Publication 10/92. The Effect of Wind Speed on Escape Behaviour through Emergency Exits.

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HOME OFFICE

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Kirsty Bosley

FIRE RESEARCH & DEVELOPMENT GROUP

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THE EFFECT OF WIND SPEED ON ESCAPE BEHAVIOUR THROUGH EMERGENCY EXITS

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Home Office
Fire Research and Development Group
Horseferry House
Dean Ryle Street
LONDON
SW1P 2AW

ABSTRACT

In the event of a fire in a new shopping mall or public building, smoke control systems would come into operation to prevent the area becoming smoke logged. Some of these systems include mechanical ventilation, where fans remove smoke at a high level to be replaced by fresh air at lower levels.

Where the fresh air enters the building through an emergency exit it can reach relatively high speeds. The air speed through these exits is currently restricted to a maximum of 3 metres per second to prevent any adverse effects on people trying to leave the building. However this limit also has implications on the design of the building.

This study aims to establish whether the current incoming air speed limit could be increased without introducing any danger to the public.

Cranfield Institute of Technology carried out the study to establish the effects of a range of air speeds on members of the public escaping through an emergency exit. Various categories of volunteers, including those considered to be vulnerable, made escapes from a simulated emergency exit. Their psychological and physical reactions to the wind were monitored and analysed.

It was concluded that the air speed limit could be increased to a maximum of 5 metres per second in the emergency exit with no adverse effects on members of the public. Hence building efficiency can be improved with no reduction to the safety of those using it.

MANAGEMENT SUMMARY

Introduction

Where mechanical ventilation is a part of the smoke control system of a building, the fresh air intake through an emergency exit is currently limited to 3 metres per second. This figure was chosen because it does not affect the ability of any member of the public to leave through an emergency exit.

The objective of the trials described in this report was to investigate the validity of this air speed limit and if necessary to propose a revised limit.

As part of the Home Office Fire Research Program the Fire Experimental Unit of the Fire Research and Development Group was requested to undertake a series of tests to look at the influence of air speed on members of the public as they tried to escape through an emergency exit.

The psychological effect of the wind speed on people leaving through an emergency exit was felt to be as important as the physical effect. The work was therefore contracted out to the Applied Psychology Unit of Cranfield Institute of Technology, who have experience in investigating escape behaviour.

Test Procedures

The approach adopted was to simulate the conditions likely to prevail when a building's smoke control system comes into action. To this end a wind tunnel test rig was constructed based on the emergency exits of a large shopping mall. Volunteers were recruited to escape through it under varying headwind conditions, having entered it under a crosswind. The wind speeds for the tests ranged from the current limit of 3 metres per second to just over 10 metres per second.

The physical and psychological effects on a range of volunteers were then assessed by means of statistical analysis of escape times and questionnaire responses.

The work was carried out in two phases. The first, a preliminary survey, looked at low risk situations. Healthy individuals escaped from the corridor one at a time; two tests were carried out at each wind speed, one at walking pace and one running.

The second phase was itself divided into two parts. The first part involved individual volunteers from categories considered to be vulnerable, while the second involved groups of healthy volunteers escaping from the corridor together. The tests in phase two were all carried out "as fast as was comfortable".

The vulnerable volunteers were selected from the following categories :

1. Adults with young children in pushchairs

2. Adults over the age of 60

3. Children between the ages of 12 and 14

4. Experienced wheelchair pushers and occupants

5. Adults with some form of restricted mobility

Results

The physical effect of various wind speeds, that is the amount by which people were slowed down, was established by timing video recordings of each test. The psychological effect of the wind was derived from questionnaires assessing the volunteers' perception of safety. All of these results were then statistically analysed.

Escape times were significantly affected by wind speeds of 6.5 metres per second and above. There were instances of significant effects at lower wind speeds, with some categories of volunteers in certain sections of the corridor, but the broad picture was that wind speeds under 6.5 metres per second did not affect escape times.

Most categories of volunteers felt safe at wind speeds up to 6.5 metres per second. At and above this speed, volunteers' perceptions of safety were significantly decreased.

On this basis a wind speed of over 6.5 metres per second could present physical and psychological problems to people. However a wind speed of 5 metres per second would not reduce anyone's ability to escape or their feelings of safety. A wind speed limit of 5 metres per second in the emergency exit would therefore be more appropriate than the current 3 metres per second.

Conclusions

The maximum intake air speed value is referred to in BS 5588 : Part 10 (1991) - Fire Precautions in the Design, Construction and Use of Buildings - Code of Practice for Shopping Complexes. This standard has adopted the Building Research Establishment (BRE) current advised limit of air speeds no greater than 3 metres per second and is referred to in the Building Regulations Approved Document B.

The results of this project have been discussed with the BRE and with G2 Division of the Home Office. It has been agreed that a maximum air speed of 5 metres per second through the emergency exits is acceptable for all users of shopping malls and should be proposed as an amendment to the relevant British Standards.

This value takes into account not only the physical effects of wind speed on escape behaviour but also the psychological perceived effects.

The air speed value is equally relevant in other situation similar to those encountered in a shopping mall. The only exception would be where the siting of the air inlet and the air speed may disturb a smoke layer and cause general smoke logging.

In situations where severe design problems are encountered e.g. in upgrading old buildings, it might be possible to accept higher limits of up to 10 metres per second based on these figures.

The findings of this project are directly applicable to the exit corridors from a shopping mall but are equally valid in any situation where an approach corridor leads to an exit door e.g. hospitals, schools, prisons etc.

Air flows through doorways not only occur when a mechanical smoke control system is used but also occur with systems based on pressurisation (BS 5588 : Parts 4 and 5). Pressurisation systems cause air to flow out through the final exit door of a pressurised escape route. Although the project does not cover evacuations in a tail wind, everyday experience suggests that progress is easier and more stable in that situation. The maximum values for air flows derived from this project are thus equally valid under these circumstances.

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1. INTRODUCTION

In the event of a fire in an atrium building, such as a shopping precinct, the major danger to the public is from the smoke produced. To reduce this danger, smoke control measures are a required part of the fire safety system. These measures involve removing smoke from the region affected and allowing fresh air to replace it.

Two main smoke removal methods are prevalent:

> **natural ventilation**, where vents are opened and the smoke flows out, drawn by the buoyancy of the hot gases
>
> **mechanical ventilation**, where smoke is pumped out using fans.

In the latter case, fresh air is effectively sucked in through available openings. Where this happens the air may enter through low level air vents and through the emergency exits. Where the emergency exits are used then the incoming air speed is currently recommended not to exceed 3 metres per second (Reference 1).

The design of the smoke control systems in a building is thus affected by this air speed limit. If the limit is exceeded, it may be necessary to reduce the air intake speed by increasing the intake area with either automatic air vents, or extra doors.

The current limit of 3 metres per second is based on previous research work by the Building Research Establishment (Reference 2). This research suggested that wind speeds over 5 metres per second could cause discomfort to pedestrians. However, that research related to the level of discomfort occasioned by high wind speeds in and around shopping centres making it too cold to sit on benches or stand around, or causing dust and litter to be blown about. It was considered that a maximum intake air speed figure based on this criterion was open to challenge.

The Home Office Fire Experimental Unit of the Fire Research and Development Group was asked to look at the influence of the intake air speed on people's ability to escape through an emergency exit of a shopping precinct, to investigate the validity of the current air speed limit of 3 metres per second, and if necessary, to advise on an acceptable alternative limit.

In September 1990 Cranfield Institute of Technology[1] (superscripts refer to notes on page 15) was commissioned by the Home Office Fire Research and Development Group to undertake a series of tests to look at the influence of intake air speed on people's ability to escape through an emergency exit of a shopping precinct.

The work was awarded to the Applied Psychology Department at Cranfield which has considerable experience of studies into escape behaviour, including recent work on aircraft evacuations.

The College of Aeronautics at Cranfield also has experience of building and calibrating wind tunnels.

The tests were carried out in two phases: The first phase involved fit healthy people who were not expected to have any trouble escaping from the corridor. The second phase involved several categories of volunteers considered to be more vulnerable in the event of a fire; it also investigated the effects of people leaving the corridor in groups, as would happen in an emergency situation.

The Cranfield reports for both phases are reproduced as Annexes A and B. The following is a summary of these reports.

2. THE TEST RIG

The approach adopted by Cranfield Institute of Technology was to simulate the conditions likely to prevail when a smoke control system comes into action. To this end a wind tunnel test rig was constructed and volunteers recruited to escape through it under varying headwind conditions, having entered it under a crosswind. The physical and psychological effects on the whole range of volunteers could then be assessed at a number of different air speeds.

The initial corridor design (see Figure 1) was based on a large shopping complex in Milton Keynes, close to Cranfield. The main part of the corridor was a straight run, with the fan 'sucking' air out as it would in a smoke control system. Near to the open end was an open doorway, a constriction which increased air speed around that region. The doorway was 2.1 m wide in the phase one tests, as they are in Milton Keynes. In the second phase it was reduced to 1.8 m wide - the minimum size for an emergency exit, an important factor where groups are leaving the corridor together.

The corridor was painted in off-white with normal office levels of lighting. The floor was linoleum-tiled with the preferred path to be taken by the volunteers marked with black lines. The exit from the corridor was down a ramp.

Opening on to the main corridor was an ante-room, in which the volunteers waited prior to the tests. The volunteers had to walk from the ante-room into a side wind and then turn to face into the wind.

For data analysis purposes the corridor was divided into three sections. Section A was taken from the ante-room, around the corner, taking in the effect of entering an air flow from the side. Section B was the straight length of corridor into a constant air flow and section C was the end of the straight length including the doorway constriction. Because the doorway constriction reduced the cross-sectional area through which air could flow, the air speed increased through the doorway and for a short distance either side of it. This last section ended before the end of the corridor to avoid including the effect of the volunteers slowing as they approached the exit ramp.

The wind was generated by a 2 metre diameter centrifugal fan[2] driven by a constant speed 90 kW motor located at the downwind end of the corridor.

Wind speeds were varied by changing the size of the fan outlet with a winch-operated shutter. Five wind speeds were calibrated ranging from the current minimum 3 metres per second to a top speed of just over 10 metres per second. The table below summarises the wind speeds.

Wind Speed Calibration			
Throttle Position	Mean Wind Speed (m/s)	Maximum Wind Speed (m/s)	Maximum Wind Speed with 8 People in Doorway (m/s)
1	3	4	7
2	4	6	11
3	7	10	15
4	8	12	18
5	10	15	21

The values here are rounded to whole numbers, the figures are set out more fully in Table 4.1, Page A7, Annex A and Table 1, Page B11, Annex B.

Calibrations were carried out by the College of Aeronautics. Initial tests to check the flow quality of the fan and corridor were made with vane anemometers and smoke filament flow visualisation. These aided the corridor design.

Wind speed calibrations were made using a Pitot static tube at various points along the corridor. Measurements for phase one of the tests were taken with the corridor empty and with a person standing in the corridor. Measurements for phase two of the tests were taken with the corridor empty and with eight people in the corridor.

Throughout the text of this report the figures quoted as wind speeds are the mean speeds. Therefore the actual maximum wind speeds to which volunteers are subjected are higher than the nominal speeds quoted.

Further details of the measurements and procedures are given in Annex A section 4.2.

Video cameras were placed along the corridor (fitted flush with the walls) with one at the open end looking in. All of the cameras recorded a single time code which was used in subsequent data analysis. The start signal for the tests was a whistle which was also recorded on the video sound tracks.

3. VOLUNTEERS

3.1 General

The work was carried out in two phases. The first, a preliminary survey, looked at low risk situations. Healthy volunteers escaped from the corridor one at a time. The report from this phase is provided in Annex A.

Previous work in this area had also used volunteers who were fit and healthy. It was decided that, in this project, the effects on the more vulnerable members of society also had to be taken into account when considering a maximum safe speed. However, in addition to collecting test data, this preliminary survey allowed the safety of the test procedure to be established without risk to any of the vulnerable volunteers.

The second phase was itself divided into two parts. The first part involved individual volunteers from categories considered to be vulnerable. The second involved groups of healthy volunteers escaping from the corridor together. The report from the second phase is provided in Annex B.

3.2 Phase One - Healthy Individuals

In phase one, 12 volunteers were recruited from each of the following categories:

1. Females between 20 and 39
2. Males between 20 and 39
3. Females between 40 and 54
4. Males between 40 and 54.

Volunteers were recruited by means of advertisements on local radio and in newspapers. They were asked to come dressed as they would be for a shopping trip, that is wearing outdoor shoes and coats.

3.3 Phase Two - Vulnerable Individuals

In phase two, where more vulnerable members of the public were selected, the target was to test a cross section of people who might have difficulty evacuating a shopping precinct, but who nevertheless represented regular shopping centre users.

Five categories were covered :

1. Adults with young children in pushchairs

   For this category the same pushchair was used in all of the tests. Nine women and three men were tested, this was regarded as appropriate and reflecting the expected ratio of adults with children in a shopping mall.

2. Adults over the age of 60

3. Children between the ages of 12 and 14

   It would have been preferable to include younger children in this category, but the ethical and insurance implications involved prevented their inclusion. The children were all recruited from the same class of a local secondary school.

4. Experienced wheelchair pushers and occupants

   Due to the lack of any facilities for the disabled at the test site in Cranfield, this category became entirely restricted to wheelchair pushers. The same wheelchair and occupant was used every time for consistency.

5. Adults with some form of restricted mobility

   Adults with restricted mobility who were willing to participate in these tests were particularly hard to come across. Because of this, fewer participants were tested in this category than was originally intended. A total of ten adults, seven male and three female were tested in this category.

The aim was to recruit 12 volunteers for each category. Ideally the volunteers would have been equal numbers of each sex. However, in Category 1 - Adults with young children, a preponderance of women was deemed preferable as a reflection of the likely population of a shopping mall.

3.4 Phase Two - Groups

In addition to vulnerable individuals, phase two of the work also investigated group evacuations. These represented the likely scenario in the event of a fire, where people leaving en masse would restrict the emergency exit. This would alter the evacuation situation not only by impeding the progress of other volunteers, but also by increasing the wind speed around the doorway constriction by reducing the area through which air could flow.

Groups of eight people were evacuated, firstly in a close-knit unit and then in a more dispersed group. The two types of groupings simulate different situations :

1. Where the danger is obvious and everyone is trying to leave at once (the close-knit unit).

2. Where the danger is not obvious and people are leaving in their own time with no urgency (the dispersed group).

4. EXPERIMENTAL PROCEDURE

During phase one of the tests, two practice and ten proper evacuations were completed by each volunteer, that is one evacuation walking and one running at each of the five wind speeds. During phase two, the individuals and groups each completed one practice and five proper evacuations, each evacuation made as quickly as the volunteer felt comfortable. The practice evacuations were made at an intermediate wind speed, i.e. not one of the calibrated speeds. The test evacuations were made with the wind speed settings selected in a randomised order to avoid any preconceptions or learning.

Before the tests, volunteers were briefed about the aims of the project and about what was expected of them. They were offered ear defenders if they wanted them (the fan was very noisy). Before being taken to the wind corridor each was given a questionnaire, to be filled in after each test, designed to determine their perception of the effect of the wind. They also completed a medical questionnaire to ensure their fitness to take part in the tests.

In phase one, the volunteer was asked to step up to the starting line in the ante-room and asked either to walk as fast as possible or to run. The test started when the whistle was blown. The same routine was used in phase two, except that volunteers were asked to escape as quickly as they felt comfortable.

During the group evacuations, volunteers were randomly assigned a start position in the ante-room (see Figure 2). All the volunteers started from their assigned positions and were asked to leave the corridor as quickly as they felt comfortable. For the close-knit groups all volunteers started at a single whistle blast. For the dispersed groups each of the three rows of volunteers started separately, requiring three blasts of the whistle at 2 second intervals.

When each volunteer reached the end of the tunnel he or she returned to the ante-room and completed their questionnaire. At the end of all of the tests, the volunteers were taken to a quiet room for debriefing.

