The Interaction Between Occupants and Fire Alarm Systems in Complex Buildings

by

Paul J Haydock

A thesis submited in partial fulfilment for the requirements for an MSc (by Research) degree in the Department of Built Environment, University of Central Lancashire, Preston.

August 2000

ABSTRACT

This Masters dissertation reviews the present methods of research in evacuation, various major fires are reported as part of this process. The findings of this research indicates that a delay in warning occupants in a building, to the threat of a fire, is a constant feature in fire disasters. Further the provision of early warning and an appropriate response are considered with reference to the reduction of the number of fatalities in fires.

The thesis concerns the hypothesis that people with enhanced alarm information exhibit diminished panic. The resultant technological developments such as voice alarm messages and Informative Fire Warning systems [IFW] are reported. The effect of these systems by the minimisation of pre-movement or occupant response time in the decision making process are studied. Effects concerning the influence of, for example, mobility and alcohol upon human behaviour are also reported

The main thrust of this thesis is to examine the methods by which the time of evacuation to safety in complex buildings can be observed and assessed. Two evacuation experiments on a shopping centre are studied and measurements were taken using digital technology to count occupants during the evacuations. The findings of the experimental work are summarised and reported and the adequacy of the fire evacuation system is assessed. The importance concerning management arrangements and alarm systems and future research are discussed.

The two experiments were carried out using the Footfall digital counting mechanism proved very successful and the recording of all the data was carried out by the author with no additional assistance. The fire drills resulted in some interesting findings regarding occupant behaviour. The occupants appeared to place considerable trust in the information they received. The observed behaviour in the response to both fire evacuation drills in a similar environment may be explained in part by the task characteristics of the perceived emergency and the mode of cognitive processing created

by such circumstances. This suggests that untrained, unprepared occupants tend to resort to informal or intuitive processing, which can be influenced by instruction from either an alarm system or by persons in authority.

The prospects for further work are the carrying-out of more evacuation experiments in order to develop reliability in the determination of pre-movement times. Further experiments would be in other types of premises of varying configurations and occupancies, using the same type of recording equipment that proved effective in the two experiments carried out.

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CHAPTER ONE

OUTLINE OF THE PROBLEM

1.1 INTRODUCTION

Since the earliest times of man, the *flight or fight response* has been used to mitigate against the effects of a variety of disaster scenarios. A Chinese proverb recommends that "of the 36 ways to escape danger, running away is the best". Evacuation or *running away* has been used by man, to escape a diversity of dangerous occurrences. In our modern society and with the complications of different types of warning systems; it is important that designers understand the circumstances under which people will evacuate. This will enable designers of advanced buildings such as shopping complexes the ability to produce innovative and safe buildings.

With regard to complex buildings, the efficiency, accuracy and clarity of evacuation messages by warning systems has had relatively little systematic study. In particular there has been a reluctance in building safety design to study aspects involving human factors and behaviour. Many studies [1] concerning exit design consider occupant movement similar to ball bearings being emptied into a box, i.e. movement regular and subject to the laws of mass transfer. When such models are applied to human beings in complex buildings the result is neither accurate, scientific nor realistic.

Buildings vary according to their structure, form and function and when one of these fall outside the prescriptive codes that are predominately used, the resultant building could be described as unconventional or complex. Designers of unconventional or complex buildings require techniques' which depart from traditional fire safety concepts, and yet still achieve an acceptable and visible level of fire safety. Therefore, designers must decide upon the fire safety measures required to produce a realistic and reasonable level of risk. Before considering how the various principles and technical concepts are applied in the process of design, it is important to analyse the framework of the legislation that covers buildings designed for occupation.

Over recent years, a great deal of money has been spent on research by the fire engineers working for commercial companies, particularly in the areas of smoke control and fire detection. The evidence for this being the technological advancement in new systems on the market at the present time. The main motive has been to achieve a competitive edge over rival manufacturers of similar equipment. This has resulted in the commercial interests of manufacturers leading the designers and architects but this has not necessarily resulted in an improvement in life safety in buildings. The evidence for this can be seen in **Figure 1.1** which indicate that the number of fatal casualties in occupied buildings (other than domestic property) has remained steady between 1984 and 1995.

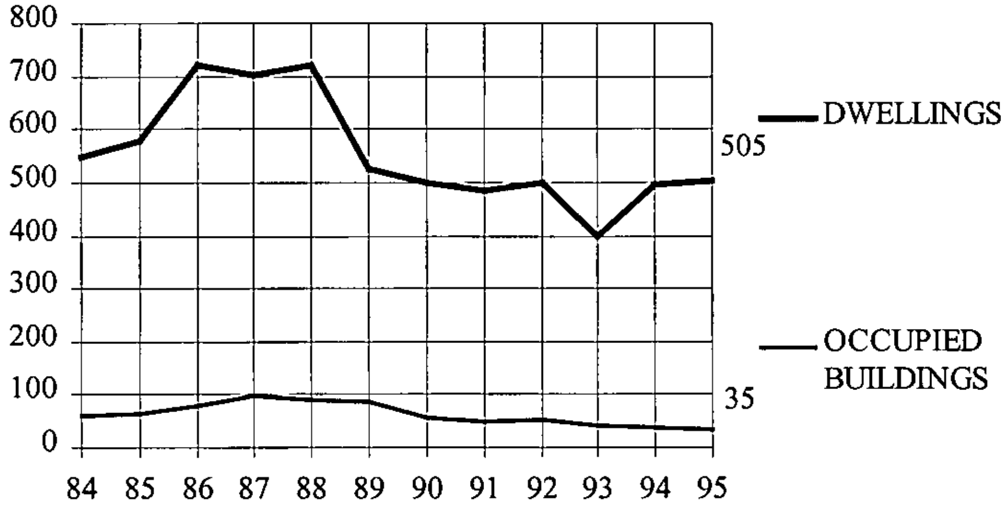


FIGURE 1.1 FATAL CASUALTIES FROM FIRE BY CATEGORY OF PREMISES

Statistics supplied by the Home Office [6]

Over the same period only a modest amount of research has taken place concerning safe means of escape [2]. The reason for this could be that that the fire engineering trade has no direct interest in these fundamental matters. It makes no difference to fire alarm manufacturers whether a person has to travel 10 metres or 100 metres to escape from a building or if it takes that person two and a half minutes or twelve minutes to reach a point of safety. Therefore there has been no recent alteration in evacuation times, escape routes and travel distances; those used today originate from the Government paper titled "Post-War Building Studies". published in 1946 [1].

1.2 HISTORY

The Government is responsible for formulating rules and regulations that attempt to limit fire hazards in buildings. The origin of these regulations can be traced back to codes that were introduced following the Great Fire of London in 1666 [3]. The Great fire of London burned for several days and although it destroyed a major part of the city, there were relatively few fatalities.

Following this serious fire, rules were put in place that attempted to prevent such a major disaster occurring again. These rules controlled the proximity of buildings to prevent external fire spread. This aspect of fire safety differs from other fire legislation in that it covers the safety of people in buildings other than that where the fire has occurred. This control was put in place to prevent a major conflagration that could involve many buildings and has a greater bearing on property protection than life safety. It could also be argued, however, that such controls can be justified on life safety grounds by the demands of society. The Great Fire resulted in the introduction of the Rebuilding Act for the City of London 1667. The Act provided a code with a means of enforcement, and served as a model for other provincial towns in subsequent years.

The history of regulations concerning life safety through the provision of adequate means of escape is more recent and is the main aspect of fire safety around which all other aspects revolve. Standards which concern the provision of means of escape have developed by a similar process to those introduced following the Great Fire of London, and may be described as *stable door legislation* [4]. Following fire incidents where there has been significant loss of life, legislation has been introduced to either upgrade or initiate standards to appease the expectations of society. The fire at the Theatre Royal Exeter in 1887 was one of the forerunners in producing regulations that referred to the principles of means of escape. There were 186 deaths and subsequently the Public Health Act 1890 included provision for safe means of egress in places of public resort [3].

Probably the most significant incident in the last century that has influenced means of escape principles was the Empire Palace Theatre fire Edinburgh in 1911. A magician on stage was carrying out a stunt with the use of fire, but unfortunately it went wrong. A safety curtain was lowered and the auditorium was safely evacuated of its 3000 spectators but the magician and some staff died. During the evacuation the orchestra played the national anthem which took 2.5 minutes; although not formally documented, many recent researchers [2] have suggested that this was how the average standard of 2.5 minutes to evacuate from a compartment fire was originated. This standard is still used today for small simple buildings.

1.3 RATIONALE

This reactionary process to formulate legislation has now been replaced by the use of statistics [5] that are compiled with ever more complexity. The interpretation of these, are now used to reduce the level of prescriptive guidance, and to concentrate resources on community fire safety. Statistics over recent years [5] has shown no increase in the number of fatal casualties in occupied buildings (other than domestic dwellings). In 1995 the figure was 35 deaths. This is compared with the more serious problem of fire deaths in domestic property of 505 deaths in 1995 (**figure 1.1**). These statistics are now used by legislators to redefine the method of application from prescriptive control to risk assessment and self compliance. In the main these statistics are compiled by the Home Office Fire Research Department in Garston Hertfordshire [5] and have now begun to influence the direction of decision making by the Government. The Home Office are now pushing for resources to be channelled into reducing the number of fire deaths by education of the population in domestic property [6].

The use of these statistics over the past twenty years have led to questions being asked upon the validity of prescribed evacuation times [2]. Architects and builders have criticised the rigidity of the control systems, which have placed restrictions upon the design of complex buildings. It is thought that a more realistic approach is now required

[7] in the design of a variety of building types including open plan offices, atria, shopping malls and multipurpose entertainment complexes.

The result of this criticism was the introduction of the new Building Regulations in 1985, where fire safety needs were expressed as a functional statement. The existing method defined by the Building Regulations Approved document B [8] was retained to cope with the design of small and conventional design, as described in Chapter 2. This document is one of a series that has been approved by the Secretary of State as a practical guide to meet the requirements of schedule one and regulation seven of the Building Regulations. The details in the guidance are intended to provide minimum, but appropriate solutions to the more common building situations and as such provide a one route design for simple buildings. There is no obligation for designers to adopt any particular solution in the Approved Document, as the functional statement also permits designers to pursue the requirement of any given situation and to design fire safety to meet identified hazards; this has been called the Fire Engineered solution. If this route is taken, then documentary evidence is required to demonstrate how that the functional statement has been satisfied.

This change in approach has permitted designers to quantify the fire hazard and to prepare an integrated package of fire safety measures to achieve the declared fire safety objectives. Many of the buildings erected on Londons' Canary Wharf development in the 1980's were the first using such design criteria. One example of this approach was the former Geological Museum in South Kensington, which has been transformed into a contemporary design now called the Earth Galleries [9]. The radical alterations were outside the parameters of Approved Document B, therefore a Fire Engineered solution was used to satisfy designers and enforcement agencies. This solution proved that the maximum population of 2,500 could be evacuated before a fire could produce hazardous conditions that could become untenable. The full process requires the quantification of the fire hazard, the design objectives and the required control measures. This technique has been developed using available knowledge, and consists of statistical data concerning fires, experimental data from studies and the theoretical analysis of particular fire risks.

This approach by Fire Safety Engineers can be described as the creation of structural and managerial arrangements, which in the event of an emergency ensure that a determined proportion of the occupants can safely evacuate. That is, to ensure that the time occupants would take to evacuate a building is less than the tenability levels within the building with a built in safety margin. The latest document to describe how to achieve such a goal is the British Standards Institute Draft for Development, Fire Safety Engineering in Buildings 240 [7]. Architects and Designers, as previously mentioned, have indicated there is a need to understand the relationship between occupant movement and the environment in which they move. This includes the time that is taken for the occupants to recognise and react to the necessity for evacuation, this is defined as the pre-movement time.

1.4 OBJECTIVES

The objective of this research is to develop and investigate the framework of critical factors that influence the design criteria for means of escape, with regard to the safety of occupants during evacuation. An important aspect of this study will be to incorporate an interdisciplinary approach to the investigation of those safety parameters which may influence design standards.

The first aim of this research is to provide an overview of the previous studies that have been undertaken. In this part of the study the latest design principles will be discussed in addition to current research in occupant behaviour. This project will also consider the principles of current means of escape design for simple and complex buildings. These principles include the need to make numerous assumptions regarding occupant behaviour and movement when involved in fire emergencies. These assumptions will be investigated as part of the study since there is a dearth of empirical studies having been undertaken in this area.

Psychological principles have been adopted by Canter [10], Sime [11] and Bryan [12], who have become the modern pioneers of research in evacuation behaviour and the effects of various types of alarm systems upon occupants. These studies have been carried out using either modelled computer scenarios or street surveys. It is proposed in this project to study methods of recording evacuations, using the latest electronic technology for counting people in and out of complex buildings to gather this data and to compare it with published pre evacuation/occupant response times.

The psychological reactions of occupants in a fire situation have been identified by Bryan [12] as a series of decision making processes starting with recognition. Sime [13] suggests that the first reaction of the occupants is to assume that the nature of the incident is minor in nature and that the threat to life is minimal even when this is not the case. He suggests that following the initial information evaluation a response will be made; to either do nothing, fight the fire or to evacuate the building.

This study will evaluate the effectiveness of alarm systems with particular attention to the time from the beginning of a fire to the first movement of the occupants (pre-movement time). Advances have been made in understanding the movement of smoke and people in fires. Calculations now enable fire engineers to estimate the time from the start of a fire to the onset of hazardous conditions. These hazardous conditions are described as the time at which smoke entering the escape routes affects visibility, temperature, toxicity and the ability to breath. Active and passive fire safety measures within a building can have a significant influence on the time to hazard. The fire protection industry is now capable of providing smoke control systems that exhaust the products of combustion for a calculated period of time to enable occupants adequate escape time.

