought advice from any of the following organisations to help you with your work with smoke control systems?

tick all that apply

☐ Fire Authority
☐ Fire Research Station
☐ Fire Protection Association
☐ Manufacturers
☐ Fire Safety Consultant
☐ National Institute for Science and Technology (USA)
☐ Trade Organisations
☐ Other (please specify)

6. Some smoke control systems have been found to perform badly, so that they fail to meet their objectives. Have you ever had experience of a system that performed badly?

tick one box

YES

☐ 1

NO

☐ 2

if NO, please go to
to the next page

7. Which elements caused the system to fail?

If you have had no experience of a method, or have always found it to perform well, tick a box in one of the first two rows.

For methods you have found to perform badly, please indicate the causes.

METHODS OF SMOKE CONTROL

	Natural Ventilation: simple shed	Natural Ventilation: complex	Stairwell Pressurisation	Corridor Pressurisation	Zoned Pressurisation	Depressurisation	Passive Containment	Other (specify)
No experience of this method	☐	☐	☐	☐	☐	☐	☐	☐
Always performed well	☐	☐	☐	☐	☐	☐	☐	☐
CAUSES								
Components								
Ventilators	☐	☐	☐	☐	☐	☐	☐	☐
Louvres	☐	☐	☐	☐	☐	☐	☐	☐
Curtains	☐	☐	☐	☐	☐	☐	☐	☐
Screens	☐	☐	☐	☐	☐	☐	☐	☐
Fans	☐	☐	☐	☐	☐	☐	☐	☐
Dampers	☐	☐	☐	☐	☐	☐	☐	☐
Doors	☐	☐	☐	☐	☐	☐	☐	☐
Component interfacing	☐	☐	☐	☐	☐	☐	☐	☐
Other (please specify)	☐	☐	☐	☐	☐	☐	☐	☐
System								
Performed to expectations...	☐	☐	☐	☐	☐	☐	☐	☐
...but oversized	☐	☐	☐	☐	☐	☐	☐	☐
...but undersized	☐	☐	☐	☐	☐	☐	☐	☐
Subsystem fault or other (please specify)	☐	☐	☐	☐	☐	☐	☐	☐
Associated Systems								
Detection	☐	☐	☐	☐	☐	☐	☐	☐
Communications	☐	☐	☐	☐	☐	☐	☐	☐
Control Systems	☐	☐	☐	☐	☐	☐	☐	☐
Escape methods	☐	☐	☐	☐	☐	☐	☐	☐
Power	☐	☐	☐	☐	☐	☐	☐	☐
Other (please specify)	☐	☐	☐	☐	☐	☐	☐	☐

8. Now go back and select the major cause of poor system performance for each method from your selection above.

circle one box for each method

9. In projects with which you have been involved, which methods of testing would usually be specified for commissioning for most smoke control systems?

tick all that apply

☐ Sequence of operations	☐ Small heat source (10kW) without heat measurements
☐ Air flow measurements	☐ Small heat source (10kW) and heat measurements
☐ Pressure measurements	☐ Large heat source (0.5MW or larger)
☐ Cold smoke	☐ Other (please specify) _____

10. Now go back and indicate the methods you would prefer to use if resources were available. circle all the boxes that apply

11. In buildings with which you have been involved, which methods are usually specified for testing for routine maintenance purposes for most smoke control systems?

tick all that apply

☐ Sequence of operations	☐ Cold smoke
☐ Air flow measurements	☐ Small heat source (10kW) without heat measurements
☐ Pressure measurements	☐ Other (please specify) _____

12. Would you be willing to...

tick one box for each row

	Yes	No
...contribute information for a case study?	☐ 1	☐ 2
...respond to detailed questions about the performance of smoke control systems?	☐ 1	☐ 2

If Yes: please write your name and address in the space provided here.
This information will be sent separately to the authors of the survey, who will contact you within the next few months.

I am willing to contribute information to a case study and/or answer a more detailed questionnaire:

NAME: _____

POSITION: _____

ADDRESS: _____

If you do not wish to be involved any further, but have additional comments that you wish to make, please include them on a separate sheet of paper and staple to the questionnaire. Thank you for your assistance.

Please return the completed questionnaire to:

CES Survey Team
FREEPOST
The University of Edinburgh
34 West Richmond Street
Edinburgh
EH8 0LW

Appendix 12

Fire growth rates:

Fire growth rates for t^2 fires are presented in the Draft Code of Practice for Application of Fire Safety Engineering Principles to Fire Safety in Buildings.

$$Q_f = \alpha t^2 \quad \text{kW}$$

where α is the fire growth parameter in kJ/s.

Fire Growth Rate	Typical equivalent materials	Fire Growth Parameter kJ/s	Time for Q_f to reach 1000 kW
Slow		0.0029	584
Medium	Cotton mattress	0.0117	292
Fast	Mail bags, plastic foam	0.0469	146
Ultra-fast	Alcohol pool fire Fast burning furniture	0.1876	73

Occupancy Type	Fire Growth Rate
Dwelling	Medium
Office	Medium
Shop	Fast
Hotel Bedroom	Medium
Picture Gallery	Slow