5. DATA ANALYSIS

5.1 Video Recordings

The physical effect of various wind speeds, that is the amount by which people were slowed down, was established by timing video recordings of each test. Video cameras were set up to record the start and end of each section of the corridor. The time for each volunteer to complete each section was noted and also the total time taken to negotiate the whole corridor.

The video recordings also allowed analysis of any problems experienced by the volunteers (being knocked off balance for example) although in the event this was unnecessary as problems were not encountered.

5.2 The Questionnaire

In all tests the psychological effects of the air speed were gauged by means of a questionnaire. The questionnaire aimed to ascertain volunteers' perception of safety and wind effect. The following is a summary of the questionnaire, the complete questionnaire is contained in Annex A (page A30).

All aspects were evaluated on a scale of 1 to 10. For each separate section of the corridor volunteers were asked:

> "To what extent did the **air flow** affect your progress along the corridor ?"

Then for the corridor as a whole they were asked:

> "To what extent did the air flow affect your:
> clothes
> hair
> face and eyes ?"
>
> "How **safe** did you feel whilst escaping from the corridor?".
>
> "Did any other factors impede your progress along the corridor?"

Space was allowed for the volunteer to explain what had impeded them and how. During phase two of the project an extra question regarding the effects of other people on the individual's progress was asked.

6. RESULTS

6.1 Phase One - Healthy Individuals

Running and walking evacuations were considered to represent different situations and were treated separately.

The mean and the standard deviation of the escape times for walking and running were calculated for each wind speed, firstly taking into account the whole corridor and then considering each section separately (Tables 5.2 - 5.5, Annex A). These values were then analysed to establish whether significant[3] differences in escape times were encountered and which wind speeds (if any) were primarily responsible.

The volunteers' perceived safety values, derived from the questionnaires, were analysed in a similar way to the evacuation timings (Tables 5.6 - 5.10, Annex A).

Higher wind speeds did produce slower escape times than lower wind speeds, and the highest wind speed (10 metres per second) had a significantly worse effect than other wind speeds when healthy adults were tested at walking pace.

With volunteers running, the second highest wind speed (7.5 metres per second) also had a significant effect on escape times, though the effect of the highest speed was even greater.

It was clear in the responses to the questionnaire that volunteers were able to distinguish differences between the wind speeds, despite the randomised order of wind speeds when testing.

The volunteers felt that the three highest wind speeds (at and above 6.5 metres per second) were significantly more unsafe than the lowest two. This finding was evident throughout phase one, both walking and running.

Further factors such as age, height and weight had no effect on individual evacuation rates, although there was, surprisingly, a difference due to clothing: people wearing loose clothing were less affected by the higher wind speeds than those wearing tight clothes. The effect however was only slightly significant and based on an arbitrary classification of clothing into 'loose' or 'not loose' clothes. It was felt that the effect was not of great importance and could be attributed to a number of factors with no relevance to this project (e.g. tight clothes are restrictive, classification was subjective etc.).

6.2 Phase Two - Vulnerable Individuals

A similar general approach was taken in analysing the escape times and perceptions of safety of potentially vulnerable individuals. The means and standard deviations of the times and perceptions of safety were calculated for each category of individuals (Table 4, Annex B).

As before, these values were then analysed to establish whether significant differences in escape times were encountered and which wind speeds (if any) were responsible.

The escape times for section A of the corridor were not significantly affected. That is, walking into a crosswind and turning to face it, did not present a problem. However problems were encountered on the straight section and, in most cases, on the doorway constriction section. Also, when the corridor was taken as a whole, significant differences in escape times were noted.

In order to establish which wind speeds were primarily responsible for the differences indicated above, each wind speed was compared with every other. In most of the cases only the top speed of 10 metres per second was found to affect progress significantly. There were cases however (e.g. adults with pushchairs in section C, children from 12 - 14 in the whole corridor) where the 7.5 metres per second wind also significantly altered progress. In three cases only (children 12-14, mobility restricted people when the whole corridor is taken into account, and wheelchair pushers in section C) the mid-range wind speed significantly impeded progress.

The perceived safety ratings were subjected to the same kind of analysis and it was found that the wind speeds that made the significant difference were the three highest (at and above 6.5 metres per second). However, these ratings were not felt to be sufficiently high to prevent people from progressing on safety grounds alone.

An indication of the susceptibility of a category of volunteers was derived by comparing their escape times at the highest wind speed and their times at the lowest. These values showed that healthy adults were least affected by the highest wind speed, their escape times increasing by 7%, and people with restricted mobility and those over 60 were most affected with an increase of 17%.

The questionnaire also asked whether any factors other than the air flow had affected their progress. In answer to this two wheelchair pushers had noted that their progress had been slowed by 'lift' under the wheelchair.

6.3 Phase Two - Groups

For the group evacuations the close-knit group and the dispersed group were treated separately. The time taken for the whole group to escape at each wind speed was analysed to find the mean and standard deviation, and to establish any significant differences. Additionally the times were analysed by the start position of the individual within the group. The perceived safety ratings were treated similarly.

For the group evacuations virtually every wind speed made a significant difference to escape times. The only section of the corridor which was not significantly affected was section A, the entry section (although even that was affected by the highest wind speed during the close-knit tests).

When the escape times were analysed by start position, volunteers starting at the outside positions (1,4,6 in Figure 2) and at the back (6,7,8 in Figure 2) were found to be significantly slower with the highest wind speed (10 metres per second) than those at the front. This was true of both close-knit and dispersed groups, although in the close-knit groups the volunteer in the inside second row position (5) was also affected by the highest wind speed. Additionally the volunteer in the outside second row position of the close-knit groups was significantly affected by the second highest wind speed (7.5 metres per second).

The perceived safety ratings show the same trends as earlier tests with significantly lower safety ratings at wind speeds at and above 6.5 metres per second.

Group members were also asked how much they felt that other volunteers had impeded their progress. For the close-knit tests no significant differences were found at the various wind speeds; however, the volunteers in the dispersed tests felt that they were significantly impeded at the middle and highest wind speeds (6.5 metres per second and 10 metres per second).

Analysed by start position, in a close-knit group the front row were less affected by other volunteers than the middle row, with the back row most affected. However in the dispersed group the front two rows gave very similar ratings and only the back row felt that they were impeded by others.

In answer to the final question about whether any factors other than wind speed had affected their progress, several volunteers noted that they had hit either the door frame on leaving the ante-room or the doorway constriction at the end of the corridor. This was more often noted by people in dispersed conditions than in close-knit conditions.

Further analyses were carried out to establish whether any other factors affected volunteers' performance. This was done by comparing the 'actual' and 'expected' performance of an individual, based on their start position. From this it was found that males, taller people, younger people, those with flat shoes and those not carrying a bag were likely to perform better in a group. These results are not surprising but give confidence in the other less predictable results which have been reported.

The original calibrated wind speeds had been measured at various points in an empty corridor. The wind speed was also measured with eight people standing in the doorway restriction. The percentage increases in wind speed through the crowded doorway ranged from 91% with a calibrated wind of 4 metres per second, to 50% with the highest calibrated wind speed of 10 metres per second (Tables 1 and 2, Page B11, Annex B).

7. DISCUSSION

The tests undertaken at Cranfield examined a number of different parameters, yet involved a relatively small sample of people. This, although it was not ideal, was inevitable to keep the project within a reasonable budget. Another compromise made was for each volunteer to make several evacuations - the ideal would have been for each to make one evacuation only. The learning effect was kept to minimum by randomising the order of wind speeds, and the results were treated with caution during interpretation by typically using a 1% criterion for statistical significance.

Escape times were significantly affected by wind speeds of 6.5 metres per second and above. There were instances of significant effects at lower wind speeds, with some categories of volunteers in certain sections of corridor, but the broad picture was that wind speeds under 6.5 metres per second did not affect escape times.

More important than the small change in escape times was the volunteers' perception of safety. Most categories of volunteers felt safe at wind speeds up to 6.5 metres per second. At and above this speed, volunteers perceptions of safety were significantly decreased, although their safety ratings still remained relatively high (at the highest wind speed the mean safety rating value was around 8.5 on a scale where 1 represented 'not at all safe' and 10 represented 'completely safe'). Bearing in mind that the tests were held in controlled conditions with plenty of light, space and assistance near by, the high safety ratings are understandable, therefore it is important to concentrate on the changes in the volunteers' safety ratings rather than their absolute value.

On this basis a wind speed of over 6.5 metres per second could present physical and perceived problems to people, however a limit of 5 metres per second would be more appropriate than the current 3 metres per second. This value does not discount or ignore the occasional occurrence of significant effects at wind speeds lower than the suggested revised limit. These tests have indicated that significant problems will happen rarely enough, and with sufficiently minor consequences, to confirm that wind speeds up to 5 metres per second pose no serious threat to a person's ability to escape.

In situations where severe design problems are encountered e.g. in upgrading old buildings, it might be possible to accept higher limits of up to 10 metres per second based on these figures.

The findings of this project are directly applicable to the exit corridors from a shopping mall but are equally valid in any situation where an approach corridor leads to an exit door e.g. hospitals, schools, prisons etc. The only exception would be where the siting of the air inlet and the air speed may disturb a smoke layer and cause general smoke logging.

Air flows through doorways not only occur when a mechanical smoke control system is used but also occur with systems based on pressurisation (BS 5588 : Parts 4 and 5, Reference 3). Pressurisation systems cause air to flow out through the final exit door of a pressurised escape route. Although the project does not cover evacuations in a tail wind, everyday experience suggests that progress is easier and more stable in that situation. The maximum values for air flows derived from this project are thus equally valid under these circumstances.

8. CONCLUSIONS

The maximum intake air speed value is referred to in BS 5588 : Part 10 (1991) - Fire Precautions in the Design, Construction and Use of Buildings - Code of Practice for Shopping Complexes (Reference 3). This standard has adopted the BRE current advised limit of air speeds no greater than 3 metres per second and is referred to in the Building Regulations Approved Document B (Reference 4).

It must be borne in mind that, in the work described in this report, the wind speeds quoted represent the mean wind speed calculated from measurements taken along the whole length of the corridor. The volunteers were actually subjected to greater wind speeds than these as they moved up to and through the doorway (see Appendix C, Annex A, Pages A32-A37 and Appendix B, Annex B, Pages B34-B42) The air speed limits quoted in the BRE guidance document and in BS 5588 (References 1 and 3) refer to the air speed through the emergency exit.

The results of this project have been discussed with the Building Research Establishment (BRE) and with G2 Division of the Home Office and it has been agreed that a maximum air speed of 5 metres per second is acceptable for all users of a shopping mall or similar building and should be proposed as an amendment to the relevant British Standards (Reference 3). The only exception to this limit is a situation where the siting of the inlet air provision and the inlet air speed may disturb a smoke layer and cause general smoke logging.

This value of 5 metres per second represents the maximum wind speed acceptable through the emergency exits of the building. It takes into account not only the physical effects of wind speed on escape behaviour but also the psychological perceived effects.

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ISBN 0-85125-462-4

2. Building Research Establishment CP 1/74 1974, Acceptable Wind Speeds in Town, A.D.Penwarden

3. British Standards Institute BS 5588 : Fire Precautions in the Design, Construction and Use of Buildings

Part 4 (1991) - Code of Practice for Smoke Control in Protected Escape Routes Using Pressurization.

Part 5 (1991) - Code of Practice for Firefighting Stairs and Lifts.

Part 10 (1991) - Code of Practice for Shopping Complexes.

4. Department of the Environment and the Welsh Office, The Building Regulations 1991, Part B1 - Means of Escape, HMSO
ISBN 0-11-752313-5

NOTES

1. Applied Psychology Unit
   College of Aeronautics
   Cranfield Institute of Technology
   Cranfield
   Bedfordshire
   MK43 OAL

2. The fan motor is a Brook Compton Parkinson 90 kW 3 phase 50 Hz unit running at 1480 rpm. It draws 120 amps.

   The design data for the fan is :

Volume m^3per second	:	38.00
Static pressure Pa	:	1200.00
Power at STP kW	:	66.24
Fan speed rpm	:	664
Static efficiency %	:	68.84
Total efficiency %	:	76.65
Outlet velocity m/s	:	15.02
Velocity pressure Pa	:	136.21
Tip speed m/s	:	61.80
Fan size		1800 SISW
Fan type		V/AERO/2
Blade type		Backward
Arrangement		1

3. 'Significance' is used here in the statistical sense, where, at the 5% significance level an occurrence would happen **by chance** 5 times in every 100, and at the 1% level it would happen only once every 100 times. Thus if an increase in mean evacuation times from 5.78 seconds to 6.1 seconds is significant at the 1% level (highly significant) it is likely to happen by chance fewer than one in every 100 tests, therefore the increase is judged to be caused by the wind.

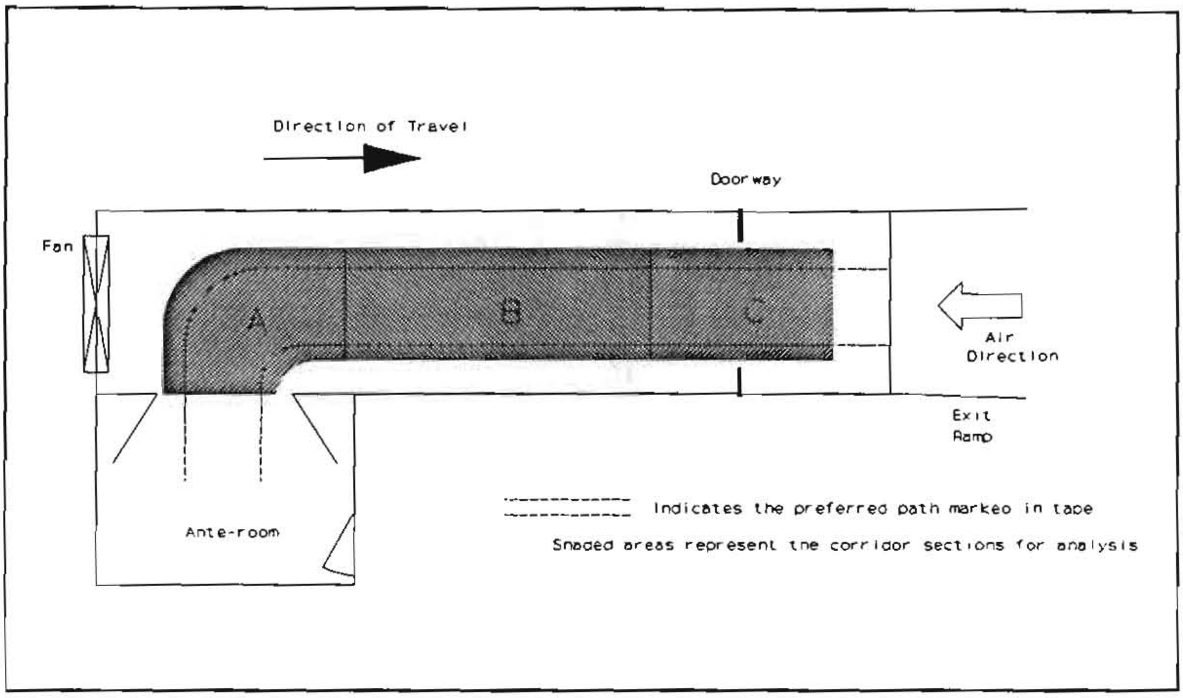

Figure 1 : Plan View of the Test Facility showing the Three Sub-Sections

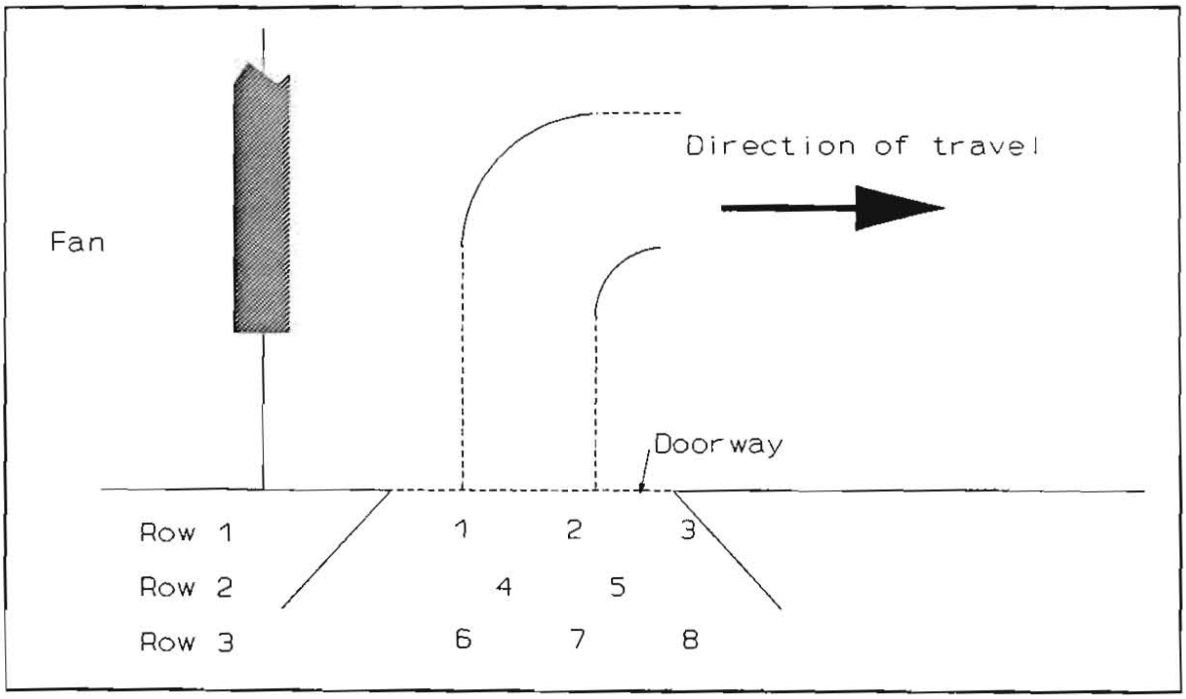

Figure 2 : The Start Positions for the Group Tests

ANNEX A : A Preliminary Investigation of the Influence of Wind Velocity on the Ability of Members of the Public to Evacuate through the Exit of a Shopping Precinct