CHAPTER TWO

RESEARCH METHODOLOGY AND FIRE STUDIES

2. 1 PREAMBLE

The few fires that result in the loss of human life in buildings other than domestic dwellings, make it difficult to study human behaviour in fires. Due to unpredictability, it is impossible to set up studies in advance of an incident. There have been attempts to gain information from people after an incident. One such study was carried out following the 1980 MGM hotel fire in America [14] in which a questionnaire was sent out to all those affected by the fire. However, the people that could have given the greatest information into human behaviour were unfortunately those that were killed in the incident. The current basis of knowledge on human behaviour in fires is extracted from a variety of data. Each in its own way has its own strengths and weaknesses, but all of them can be complemented by a scientific approach.

When major incidents occur, a range of forms of enquiry may be set up, to try to establish a cause of the incident. These types of enquiry may take the following forms; judicial enquiries, technical reports, psychological surveys, psychological laboratory simulations, computer simulations and case studies; all aim to provide information that in the future may make the built environment a safer place to live. All of these enquiries to some extent overlap in the detail produced, but their effect upon understanding human reaction in fire is of variable quality.

2. 2 JUDICIAL ENQUIRIES

A series of judicial reports have reviewed major incidents that have resulted in the loss of life in the twentieth century. These have either involved fire and the lack of provision of means of escape or the inadequacy in the provision of means of escape following disorder incidents. Football stadium incidents have been subject to a number of judicial enquiries, the nature of occupancy in sports grounds offer a number of similarities to those experienced in complex buildings such as shopping malls with occupants visiting on a casual basis.

One of the first of these was the Shortt Report of 1924 followed disorder at the Cup Final of 1923 [3]. The Moelwyn Hughes Report of 1946 followed the disaster at Bolton Wanderers ground when overcrowding caused 33 deaths. In 1966 the Government commissioned the Chester Report on "The State of Association Football". The Harrington Report of 1968 drew attention to problems of crowd behaviour and led to the Lang Report of 1969 on the same subject. In 1972, Lord Wheatley's Report on Crowd Safety at Sports Grounds followed the disaster at Ibrox Park, Glasgow, where 66 spectators died. The McElhone Report of 1977 on Football Crowd Behaviour of Scottish supporters was commissioned by the Secretary of State for Scotland following disorder at the Wembley Stadium. As a result of the Wheatley Report, Parliament passed the Safety of Sports Grounds Act 1975. In January 1986, Mr Justice Popplewell, whose judicial enquiries, following the Bradford Disaster was the eighth in the series, summarised those of his seven predecessors.

Finally the most recent inquiry was carried out when Lord Justice Taylor was instructed by the Home Secretary to inquire and to make recommendations about the needs of crowd control and safety at sports events. The first stage of the Inquiry was primarily concerned with the investigation of events at Hillsborough Stadium on 15 April 1989, when 95 people were crushed to death at a Cup semi-final match between Liverpool and Nottingham Forest. This report and the final recommendations are instrumental in promoting better and safer conditions at sports grounds in the future.

Judicial enquiries conform to defined procedures as a pre-enquiry to the coroner's investigation. In analysis of these reports, although not their prime responsibility, they can guide legislation and education to mitigate against future tragedies. Whilst the value of these enquiries cannot be doubted, their advancement in the understanding of human behaviour is limited. This type of enquiry is rare and therefore only occasionally brings about change. A typical example was the inquiry following the Valley Parade Bradford City Football Club fire in 1985. Following this fire, where there were 56 deaths and many injuries. This event led to a working party, established under the aegis of Lord Justice Popplewell's [15] Inquiry into Crowd Safety and Control at Sports Grounds, which made recommendations and resulted in the Fire Safety and Safety of Places of Sport Act 1987, which amended the Safety of Sports Grounds Act 1975. Following the enquiry Lord Justice Popplewell stated:

" almost all the matters into which I have been asked to inquire and almost all the solutions I have proposed, have been previously considered in detail by many distinguished Inquiries over a period of 60 years. "

If we consider the high standard of Football Stadiums in the U.K. in the 1990's it can be seen that this legislation has been a major influence upon crowd control and stadium safety. The value of such enquiries cannot be doubted and their significance upon the legislation that has emerged from Parliament has been enormous, they have done little to help us understand human behaviour in fires. The fact that they only occur in history on a very few occasions means that though they may make a significant change to the legislation and standards at that particular moment in time they may not provide any useful guidance regarding new practices or technologies. Further the reactive nature of such enquiries are limited to that particular incident and do not have a broader base to look at minor incidents or near misses which may have occurred.

2. 3 TECHNICAL STUDIES

Technical studies are another source of information about major incidents, where a major loss of life has occurred in a fire. These studies are carried out under laboratory conditions for example at the Building Research Station or a similar research establishment. They are mainly concerned with the source of ignition, the process of combustion, the progress of the fire and how the various components of the building inter-reacted. An example of such a study undertaken was following the Stardust Disco fire in Dublin [3] in 1981 in which 48 people died. A main feature of the study was the interaction between wall linings, heat radiation from low ceilings, and the use of foam backed carpet for wall coverings which contributed and aided rapid fire growth. These studies may give an insight into the physical conditions that the occupants were faced with, but rely upon assumptions and circumstantial evidence concerning human behaviour. Experiments which are carried out recreating the technical aspects of the fire and its progress, rely on rigid details. Even so some of these details are based on assumptions, for example with regard to the means of escape design, all British Standard 5588 building codes [16] rely on the following assumptions:

- 500mm is the maximum shoulder width of a person and therefore exit widths should be designed to cope with multiples of this width.
- Two people exiting will exit side by side and therefore the exit with will be 1050 mm there will be no overlap.
- To provide for additional exit capabilities simply add the provision of the extra person.
- Psychological considerations are ignored with regard to exit width capacity, on the assumption that people will react the same as ball bearings.

Pauls [9] criticised such design criteria and the assumptions, that are still in use today. He stated that:

"Not only do emergency responders appear to operate without a clear understanding of occupant evacuation, the building occupants face rude surprises when an emergency occurs. For example, occupants might not properly appreciate that, in a total evacuation, queuing and long evacuation times are inherent in our traditional and current approaches to means of escape".

A typical example would be a large occupancy office block, department store or football stadium. In this type of building the large number of people leaving may mean that some people will block the evacuation of others. The effect of reduction in the escape route width and the potential of stair accidents can be disastrous, when large numbers of people are involved.

2.4 LABORATORY SIMULATIONS

The first attempt to make a systematic research investigation of the behaviour of people in fire was made at Loughborough University. Wood [17] carried out surveys attempting to study such human behaviour, both interview and questionnaires were used to evaluate human behaviour. Data was collated from over 1000 fire incidents from more than 2000 people. He concentrated his research on two main aspects of human reactions, movement through smoke and evacuation from the building. The main findings were that the reaction of occupants fell broadly into three categories;

1) Concern with the evacuation of the building either by oneself or with others.
2) Concern with firefighting or at least the containment of the fire.
3) Concern with warning or alerting others, either individuals or the fire brigade.

Studies were also carried out at the Fire Research Station concerning the means of escape. Data concerning the movement of crowds was used to construct a mathematical model to predict the time necessary to evacuate high-rise buildings. Predictions from this model compared favourably with data from fire drills. Evacuation exercises were carried [19] out at Hackney hospital, with different staff and patient samples. Studies at Dundee University investigated occupant's attitude towards risk. Studies at Surrey University [22] have investigated informative fire warning systems and the reactions of building occupants to alarms from fire detection systems.

These psychological surveys are another type of study, which provides a picture of human reactions in fires; the scientific psychological approach, using as few assumptions as possible. This information is collected from as many groups of people as possible affected by the fire. Therefore a framework from as many incidents is built up to predict what would happen in any future event. This said, there are many problems locating people who have evacuated or have been affected by a fire; once located they may not remember their actions in detail or may be psychologically affected by the experience and therefore find it difficult to discuss the event.

A criticism that can be levelled at questionnaire techniques such as previously described is that they rely upon what people say they did and not on what they actually did at the time of the incident [18].

2.5 PSYCHOLOGICAL EXPERIMENTS

Psychological laboratory simulations endeavour to recreate aspects of human behaviour which may occur during a fire. Peschl [21] attempted to create controlled situations to examine human responses to various stimuli. The creation of situations where people may be in danger raises ethical arguments and if the people are not put in danger then only certain specific information can be gained. An example of this is the choice of exit routes or the visibility of exit signage through smoke.

The Building Research Establishment (BRE) [22] has undertaken laboratory experiments between different fire warning systems, the purpose of the experiments was to evaluate the effectiveness of different systems to promote fast evacuation from buildings. One of the catalysts for the research was a report by Sime [23] who stated:

" In fires. . . . . . . the early stage of the recognition was often characterised by ambiguous information cues. In a number of cases there was a serious delay in people taking these cues seriously before they realised there was a fire. "

The experiments were carried out in the laboratory using a computer and a random selection of people. Two types of alarm system were tested they were (a) an ordinary fire bell, and (b) an Informative fire warning system (IFW). The aim of the IFW is to reduce this realisation by providing correct detail information, rather than a simple conventional fire warning bell. In the experiment, 13% of the population immediately evacuated when a simple fire bell was sounded this was similar to those findings by Tong and Canter [24]. Canter collected his data by street interview rather than a simulated laboratory experiment, but his results concluded that 14% of those interviewed thought that the most recent alarm that they had heard was a genuine fire emergency and out of this only 11% immediately evacuated.

Because of the close comparison between the fire bell results of Canter and the BRE experiments, the BRE use this as a control and draws parallels between the real world conditions and the laboratory conditions. Canter did not carry out experiments on IFW systems, but because of this close comparison with a fire bell, Canter has suggested that the BRE experiments would reflect the real response times to an IFW system.

The results of the BRE experiment for IFW systems were that a six-fold increase in the correct interpretation of the alarm system compared with a conventional fire bell. The results also suggested that interpreting a fire warning as genuine does not guarantee an immediate evacuation by occupants. This indicates that the development of IFW systems and their introduction would reduce evacuation times and help overcome the problems encountered with the evacuation of complex buildings. In the early stages of a fire when a simple fire bell is sounded Tong and Canter [24] suggest;

". . . people have to cope with a prevailing state of uncertainty. This uncertainty results from the ambiguous nature of the information available so that fire victims consistently become involved in investigative and exploratory actions to determine the nature of the threat they are facing. The cues which most commonly motivated an initial inquiry by building occupants were strange noises, unaccustomed behaviour of others, such as running, and occasionally there was a direct encounter with smoke or flame".

The suggestion that strange noises motivate people could be interpreted as a fire bell, but as can be seen from the experiments of Canter and the BRE an occupant is unlikely to recognise or interpret correctly the fire bell in the early stages of the warning. Those who do not ignore the alarm will choose to seek further conformation of an alarm and possibly seek a person in authority to confirm the appropriate response.

In the BRE laboratory, [22] experiments involving different types of buildings were assessed. The result may seem obvious in that those familiar with the building interpreted a genuine fire warning, compared with those who were unfamiliar with the building layout. This adds weight to the argument that IFW systems should be installed in pubic building, where the occupants are unfamiliar with the sound of the building.

During the composition of the BRE research, The Channel 4 Television Company approached the BRE to conduct an experiment for the Equinox television programme which was broadcast in 1991. The programme makers wished to test the hypothesis, that

IFW systems are more likely to promote a faster evacuation response than a simple fire bell warning system. They set out by arranging two groups of 10 subjects to visit Research House, London, informing them that they were to take part in market research. The two groups were introduced to a basement room which had a one-way mirror on the wall, behind which filming could take place.

The first group were introduced to the room and asked to complete a security questionnaire, after 5 minutes, a fire bell was set off in the corridor outside the room. After 3 minutes of the alarm sounding one female subject decided to investigate and left the room, the other occupants stayed and appeared to wait for her return. A further 6 minutes later (9 minutes after the first alarm) one further occupant left the room, 11 minutes after the start of the alarm all the occupants left the room.

In the second group in the Channel 4 documentary, they were again put in the room and left. After 5 minutes the alarm bell was sounded for 5 seconds followed by the following announcement,

"This is an intelligent fire warning system. There is a fire above you on the ground floor, evacuate now".

Following the message the bell rang again for 5 seconds. As the message finished one occupant stood up and walked out followed by all the other subjects.

This experiment provided a simple yet explicit demonstration of the advantages of an IFW. In the first test a bell alone did not provide sufficient warning to motivate an immediate evacuation for this type of occupant. However, in the second test the speed that the occupants evacuated was swift, in fact within one minute of the alarm being raised, the occupants had left the building. It can be presumed that the reaction in the second test was due to the explicit nature of the information that they received.

2. 6 COMPUTER SIMULATIONS

Due to their increasing popularity, computer modelling techniques are establishing a successful track record having been used to analyse some of the major fires in recent times such as the MGM Grand fire [14]. This type of modelling in post-fire investigation has the benefit that only one fire scenario is modelled, as opposed to the design environment where there maybe many possibilities.

Computer simulations are now being developed, using the best available knowledge from a range of sources. Canter [20] first experimented with simple computer programmes to simulate a fire event. Computer software has been developed, which models evacuation of large populations through multi-storey buildings. Two such systems are Simulex [25] and Exodus [26], which aim to provide a realistic prediction of building evacuation scenarios.

The Exodus model was developed to provide simulated human responses to aircraft emergency situations, but the aircraft components can be switched off, to provide a modified version for the simulation for simple public building evacuations. The Exodus software comprises of five core interacting components, the occupant, movement, behaviour, hazard, and toxicity submodels. Values are set for each individual, thus creating different attributes to each individual with unique performance capabilities.

The spatial dimensions within the exodus model are extended over a two-dimensional grid with a simulation clock. The grid maps out the geometry of the enclosure, locating exits, internal walls and obstacles. Multi-storey models can be made up by using multiple grids, which can be connected by stair nodes, this type of building geometry can be stored in a geometry library for later use.

The latest version of Exodus is suitable for application in the design of supermarkets, hospitals, industrial premises, rail stations, airport terminals, sports stadia, cinemas, shopping malls and high-rise buildings. These are the type of buildings typical of those considered in this study.

This model can run with three different types of population; population A comprises of people with an instantaneous response time and with identical travel speeds. Population B comprises of people with an instantaneous response time but with a range of travel speeds and population C consists of people with a range of response times and a range of travel speeds. These response times are set between 0 and 120 seconds, this is an approximation that seems to underestimate the response time in reality. Such models can only be as accurate as the inputted information with regard to response times and travel speeds.

The Simulex model is also a software tool, which models the evacuation of large populations through complex multi-storey buildings. This system can be used with computer aided design [CAD] based information of the building layout. The system models a number of psychological factors, including choice of exit and response time to alarm. Simulex allows the user to specify a response time for the occupants, this as yet is a pre-set time for all the occupants. It is intended that a future version of Simulex will incorporate a function, which will assess certain factors and estimate the time taken for an occupant to assess her/his response times.

Both systems could become useful design tools for the fire safety engineers, provided that accurate information is fed into the programme. The correct estimating of the pre-movement times or response times is important in order to attain a correct solution. Thus more data and research is required to establish a realistic and accurate response time, which should vary depending on the type of alarm system installed in a particular building. The type of alarm system would then be seen to have a definite effect on the evacuation time and could be taken into account with regard to relaxing prescriptive travel distances. Draft for Development 240 (third draft October 1996) Fire Safety Engineering in Buildings issued by British Standard Institution [27] and the 1991 Australian Building Fire Safety System Code [28] proposed a risk assessment system, which takes into account various subsystems. One of these is the response time of the occupants, even though these guides have been superseded, this subsystem is still in the research stage and the use of the pre-movement part of the codes and cannot be considered accurate at this point in time.

2.7 CASE STUDIES

Case studies of individual fires or incidents can achieve a great deal in understanding events in particular cases. If this information is used in conjunction with other events in similar types of buildings, an act of frequency can be achieved, which can be displayed in terms of percentages. The analysis of behaviour at major incidents can help clarify and refine a model of human behaviour in emergencies. These behaviour patterns have been described by Canter [10], following his case study into the fire at King's Cross Station as recognition, action and evacuation.

At the Woolworths' fire, Manchester in 1979 [29] with 500 people on the premises, a rapidly growing fire broke out in the furniture department at about 13.20 hours on the second floor of the four-storey store; which did not benefit from a water sprinkler system. There was delay in sounding the alarm and subsequent delay in calling the fire brigade. Ten people died in the fire, a study of the event suggested that many of the victims were in the restaurant at the time of the fire. Locked exit doors hindered escape and smoke logging of the one staircase open prevented its use. In this fire people had to be rescued from windows and the roof of the building. The spectre of another store tragedy reared its head again after a fire swept through a department store in Chesterfield, Derbyshire on 7 May 1993 [30], killing an elderly couple and forcing hundreds of other shoppers to flee the smoke and flames. Four fire-fighters and three children were among the 34 taken to hospital. The blaze broke out on the first floor of the three-storey Littlewoods store shortly before 10.00 hours. The floor housed rows of clothing racks and kitchenware displays, with a third of the floor space taken up by a restaurant area. On the day of the fire the store was holding a cheap breakfast offer and the restaurant was crowded with elderly people and mothers with children in pushchairs. The two people who died were in the restaurant when the fire broke out. The fire is thought to have started among some clothes racks towards the centre of the floor, close to one of the walls. According to a spokesman for Derbyshire Fire and Rescue Service,

"the fire spread extremely rapidly through the first floor area causing severe damage, but it was contained to that floor."

The store did not have a sprinkler system, nor did it have a smoke detection system, but it did have automatic fire doors, which protected the elevator shafts. The severity of the fire may have been increased by a chimney effect caused by the flow of air from open doors and windows through the aisleways between the rows of clothes racks.

Experts from the Fire Research Station [30] recreated the conditions of the fire, using their department store test rig at the Cardington laboratory. These case studies have given the researcher themes to investigate in incidents. The main theme from the above tragedies being, that of deaths from fire, in department stores, that contain restaurants. The Home Office have recognised this theme and have commissioned research into the problem of fire in Department stores with restaurants.

In a comparable type of building and occupancy, recent major fires have occurred at airports. The most recent of these involved the fire at Dusseldorf International Airport [31] on the 11th April 1996 when 17 people lost their lives. This follows airport fires at John F. Kennedy in 1989 and one at Kuala Lumpur in 1993, both of which had fatalities. In December 1997 a large fire occurred at Heathrow Airport in Terminal 1 [31], the fire originated in a roof space above a fast food outlet and spread right along a row of shops. There were no casualties and all the occupants evacuated with no help from the Emergency Services.

The incident at Dusseldorf happened at the second largest airport in Germany serving 15.2 million people each year. On the day of the incident at Dusseldorf, welding was being carried out on the roof structure above a flower shop. This caused a fire in the roof space and a flashover occurred sending flames and smoke throughout that section of the airport terminal. The lack of smoke detection in the ceiling void initially delayed the activation of the fire alarm system, when the smoke eventually percolated the false ceiling, it set off the fire alarm system and the evacuation should have begun.

At the start of the fire several people were in the multilevel car park and even though they could see smoke coming from the terminal they used the lift to escape. This lift descended into the terminal and when the doors opened, all the occupants died inside from the inhalation of smoke. The fire spread rapidly up through the building and several people were killed in a second floor departure lounge. The rapid progress of the fire throughout the building could be contributed to the lack of sprinklers, as this part of the airport building dated back to 1972. The total cost of the damage to the building was estimated at £50 million, seventeen people lost their life and sixty-seven people were injured.

One of the main reasons for the loss of life was the poor communication caused by the loudspeaker announcements informing the 2,500 people to evacuate by the ground floor exits; this was the area at the seat of the fire. Fire-fighters reported that many of the occupants ignored instructions to use the fire exits and panicked. As the instructions given by the announcements were given in German but many of the foreign occupants could not understand the instructions. Approximately 250 people were trapped on the upper levels of the terminal and had to be released by fire-fighters using ladders.

It can be seen from studying the Dusseldorf fire, that initially the people on the car park level were in no immediate danger. They could see the smoke coming from the terminal and yet decided to proceed into the terminal via the lift and subsequently to their deaths. They must have gone through the process of recognition that it was a fire then the validation that their assumption was correct. They then would have defined the seriousness of the incident by the amount of smoke and then evaluate the information to make their fatal decision to proceed into the lift and into the terminal.

This incident highlights problems which occur when attempting to evacuate a complex building. People will further investigate the incident and ignore warning signals to answer questions such as; a) is it a real fire, b) a fire alarm test, c) a false alarm or d) some other type of warning signal. Even when occupants see smoke, it is not always seen as a trigger to suggest that escape is necessary. Incidents at the Bradford City Football Club [15] and the Woolworth's fire in Manchester [10] have generated accounts of people, who had seen the fire and smoke, but choose not to escape until it was too late.

Human behaviour in a fire situation have been identified by Bryan [12] as a series of decision making processes which start with recognition. This may be either hearing the fire alarm; abnormal reactions of other occupants; seeing smoke or flame; or by gaining information from other people. This is based upon the assumption that people know what the fire alarm is and what it sound it makes. Following this recognition the occupants attempt to validate the information given either by investigation or by questioning other people. If the evidence has been validated as accurate then the occupant will proceed to gain further information as to the qualitative nature of the threat, for example the intensity of the smoke and the size of the fire. Proulx [23] suggests that the first reaction of the occupants is to assume that the nature of the incident is minor in nature and that the threat to life is minimal, even if this is not the case. Following this evaluation of information a response will be made for example; to do nothing, to fight the fire or to evacuate.

Any person watching the football match on television in 1985 live from the Bradford City Football ground would see that the majority of the spectators could see the fire, but assumed that it would not affect them. Therefore many did nothing in the early stages, even though the suggestion for evacuation appear obvious to anyone watching a video recording of the event. This defensive behaviour must have been the cause of death of many people in similar situations. Deaths in fires in complex buildings are thought to be more likely to be due to either delays in actuating alarm systems or the delay in the response of the occupants to the alarm system [13].

Another assumption has been that the occupants will move immediately the alarm has been sounded. This cannot be relied on however the time delay will vary will depend on the occupancy. If the occupancy is primarily staff who have been well trained, then the response time will be less than in the case of untrained staff. If the occupants are the general public, then the length of response time will depend on the type of alarm system and the staff management of the evacuation. An example of this occurred at the Arndale Centre in Manchester in July 1996 following a coded message to the Authorities from the IRA. The Centre was evacuated in approximately 12 minutes prior to the IRA bombing, at the time the shopping centre and office block contained between 30,000 and 40,000 people. Mr Walker [33] the centre manager stated that:

"the fast evacuation was carried out only because of the quality of the training and drills that the management carried out on a regular basis".

As part of this study some of the shop workers were interviewed, who were on duty on the day. It was found that even though a fast evacuation was carried out, they still had difficulty motivating members of the public. The trained staff had to be insistent with the public who initially did not want to leave and could not perceive the risk. There was also a problem with the 'Saturday only' staff who did not understand the evacuation procedures, as they had not received regular training. As a result of this the centre management have now have now improved the training given to Saturday staff.

Once the alarm has been raised, the decision making process regarding evacuation is dependent upon the information a person has prior to the outbreak of fire. This is in the form of knowledge of the building with regard to exit routes, the ability to identify that the alarm is indeed a fire alarm and the knowledge of what to do when the fire alarm is activated. In most British workplace buildings this knowledge is a requirement of Health and Safety Legislation under the 1974 Act. In buildings used by members of the public they do not necessarily have the information required to make the correct decisions, when required to evacuate the building. To enable the general public to make correct decisions; escape routes should be recognised; for example a route, which is used to gain access to the building will be of much more value than one which is only used for emergency purposes. The notion that when visiting a shopping centre, escape routes down dark service corridors will be readily used by members of the public, who are under stress, does not appear a logical assumption [2]. This gives rise to the idea that exit routes should have a weight value put on them, where routes in normal use would have a higher rating than those not usually used by the occupants. This would make the initial design of buildings more realistic with regard to the possible location and use of the exit routes.

2.8 SUMMARY

Research methodologies and fire studies of various kinds have shown that the nature of an individuals behaviour during the different stages of an emergency evacuation will be dependant upon many factors, such as prior knowledge, experience and training. Over the years various types of enquiries have investigated these factors, but as we enter the twenty-first century a more structured and scientific approach using some of the information already gained has been initiated. This approach is discussed in the following chapters.

CHAPTER THREE

DESIGN CRITERIA FOR MEANS OF ESCAPE

3. 1 PREAMBLE

The need for a basic safety criteria Fire Safety Engineering can be clearly understood by understanding the primary goal; that is to ensure that in the event of a fire emergency, building occupants have sufficient time to evacuate from the building, without being seriously affected by the products of combustion. With this concept in mind the method to achieve this goal can be dependant upon the type of building and the nature of the occupants. Age, mobility, influence of alcohol, sleeping risk and the occupant's knowledge of the building are just a few of the determinants that may influence evacuation speed. Studies by researchers such as Bryan [12] and Proulx [32] have considered the psychological behaviour of people but this has not as yet been fully taken into account in the design of complex buildings.

3. 2 DESIGN STRATEGY FOR SIMPLE BUILDINGS

Conventional methods of escape design are based on principles that are simplistic, so that at all times the occupants of a building can turn their backs on any fire and move away from the fire to a place of safety. This place of safety should be outside the building. To achieve this, occupants should be able to use either, their own efforts or the assistance of other occupants of the building at the time an emergency occurs. In order to achieve an acceptable standard the following basic principles must be applied. These standards are the basis for current guidance in the British Standards 5588 series [16] which relates to all types of building in use today. These standards maybe summarised as;

- there is an adequate detection of fire and a means of giving an alarm; in a small open plan premises this may be achieved by detection with the human nose and voice;

- there should be sufficient escape routes from all parts of the building, enabling the occupants to move away from danger to a place of ultimate safety that is outside the building;

- the escape routes should be sufficient in number and width to avoid congestion;
- the distance that a person may have to travel to a protected route must be limited;
- escape routes must be clearly identifiable by strangers to the building.

In 1946 the Fire Post War Studies Report [1] included some of the first research concerning occupant movement through exits and stairways. Physical tests were carried out on building evacuations and calculations were made following observations. More extensive tests had already been carried out were carried out in America, especially by the United States Bureau of Standards, the results of which were published in the Design and Construction of Building Standards in 1935 [1]. These tests were carried out under random flow conditions, i.e. in the course of normal use of the buildings and during fire drills. This exit research, was continued by researchers such as Peschl [21], who also analysed queuing behaviour. This type of research has helped identify the potential congestion in stairwells and at exits. The research has resulted in evacuation modelling to serve as tool for identifying and analysing the factors that influence evacuation time of occupants in fire emergencies such as computer models. The simplest of these is the mathematical model, which emphasises the physical parameters associated with occupant movement and the buildings dimensions. The core of this form of modelling is, flow, unit width and time which provide a basis for the mathematical solution as presently used in Building Regulations [8]. Flow times and total evacuation times, derived from these parameters are of primary interest. Flow can be described as the number of occupants, who pass some reference point in a unit of time.