A PRELIMINARY INVESTIGATION OF THE INFLUENCE OF WIND VELOCITY ON THE ABILITY OF MEMBERS OF THE PUBLIC TO EVACUATE THROUGH THE EXIT OF A SHOPPING PRECINCT

REPORT PRESENTED TO THE HOME OFFICE
FIRE EXPERIMENTAL ESTABLISHMENT
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DAVID BOTTOMLEY MSc
HELEN MUIR PhD
KEVIN GARRY PhD

College of Aeronautics
Cranfield Institute of Technology
Cranfield
Bedford

ABSTRACT

The rate at which smoke can be extracted from shopping malls is governed by the speed at which fresh air can enter the building to replace the extracted air. The aim of this exploratory study was to establish the maximum air flow rate that can be tolerated without detracting from people's ability to evacuate from such a building as quickly as possible. A wind tunnel was constructed to simulate a shopping precinct exit corridor, incorporating a large fan to create the air flow. Volunteers were 48 members of the public who were asked to both walk and run along the length of the corridor against a variety of headwind speeds.

The results showed that, when walking as quickly as possible, volunteers were significantly impeded by the highest wind speed investigated. When running, volunteers were significantly impeded by the two higher wind speeds. In addition, volunteers' perception of safety under each of the conditions were investigated, the results showed that they felt more unsafe under the two higher wind speeds when walking, and the three higher speeds when running to evacuate.

Several recommendations for further research were suggested. These involved investigations into group evacuations, evacuations involving younger and older members of the population, people with restricted mobility and competitive evacuations.

CONTENTS

1. BACKGROUND

The Building Research Establishment have produced recommendations that fans or vents are installed in modern shopping malls to enable smoke to be extracted as quickly as possible in the event of a fire breaking out in the building. One of the main factors which determine the rate at which smoke can be extracted is the rate at which fresh air is able to replace the extracted smoke. When the design dictates that fresh air enters through emergency exits, the current recommendation states that the air flow through these exits should not exceed 3 metres per second, equivalent to a mild breeze. However, when extraction fans are in use, it is likely that the air flow through the emergency exits would exceed this recommended limit, and possibly inhibit the ability of people to evacuate the building. It can be shown that if the air flow rates through emergency exits could be increased without causing any detrimental effect to people's ability to evacuate from a building, the smoke could be extracted more efficiently, thereby reducing the risk of fatalities due to smoke inhalation.

2. OBJECTIVES OF THE RESEARCH

The primary objective of this research was to investigate the effects of a variety of air flow velocities upon the time taken for people to evacuate from a simulated shopping precinct, both under normal conditions and in a simulated life-threatening situation. The long-term aim of the research programme is to determine the optimal air flow velocity allowing for rapid evacuation of people and extraction of smoke. For these initial series of tests, only the behaviour of individuals was studied.

In addition, it was felt that it would be useful to determine how people perceived the different air flows in terms of safety and willingness to proceed. It was also felt to be important to determine how they felt the wind affected their clothing, hair, face and eyes.

3. RESEARCH PROGRAMME

3.1 Equipment

The requirement for a test facility capable of simulating the air flow rates was met by constructing a simplified open return, closed working section wind tunnel.

Since the primary requirement is to simulate the actual conditions in a typical shopping mall exit corridor, high test section flow quality in terms of flow linearity and freestream turbulence is not required. In fact this is actually undesirable. Consequently, the relatively complex arrangement of a normal low speed wind tunnel was abandoned in favour of a simple rectangular cross-section tube (the test corridor) serving as the intake for a centrifugal fan. The only aerodynamic streamlining of the structure was:

i) a hemispherical intake on the vertical sides and roof of the corridor intake and

ii) corner fillets at the fan intake downstream of the usable section of the test corridor.

Both of these features served to improve the aerodynamic efficiency of the system in order to reduce size of the fan and motor needed to achieve the required flow rates.

The air flow was generated by a 2 metre diameter centrifugal fan, driven by a constant speed 90 kW motor. This type of fan was chosen to ensure that aerodynamic loading of the test section, sometimes referred to as blockage, would not result in a reduction in fan efficiency and consequently mass flow rate. It was considered important to ensure that mass flow rate through the test section was independent of the number of volunteers undergoing a test. It was not known whether such conditions would prevail in the actual exit corridor but for assessment purposes a constant flow rate was considered important.

Variation of the mass flow rate was achieved by chocking the fan exit nozzle with a winch operated shutter. A total of 5 pre-set shutter positions, corresponding to required test section flow conditions, were calibrated in terms of both the flow velocity in the plane of the aperture and along the axial centre-line of the test corridor.

The corridor was illuminated at normal office levels, the walls painted a uniform cream colour, and the floor covered with 30cm square floor tiles, the two colours (dark grey and off-white) arranged in groups of four to give a series of 60cm squares of alternating colours. In addition, red tape was used to mark out the intended path for the volunteers to walk, or run, along down the centre of the corridor.

A small ante-room was incorporated into the design of the test facility, this being used as a starting point for the volunteers and a monitoring centre for the researcher. A plan of this facility can be found in Appendix A.

3.2 Volunteers

Participants were members of the public who were recruited by posters and advertisements on local radio. They were paid a fee of £10 for successful completion of the tests, which lasted for approximately half and hour. All volunteers were required to wear the type of clothing which they would normally when shopping in a typical covered shopping precinct.

For the initial test programme, 48 volunteers were used, 12 from each of the following four groups:

Females ages between 20 and 39

Males ages between 20 and 39

Females aged between 40 and 54

Males aged between 40 and 54

Prior to participation in the test session, each volunteer was given a briefing which explained the nature of the research and the task they were required to complete. In addition, they were asked to read and complete a brief medical questionnaire to indicate they did not suffer from any of the states which it was felt, by the Applied Psychology Unit's Medical Advisor, should preclude potential volunteers from participation. A copy of the medical information provided to participants can be found in Appendix B.

3.3 Research Design

The main part of the task required that volunteers walked or ran along the test corridor against a variable headwind. Prior to the main test, each participant was required to perform two practice evacuations, one walking and one running at an intermediate wind speed not used for the main tests, to familiarise them with the test facility. All volunteers performed two evacuations under each of the five wind speeds under study, one whilst walking as quickly as possible without running, the other running as quickly as they were able. The air flow velocities that were used were:

1) 2.99 metres per second

2) 4.37 metres per second

3) 6.51 metres per second

4) 7.54 metres per second

5) 10.32 metres per second

Details of the calibration of the wind speeds are described in Section 4.2

The order in which the various configurations were performed was varied for each volunteer to counteract possible effects due to practice and fatigue. After each evacuation, the volunteers were asked to complete a brief questionnaire concerning the effects of the wind on their ability to progress along the corridor, as well as on their clothing, hair, face and eyes, and also how safe they felt whilst evacuating. In addition, volunteers were asked to note any additional factors which impeded their progress. A copy of this questionnaire is included in Appendix B.

It has been found during the pilot exercises that there were often relatively long gaps between escapes whilst participants completed questionnaires and it was therefore decided that it would be more efficient if more than one person was tested during any half hour session. As the initial tests showed that the presence of an additional volunteer did not interrupt the flow of the experiment, it was decided to proceed with this system whenever possible, as dictated by volunteer availability.

3.4 Data Collection

The progress of volunteers along the length of the corridor was recorded using four sets of video cameras and recorders: three along the wall (fixed at the top of the wall on the outside of the corridor) and a further one at the open end of the corridor, mounted on a tripod, and covering the entire length of the corridor. These can be seen in the plan contained in Appendix A. Four flat, omnidirectional microphones were located in the ante-room, each linked to a video recorder. Using the timebase facility on the cameras, this enabled the calculation of the elapsed time from the start signal to the moment when a volunteer crossed a reference point.

The corridor was split into three sections to enable the effect of changes in the wind speeds upon different components of the escape task to be determined. The first section (labelled 'A' in Appendix A) covered the first part of the task as the volunteers entered the air stream along the curved section of track. The second section ('B') contained the straight section along the main section of the corridor. Finally, Section C covered the part of the corridor immediately preceding the aperture, where the maximum air flow was recorded (see Figure C.1) through the aperture, to a point an equal distance beyond the aperture. The times for people to each the end of the corridor were not recorded as the pilot tests had revealed that most volunteers began to noticeably slow down prior to reaching the ramp at the end of the corridor.

3.5 Procedure

Volunteers were booked in at half-hourly intervals, either individually or in pairs as previously noted. Upon arrival at the Applied Psychology Unit, each volunteer, or pair of volunteers, was given a briefing concerning the nature of the tests, and what they would be expected to do. After receiving their clipboards containing questionnaires and completing the medical questionnaire, they were escorted to the test facility, where they were asked to leave their clipboards on the table provided.

In turn, and according to their allocated volunteer reference number, the participants were instructed by the experimenter that they were to perform the two practice tests prior to the main series. The first volunteer was asked to step up to the starting line, at the point where the ante-room adjoined the main corridor, and instructed whether to walk as quickly as possible without running or to run as quickly as possible. A whistle was used by the experimenter to denote the start of each test as this could be recorded by the microphones and transmitted to the video recorders. Upon hearing the whistle, the participant was required to proceed along the marked track in the manner requested. When the first volunteer had completed this, and been guided back to the administration point by a second researcher, the other volunteer of the pair (when applicable) was requested to perform the identical procedure.

After the second practice test, the volunteers were asked if they had any questions. The researcher then explained that the participants would be expected to complete a brief questionnaire after each subsequent test, and then continued with an identical procedure to that used for the practice tests, asking volunteers to either walk or run according to a pre-determined order. The researcher was responsible for changing the wind speed between tests, having sufficient time in which to do this whilst volunteers completed questionnaires.

After the completion of the ten test conditions, volunteers were paid their fee and thanked for their participation.

4. CALIBRATION OF WIND TUNNEL

4.1 Flowfield Calibration

In order for an accurate assessment of the corridor flowfield to be made the calibration was carried out in three phases:

1) Initial tests were carried out using vane anemometers and smoke filament flow visualisation to check the flow quality of the fan and basic corridor only, ie before the intake, fillets and aperture were fitted. These tests were primarily for design purposes and are not reported here.

2) A velocity calibration was made using a Pitot-static tube to measure local flow velocity at pre-set locations both in the plane of the aperture and along the corridor axial centre-line. These measurements were made with the corridor empty.

3) An assessment of the likely interference effect of a person passing through the corridor was made by Pitot-static tube velocity measurements at locations both in the plane of the aperture and in a plane 1 metre downstream, with and without a person standing in the corridor.

An additional calibration of a ring of surface static pressure tappings was made in terms of the flow velocity on the test corridor centre-line in the plane of the aperture. This makes it possible to monitor the flow velocity without any instrumentation in the corridor.

4.2 VELOCITY CALIBRATION

Pitot-static tube measurements of the dynamic pressure along the designated track (axial centre-line of the corridor), 1500mm above floor level, are presented in Figure C.1 (A.1 in Appendix A)for the 5 pre-set fan throttle positions - number 1 (minimum flow rate) to number 5 (maximum flow rate). The flow velocity is seen to increase as the aperture is approached (from downstream), reaching a peak approximately 1 metre downstream. Thereafter the velocity falls off towards the intake of the corridor.

The same data is presented in Figure C.2 with the local velocity at each point non-dimensionalised in terms of the velocity in the plane of the aperture. This shows that the aerodynamic characteristics of the facility are constant within the limits of the experimental technique. The differences in velocity at stations between 4 and 9 metres downstream of the aperture is due to the unsteady nature of the flow. This characteristic is emphasised by the data presented in Figures C.3 - C.5 which show the repeatability of velocity measurements at the same height above the corridor floor.

The Table 4.1 summarises the salient features of the velocity calibration:

Table 4.1 Velocity Calibration

Throttle Position	V_{max} (m/s)	$V_{aperture}$ (m/s)	V_{mean} (m/s)
1	4.47	3.59	2.99
2	6.27	4.85	4.37
3	9.62	7.46	6.51
4	11.57	8.90	7.54
5	15.04	11.54	10.32

Note:

1. V_{max} corresponds to the maximum recorded velocity on the designated track
2. $V_{aperture}$ is the velocity in the plane of the corridor aperture.
3. V_{mean} is the average velocity measured at 15 points on the designated track.

4.3 Static Pressure Reference

The velocity in the plane of the aperture can be monitored by reference to the difference between the static pressure in the test corridor (taken from tappings in the wall of the corridor) and atmospheric pressure. The purpose of such a system is to provide a means of measuring mean flow velocity without having instrumentation in the test section.

The reference static pressure tappings consist of two flush mounted static tubes in the wall of the test section, 1 metre downstream of the aperture. The difference in the average pressure at these locations and the atmospheric pressure is calibrated against the dynamic pressure, measured by a Pitot-static tube, in the plane of the aperture. This calibration data is given in Figure C.6 and shows that the test section dynamic pressure (q) is given in terms of the difference in test section static pressure and atmospheric pressure (p) by the relation:

$$q = 0.618\ p$$

4.4 Interference Effect of a Person Passing Through the Corridor

The corridor velocity calibration tests were carried out with the test section empty. In order to assess the likely effect on the local flow velocity of the "blockage" caused by a person in the corridor, a series of measurements were made at specific locations in the plane of the aperture, for the range of pre-set throttle positions.

Measurements were made using a Pitot-static tube, at heights above the floor level of 1250mm, 1500mm and 1750mm in the plane of the aperture both with and without a person standing on the designated track. A set of readings both to the right and left of the person were made and are shown in Table 4.2 below. The mean increase in local velocity for the range of throttle positions is given as a percentage of the velocity for the empty test section.