The determination of a suitable clearance time to be used as a basis for calculation appears to have been taken from a single incident under actual fire conditions. The Empire Palace Theatre incident, of 1911 [3] which appears to be the origins of the evacuation time used not only in Great Britain, but in many countries around the world. The evacuation time of 2.5 minutes has been a standard that has now come into question with many escape planners. This was a consequence of the development of new types of building products and building systems that evolved in the 1970's and 1980's [2]. The provision of fire containment and protection of the means of escape is the prime objective of this basic design criteria. The escape time limit of 2.5 minutes is based upon a unit exit width of 500mm allowing a flow rate of 40 persons per minute. This simple formula is used by the relevant codes [16], [4] in use today in the U. K. which are used to estimate the number of exit widths required from any room or building.

$$U = \frac{N}{40 \times T} \quad \text{.......... Equation (1)}$$

Where:

N = the total number of occupants

T = the time to escape in minutes

U = the number of exit widths of 500mm

To calculate the number of exit routes required the following equation is used

$$E = \frac{U}{40} + 1 \quad \text{.......... Equation (2)}$$

Where:

E = the number of exits required

The purpose group of the occupants in most fire safety evacuation codes and guidance documents give consideration to human characteristics. These are sleeping risks, familiarity with the building and mobility. Those groups that require more time to evacuate are given less distance to travel. Typically the recommended maximum travel distance to a protected route for shops and offices is 12-18m, where there is only one exit route and 30m if there are two or more exits. The effect of internal walls and fittings infers that the actual travel distance to a staircase should not exceed 1.5 times the maximum direct distance.

The staircase widths are designed to enable all the occupants of a floor to enter the staircase within the evacuation time and for multi-staircase buildings it is assumed that one of the staircases is affected by the fire and must therefore be unusable. The maximum flow rate on staircases [34] is assumed to be 80 persons per metre width per minute. If this flow rate is assumed and the evacuation time of 2.5 minutes is allowed, then the maximum number of people, who can enter the staircase is expressed by Melinek [35] as;

$$M = 200\,b + (18b + 14b^2)\,(n-1) \quad \text{Equation (3)}$$

Where;

M is the number of people who can be enter the staircase in the acceptable time;

b is the aggregate width of the stairs (in metres);

n is the number of stories in the building;

This equation is very similar to the equation used in Building Regulations [35] for buildings not exceeding 30 metres in height which is given as;

$$M = 200\,b + 50(b - 0.3)\,(n-1) \quad \text{Equation (4)}$$

Using equation 3 the calculation for a three storey building with a one metre staircase is equal to a maximum 264 people and using equation 4 the calculation is 266 people.

Equation 4 is the basis for tables contained within all codes for buildings in the U.K. these are the Building Regulations Approved Document B [8] and the British Standards Institute 5588 part 1 to 11 [16].

The Building Regulations allow designers to provide a variety of solutions provided that the controlling authorities can be satisfied of the adequacy of their design. This design model suggests that there should be no surges or queues, but rather a constant use of an exit to full capacity, until the last occupant safely clears the exit. Also assumptions are made that can and have proved fatal in recent times, for example in incidents such as the Bradford Football stadium fire (1985), the Woolworth's fire Manchester (1979) and the Stardust Disco fire Dublin (1981).

The shortcomings of these models can be seen to be [22]:

- the assumption that the building occupants are alert and able-bodied;
- the assumption that occupants will start to move at the same time when the alarm has been activated;
- the assumption that contra-flow of occupants will not occur in their attempts to escape. i.e. ; unidirectional flow only;
- many behavioural movements, such as perception of cues, investigation of the incident which does not involve movement towards exits or along exit routes is not considered.

A particular weakness in the simple escape model is the fact that it does not calculate times explicitly in relation to the architectural complexity of the setting, the type of alarm warning system and the nature of the occupants. The user categories of a building are described in Building Regulations and can have a major influence on the escape time for the occupants can be seen in **figure 3.1**, these are:

- familiar with the building and awake.
- familiar with the building but possibly asleep.
- unfamiliar with the building but awake.
- unfamiliar with the building but possibly asleep.

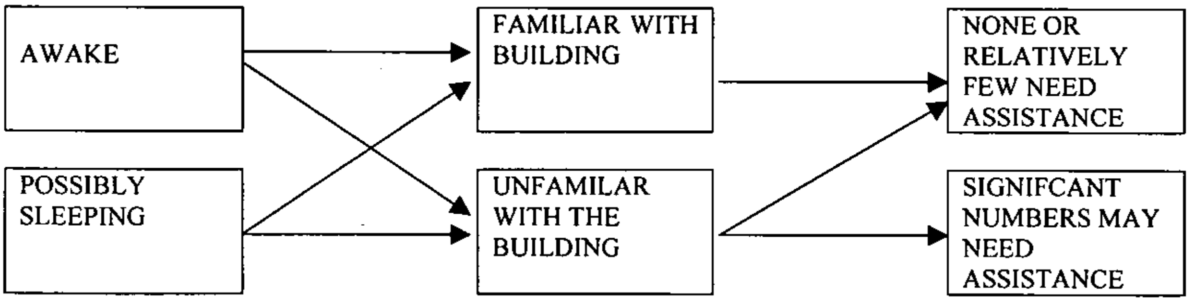


FIGURE 3. 1 FACTORS THAT AFFECT ESCAPE [3.1]

In each of the above categories there could be a number of occupants who also require assistance to exit the building due to physical or mental disabilities.

The U. K. building codes do not take into account the type of warning system or the number of staff that could assist in the evacuation process, all refer to British Standard 5839 : Part I : 1988 Fire detection and alarm systems for buildings, system design. The code provides recommendations for the planning, design, installation and servicing of fire detection and alarm systems used in and around buildings. It does not recommend whether a fire alarm system should be installed in any given premise. Within the code it is recommended that the design of the fire alarm system will depend on the actions required after the alarm has been given. It suggests that in premises in which normally active persons resort that they will react in a rational manner. This does not accord with the finding of most of the researchers in this field.

To cover the legislative requirements of small volume, simple buildings the Government has introduced The Fire Precautions (workplace) Regulations 1997 which have been put in place under the fire Precautions Act 1971 and became effective in December 1997. The Regulations give effect to the European Community Council Directive 89/391 [3] requiring the introduction of measures to encourage improvements in the health and safety of workers at work. The regulations apply to Great Britain and effectively bring in the risk assessment duties that apply under the Management of Health and Safety at Work Regulations 1992 in relation to the assessment of risks from fire at the workplace and the need to take the necessary precautions. It places the responsibilities on the employer for small premises for protecting staff from identifiable risks in the workplace and for the removal or reduction of such risks to protect employees. This method of self compliance through a written risk assessment to reduce the hazards in the workplace it is suggested by the associated guidance documents should not be burdensome or costly. The notion that employers of small premises can carry out their own risk assessment and decide on the required level of safety may prove costly in terms of loss of life in the long run.

3.3 DESIGN STRATEGY FOR COMPLEX BUILDINGS

The full evacuation strategy of large complex buildings cannot cope with this guidance. If this philosophy is applied for example to the Kuala Lumpur City Centre project [36], which is the tallest building in the world (Petronas Twin Towers), it would be impossible to evacuate the building in 2.5minutes. In fact the total evacuation time is 93 minutes, with 30 minutes for the occupants to gain access to the protected staircases [36]. If one staircase is considered as unusable, as suggested in the Malaysian Uniform Building By-law 1984, the evacuation time would increase to 90 minutes for all the occupants to enter a protected staircase and the total evacuation time would be 140 minutes. A complex zoned evacuation technique has been used to address the problem using the latest telemetry technology. Zoned evacuation relies upon only part of the occupants of the building, to initially evacuate. The occupants in the part of the building closest to the fire are evacuated first immediately, whilst the occupants of the other parts of the building remain until their evacuation is necessary. In practice, this usually means the occupants of the storey on which the fire starts, and those on the floor above are evacuated first, along with any person within the building that may require assistance to evacuate, for example those with reduced mobility or those with impaired vision. The order of subsequent phases of evacuation will usually be dependant upon the development of the fire, however the next phase would be those above the fire rather than those below the fire floor.

An example of this type of evacuation occurred in the World Trade Centre in New York in 1993 [37] when a bomb was exploded in the basement. This resulted in the evacuation of approximately 10,000 people, which took two and a half hours, in this incident six people died and one thousand people were injured. The occupants who were subsequently interviewed realised it was an emergency, not only because of the vibration felt throughout the building but also because of the smoke that infiltrated the building a few minutes after the shock-wave. It was reported that people within the building carried out their duties as they had been instructed. However, as Donald [38] suggested, people in an emergency situation seldom recognise the urgency and generally do not respond immediately to the hazard. According to evacuees of the Trade Centre incident, in the early stages the crowd was so tightly packed that it restricted movement, also it was reported that reverse flow of evacuees took place to escape the smoke in the staircases. The smoke logging of the staircase and the length of time the smoke took to clear the staircase has been attributed to the extraordinarily height of the buildings, and to the potential for the stack effect.

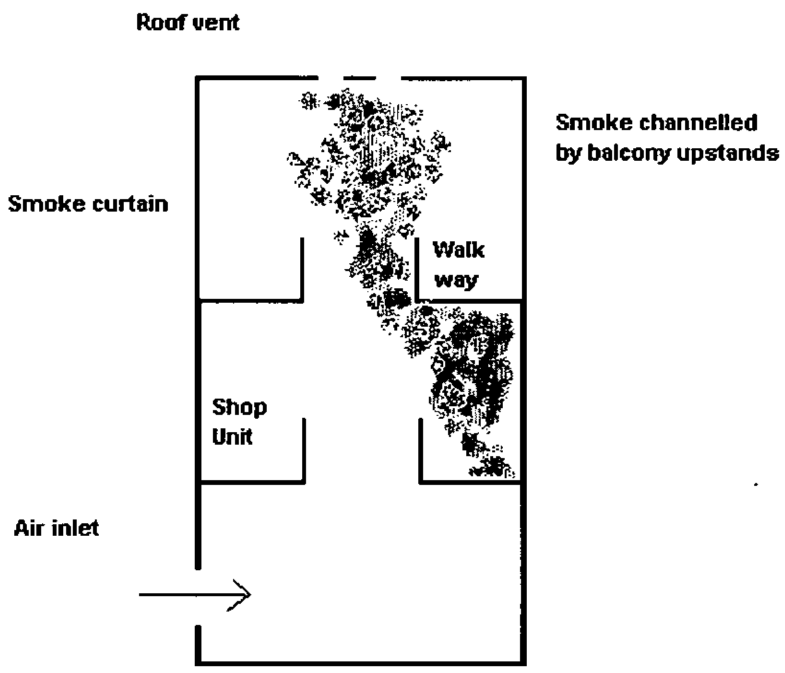


FIGURE 3.2 THE STACK EFFECT

The stack effect as illustrated in **figure 3.2** is one of the most important influences on smoke movement in a high-rise building [39]. The vertical movement of air through a building caused by a difference in density between the air inside and that outside the building. In simplistic terms, if a tall shaft in a high-rise building is vented at the roof and street levels, and the air inside is hotter than the air outside, air will flow in at the bottom and out at the top, creating an upward flow. Conversely, if the air inside is cooler than the air outside, the flow will be in the opposite direction.

3.4 PRE-MOVEMENT TIME

A delay in the time for occupants to initially start to evacuate is a fundamental problem that has characterised large scale fire disasters involving injury such as the Bradford City Football Club ground and King's Cross Underground Station. With the background of such incidents and design problems on the development of the Canary Wharf project London in the early 1980's, a demand to resolve this problem was made by the Department of Trade and Industry [DTI]. The aim was to create a more scientific and flexible solution for designing complex buildings. Fire Engineering techniques in the U. K. have now progressed to a high enough level of understanding, for a code or guidance document for complex projects issued in 1997 the British Standards Institute issued a Draft for Development document [7]. In this document all buildings are incorporated into one code, whereas previously complex buildings had a variety of codes issued by various agencies.

3.5 BUILDING MANAGEMENT

The nature and type of complex buildings has changed over the past twenty years and to reflect this from the beginning of the 1990's. The British Standards Institution has adopted guidance, which not only deals with the design of buildings, but this incorporates the concept of safety management [16]. This is reflected in the new standards now issued with *use of the building* included in the title of the documents. The first document to reflect this shift was British Standard 5588 part 6 Code of practice for Assembly Buildings issued in 1991 [40]. This highlights the view that major loss of life in complex building fires is not only caused by poor design of buildings but also by inferior building management, as highlighted by the enquiry following the Woolworth's fire of 1979 [3]. To understand the problems caused by inferior design/management and the interaction with the alarm system, which has resulted in major loss of life it is worthwhile to investigate examples of such incidents. The type of alarm system and how the occupants reacted, may give Fire Engineers an improved cognisance of human reaction to alarm systems. However, some disasters if researched, would have little or no value with regard to human reaction to alarm systems, but would prove the inadequacies of the management systems and procedures.

A notable example of poor management influencing the loss of life was the Summerland fire in August 1973 [41]. In this case, even though there was a fire alarm, it was not activated. The person left in the control room had not been trained in emergency decisions and had no knowledge of the various systems built into the leisure complex. In fact the first call to the Fire Brigade was originated from a ship eleven miles out at sea and the subsequent enquiry criticised the lack of staff training. Staff need effective training in what to do in a fire to reduce delays in evacuation. Their role is crucial and they should know the building and what actions they might or might not be expected to carry out.

3.6 FIRE BEHAVIOUR IN BUILDINGS

The methods derived from heat transfer engineering have long been available for assessing structural behaviour in fires. Fire Engineering has now developed well beyond solely structural considerations [42]. The theory of fluid dynamics is now used to model the movement of gases and smoke and it is now recognised that the physical and chemical processes interact in a complex way [25]. The physical theory itself is a branch of fluid dynamics which places heavy demands on the computing resources that may be used to solve practical problems. The experimental validation of fire models usually depends on a handful of tests because large-scale fires are expensive to stage. Experience of accidental fires is also limited because they are relatively rare events. Most fires develop through their early stages without observers, and therefore analysis depend on careful examination of the debris.

To bring together the recent research in fire dynamics a guidance document has been issued by the British Standard Institute. The Fire Safety Engineering in Buildings, Part 1. 1997, Guide to the Application of Fire Safety Engineering Principles [7], has been issued as a working draft for development, but not as a complete British Standard. In this document an attempt has been made to distinguish between the levels of requirement necessary for life safety purposes and for the prevention of conflagration. One of the most important features of the document is the fire safety requirement of a total system in which both active and passive measures are required and in which flexibility is permitted [7]. By adopting a fire safety engineering approach taking into account the total fire safety package it is hoped to provide a more fundamental and economical solution than some of the more prescriptive approaches to fire safety. The document [7] attempts to adopt a systemic approach to develop a framework consisting of fire safety sub-systems interacting with each other. The Code intends to provide a standard method for building designers to depart from traditional fire safety concepts, with the provision that they can demonstrate that the building will still achieve an acceptable level of fire safety.

The Code of Practice defines the following basic stages:

a) Define the problem.

b) Analyse the problem using fire safety engineering principles.

c) Repeat stages a and b until an acceptable solution is found.

d) Report the findings.

The Code of Practice names the stages involving fixing the limits of the problem as the 'Qualitative Design Review' [QDR]. When the QDR comes to an end the following questions must have been answered:

- What level of fire safety is acceptable?
- What are the precise features and dimensions of the building?
- What factors limit possible solutions?
- What are the main hazards and consequences?
- What fire safety measures are going to be in place?
- What scenarios are going to be studied?
- What method of analysis is going to be used?

When all these questions have been answered the analysis of the building can begin. For the analysis phase, the Code of Practice provides two alternative ways of analysing the building. The first method relies upon probabilities to determine the likelihood of death or injury. The second method uses complex calculations that describe the properties of fire, to determine whether occupants can escape safely.

In the Draft Design 240 guide sub-system 6 [7] draws on the characterisation of the occupants taking into account their number, their distribution, and their physical abilities. These factors are given weight so that the escape design encompasses this information. The designer must also take into account the building type and design and in particular the types of alarm system that is to be provided. Irrespective of any other devices that may be installed in a complex building; to detect and give warning of a fire outbreak (such as automatic fire detection or extinguishing systems) is fundamental. Also all premises are required by law to have some means whereby the alarm of fire may be given by a person discovering an outbreak of fire.

3.7 SUMMARY

This chapter has discussed how a more scientific approach by fire engineers is now beginning to be used. The nature of the occupancy and the role of the individual in a particular setting could prove critical to successful evacuation. With a more scientific approach to evacuation problems it is hoped that future deaths and injuries in complex buildings may be significantly reduced.

CHAPTER FOUR

REQUIRED SAFE EXIT TIME

4. 1 INTRODUCTION

The objective of studying the evacuation of occupants from buildings is to provide a practical technique for estimating the safe available egress time subsequent to the detection of a fire. The available safe egress time can be defined as the interval between the time of successful fire detection and alarm and the time when the products of combustion create a hazardous condition.

The movement of crowds in buildings have been the subject of comprehensive research mainly by Pauls [43] and Kendik [44] and to a limited extent in the past by Melinek [45]. This research suggested that various types of information will be required, for instance, staircase width, number of stories served by the staircase, and rate of flow of people to produce a satisfactory result. This research has now been coupled with the rapidly evolving computer technology, which has facilitated the analysis of emergency evacuation in comparing different building designs and escape routes. This has resulted in the development of models, which analyse different escape routes, and can produce an average value and standard deviation for the evacuation time for a building with known design features.

4. 2 THE CONCEPT

The objective of studying available safe escape time (ASET) [13] is to develop a practical technique for estimating the available safe egress time subsequent to the detection of a fire. ASET can be described as the interval between the time of successful fire detection and alarm, and the time when hazardous conditions prevail in the building space. Designers should also take into consideration an occupant's required safe escape time [RSET].

It can be assumed that time will elapse before the fire has been detected, each occupant then requires time to become aware of the alarm. A decision is then made to evacuate or investigate the alarm and then the occupant travels to a place of safety. This is a somewhat simplistic model of the process that makes up RSET. A comparison is then made between RSET and ASET, in which RSET must exceed ASET to give the occupants a safety margin to escape as illustrated by **figure 4.1**. The size of the difference between the two times gives the safety margins, identifying these safety margins requires consistent research as the design perimeters of building and investigations into human behaviour which are both in a continually evolving state.

This information is recognised and influences RSET.

The formula given for calculating the RSET is given as;

Pre-movement Time + Travel Time = RSET

The pre-movement and evacuation time can both be sub divided again into categories which need to be identified and assessed before an estimated evacuation time can be made.

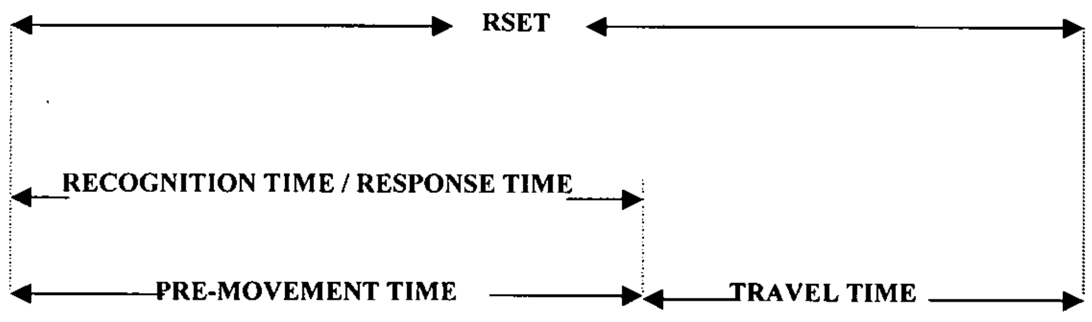


FIGURE 4.1. EVACUATION COMPONENTS

The pre-movement time is sub divided into recognition time and response time. Each of these will depend on the nature of the occupants, familiarity with the building, whether asleep or awake and the need for occupant assistance in evacuation. Occupants [13] who use the building daily and who are given staff fire training, it is suggested, will more readily recognise the alarm as a fire alarm, unlike those who are unfamiliar with the building.

The recognition time is the period after the alarm has been sounded or a cue has been given, but before any response or movement by the occupants. The Australian draft code [28] for fire engineering was the first to include human actions with regard to occupant response and included a prototype occupant classification and rating. Also under development in Canada [46] is a prototype model in which the relationship between the occupant's response and different types of cues or type of warning is taken into account.

The most important findings of recent research [23] is in the fact that the start up time (i.e. people's reactions to an alarm) is as important as the time it takes to physically move and reach an exit. The Pre-movement time and it has been suggested by Sime [13] could be up to two thirds of the total RSET, this is supported by investigations into the majority of major fire disasters. This propounds that there is a disproportionate emphasis on travel time and exit flow rates compared with the pre-movement time in existing codes [13].

Modern engineering systems now provide an increase in the ASET. The engineering techniques to support this advancement are:

- smoke movement systems
- suppression systems
- detection systems that continually sample the atmosphere within a given space.

Whereas to reduce the RSET the following can be utilised:

- information warning systems (IFW)
- good definition of escape routes
- clear and unambiguous signage
- a high level of lighting
- good management control with sufficient numbers of suitably trained staff/stewards.

Early warning detection systems and IFW providing clear information all aid the move to a fire engineered approach to design safe time. Canter [10] suggested, lack of information for the associated *information gathering* phase can lead to extended escape times.

A technique given in the document for estimating the time available for evacuation from a fire is by the introduction of the Qualitative Design Review [QDR] the object of which is to review the building design, identify potential fire hazards and to define the problem in qualitative terms. Following on from this a Quantified Design Analysis [QDA] can be carried out by studying individual sections of the fire strategy and then comparing this with the model of hazard development. The guidance takes into account many factors, including building construction, means of escape, smoke control, fire detection, alarm systems, suppression systems and most importantly human factors all of which contribute to achieving fire safety objectives.

The guide achieves this by defining each category into sub-systems, sub-system 6 deals with evacuation. It acknowledges that the information to date on human behaviour in fire and the method on how to calculate RSET is incomplete. In an emergency it is suggested that people will tend to evacuate via the route by which they entered. The design of the building must also be taken into account with regard to its visual accessibility of alternative exit routes, the openness of the design, open-plan or divided by walls, and the complexity of the design. The design guide advises that assumptions have been made, with this in mind the guidance encourages the designer to put in place safety margins by providing evacuation and means of escape principles based on previous guidance issued by the British Standards in the 5588 series. Once the evacuation time has been established, it should be compared with the outputs from results in the other sub-systems in the QDR.

The QDR can have three types of approach:

Deterministic:
Where the object is to show that, on the basis of the initial assumptions of the worst case scenario, a defined set of conditions will not occur.

Probabilistic:

Where the criterion is set is that the probability of a given event occurring is acceptably low. The risks are usually expressed in terms of the annual probability of the unwanted event occurring. This concept acknowledges the repugnant nature of multiple fatalities or injury from fires and expressed as a societal risk. This method of understanding the way in which a risk can be assessed and the use of such information requires a data base of information of previous incidents and then a numerical element is put on various situations. This information must be viewed with caution. An example is the Bradford City Football fire. The event would have attracted a figure of zero as no other fatal fire had occurred in the previous eighty years at the ground. It is difficult to establish what level of probability is permissible or achievable in absolute terms for both the designer the users of the building or structure.

Comparative:

It is relatively straightforward to demonstrate that the design provides a level of safety equivalent to or greater than those in more prescriptive codes. Since such a study is wholly comparative, any assumptions, such as choice of smoke modelling procedures, are unlikely to have consequential effect on the conclusion.

The interaction of people and fire in a building can create an infinite number of fire engineered solutions. In order to evaluate fire safety in large complex buildings by deterministic calculations, some experienced assumptions need to be made by a suitably qualified designer, architect or fire engineer.

4.3 SUMMARY

Research indicates [13] that the response of occupants will vary depending upon the nature of the setting e.g. shopping complex, stadium, hospital, hotel or office complex. Since the procedure for assessing pre-movement time is key to the production of an accurate fire engineered solution, research to date indicates that further definition and refinement is needed so that the time required by occupants to avoid danger can be assessed accurately.

CHAPTER FIVE

ASPECTS OF HUMAN BEHAVIOUR

5. 1 PSYCHOLOGICAL FACTORS

In recent years, the psychological requirements of occupants have been recognised as an important factor which influences evacuation these factors have been taken into account in many evacuation models [13][25][32]. The purpose of psychological evacuation modelling is to identify the critical parameters and their interaction during evacuation. Psychologists now emphasise the human behavioural aspects of evacuation in addition to the structural designers who have dominated evacuation modelling for the past fifty years. Neither aspect can be ignored and both approaches ideally require a balance, to form a multi-disciplinary approach.

5. 2 PSYCHOLOGICAL MODELS

Psychological models describe the behavioural stages of evacuation or the discrete time frames that occur during an evacuation. The model developed by Proulx [32] describes the stages of the occupant's experience as the fire or emergency develops. These stages are described as occurring either:

- Within a series of time frames, with no duration given for each frame.
- Within discrete time frames where every specific frame is given a duration as a result of analysing the surrounding environmental conditions. The development of stages in behaviour are not discrete, because of changes in the surrounding conditions.

Most models are founded on the principles of cognitive psychology and are designed to examine the principles of decision making and behavioural patterns during fire emergencies. In the late 1960's Wood [17] carried out a systematic study into human behaviour during fire evacuations and was simplistic in his approach. In this work emphasis was placed upon the occupants either escaping or not and an analysis of the occupant's actions was not considered necessary. Even though this approach was simplistic it started the move towards scientific investigations into human escape

The assumption that occupants panic and cease to act rationally, when faced with fire conditions has been the view for many years, this has now been presented as an inaccurate generalisation [24]. The assumption does not take into account the multitude of human responses that could be generated. The Woolworth's fire, in Manchester [29] was a case when even though some of the occupants were on the open plan floor of origin and could see the fire they failed to escape. The majority of the occupants who died were in the restaurant at the time. Statements from eye witnesses who escaped, stated that the victims were told to evacuate, but refused to as they had paid for their meal. The subsequent inquiry [3] found that staff training problems and a failure of staff to activate the alarm was responsible for the disaster that caused 10 deaths. This example give additional proof that panic is an individual response to fire situations, and cannot be linked to simplistic physical science approach to evacuation solutions.

5. 3 FIRE WARNING SYSTEMS

A major weakness of existing simple alarm systems is that they often fail to stimulate any public reaction. They seemingly fail to get across the intended message. One reason for this in non-public buildings could be associated with the fact that occupants may hear the alarm many times for test or false alarms, when there is no fire or emergency. This supports the theory Matte [49] suggested that desensitisation of a population can occur. If this is applied to fire warning systems an increase the pre-movement time can be expected over a number of years. The problem of false alarms can be resolved through well installed detection systems and increased reliability in mechanical terms. The type of information provided by alarm systems is discussed later in this chapter and research has now indicated that the credibility of alarm systems is dependant on them providing clear information to the occupants. In a fire drill, Pauls and Jones [50] found that by adding a message to the alarm system ;

' 32 out of 51 persons who changed their initial interpretation of the situation to the belief that there was a fire emergency reported doing so because of the public address announcement'.