Table 4.2 Interference Effect of a Person Passing Through Corridor: Local Velocity

Height (mm)	LEFT	RIGHT
1750	10.9%	10.2%
1500	12.1%	13.1%
1250	12.7%	12.4%

In view of the acceleration of the flow downstream of the plane of the aperture, a similar series of tests were made at a station 1 metre downstream of the aperture, the results of which are given in the Table 4.3 below:

Table 4.3 Interference Effect of Person Passing Through Corridor: 1 Metre Downstream of Aperture

Height (mm)	LEFT	RIGHT
1750	7.9%	21.8%
1500	1.3%	0.8%
1250	0.2%	0.8%

The results show that the increase in velocity out of the plane of the aperture is much less, as would be expected. The exception being the point at the right of the person, 1750mm above the floor. This unexpected result was found to be due to a longitudinal vortex, shed from the right hand corner of the aperture. A similar (but contra rotating) vortex would also be shed from the left hand corner, but does not pass through the measuring point in this instance.

5. RESULTS OF EVACUATION TESTS

5.1 Demographic Details

Table 5.1 (below) shows the mean ages for volunteers in all four groups, with the standard deviations for these means presented in parentheses. Volunteers were also asked to provide estimates of their weight and height, and the descriptive statistics for these are also shown in Table 5.1.

Table 5.1 Demographic Details for all Volunteer Groups

	Groups				
	Females (20-39) (n=12)	Males (20-39) (n=12)	Females (40-54) (n=12)	Males (40-54) (n=12)	TOTAL
Mean Age (years)	29.92 (6.96)	27.42 (5.05)	46.00 (4.79)	44.67 (3.03)	37.00 (9.84)
Mean Weight (kg)	57.42 (5.23)	80.75 (6.34)	63.83 (8.33)	74.58 (12.35)	69.15 (12.33)
Mean Height (cm)	160.33 (7.89)	179.92 (6.29)	164.50 (6.45)	176.00 (6.05)	170.19 (10.39)

5.2 The Influence of Wind Velocity Upon Escape Times

The primary aim of the research was to investigate the effect of differing headwind speeds upon people's ability to evacuate a simulated shopping precinct. In this section the times taken to negotiate the task under the different conditions are described. It was felt that the evacuations whilst walking and whilst running represented two distinct situations, and therefore the results for these two forms of escape will be treated separately in this and all subsequent sections. It should be noted that the number of cases (N) for all statistics presented in this section is 48, and that '1' refers to the slowest air flow, '5' the fastest.

5.2.1 Evacuations Whilst Walking

In Table 5.2 the mean escape times (in seconds) for the volunteers under each of the five air flow conditions when walking as quickly as possible along the corridor are presented. In addition to the total times taken to complete the task, the times taken to negotiate each of the three sub-sections of the corridor (see Section 34. and Appendix A) are given. A plot of the total times can be seen in Figure 5.2 whilst plots for Sections A to C can be seen in Figures 5.2 to 5.4

Table 5.2 Mean Escape Times - Walking

Air Flow Velocity	Sectors			
	A	B	C	TOTAL
1	1.588 (0.285)	2.944 (0.390)	1.187 (0.171)	5.719 (0.679)
2	1.561 (0.223)	2.993 (0.469)	1.223 (0.221)	5.777 (0.760)
3	1.561 (0.245)	2.965 (0.406)	1.211 (0.185)	5.737 (0.720)
4	1.594 (0.240)	3.041 (0.456)	1.223 (0.182)	5.858 (0.754)
5	1.619 (0.281)	3.198 (0.439)	1.277 (0.184)	6.093 (0.757)

Table 5.2 reveals that the general trend was for higher wind speeds to produce slower escape times, whether the total escape times or those for the three sectors are considered. The only exception to this trend was for the third air flow velocity, which produced faster escape times than the slower second category. In order to establish whether there was a significant difference between the total escape times for the five air flows, a repeated

measures analysis of variance (ANOVA) was performed on the data. The analysis produced an F-ratio of 16.30 (degrees of freedom, df=4,188), which is significant beyond the 0.1% level. This implies that the differences between mean escape times showed a high degree of statistical reliability.

One of the objectives of the research was to establish the optimum air flow velocity that could clear smoke as efficiently as possible without delaying evacuating people. It was felt that it would be useful to perform post-hoc comparisons to uncover which air flows significantly differed from each other. A Newman-Keuls test between all possible pairs of means was therefore carried out (see Table 5.3)

Table 5.3 Newman-Keuls Paired Comparisons - Total Escape Times Whilst Walking

AIR FLOW VELOCITY					
	1	3	2	4	5
1	-				**
3		-			**
2			-		**
4				-	*
5					-

* - Significant difference at the 5% level
** - Significant difference at the 1% level

The data in Table 5.3 clearly demonstrate that the maximum air flow significantly differed from all others, mostly at the 1% level, and that none of the other four significantly differed from each other.

However, it was also felt that it would be useful to consider the three sub-sections of the corridor individually. Repeated measures ANOVA comparisons of the mean time for volunteers to cover Sectors A,B and C were found to produce F-ratios of 1.58 (df=4,188, not significant), 17.12 (df=4,188, significant beyond the 0.1% level) and 2.75 (df=4,188, significant at the 5% level). The respective Newman-Keuls comparisons can be found in Appendix D. For Sector B, the fifth air flow velocity was found to be significantly slower than all others, whilst the fourth speed also differed from the lowest at the 5%

level. There was less difference between the escape times for Sector C, and the only difference (significant at the 5% level) was found to exist between the minimum (ie '1') and maximum ('5') air flows.

5.2.2 Mean Escape Times - Running

In Table 5.4 the mean escape times for volunteers evacuating under each of the five wind speeds whilst running are presented. Once again, the total times are shown along with those for the three Sectors. Plots of these mean times are shown in Figures 5.1 to 5.4

Table 5.4 Mean Escape times - Running

	SECTOR			
Air Flow Velocity	A	B	C	TOTAL
1	1.220 (0.201)	1.663 (0.300)	0.698 (0.186)	3.581 (0.560)
2	1.211 (0.202)	1.650 (0.315)	0.695 (0.183)	3.557 (0.576)
3	1.218 (0.210)	1.705 (0.309)	0.668 (0.180)	3.591 (0.605)
4	1.265 (0.170)	1.730 (0.321)	0.681 (0.157)	3.677 (0.550)
5	1.259 (0.213)	1.833 (0.366)	0.755 (0.242)	3.848 (0.695)

The above table reveals that the escape times generally increased with an increase in air flow rates, although the second speed produced the fastest escape times of all. The repeated measures ANOVA technique was again employed to investigate the differences in escape times over the five conditions, and an F-ratio of 27.14 (df=4,188) was obtained, found to be significant beyond the 0.1% level. Paired comparisons between the means were also made using the Newman-Keuls test as in the previous section, Table 5.5 showing the relationship between these means.

Table 5.5 Newman-Keuls Paired Comparisons - Total Escape Times Whilst Running

AIR FLOW VELOCITY					
	1	3	2	4	5
1	-			**	**
3		-		*	**
2			-	*	**
4				-	**
5					-
* - Significant at the 5% level ** - Significant at the 1% level					

The data in Table 5.5 clearly show that the escape times produced under the fastest wind speed (5) were significantly different (ie slower) at the 1% level to those for any other wind speed. In addition, the fourth air flow velocity was found to produce significantly (mainly at the 5% level) slower escape times than produced by the slower air flow rates.

Once again, the effects of the wind for each of the sub-sections of the corridor were also investigated. For Sectors A, B and C, f-ratios of 3.59 (df=4,188, significant at the 1% level), 25.63 (df= 4,188, significant beyond the 0.1% level) and 3.94 (df=4,188, significant at the 1% level) respectively were obtained. Paired comparison tests were also performed, using the Newman-Keuls method as before, and these are shown in Appendix D. For the first section (A), speed '5' was found to differ from '2' and '1' at the 5% level. For Sector B, speed '5' was found to significantly differ from all others at the 1% level, '4' from '1' and '2' also at the 1% level and '3' from '2' and '1' at the 5% level. Finally, the highest speed was found to significantly differ from all others mainly at the 5% level, for the final Sector (C).