The response of the occupants will be dependant on the type of alarm system, for example a warning system can be consist of a simple alarm bell or siren, a pre-recorded message or an informative visual display. This approach is reflected in **figure 5.1** and it is dependant upon the type of warning system installed and will need to be established in the qualitative design review of the building.

Occupancy type and characteristics	**Recognition times in minutes and Type of warning system**		
	W1	W2	W3
Office, industrial (occupants awake)	<1	3	>4
Shops, assembly building	<2	3	>6
Hostels, boarding schools (sleeping but familiar with building)	< 2	4	>5
Hostels, boarding houses (sleeping & unfamiliar)	<2	4	>6
Hospitals, nursing homes (sleeping & may require assistance)	<3	5	>8

FIGURE 5.1 REQUIREMENTS FOR TYPES OF WARNING SYSTEMS [7]

The guide recognises three types of alarm systems which are identified as:

W1 : live directives, using a voice system, e.g. from a control room with closed-circuit television facilities.

W2 : non-directive (pre-recorded) voice alarm systems and/or informative warning visual display

W3 : warning system using alarm bell, siren or similar.

The occupant response, it is suggested by Sime [13], is one which can be modelled as the occupants cannot be considered as non-thinking objects devoid of social ties or roles, be they staff or public. Therefore their movements and behaviour are not random, but rational and consistent. These actions will be affected by the environment or building that they find themselves in. Sime, suggests that people do not necessarily act instantaneously in response to an alarm bell and that the same alarm will be interpreted in different ways according to the nature of the occupancy and the physical setting. This suggests that there is an overlap between occupant movement and occupant behaviour, and recognition can involve pre-movement and movement e.g. investigation. The preparing and gathering phase, is usually associated with the movement phase of evacuation, but can also involve pre-movement i.e. waiting for information, exit choosing or queuing.

Paul's [51] has stated that, exit routes which carry high loads during normal use, are used most frequently for evacuation. The popularity of routes leading through a lobby or reception area gain most weight. It is suggested that this may be due to the occupants attempting to gain information from what is usually a centre for communications. This gathering phase when deciding to evacuate Sime [13] indicates that in terms of psychological 'rules of behaviour' occupants would prefer to leave by a familiar exit, rather than an exit route that they have never used before. Familiarity with escape routes seem to be at least as important as the travel distance as a determinant of occupants reaction and decision in what direction to move. This conclusion suggests there could be an inherent problem with escape routes, which are designed only to be used in an emergency. Design parameters in the majority of buildings in the last century are engineered on the principle of two different systems of circulation; the familiar route normally used and a different one, only to be used in an emergency. The cost of such dedicated escape routes and the possible realistic increase in safety is unlikely to be efficient or cost effective compared with the installation of other safety measures.

When the author has witnessed evacuations of shopping complexes, the security staff have been subjected to objections and reluctance on the part of the occupants to use alternative or dedicated exit routes. These evacuations are carried out on premises without any wayfinding exit indication problems. However these problems are evident in many complex buildings around the U.K. and it could be suggested that this would only increase the reluctance of occupants to use these exit routes.

5.4 SUMMARY

This chapter has discussed the various research studies that have investigated human factors effecting the lack of response to fire warning systems. Tong and Canter [24] have shown that there are three areas of failure with traditional alarm systems which are :-

1. A failure of people to differentiate fire alarms from other types of alarm.
2. A failure of people to regard fire alarms as authentic warnings of a genuine fire
3. A failure of fire alarms to present information which will assist fire victims in their attempts to deal with fire.

The above factors coupled with a reluctance of occupants to use all the available exits are problems which must be overcome if satisfactory escape is to be assured.

CHAPTER SIX

EXPERIMENTAL INVESTIGATION OF AN EVACUATION SYSTEM

6. 1 INTRODUCTION

The various divisions of research described in Chapter two are all possibilities for investigation. The future of computer modelling, however, will be dependant upon the validation of software. This validation of an evacuation model has been indicated by Proulx [43] and Pauls [51] to be essential to the accurate assessment of the evacuation time delay. As discussed in Chapter three, it has been suggested that this will be relative to the population characteristics and influenced by the type of occupancy of the building. One method of validation would be to carry out an evacuation of a building and to compare the data with a computer model. It must be recognised that an evacuation drill does not stress those involved or cause confusion as may be found at many fire occurrences. Therefore any data extrapolated from such experiments must be viewed with caution in an objective manner with a full understanding of the limitations. They must be carried out to the highest standards of professional integrity and responsibility and at present it appears that this comparison is the only method available to researchers.

Two unannounced evacuations of a shopping centre were carried out and a comparison made of evacuation times and speeds. The evacuations were unannounced to the members of the general public, but for security reasons and health and safety reasons the staff in the centre were informed prior to the drill. The overall aim in conducting the evacuations was to obtain data on the evacuation process this could then be compared with computer software for future evaluation against the software. Each behavioural component following the warning has a dependent probability of response accuracy as well as an associated time factor.

6. 2 OVERVIEW OF THE EXPERIMENTAL WORK

The process of evacuation was evaluated by monitoring two full scale evacuations which were part of the normal management of the shopping complex in Preston. It is widely recognised that the primary object of a fire evacuation drill is to allow the staff to gain further practice in directing the public to travelling along recommended fire escape routes. There is a tendency to overlook many other factors, e.g. to use the occasion to improve the fire safety awareness of the staff; to give the staff an opportunity to recognise the sound of the fire alarm, and to allow management to compare the actual fire evacuation time with the optimum fire evacuation time.

6.3 THE EXPERIMENT

An evacuation was carried out at the end of 1998 and one at the start of 1999; the evacuations of a shopping centre were conducted with 460 and 420 occupants in the premises at each evacuation, respectively. The evacuations were carried out without prior knowledge to the public on Wednesday 9th September and Wednesday 3rd February, both at 16.45 hours. The late time in the day was to mitigate the financial loss to the stores within the shopping centre. The cost of a fire evacuation drill can vary appreciably even within the same company, and according to the time of day which it takes place. If a fire evacuation drill with pre-warning is held in the middle of a trading period it will involve a winding down anticipatory period, during which time trading levels fall. This is followed by a stoppage of all trading during the actual drill period, then a longer than normal 'winding up' period to the more usual trading.

At the time of the first evacuation there were a total of 15 staff on duty; made up of 7 security staff, 6 cleaning staff and 2 management staff. On the second evacuation there were 10 staff on duty made up of 5 security staff, 4 cleaning staff and one management staff. All of the staff are trained on fire evacuation procedures.

The evacuations were carried out as a requirement of the Fire Certificate issued under the Fire Precautions Act 1971 [52].

6.4 OBJECTIVES

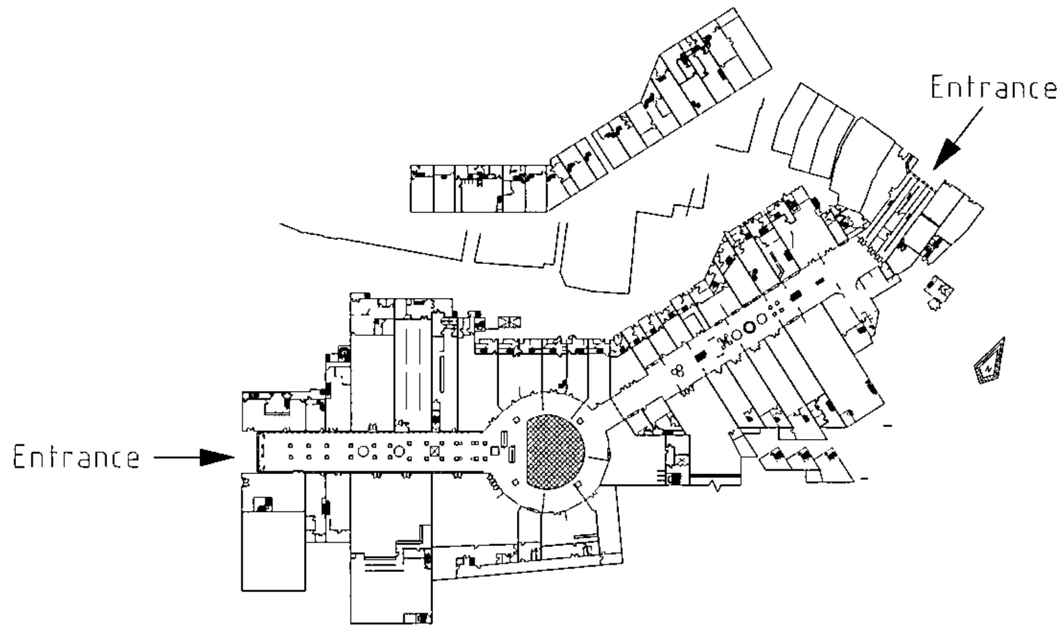
The main objective of the experiment was to investigate the behaviour and interactions of a population when engaged in the process of evacuating a shopping centre. The observations were also undertaken to assess the applicability of the monitoring methods proposed and appraise the method of measuring the data. This will include the pre-movement times and evacuation times of occupants evacuating the premises.

6.5 THE BUILDING

The shopping centre was constructed in the 1960's as an open shopping complex, which consists of multi-decked shopping malls with an adjacent multi-storey car park. When it was opened in 1966, it was at the forefront of a new generation of shopping centres, with a catchment area of 500,000 people in the North West of England. In 1981, the malls were enclosed to put the whole complex under one roof. The building consists of two storey malls terminating in a large round atrium, providing 250,000 sq. ft. of retailing space in 113 retail units. The structure of the building is a concrete frame with a light weight steel roof. There are two principal access points to the centre at the end of each mall.

Each of the retail units has at least one alternative emergency exit. The building has a smoke control system which has five separate smoke control zones, **figure 6.1 and 6.2** provides details of the layout of the Centre. The alarm system W2 non-directive (pre-recorded) voice alarm systems activated system giving a warning signal followed by a pre-recorded message which states,

" *Attention Attention This is an evacuation please leave the centre by the nearest exit do not use the lifts or escalators* ",



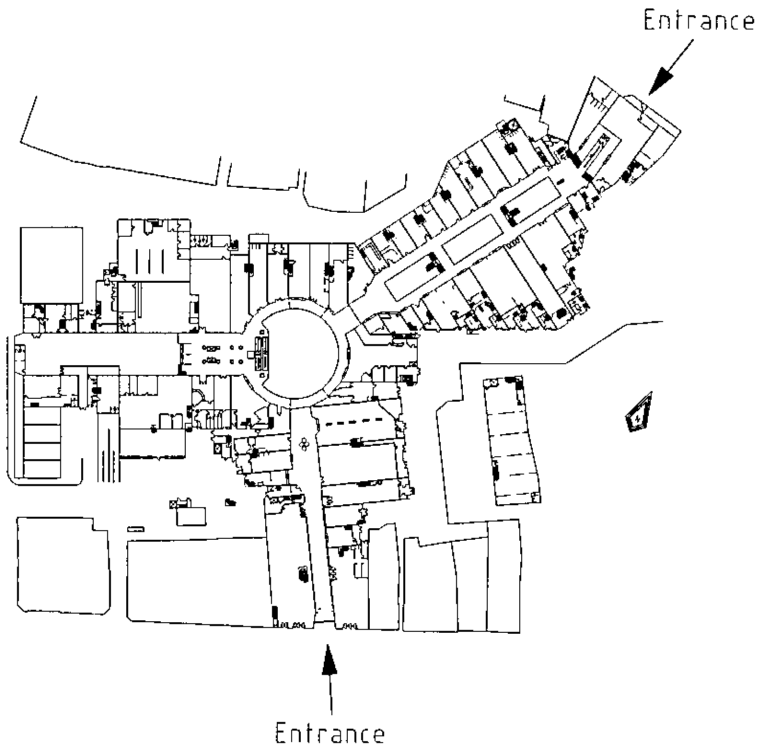
Not To Scale

FIGURE 6. 1 SHOPPING CENTRE LEVEL ONE

6. 5 DATA RECORDING

The evacuations were both recorded by 10 security video cameras and by an electronic counting system called Footfall. Footfall is a British company specialising in digital, video and electronic customer tracking systems. Pedestrian traffic flows have been developed as a key factor in helping to determine the rental value of current and future lettings. Tenants are also provided with feedback on the success of any marketing activity. The information gathered from the Footfall electronic counting system can identify the highest levels of pedestrian flow. Although this is not the primary use, this electronic tracking system was used to count occupants out of the Shopping Complex when the fire alarm was activated. The system only provides a hard copy print for every 15 minutes, which would be of little value for a means of escape record. The continual readout is provided by a television monitor however, a video was made so that the results could be recorded in ten second segments for later analysis. This created a technical problem as the tracking on the video camera causes picture flicker when videoing a monitor screen. This was overcome by using a camera that allowed the tracking to be adjusted.

The video filming of the event was on a multi-split screen unit that has the facility for slow play back. The data and information was obtained by means of 10 strategically positioned close circuit television vision cameras.



Not To Scale

FIGURE 6. 2 SHOPPING CENTRE LEVEL TWO

6. 6 RESULTS AND DISCUSSION

At the time of the first evacuation there were 460 people in the shopping centre at the time of the second evacuation there were 420 people. The time required to evacuate all the occupants from the Shopping Centre in the first evacuation was 2 minutes 30 seconds and 2 minutes 40 seconds for the second evacuation. Although there was only a slight difference in the two times and occupancies, on speaking to the staff on duty after both evacuations, they stated that the second evacuation was more difficult due to the reduced staffing levels. This is implied by the results with the first evacuation taking the shortest time with the greatest number of occupants. The evacuation times achieved were close to the recognised component time indicated in DD240 [7] i.e. 3 minutes for a W2 : non-directive (pre-recorded) voice alarm systems.

6. 7 EVACUATION 1

The following table indicates the number of persons escaping from the shopping complex over each 10 second interval for the first evacuation following the operation of the fire alarm.

T	Freq	Mid point	F*Mp	(Mp)^2	x^2(=f*TF^2)
0	0	0	0	0	0
10	27	5	135	25	675
20	22	15	330	225	4950
30	40	25	1000	625	25000
40	54	35	1890	1225	66150
50	29	45	1305	2025	58725
60	36	55	1980	3025	108900
70	31	65	2015	4225	130975
80	37	75	2775	5625	208125
90	30	85	2550	7225	216750
100	34	95	3230	9025	306850
110	37	105	3885	11025	407925
120	36	115	4140	13225	476100
130	34	125	4250	15625	531250
140	12	135	1620	18225	218700
150	1	145	145	21025	21025
160	0	155	0	24025	0
N	460		31250		2782100
Mean	67.93				
Standard Dev		37.85			

FIGURE 6. 3 MEAN AND STANDARD DEVIATION FOR EVACUATION 1

6. 8 EVACUATION 2

The following table indicates the number of persons escaping from the shopping complex over each 10 second interval for the second evacuation following the operation of the fire alarm.

T	Freq	Mid point	F*Mp	(Mp)^2	x^2(=f*TF^2)
0	0	0	0	0	0
10	22	5	110	25	550
20	19	15	285	225	4275
30	35	25	875	625	21875
40	55	35	1925	1225	67375
50	20	45	900	2025	40500
60	32	55	1760	3025	96800
70	29	65	1885	4225	122525
80	33	75	2475	5625	185625
90	35	85	2975	7225	252875
100	30	95	2850	9025	270750
110	33	105	3465	11025	363825
120	35	115	4025	13225	462875
130	30	125	3750	15625	468750
140	11	135	1485	18225	200475
150	0	145	0	21025	0
160	1	155	155	24025	24025
N	420		28920		2583100
Mean	68.85				
Standard Dev		37.53			

FIGURE 6. 4 MEAN AND STANDARD DEVIATION FOR EVACUATION 2

Using the form of grouped frequency distribution, the standard deviation was calculated using the indirect method. Analysis of the flow rates through each exit indicated that all the exits were operating substantially below their capacity. This capacity is a notional 40 persons per minute per exit width as given by the British Standard 5588 series [16]. The total number of units of exit width through the all the mall doors give a maximum flow rate of 400 persons per minute out of the premises. It can be seen that the flow rate through the final exit doors was well below the maximum flow rate.

Members of the public did not use the exits to the rear of each individual unit. It can be argued that these exits which were located down unfamiliar corridors and service areas would only be used when the malls or the exit route became untenable. It would be unreasonable to assume that because an exit is not used in an emergency that it will not be needed in the future.

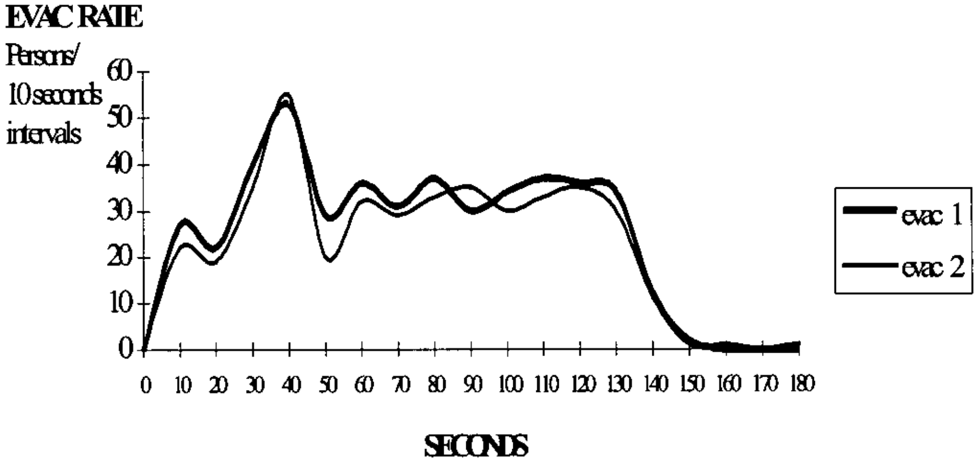


FIGURE 6.5 GRAPH OF FLOW RATES OF OCCUPANTS FROM SHOPPING CENTRE

As can be seen from the results in **figure 6.3** and **figure 6.5** evacuation **1** was carried out in 150 seconds and the peak flow rate or mode occurred after 40 seconds then levelled out at approximately 50 seconds for the next 80 seconds. Results in **figure 6.4** and **figure 6.5** show that evacuation **2** took 160 seconds and a peak flow rate occurred again after 40 seconds then levelled out for the next 80 seconds

In **figure 6.6** the data is presented by contrasting the different total frequency in the two evacuations by time compared with the percentage of the frequency of persons evacuating. From this data it can seen that the median occurs between 60 and 70 seconds but more importantly the 95th percentile and the end of the evacuation occurs between 125 and 160 seconds. This graph is very similar when compared with that produced by Ashe and Sheilds [53] on the Simulex model for evacuation of a retail store.

The tail of the graph between 95% and 100% is the critical area that requires more investigation. At this late stage of the evacuation it is realistic to assume that it is theses people who may be of greatest danger in a real emergency. This is the area where fatalities or injuries would most likely occur.

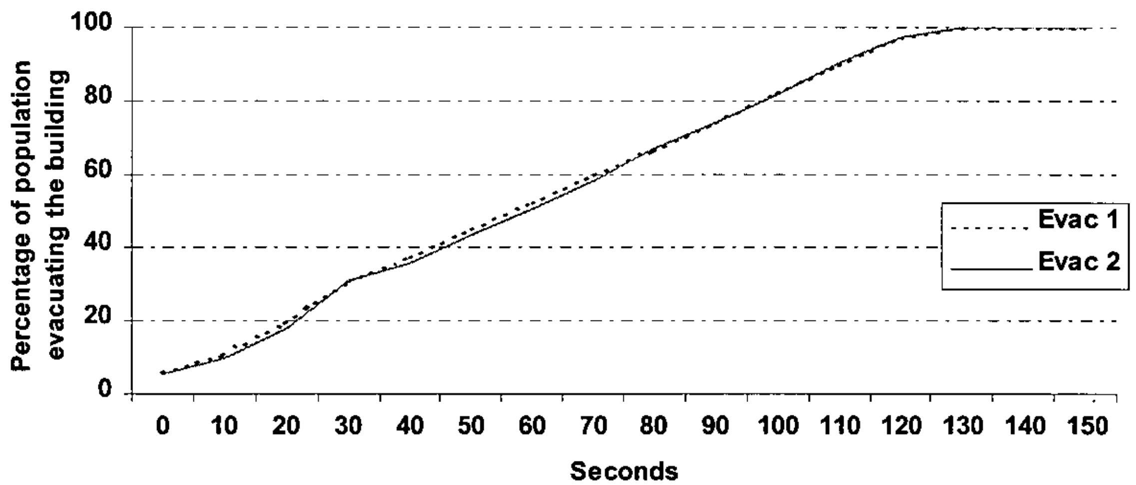


FIGURE 6.6 COMPARISON OF EVACUATION 1 AND 2 FROM SHOPPING CENTRE

6. 9 COMMENT UPON OCCUPANT BEHAVIOUR

The following observations were derived from the video recordings made during the two evacuations. The behaviour of the occupants could be characterised by self preservation, i.e. they did not warn others. As previously discussed, from the literature concerning fire-related human behaviour by Wood [17], Bryan [12] and Canter [10] all described the actions most likely attributed to people evacuating buildings this includes:-

- seeking further information
- seeking help/calling the fire service
- controlling the fire and smoke spread
- searching for other occupants
- warning/helping others
- saving property
- going to refuge area

The analysis of the video recordings and observations of the evacuations suggests that the behaviour of the occupants did not reflect the suggested behaviours. The occupants did not appear to seek additional information or take action to warn other occupants. This could be attributed to the type of warning system and explicit nature of the pre-recorded message.

It could be seen by the occupants' actions that they appear to be single-minded in their attitude to the evacuation. Human behaviour requires perception, thinking and understanding, therefore it could be implied that for a successful fire evacuation **drill** from a building must be realistic and not solely based upon physical values. These physical values are travel distance, type of alarm, the standard of staff training and the size of exits. The size of the fire and the density of the smoke cannot be programmed into experiments of this type. It can be assumed that these factors would affect the result if the evacuation was as a result of a fire.

The shopping centre is situated in the middle of the town centre and is used as a main thoroughfare. This appeared to have some bearing on the objectives of each individual occupant. For example, during the first evacuation, two males were observed to enter the building when the alarm was activated and used the centre as a thoroughfare. Thus they continued through the centre during the evacuation. Another example of this concerned a woman pushing a child in a pram, who did not only proceed through the centre, even though she was close to an exit, but she continued the longest possible route at what can only be described as slow pace. The reason for this was that they would have approximately a 500 metre detour if they had to walk around the outside the centre. In contrast two women not using the centre as a through route were observed to enter a shop when the alarm was activated, they immediately turned around and left the centre by the nearest exit

During the second evacuation, persons who were just entering shops moved quickly to an exit once the alarm had been sounded and directions given, but people observed just entering the centre tended to continue. In fact one woman that entered the centre one and a half minutes into the evacuation stopped about 30 metres into the centre and stood still for five seconds considering her next move. She then made a dash into the centre running a further 30 metres only to be stopped by a security guard and directed out to the nearest exit. If the incident had been a real fire one can only surmise what would have happened to the woman. Incorrect decision making, in times of stress appear to be irregular in nature and an unpredictable characteristic of human behaviour. How much of this erratic decision making can be predicted is the challenge that faces behaviourists.

The reactions of most of the occupants were appropriate in the circumstances since an attempt to evacuate was justified due to the voice communication system and the established fire evacuation drill operated by security staff. This included the prompt opening of exits both manually and automatically, which appeared to have a significant effect upon the initiation of appropriate occupant action in the immediate location. The appropriate action was to evacuate using the nearest main mall exit. The occupants placed considerable trust in the information received from alarm system and the direction given by staff, this is evident from the fast evacuation time. This confirms that, in most instances, when presented with correct information the public will respond correctly and responsibly. This positive response may be because the occupants perceive that the information is being conveyed by a person in authority.

The pre-movement times, for the first evacuation, from the moment the alarm sounded until movement towards an exit commenced for the captured on video are given in **figure 6.7** and **6.8**, the maximum time for this is 120 seconds. The pre-movement times, for the second evacuation, are given in **figure 6.9** and **6.10**. The maximum time for this is 130 seconds.

Pre-movement time for retail premises with a W2 : non-directive (pre-recorded) voice alarm systems is 3 minutes as indicated in DD240 [7]. These results suggest that the experiment carried out indicated a performance considerably better that the code suggests. This may not be the case, however, when the occupancy density is higher for the centre i.e. on a Saturday afternoon before Christmas. Unfortunately, no retailer will allow a researcher to carry out an evacuation at such a time for financial reasons.

On the seating area on the mall, some of the occupants in the first evacuation (two males and one female) did not immediately move when the alarm was raised. Some 60 seconds into the evacuation they were told to leave by staff; but ignored this instruction and had to be asked to leave again some 60 seconds later. After this second request, they left the centre. One can only surmise either they were waiting to meet someone or possibly they were under the influence of alcohol, but compared to the rest of the occupants their behaviour appeared inconsistent. Two minutes into both evacuations, staff were still having to tell a few occupants to leave the centre.

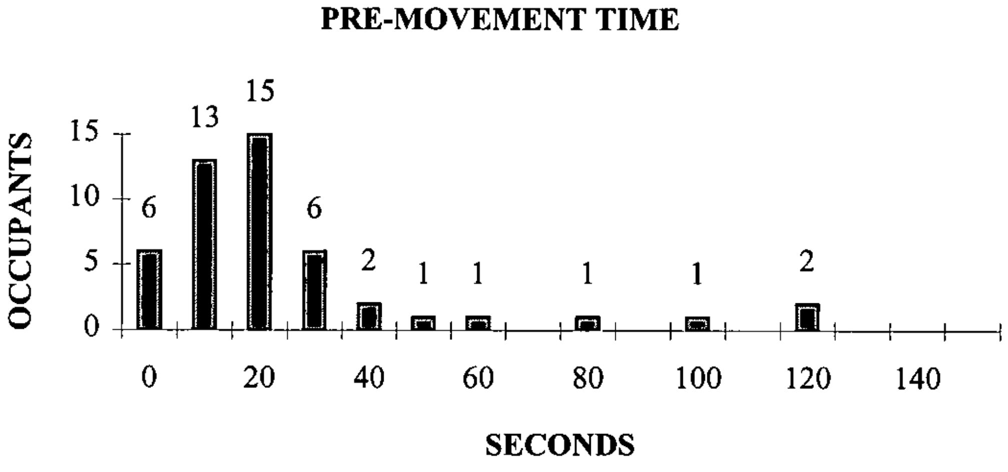


FIGURE 6.7 PRE-MOVEMENT TIME EVACUATION 1

T	Freq	Mid point	F*Mp	(Mp)^2	x^2(=f*TF^2)
0	0	0	0	0	0
10	6	5	30	25	150
20	13	15	195	225	2925
30	15	25	375	625	9375
40	6	35	210	1225	7350
50	2	45	90	2025	4050
60	1	55	55	3025	3025
70	1	65	65	4225	4225
80	0	75	0	5625	0
90	1	85	85	7225	7225
100	0	95	0	9025	0
110	1	105	105	11025	11025
120	0	115	0	13225	0
130	2	125	250	15625	31250
140	0	135	0	18225	0
150	0	145	0	21025	0
160	0	155	0	24025	0
N	48		1460		80600
Mean	30.41				
Standard Dev		27.45			