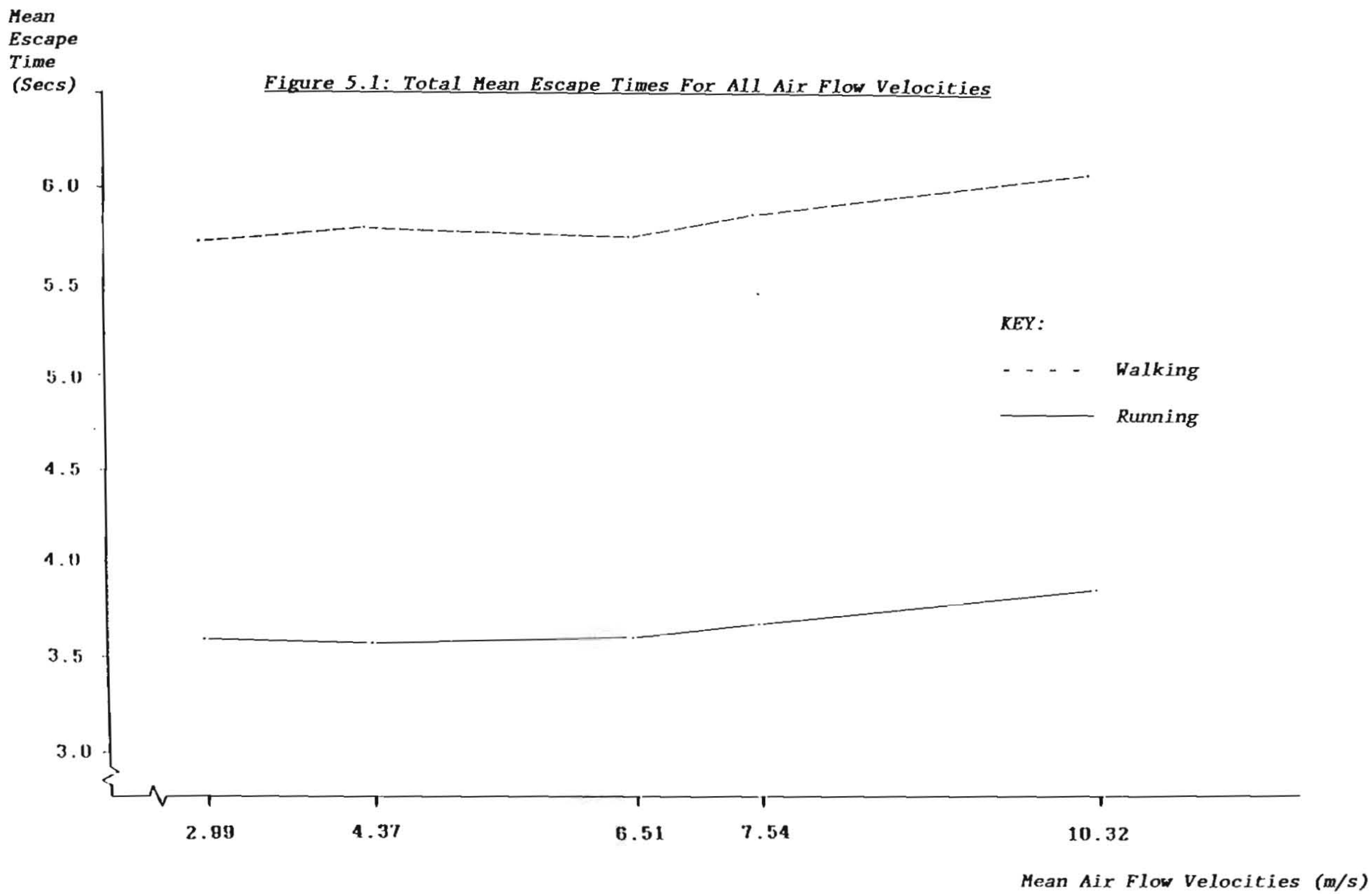

Figure 5.1: Total Mean Escape Times For All Air Flow Velocities

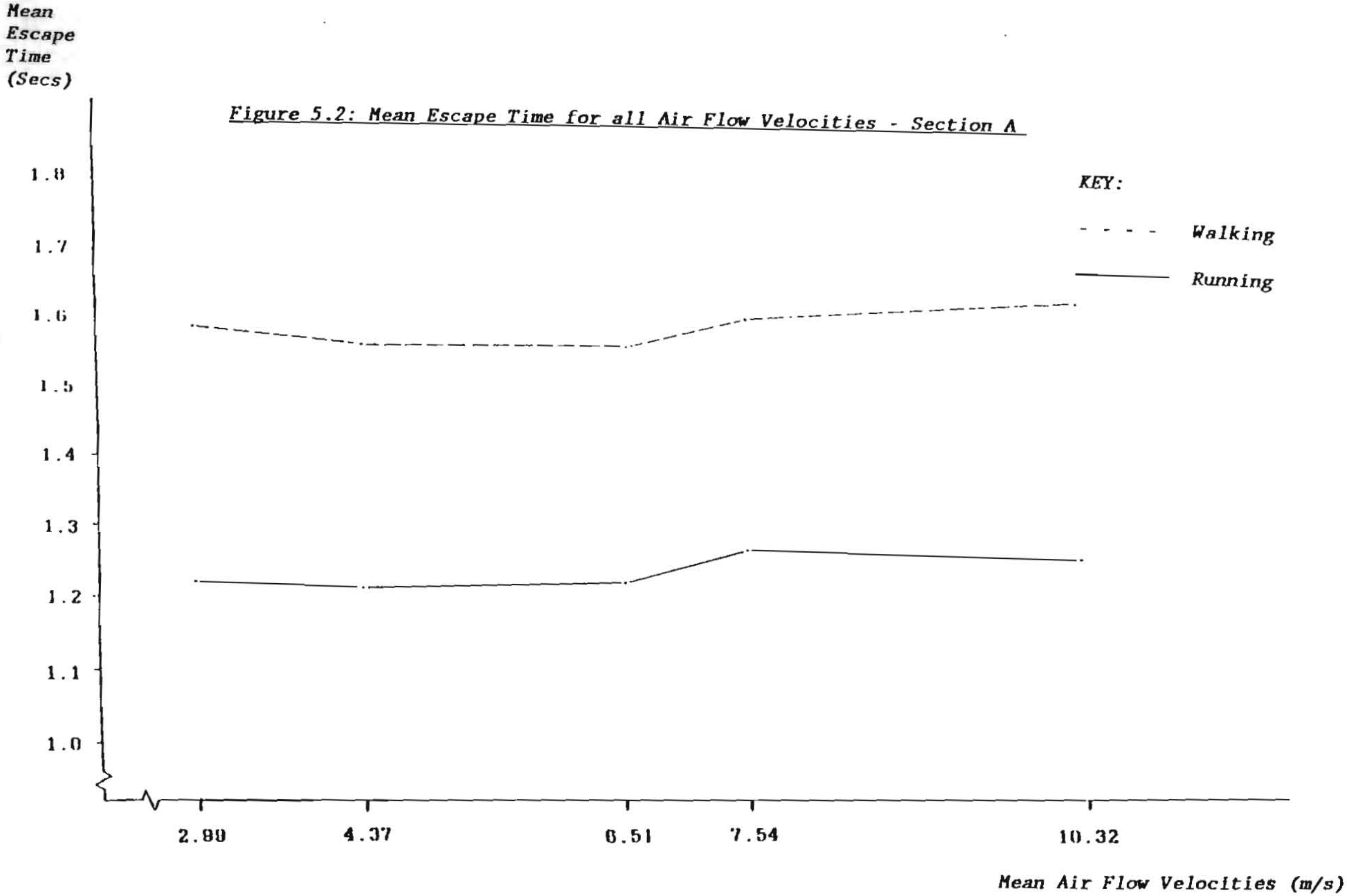

Figure 5.2: Mean Escape Time for all Air Flow Velocities - Section A

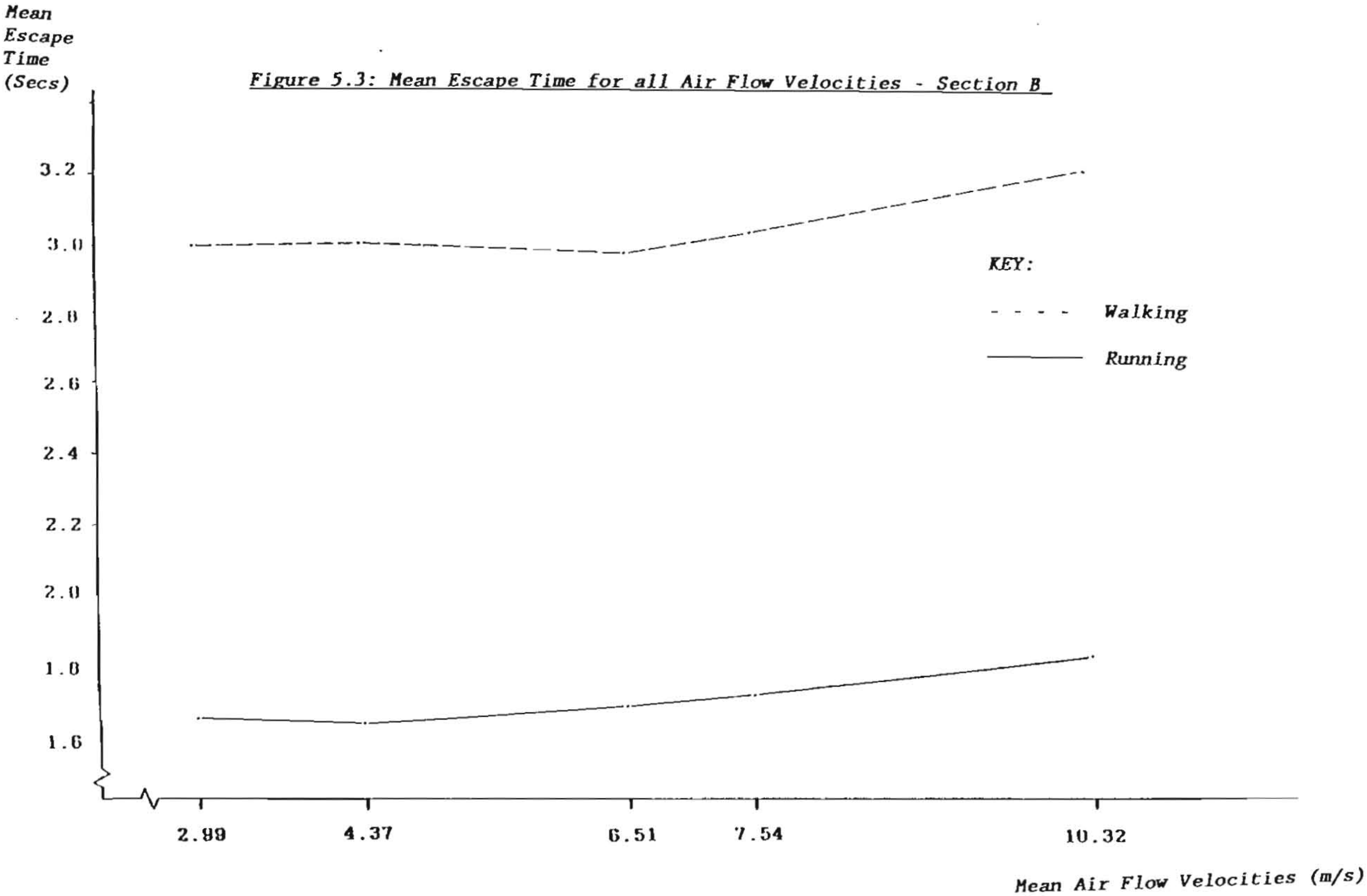

Figure 5.3: Mean Escape Time for all Air Flow Velocities - Section B

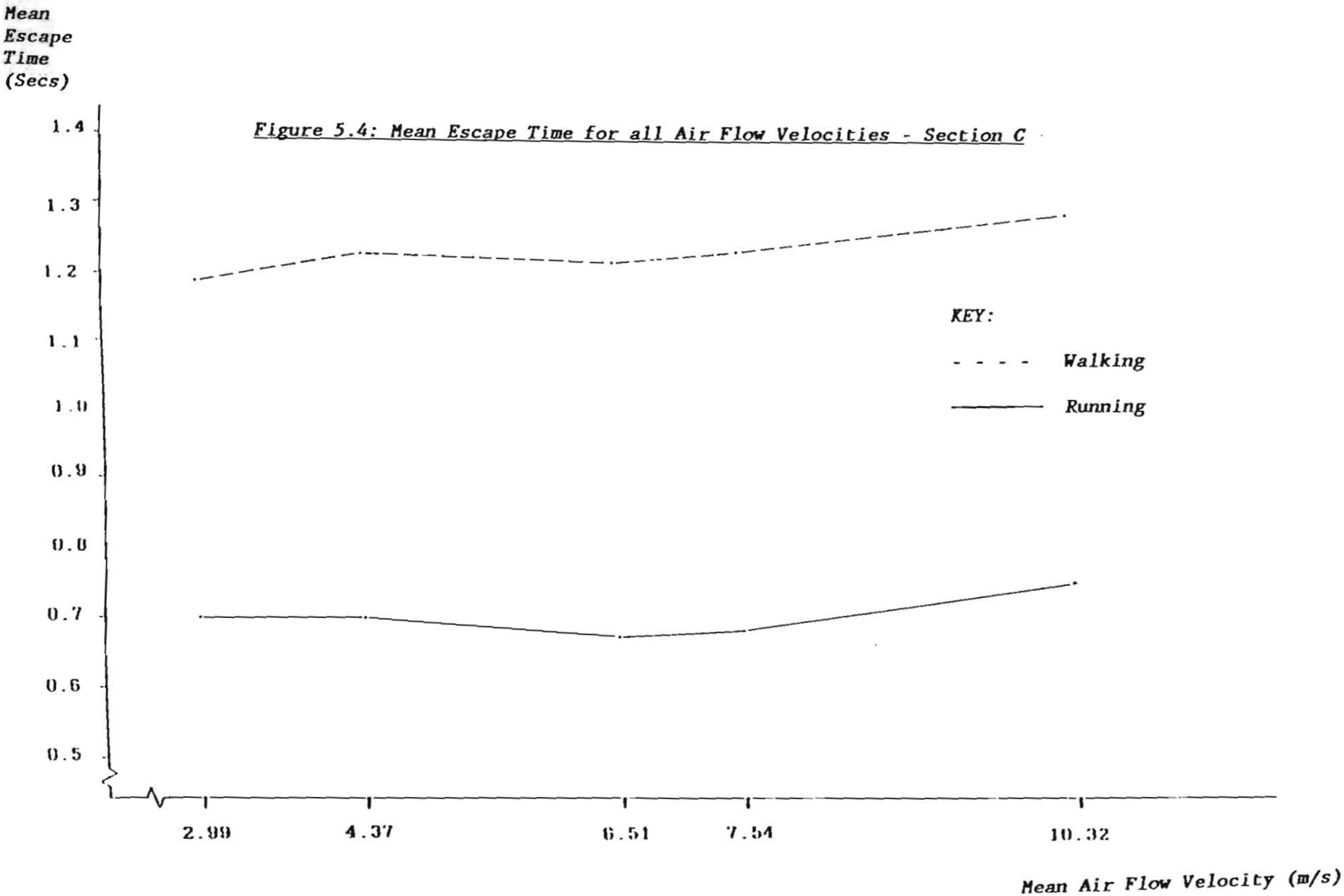

Figure 5.4: Mean Escape Time for all Air Flow Velocities - Section C

5.3 Influence of Air Flow Rates Upon Perceptions of Safety

In addition to the escape times, it was also of interest to determine how safe the volunteers felt whilst evacuating under each of the five flow rates. Table 5.6 gives the mean safety rating for each wind speed, with the distinction made between evacuations whilst walking, and those whilst running. It should be noted that a rating of '1' was labelled 'Not At All Safe' whilst 10 was 'completely safe'.

Table 5.6 Safety Ratings for Each Air Flow Rate

MEAN SAFETY RATING		
Air Flow Velocity	Walking (N=48)	Running (N=47)
1	9.521 (0.850)	9.553 (0.775)
2	9.500 (1.031)	9.553 (0.951)
3	9.188 (1.266)	9.170 (1.239)
4	9.125 (1.265)	8.979 (1.343)
5	8.458 (1.675)	8.468 (1.613)

For both types of evacuation (ie walking or running), an increase in wind speed was found to be accompanied by a decrease in perceived safety. In addition, the safety rating for these two forms of evacuation were extremely similar for each corresponding flow rate. Repeated measures ANOVAs were performed on the safety ratings for walking and running evacuations, the former producing an F-ratio of 19.77 (df=4,188, significant beyond the 0.1% level), the latter an F-ratio of 17.19 (df=4,188, significant beyond the 0.1% level). It was also felt that application of the Newman-Keuls paired comparison technique would be useful in this instance, and the results of these comparisons for walking and running evacuations are presented in Tables 5.7 and 5.8 respectively.

Table 5.7 Newman-Keuls Paired Comparisons - Safety Estimates Whilst Walking

AIR FLOW VELOCITY					
	5	4	3	2	1
5	-	**	**	**	**
4		-		*	*
3			-	*	*
2				-	
1					-
* - Significant at the 5% level ** - Significant at the 1% level					

Table 5.8 Newman-Keuls Paired Comparisons - Safety Estimates Whilst Running

AIR FLOW VELOCITY					
	5	4	3	2	1
5	-	**	**	**	**
4		-		**	**
3			-	*	*
2				-	
1					-
* - Significant at the 5% level ** - Significant at the 1% level					

The data from both tables suggest a similar pattern, with the greatest wind speed producing significantly (at the 1% level) lower perceived safety ratings than all other rates. In addition, ratings for the fourth and third rates were found to differ from those for the first and second rates at the 1% and 5% level respectively.

5.4 Effect of Air Flow Rates Upon Subjective Assessments of Progress, Clothing, Hair and Face and Eyes

5.4.1 Effect Upon Progress Along The Corridor

After each of the ten evacuations, participants were asked to indicate to what extent they felt that the air flow had affected their progress along each section of the corridor, with a score of '1' labelled 'Not At All', and '10' labelled 'Unable to Continue'. Table 5.9 shows the mean discrimination being made between the walking and running evacuations. In all cases, N=48.

Table 5.9 Mean Ratings of Subjective Assessment of Effect of Air Flow Rates Upon Progress along the Corridor

	WALKING			RUNNING		
	Sector			Sector		
Air Flow Velocity	A	B	C	A	B	C
1	1.729 (1.047)	1.521 (0.714)	1.604 (0.792)	1.854 (1.010)	1.646 (0.812)	1.688 (0.879)
2	1.833 (1.058)	1.813 (0.982)	1.729 (0.962)	1.854 (1.052)	1.771 (0.881)	1.771 (1.096)
3	2.729 (1.554)	2.688 (1.504)	2.667 (1.655)	2.833 (1.754)	2.500 (1.530)	2.604 (1.698)
4	3.229 (1.653)	3.208 (1.786)	3.167 (1.917)	3.208 (1.750)	3.229 (2.003)	3.146 (1.891)
5	4.063 (1.861)	4.083 (1.661)	4.042 (1.597)	4.271 (1.698)	4.229 (1.938)	4.292 (1.725)

The data from Table 5.9 reveal that the progress ratings gradually increased (indicating inhibited progress) with an increase in air flow rates for all conditions. Although the ratings for the three sectors are very similar for both walking and running evacuations, it can be seen that there was a slight tendency for volunteers to feel that the wind affected their progress in the first sector (A) more than in the other sectors. Progress in Sector (C) was the least affected during walking evacuations and showed no clear trend for running evacuations. In addition, ratings for running evacuations were generally marginally higher than for the equivalent walking evacuations.

5.4.2 Effect Upon Clothing, Hair and Face and Eyes

Volunteers were also asked to rate the effect of the wind upon their clothing, their hair and their face and eyes for each evacuation. Table 5.10 shows the mean ratings for each condition, with the information for walking and running evacuations being presented separately. It should be noted that the scales were identical to those described in the previous section.

Table 5.10 Mean Ratings for Subjective Assessments of Effect of Air Flow Upon Clothing, Hair and Face and Eyes

Air Flow Velocity	Walking			Running		
	Clothing (N=47)	Hair (N=48)	Face/ Eyes (N=48)	Clothing (N=48)	Hair (N=48)	Face/ Eyes (N=48)
1	2.021 (1.277)	2.167 (1.449)	1.813 (1.003)	1.979 (1.101)	2.187 (1.161)	1.854 (1.031)
2	2.213 (1.102)	2.354 (1.211)	1.958 (1.010)	2.250 (1.120)	2.333 (1.136)	1.958 (1.010)
3	2.936 (1.762)	3.167 (1.642)	2.917 (1.514)	2.917 (1.582)	3.063 (1.616)	2.604 (1.540)
4	3.511 (1.705)	3.750 (1.756)	3.438 (1.649)	3.521 (1.856)	3.750 (1.919)	3.438 (1.700)
5	4.511 (1.792)	4.604 (1.943)	4.146 (1.663)	4.646 (1.973)	4.729 (2.091)	4.250 (1.828)

The data in Table 5.10 also reveal a consistent trend indicating that an increase in wind speed was found to be reported to have had more effect upon clothing, hair and face and eyes. Of the three components studied, hair was consistently reported to be the most affected by all wind speeds, with this having less effect upon the face and eyes. However, it should be noted that the differences are slight. Additionally, there appears to be little difference between ratings for evacuations performed when walking and those when running.

5.5 Effect of Demographic Factors Upon Reduced Performance due to Increased Air Flow Rates

The majority of respondents (83.3% for walking evacuations, 89.6% for running evacuations) were found to escape from the corridor more quickly when the minimum wind speed was used than when the maximum rate was in operation. However, it was felt that the extent to which the maximum speed slowed down (or speeded up in the minority of cases) progress along the corridor could be investigated, particularly if 'susceptible' groups of people, ie those more prone to having their progress impeded by a higher wind speed, could be identified. This was achieved by calculating the ratio of the time taken to evacuate under the highest and under the lowest air flow rates for both walking and running evacuations. In addition, similar ratios were also calculated for perceptions of safety ratings and the perceived effect of wind speed on progress ratings. The ratios were then compared (using T-tests) on a variety of demographic variables, such as age, sex, wearing of contact lenses, wearing of glasses, wearing of high-heeled shoes, wearing of loose-fitting clothes and wearing of outdoor coats.

The results produced only one significant pair of tests, in which the ratios of the ratings for subjective effect of the air flow at the maximum and at the minimum speeds were compared for volunteers wearing loose-fitting clothes and those wearing tight-fitting clothes. The test for walking evacuations produced a t-value of 2.45 (df=20.38, significant at the 5% level) whilst the equivalent test for running evacuations produced a t-value of 2.18 (df=16.75, significant at the 5% level), both indicating that people wearing loose-fitting clothing were less likely to be impeded by a higher wind speed. No significant relationships due to age, sex, wearing of contact lenses or glasses, wearing of high-heeled shoes and outdoor clothes factors were noted.

6. DISCUSSION

6.1 Discussion of Experimental Procedure

The test facility and procedure used for this preliminary investigation were found to work extremely well and few problems were encountered. Perhaps the main procedural concern was over the fact that relatively few (27.1%) volunteers arrived wearing outdoor clothing, despite the emphasis that had been placed on this when recruiting. Nevertheless, it was found that the presence or absence of such outdoor clothing had no effect upon the extent to which the maximum wind speed impeded progress, and therefore it would appear that this was not a major problem. However, it is suggested that this would be more effectively controlled in future research if outdoor clothing was provided by the research team rather than by the volunteers.

6.2 Selection of an Optimal Air Flow Rate

Although the time differences between the slowest and fastest evacuations were not great, it was found that a significant proportion of the variance in escape time, for both walking and running evacuations, was due to the experimental conditions (ie the different air flow rates) rather than to individual differences. However, it should be noted that the task the volunteers had to perform was a relatively brief one, and it is likely that in a real-life situation, escapees would have to cover greater distances to reach the exits. In these circumstances, it could be seconds, rather than fractions of seconds, that are saved, possibly greatly increasing chances of survival.

It was reported in Section 5.2.1 that for walking evacuations the highest wind speed (5) was the only one that produced significantly different escape times to the other four speeds for the whole task. This implies that increasing the air flow rate up to the level of the fourth speed does not impede people's progress whilst walking, and therefore that the optimal wind speed for 'controlled' evacuations is somewhere between the fourth and fifth air flow rates (ie between 7.54 and 10.32 metres per second). Analysis of the sub-sections of the corridor largely confirmed this finding, although an additional significant difference between the fourth and first speeds was found for Sector B (the straight section of the corridor). Therefore, it may be argued that a more conservative estimate would be to select a criterion somewhere between the third and fourth flow rates (6.51 and 7.54 metres per second), particularly if it is anticipated that escape routes would incorporate long sections similar to Sector B.

The differences in escape times when volunteers were instructed to run conformed to a similar pattern, and total escape times for the fifth and fourth air flow rates were found to significantly differ from each other and from the remaining flow rates. This implies that the optimal air flow rate when people are evacuating in a, presumably, more life-threatening situation is somewhere between the third and fourth flow rates, ie between 6.51 and 7.54 metres per second. The equivalent results for the individual sectors of the corridor revealed a similar pattern, although additional significant differences (at the 5% level) were found to exist between the third and both the first and second flow rates for Sector B. However, for the sector including the aperture (C), only the highest flow rate was found to significantly differ from the remaining rates. As the current recommendation for air flow velocities through such apertures is 3 metres per second the comparisons of escape times for volunteers passing through the aperture whilst running suggest that this could be increased to somewhere between 7.54 and 10.32 metres per second without significantly reducing people's ability to egress.

An additional consideration for selection of an optimum air flow rate is the perceived effect that the wind has upon people, particularly with reference to their perceived level of safety. Clearly, it would be detrimental to rapid evacuations if an air flow rate that was felt to be more unsafe was adopted. The results were consistent for walking and running evacuations, and suggested that all air flow rates greater than the second (4.37 metres per second) were perceived as being significantly more unsafe than the second and first flow rates. However, it should be noted that mean safety ratings for the most severe wind speed, for both walking and running evacuations, were in the region of 8.5 on a scale from 1 ('Not At All Safe') to 10 ('Completely Safe') and it is not felt that the perceived level of safety at the highest air flow rate would be sufficient to prevent anyone from continuing on safety grounds alone.

Selection of an optimum air flow rate would have to account for all possible types of evacuation, whether orderly (walking) or under more life-threatening circumstances (running). On the basis of the evidence presented here, the most suitable air flow rate for evacuating individuals is in the region of 6.51 to 7.54 metres per second (ie between the third and fourth rates used in this study), although the evidence suggests that if consideration is only given to progress through an exit aperture, a higher criterion (between 7.54 and 10.32 metres per second) could be adopted.

6.3 Subjective Effects of Air Flow on Other Factors

In their response to the items requesting ratings for the effect of the wind upon their progress along the corridor, the volunteers demonstrated that they were able to distinguish between the intensity of the five rates used, the means indicating that they tended to rate higher wind speeds as having more of an effect. It may be remembered that the actual escape times did not strictly conform to this pattern, and this appears to suggest that participants felt that some air flow rates, particularly '2' and '3' had more of an effect on their progress than was shown from their mean evacuation times. It is interesting to note that for these ratings, and also for those indicating the effect of the air flow upon clothing, hair face and eyes, mean ratings remained in the lower half of the scale, and therefore did not approach an 'Unable to Continue' rating.

6.4 Recommendations for Further Research

The research has so far only included the study of individuals of certain demographic groups, mainly defined by age. Although there were not found to be any differences due to demographic factors in the extent to which the maximum air flow rate affected escape times or feelings of safety, the technique adopted may be useful in targeting vulnerable subgroups of the population. Indeed, it is felt that in order to obtain a more complete picture of individual evacuation behaviours, it would be advantageous to investigate the effects of air flow rates upon people not included in this initial investigation. It is suggested that the study presented in this report be replicated using elderly people and children. An additional concern in any evacuation procedure is the ability of people with restricted mobility, such as those that are wheelchair-bound, to evacuate, and it is felt that such people could also be incorporated into future research designs.

In the research described in this report consideration was only given to the effects of air flow rates upon the ability of individuals to evacuate a shopping mall. It is suggested that in a true emergency situation, people are more likely to evacuate in groups rather than individually. This may have implications for escape behaviours, as it has been shown that confined spaces with higher densities of people tend to produce higher levels of individual arousal. It is suggested that this increase in arousal may affect how people behave in an emergency situation (Saegert, 1974). There have also been suggestions (Pauls, 1974) that people may require more personal space when confronted with emergency situations. It is therefore recommended that a further stage of the research should aim to replicate the study reported herein using groups of people evacuating from the corridor.

One of the limitations of this research has been that it has not involved the simulation of all of the circumstances that would arise in a real evacuation from a shopping mall. Although there is evidence to suggest that panic reactions are quite rare (eg Canter, Breaux and Sime, 1978) any recommendations that are to be made should account for circumstances which may arise if some people do panic. Although panic cannot be induced in volunteers in an experimental setting, it is suggested that it may be possible to simulate such behaviour to some extent by introducing a competitive element into the experimental design. For example, it has been found (Muir, Marrison and Evans, 1989) that the introduction of a bonus scheme to induce competitive behaviour in people evacuating from a stationary aircraft did indeed produce the motivated behaviour seen in some of the accidents without endangering any of the participants. Using small groups of people, and providing bonus payments to a proportion of them, it may be possible to investigate the effects of differential air flow rates in more 'realistic' circumstances.

When asked to note any additional factors that had impeded their progress some of the volunteers reported slipping on the floor of the corridor. Indeed, this was the most commonly cited response, suggested by 4 (8.3%) of the volunteers. This implied that the type of floor surface used, and the type of shoes worn by escapees, may have an effect upon escape times, and it is suggested that further research may be performed to investigate this factor.

7. CONCLUSIONS

1. When evacuating from a simulated shopping precinct, the progress of volunteers when walking was significantly impeded by the highest air flow rate investigated (10.32 metres per second). The volunteers were found to perceive the three highest wind speeds (from 6.51 to 10.32 metres per second) to be significantly more unsafe than the remaining two which were tested.

2. When evacuating whilst running volunteers were asked to run along the length of the corridor, the two faster air flow rates (7.54 and 10.32 metres per second) were found to significantly impede volunteers. In addition, volunteers rated the three highest flow rates (from 6.51 to 10.32 metres per second) as being significantly more unsafe.

3. Volunteers were found to be able to distinguish between the different air flow rates in terms of their perceived ability to progress along the corridor, although this did not completely correspond to these escape times.

4. No differential effects were found to be due to demographic or clothing factors, other than the fact that volunteers wearing loose-fitting clothing were found to be less likely to be impeded by a higher air flow rate than those wearing tight-fitting clothing

5. Several recommendations for further research were made. These include the additional investigation of the effects of air flow rates upon younger and older members of the population, as well as upon people with restricted mobility and upon groups of people evacuating at the same time. Additional suggestions concerned the possibility of introducing competitive behaviour to more closely resemble an emergency situation and the study of the effect of alternative floor surfaces and shoe-types upon evacuation rates.

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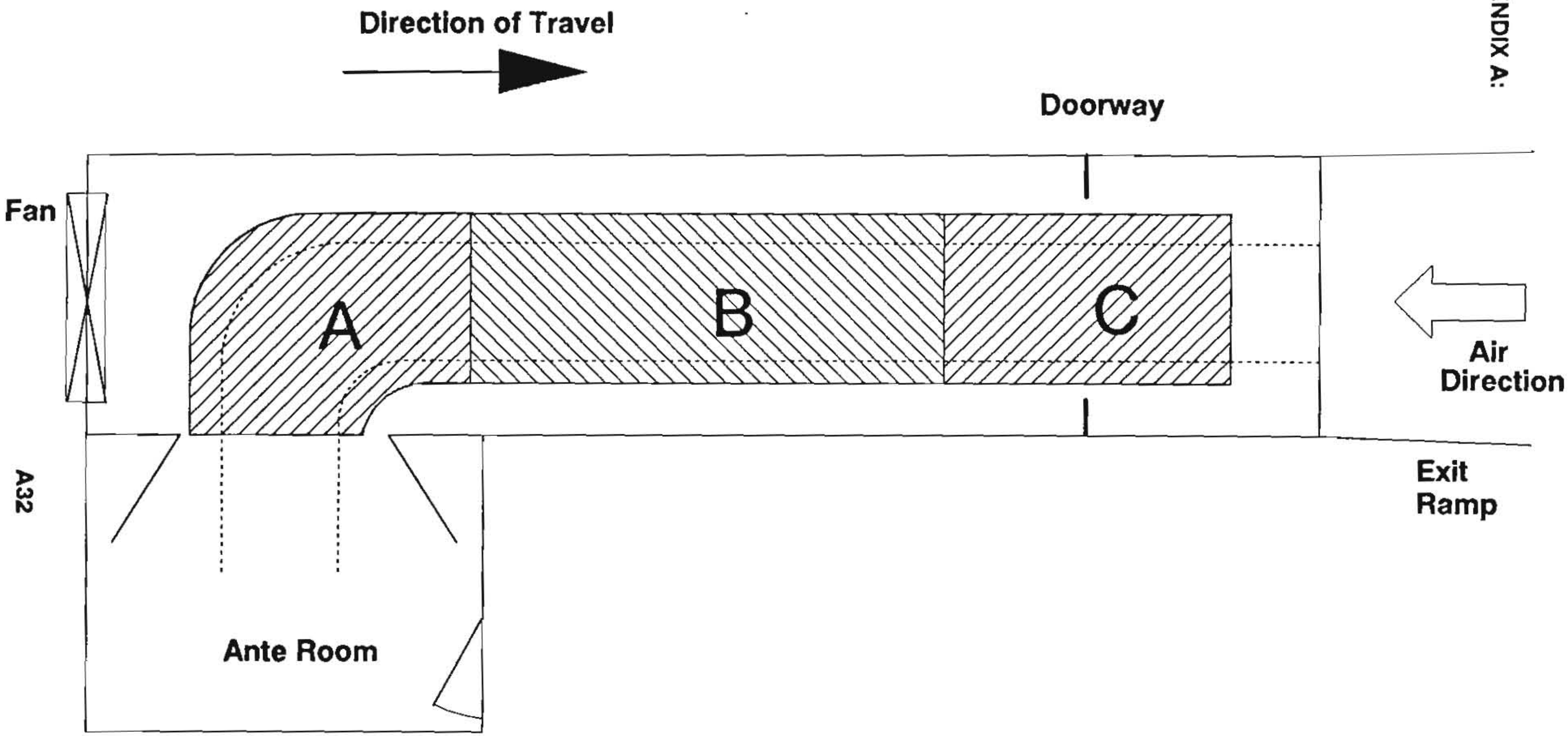


Figure A.1 : Diagram of the Test Facility Showing the 3 Sub-sections

APPENDIX B:

MEDICAL INFORMATION - SHOPPING PRECINCT EXPERIMENTS

The evacuations that you are about to undertake will involve some degree of physical exertion, and you are requested to withdraw if you have suffered, or are currently suffering, from any of the following conditions:

Severe anxiety:
Fear of enclosed spaces:
Fainting attacks, blackouts or uncontrolled epilepsy:
Heart disease or ankle swelling:
Active asthma, general breathing difficulties or chest trouble:
Active asthma, general breathing difficulties or chest trouble:
Deafness:
Current infections or other significant illness:

In addition, those women who are, or who suspect they may be, pregnant should not agree to participate.

Participants should note that there are trained medical staff, fully informed about this series of tests, on duty at the Institute's Medical Centre at all times during the course of the tests.

Please complete the following details:

AGE: __________ **SEX:** __________

HEIGHT: __________ **APPROXIMATE WEIGHT:** __________

Additionally, do you wear contact lenses? Yes [ ]

No [ ]

Now please sign the following declaration:

I, ______________________________, have read and understood the information provided and believe that I am fit enough to cope with the work involved with the evacuations I am about to undertake. All the information I have provided is correct:

Signature: ________________________________ **Date:** ______

APPENDIX B:

QUESTIONNAIRE - SHOPPING PRECINCT EVACUATIONS

Volunteer Number : __________ Evacuation: __________

(1) To what extent did the air flow affect your progress along the corridor as you turned from the side-room into the main section of the corridor - Section 1 in the diagram. Please circle the appropriate number on the following scale:

Not At All — Unable to Continue

1------2------3------4------5------6------7------8------9------10

(2) To what extent did the air flow affect your ability to maintain your course along the main section of the corridor - Section 2 in the diagram. Please circle the appropriate number on the following scale:

Not At All — Unable to Continue

1------2------3------4------5------6------7------8------9------10

(3) To what extent did the air flow affect your ability to maintain your course as you passed through the doorway near the end of the corridor - Section 3 in the diagram. Please circle the appropriate number on the following scale:

Not At All — Unable to Continue

1------2------3------4------5------6------7------8------9------10

(4) In addition, what extend did the air flow throughout the corridor affect your:

a) Clothing:

Not At All — Extensively

1------2------3------4------5------6------7------8------9------10

b) Hair:

Not At All — Extensively

1------2------3------4------5------6------7------8------9------10

c) Face & Eyes:

Not At All — Extensively

1------2------3------4------5------6------7------8------9------10

APPENDIX B:

(5) How *safe* did you feel whilst escaping from the corridor?

Not At All ... Completely Safe

1------2------3------4------5------6------7------8------9------10

(6) Did anything else impede your progress along the corridor?