FIGURE 6.8 MEAN AND STANDARD DEVIATION EVACUATION 1 PREMOVEMENT TIME

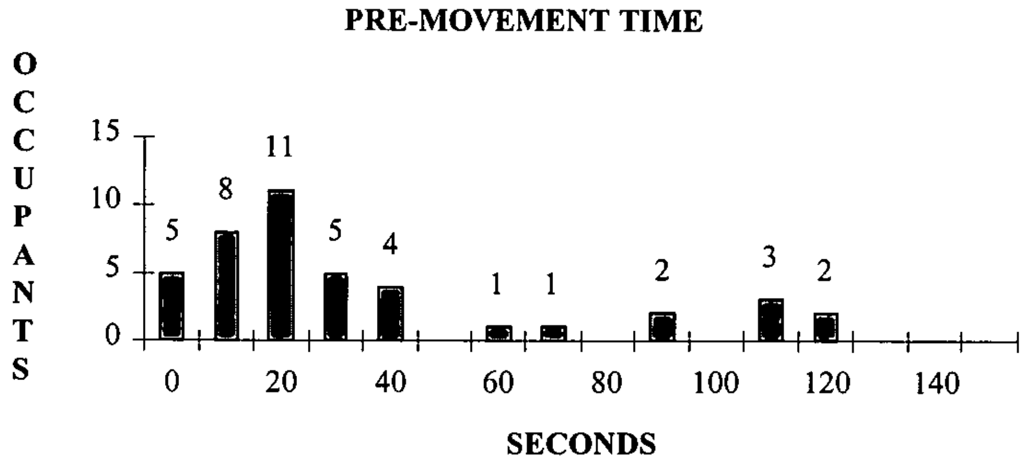


FIGURE 6.9 PRE-MOVEMENT TIME EVACUATION 2

T	Freq	Mid point	F*Mp	(Mp)^2	x^2(=f*TF^2)
0	0	0	0	0	0
10	5	5	25	25	125
20	8	15	120	225	1800
30	11	25	275	625	6875
40	5	35	175	1225	6125
50	4	45	180	2025	8100
60	0	55	0	3025	0
70	1	65	65	4225	4225
80	1	75	75	5625	5625
90	0	85	0	7225	0
100	2	95	190	9025	18050
110	0	105	0	11025	0
120	3	115	345	13225	39675
130	2	125	250	15625	31250
140	0	135	0	18225	0
150	0	145	0	21025	0
160	0	155	0	24025	0
N	42		1700		121850
Mean	40.47619				
Standard Dev		35.53			

FIGURE 6.10 MEAN AND STANDARD DEVIATION EVACUATION 2 PREMOVEMENT TIME

A sample in the first evacuation of 48 occupants observed represented 10.4% of the population in the centre. In the second evacuation 42 occupants were observed representing 10%.

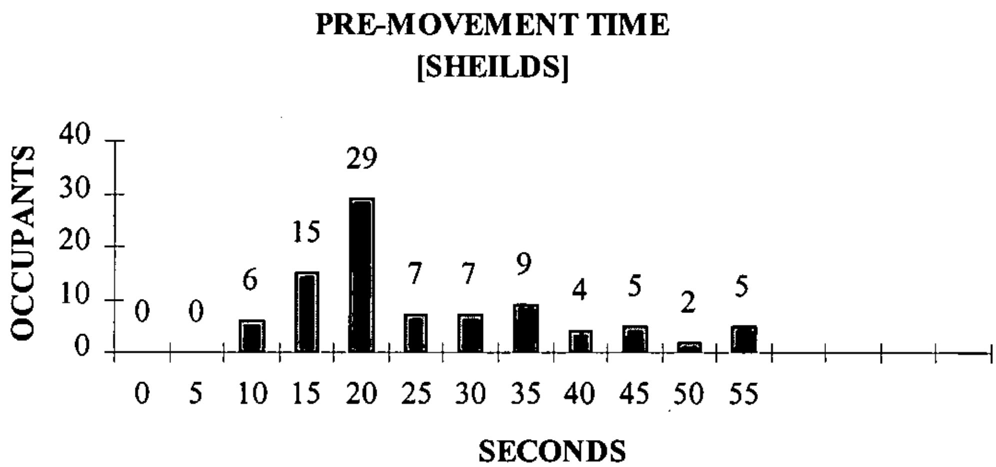


FIGURE 6.11 PRE-MOVEMENT TIME EVACUATION (SHEILDS) [53]

The comparison with the work of Sheilds [53] can be seen by comparing **figures 6.7, 6.9 and 6.11** all have a peak after twenty seconds yet all have a long *tail* or negative skew which equates to a Poisson distribution. This trend represents those most at risk in an evacuation. The nature of the activities being carried out by those persons exhibiting this form of behaviour presents an interesting area for further research.

6. 10 CONCLUSIONS.

The experiments using the Footfall digital counting mechanism proved very successful and the recording of all the data was carried out by the author with no assistance. The fire drills resulted in some interesting findings regarding occupant behaviour. The occupants appeared to place considerable trust in the information they received. The level of familiarity which the occupants possess in relation to their environment would certainly have had an influence on their actions when asked to respond to an emergency.

Information regarding the occupant's familiarity to the centre could be gathered by using a questionnaire to be handed out at the exits. This questionnaire could also gain information on the occupant's age, sex, frequency of visit, location or area of the centre when the alarm was raised, and the individuals perceived actions when the alarm was raised. This type of information was too labour intensive for this project, however when this type of experiment has been carried out in other cases i.e. NFPA or Shields [14],[54] the response rate to the questionnaires has been between 30% and 50%. This requires a high labour requirement which would not be realistic for this study. Higher return rates have been achieved by questionnaires that have been carried out following a real fire event in residential accommodation by Sekizawa [55] and Proulx [56]. Proulx carried out a questionnaire in 1997 in Canada and achieved a return rate of 80%, when Sekizawa carried out a similar exercise in 1996 and achieved a return rate of 48%.

The reaction of most of the occupants appear to be appropriate in the circumstances, since the information that they received justified there was an emergency in the centre. This confirms that in most instances the public are prepared to follow instructions especially when this information is provided by a person in authority.

One area for concern regarding the recent decision of many operators of shopping centres to move away from the usual military style uniform to a informal blazer in an effort to make the security staff more customer friendly. British Standard 5588 part 10 [16] recommends that security staff are identifiable by dress this leaves the question of the uniform open to interpretation.

It is of note that as a member of the fire service, my personal experience whilst visiting shopping centres in fire service uniform, is that the members of the public approach me for information and ignore the security staff in their customer friendly uniform.

The similarity in the observed behaviour in the response to both fire evacuation drills in a similar environment may be explained in part by the task characteristics of the perceived emergency and the mode of cognitive processing created by such circumstances. This suggests that untrained, unprepared occupants tend to resort to informal or intuitive processing, which can be influenced by instruction from either direction from an alarm system or by persons in authority.

CHAPTER SEVEN

CONCLUSIONS

7.0 INTRODUCTION

The main factor that prompts research into fire evacuation must be related to the statistics gathered regarding fire incidents from all over the world. The various approaches adopted by researchers have been varied and to a certain extent fragmented. This has prompted the holding of the first International symposium into Human Behaviour in Fire held in Belfast in August 1998. This symposium brought together the various components of the research to date, and has presented researchers with an outlook on the future of human behaviour in fire research which is more promising today than at anytime in the past. With this pro-active outlook, a realisation is emerging on the importance to determine valid evacuation times in the design of buildings under the performance codes similar to DD 240 [27].

7.1 FINDINGS FROM THE LITERATURE REVIEW

Researchers such as Proulx have reported on the method for alerting the occupants of a building will directly impact on the time delay before an evacuation is initiated. At present current models comprise of analytical components that attempt to compare data from various research studies. As the quantity and quality data from researchers is increased, the input data for these models can be refined, so that an increase in their accuracy can be achieved. In the short term, whilst this research is progressing, the greatest influence on the safety of the public in complex buildings will relate to the accuracy of the fire alarm message and the quality of the management control over the fire.

7.2 RESEARCH METHODOLOGY

In chapter two, research methodologies and fire studies of various kinds were discussed which show that the nature of an individual's behaviour during an emergency evacuation will be dependant upon many factors, such as prior knowledge, experience and training.

A more scientific approach by fire engineers is now in use and the details of this approach was given in chapter three. With a more scientific approach to evacuation problems it is hoped that future deaths and injuries in complex buildings will be significantly reduced.

Research has indicated [13] that the response of occupants will vary depending upon the nature of the setting e.g. shopping complex, stadium, hospital, hotel or office complex and this was discussed in chapter four. Since the procedure for assessing pre-movement time is key to the production of an accurate fire engineered solution. Research to date indicates that further definition and refinement is needed so that the time required by occupants to avoid danger can be assessed accurately.

7.3 HUMAN BEHAVIOUR

Chapter five outlined the various research studies that have investigated human factors effecting the lack of response to fire warning systems. Tong and Canter [24] have shown that there are areas of failure with traditional alarm systems, but technological advances in informative warning systems overcome the lack of response.

7.4 EXPERIMENTAL OBSERVATIONS

Two evacuation experiments were carried out and it can be seen that the reaction of most of the occupants appeared to be expected, since the information that they received justified there was an emergency in the centre. This confirms research by Proulx and Sime [19] that in most instances the public are prepared to follow instructions, especially when this information is provided by a person in authority.

Although the experimental observations are limited to only two evacuations, the results are similar to those carried out by Shields [54]. Specifically the pre-movement times that were observed were similar to data from experiments carried out by Shields [54]. The pre-movement time peaked after twenty seconds and the similarity of the critical *tail* or the final occupants to evacuate, can be seen by comparing the data.. This can be said to relate to human behaviour and the concepts of avoidance, commitment, affiliation and role as described by Proulx [32].

7. 6 RECOMMENDATIONS

7.6.1 STAFF TRAINING

A plan should set out a fire safety management structure that identifies the person or persons responsible for all matters relating to fire safety. A fire safety manager should have overall control of the premises relating to matters of fire safety and should be given the necessary support. He/she should have an appreciation of fire precautions within the building and their purpose. He/she should take charge of the evacuation and should liase with the fire service on their arrival. A deputy to the fire safety manager should be appointed, who will take control in the absence of the manager. The experiment detailed in Chapter 6 with the fast evacuation time and well trained staff serves to endorse this opinion.

Staff require effective training in what actions to take in a fire to reduce delay in evacuation. Their role is crucial. They should know the building and what might or might not be expected to occur. Staff should be identifiable as members of the public will seek them out (for instruction and information). They are likely to have the earliest warning of any fire and are thus in the best position to act effectively in aiding evacuation. This could be said to be the software of the *evacuation solution,* it is labour intensive with a high financial cost and a requirement by management to be proactive and enthusiastic.

Roles, status and position in a hierarchy can be seen as clear influences on patterns of behaviour. Coping with fire becomes a matter of recognising the potential of the role structure, which already exists and its inherent weaknesses. People who are in important and critical positions in the communication system do not always appreciate the significance of their role in a crisis and can have a considerably negative effect in the event of a fire e.g. the announcer in the control room at Summerland 1973 [34]. People should be aware of their role vis-à-vis the public and other members of their hierarchy.

As certain people hold such pivotal positions, they should be made aware of the appropriate actions and necessity for precise and clear communication. This is especially the case, when a rapidly developing fire means that the critical time to escape is very short as can be seen from the study conducted with regard to the Manchester Woolworths fire [6].

Staff training must take place so that individuals clearly understand their particular role and responsibilities in the event of a fire. This training should include:

1. Action to be taken on discovery of a fire;
2. Operation details of mechanical and electrical systems;
3. Routine testing and maintenance information;
4. Logs for records of tests, evacuations; etc.
5. Details of drawings of the various types of active and passive fire protection measures;
6. The fire action plan.

The plan must be tailored to include:

1. Arrangements for calling the fire service and providing the necessary information upon their arrival;
2. Procedures about evacuation, including adequate assistance for people with disabilities;
3. Arrangements for shutting down plant where necessary;
4. Arrangements for first aid fire fighting if appropriate.

The type of alarm system installed in a particular building should be of a type adequate to enable the occupants to understand that it is a fire alarm.

7.6.2 CORRECT ALARM SYSTEM

Proulx and Sime's experiment in a station of the Tyne and Wear Metro [52] indicated that success in evacuation was improved, when bells were combined with clear directive information. This coupled with a well rehearsed fire plan and trained staff will enhance the evacuation process.

It crucial that it is recognised that occupants do not necessarily immediately move to an exit once the alarm has sounded. Therefore it must be recognised that an alarm system that imparts the greatest amount of information to occupants will improve the evacuation process. In buildings such as well-managed theatres, supermarkets and offices, where regular drills are carried out, the pre-movement time may be relatively short. However, in multi-compartment buildings and buildings, where families or groups may be separated i.e. the fire Summerland fire of 1973 the pre-movement time may vary in different locations. Therefore the alarm systems required in such buildings should be upgraded, where required, to give the necessary information to occupants.

7.7 PROSPECTS FOR FURTHER WORK

The prospects for further work are the carrying-out of more evacuation experiments in order to develop reliability in the determination of pre-movement times. Further experiments would be in other types of premises of varying configurations and occupancies, using the same type of recording equipment that proved effective in the two experiments carried out.

7. 4 SUMMARY

A better understanding of the interaction between occupant behaviour and various fire alarm systems in complex buildings is closer to being fully understood. Assumptions about fire, building design and human behaviour must be balanced and yet requires to be dynamic as in modern society any of the factors could be mutable. Therefore, a shift in engineering and psychological imperatives may be necessary so that a correct relationship or balance exists between building design and fire engineered solutions.

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