YES [ ] NO [ ]

If so, what was it? ______________________________

Figure C.1

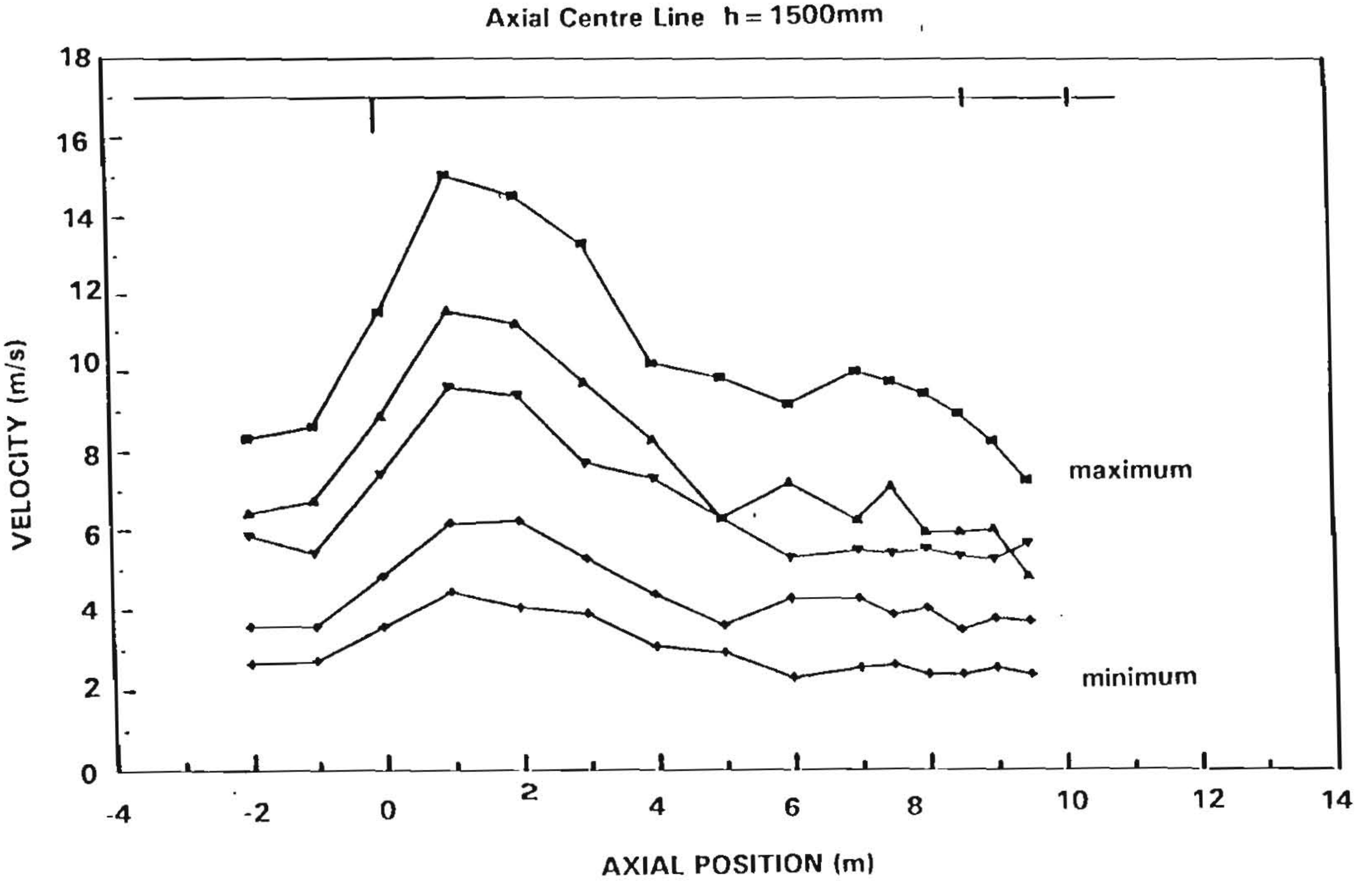

Axial Centre Line h = 1500mm
VELOCITY (m/s)
18
16
14
12
10
8
6
4
2
0
-4
-2
0
2
4
6
8
10
12
14
AXIAL POSITION (m)
maximum
minimum

Figure C.2

NON-DIMENSIONALISED VELOCITY PROFILE

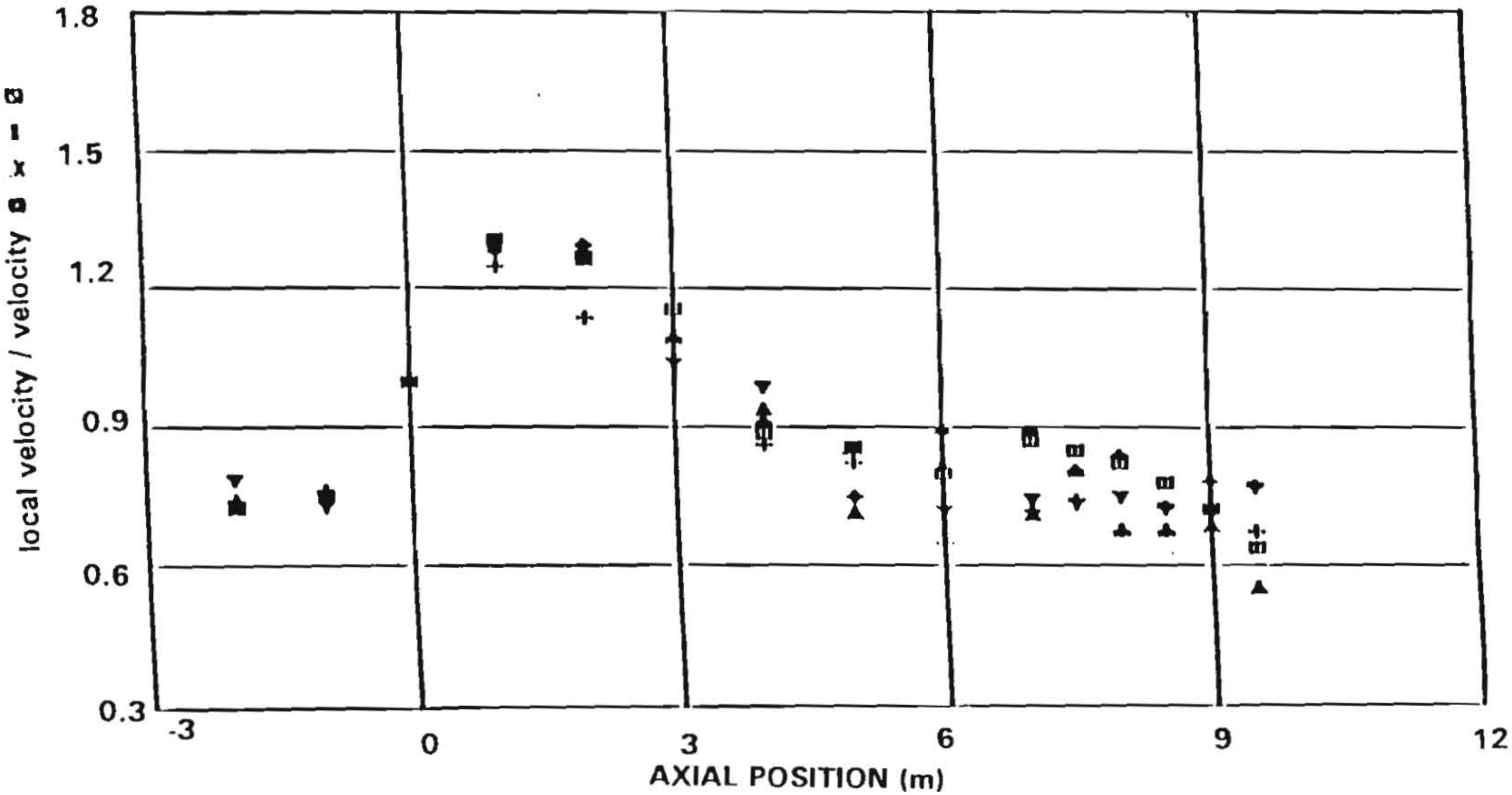


Figure C.3 :

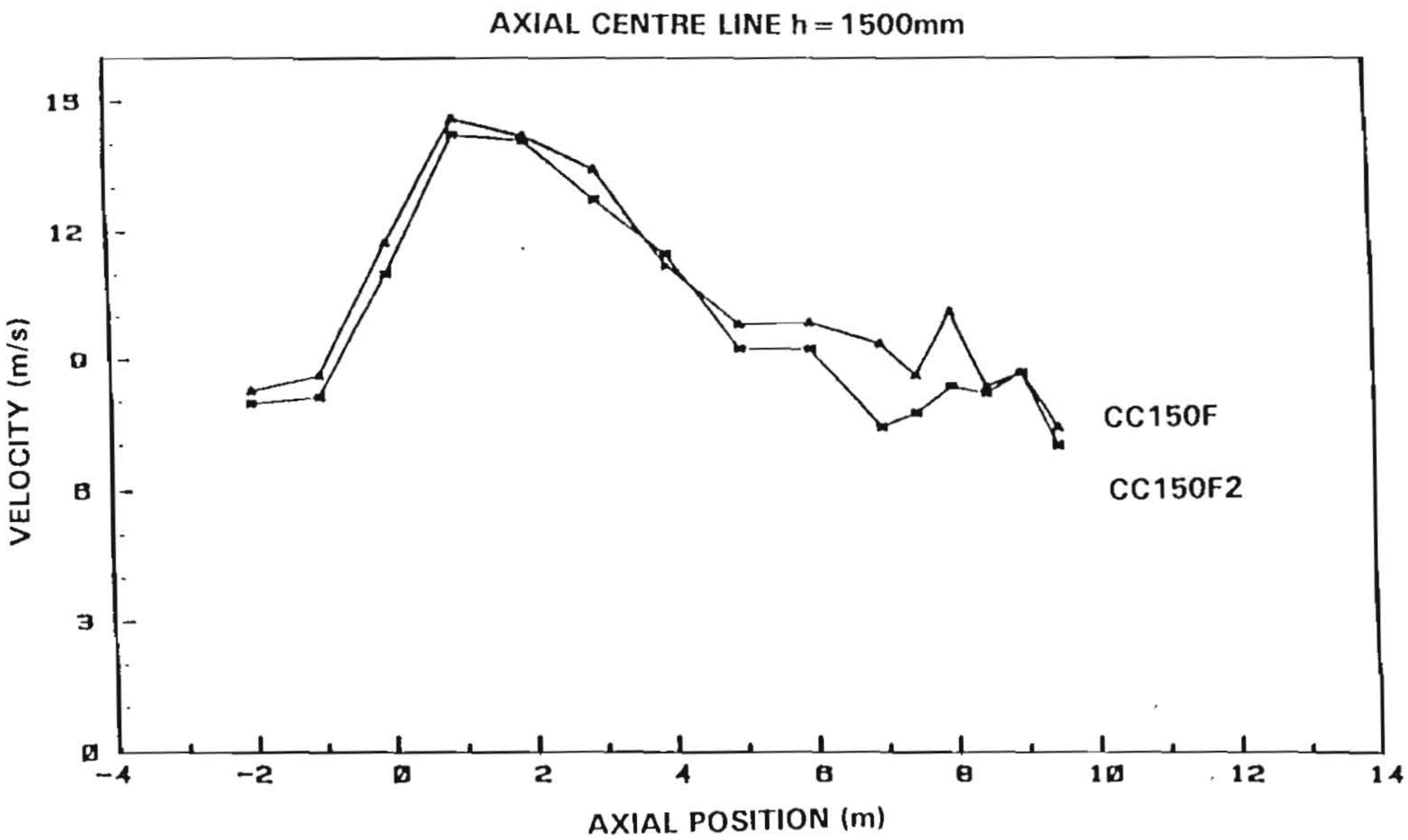

AXIAL CENTRE LINE h=1500mm
VELOCITY (m/s)
15
12
9
6
3
Ø
-4
-2
Ø
2
4
6
8
1Ø
12
14
AXIAL POSITION (m)
CC150F
CC150F2

Figure C.4

AXIAL CENTRE LINE h = 1250mm

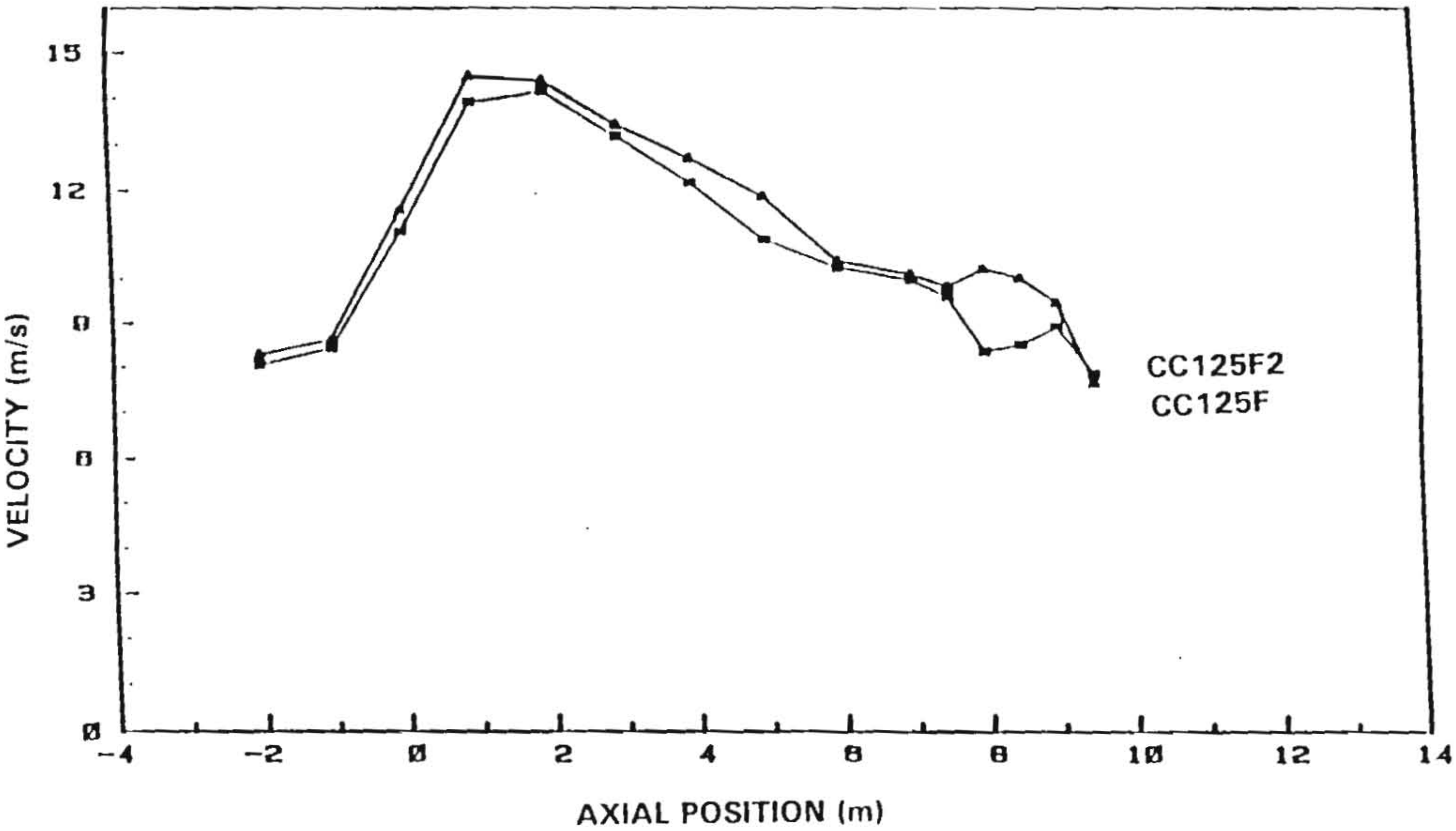


Figure C.5

AXIAL CENTRE LINE h = 1750mm

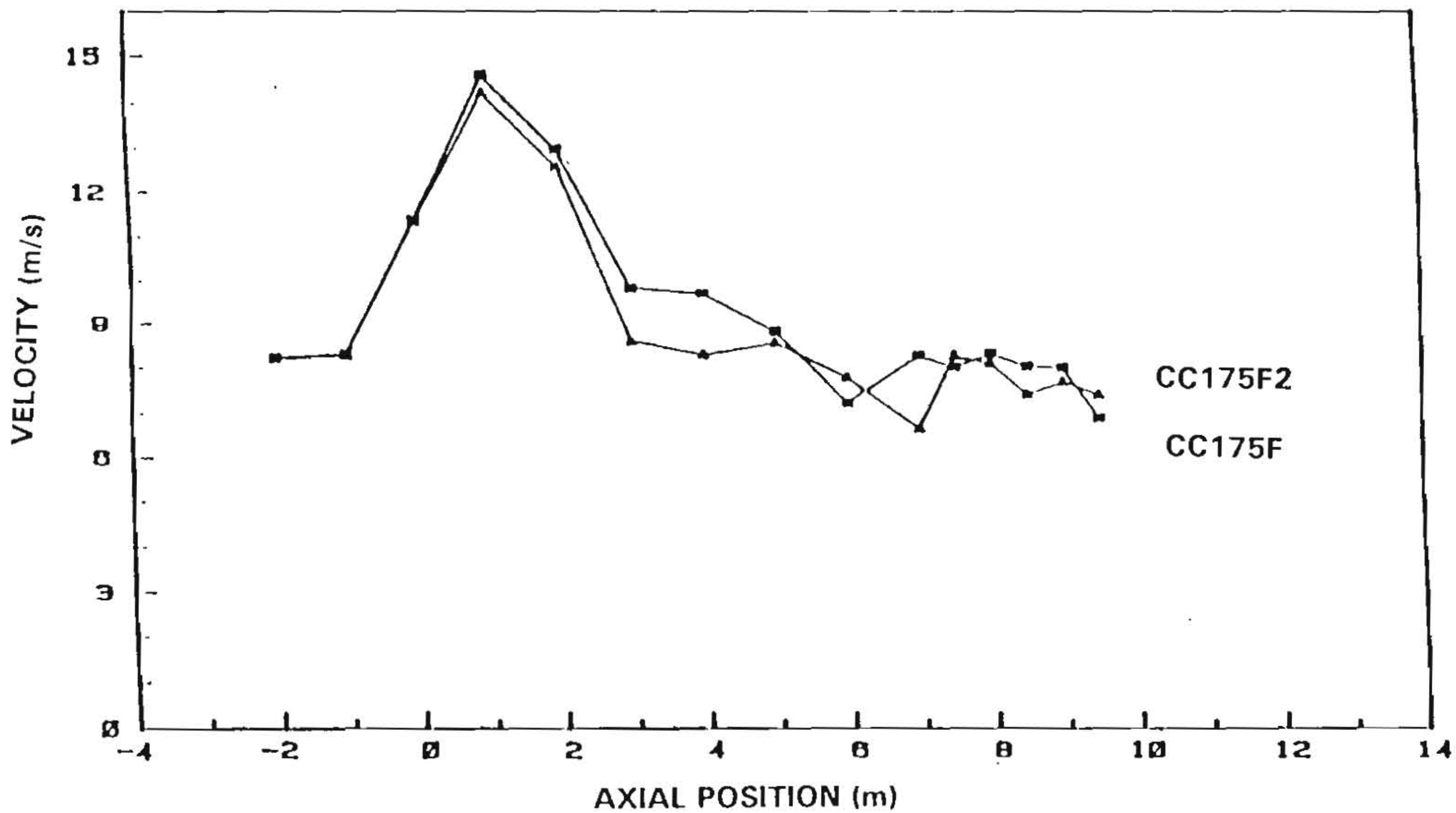
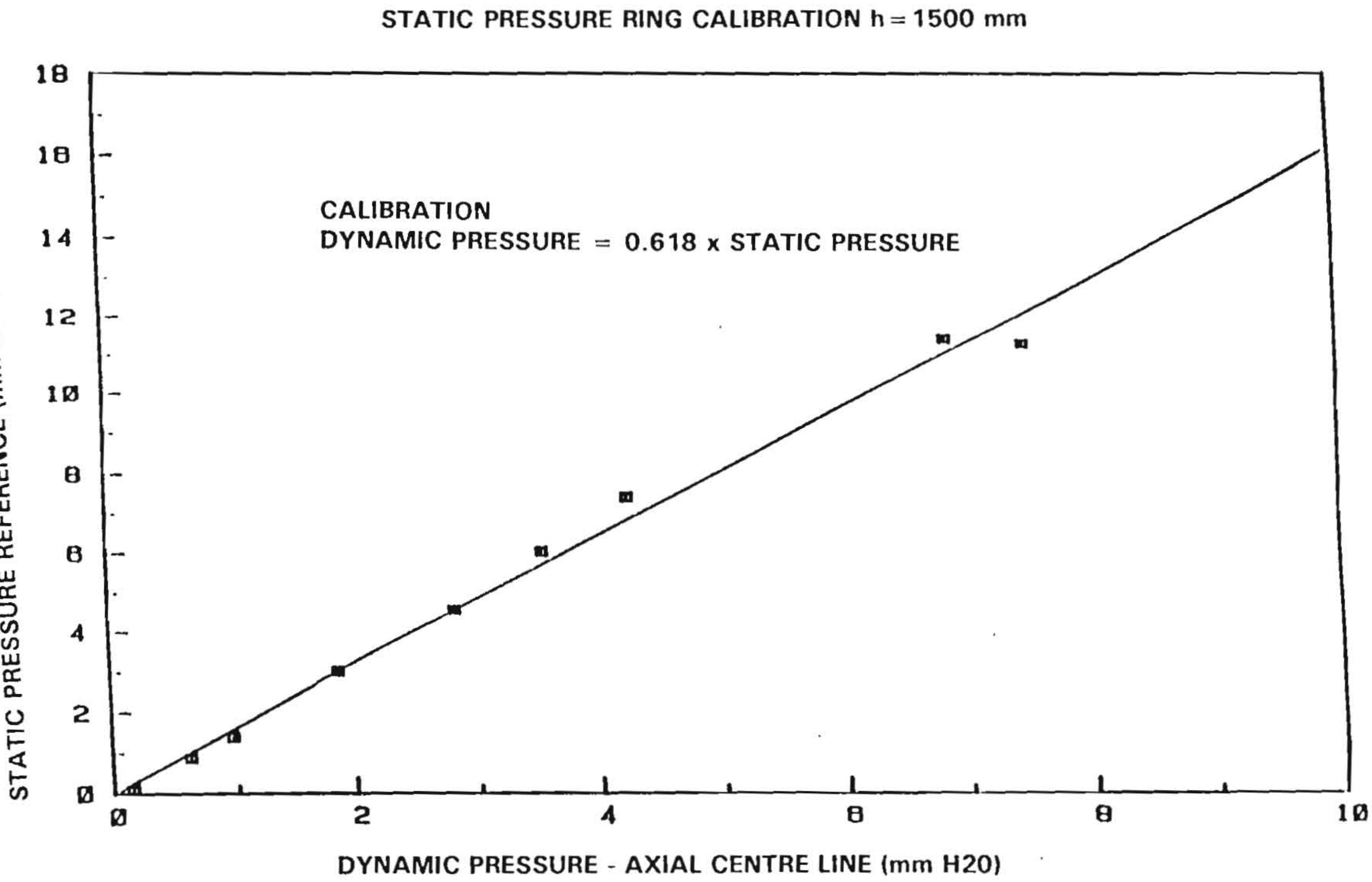


Figure C.6


STATIC PRESSURE RING CALIBRATION h = 1500 mm
CALIBRATION
DYNAMIC PRESSURE = 0.618 x STATIC PRESSURE
STATIC PRESSURE REFERENCE (mm H20)
DYNAMIC PRESSURE - AXIAL CENTRE LINE (mm H20)
18
16
14
12
10
8
6
4
2
0
0
2
4
6
8
10

APPENDIX D: Summary Tables for Newman-Keuls Paired Comparisons

Tables D.1 and D.2 (below) give details of the Newman-Keuls paired comparison tests for evacuations whilst walking for Sectors B and C respectively.

Table D.1: Newman-Keuls Paired Comparisons for Sector B- Walking

	AIR FLOW VELOCITY				
	1	3	2	4	5
1	-			*	**
3		-			**
2			-		**
4				-	**
5					-

* - Significant at the 5% level
** - Significant at the 1% level

Table D.2: Newman-Keuls Paired Comparisons for Sector C - Walking

	AIR FLOW VELOCITY				
	1	3	2	4	5
1	-				*
3		-			
2			-		
4				-	
5					-

* - Significant at the 5% level
** - Significant at the 1% level

Tables D.3, D.4 and D.5 (below) give details of the Newman-Keuls paired comparison tests for evacuations whilst running for Sectors A, B and C respectively.

Table D.3: Newman-Keuls Paired Comparisons for Sector A - Running

	AIR FLOW VELOCITY				
	2	3	1	4	5
2	-				*
3		-			
1			-	*	*
4				-	
5					-
* - Significant at the 5% level ** - Significant at the 1% level					

Table D.4: Newman-Keuls Paired Comparisons for Sector B - Running

	AIR FLOW VELOCITY				
	2	1	3	4	5
2	-		*	**	**
3		-	*	**	**
1			-		**
4				-	**
5					-
* - Significant at the 5% level ** - Significant at the 1% level					

Table D.5: Newman-Keuls Paired Comparisons for Sector C - Running

	AIR FLOW VELOCITY				
	3	4	2	1	5
3	-				**
4		-			*
2			-		*
1				-	*
5					-
* - Significant at the 5% level ** - Significant at the 1% level					

ANNEX B : The Influence of Wind Velocity on the Ability of Members of the Public to Evacuate through the Exit of a Shopping Precinct : Further Tests involving additional Individuals and Groups

THE INFLUENCE OF WIND VELOCITY ON THE ABILITY OF MEMBERS OF THE PUBLIC TO EVACUATE THROUGH THE EXIT OF A SHOPPING PRECINCT: FURTHER TESTS INVOLVING ADDITIONAL INDIVIDUALS AND GROUPS

REPORT PREPARED FOR THE HOME OFFICE
FIRE EXPERIMENTAL UNIT, MARCH 1992

D M BOTTOMLEY Msc
KEVIN GARRY Phd
HELEN MUIR Phd
P J FENNELL

College of Aeronautics
Cranfield Institute of Technology
Cranfield
Bedfordshire MK43 0AL

ABSTRACT

The rate at which smoke can be extracted from shopping malls is governed by the speed at which fresh air can enter the building to replace the extracted air. A Building Research Establishment regulation dictates that the air flow rates produced as a result of this process should not exceed three metres per second. The long-term aim of this research programme is to establish the maximum air flow rate that can be tolerated without detracting from people's ability to evacuate from a shopping mall as quickly as possible.

The initial phase of the research (Bottomley, Muir and Garry, 1991) studied the behaviour of adults aged between 20 and 54 escaping individually from a shopping mall. It was concluded that air flow rates the progress of these individuals was impeded by all air flow rates exceeding 6.51 metres per second.

The objective of the research described in this report was to expand upon the findings from the original research programme studying the effects of air flow upon people from a greater range of the population and also in groups, using the same research facility and methodology. The types of people included at this stage were: adults accompanied by infants in pushchairs; those aged over 60 years; 12 to 14 year old children; wheelchair pushers; and adults with some form of restricted mobility. In addition, the evacuation of people in small groups was also investigated to resemble more closely a likely real-life emergency scenario.

The results of both the individual and group tests largely served to confirm the initial findings. However, in several isolated examples, the third highest wind velocity (6.51 metres per second) was also found to hinder progress. In addition, although some types of individual participants reported feeling significantly more unsafe when evacuating in each of the two higher wind speeds (7.54 and 10.32 metres per second), the differences were not felt to be sufficient to cause concern.

CONTENTS Page

1. BACKGROUND

A Building Research Establishment recommendation (BRE, 1990) states that modern shopping precincts should be installed with extraction fans to enable smoke to be removed from the shopping complex in the event of a fire. These fans are located in the ceilings of the precincts and, when in operation, air is drawn in through exit doors to replace that extracted by the fans. This may result in localised air flows in the corridors of the shopping precincts. The current recommendation states that these air flow rates through exits should not exceed 3 metres per second. However, it would clearly be advantageous if this recommended air flow rate could be increased as this would enable smoke to be extracted more rapidly without inhibiting the ability of shoppers to egress the building. This also has implications for the design of new shopping malls as the increased air flow rates would necessitate the incorporation of fewer inlet vents in the building.

In July 1990, the Fire Experimental Unit of the Home Office approached the College of Aeronautics with a view to conducting research into this area, particularly in ascertaining an optimal wind velocity. During the early part of 1991, a simulated shopping precinct exit corridor containing a large centrifugal extraction fan to produce the wind was constructed at Cranfield. An initial series of tests was performed using members of the public aged between 20 and 54 (Bottomley, Muir and Garry, 1991) and was designed to arrive at an optimal wind velocity for individuals evacuating in two alternative scenarios: with volunteers walking to escape (designed to simulate a more controlled evacuation); and running to escape (to represent a more life-threatening situation). These initial tests on individuals showed that the test facility and procedure could be used effectively to investigate the behaviour of members of the public evacuating a shopping precinct under a variety of air flow rates.

The data obtained from the first phase of the research suggested that, of the five alternative wind velocities investigated, the highest (10.32 metres per second) significantly impeded the progress of volunteers when walking to escape whilst the two highest speeds (7.54 and 10.32 metres per second) significantly impeded volunteers when they were asked to run to evacuate. In addition, volunteers rated the three higher wind rates (6.51, 7.54 and 10.32 metres per second) as being significantly more unsafe than the remaining two. On the basis of these initial tests, it was concluded that air flow rates above 6.51 metres per second impeded progress when the whole task was considered. However, it was suggested that, if consideration is given merely to the effect of the wind upon people's ability to negotiate the exit rather than the whole corridor, only the highest wind speed significantly impeded progress.

On the basis of these initial stages of the research, several recommendations were made concerning non-restricting air flow rates. However, it was recommended that further research be conducted before any firm conclusions could be drawn. Among the main recommendations was the investigation of the effects of the various air flow rates upon the evacuation rates and behaviour of regular shopping-centre users not covered by the initial phase of the research. In addition, it was recognised that a genuine emergency situation would be unlikely to involve individual escapees and it was felt that evacuations using groups of people should be performed to more closely resemble such an eventuality.

2. OBJECTIVES

Since the project is an extension of the initial phase of the programme, the primary objective of the research remains unchanged. This is the determination of the effect of differing air flow rates upon the ability of people belonging to a number of demographic groupings, as well as groups of volunteers, to escape from a shopping precinct. The long-term aim is the establishment of a criteria for the maximum air flow rate through exit apertures at which it can be demonstrated that the progress of any evacuees will not be impeded.

As noted in the previous section, this second phase of the research was designed to investigate the effects of various wind speeds upon individuals not included in the original study. It was suggested that these should include representatives of each of the following groups of regular shopping centre users:

(a) Adults accompanied by young children in pushchairs;

(b) Adults over 60 years;

(c) Children aged between 12 and 14 years;

(d) Wheelchair pushers and occupants;

(e) Adults with some form of mobility restriction.

In addition, it was intended that the effects of the air flow rates upon the evacuation of groups of people be investigated and two distinct scenarios were highlighted:

(f) Groups evacuating as a unit, designed to represent an emergency situation involving a high density of people;

(g) Groups evacuating with a greater degree of dispersion, designed to represent a less dense evacuation scenario.

Each classification will be defined and receive further explanation in the following sections.

As with the previous series of tests, these tests were also designed to assess the effects of the air flow rates upon more subjective concerns, such as the volunteers' perceived level of safety, in addition to the effects upon evacuation rates.

3. METHODOLOGY FOR INDIVIDUAL TESTS

3.1 Experimental design - Individual tests

To retain consistency with the first phase of this research programme, the five air flow rates used in the studies reported in this paper were identical to those used previously (see Bottomley, Muir and Garry, 1991). These were:

1	2.99 metres per second;
2	4.37 metres per second;
3	6.51 metres per second;
4	7.54 metres per second;
5	10.32 metres per second;

As with the previous tests, volunteers were asked to progress along the length of the corridor, against the air flow. However, unlike those previous tests, it was decided that each volunteer would only be required to evacuate under each wind speed on a single occasion rather than both walking as quickly as possible and running under each speed. This procedural change was introduced primarily to overcome concerns that many of the volunteers would be placed at risk if they were to be asked to perform the tests as before. For example, it was felt that it would be unwise to ask older people and those with restricted mobility to run to evacuate from the corridor. It was also noted that in a true emergency, many shoppers falling into these classes may be physically unable to exit at anything more than a walking pace. However, this would not be true of the 12-14 year olds, for instance, and it was felt that a compromise instruction that accounted for a whole range of behaviours was necessary. Therefore, rather than simply requiring that volunteers walk as quickly as possible to evacuate, they were asked to *escape as quickly as they felt comfortable*. Although this allowed for a wide range of interpretations, this was taken into account by the method of data analysis used, in which variations in escape times for individuals over the five experimental conditions, rather than between these individuals, were considered.

Volunteers were also presented with a brief questionnaire after each of the five main test runs. This was identical to that used in the first phase of the research and contained questions on the perceived effect of the wind on the volunteers' progress, and also on their face, eyes, hair and clothing. An additional question required volunteers to estimate how safe they had felt during the course of their escape along the corridor.

The order which volunteers performed the tests was randomly varied to allow for order, learning and fatigue effects to be taken into account. Time and availability restrictions often dictated that some sessions involved two volunteers performing identical sequences of wind speeds. In these cases, the evacuations were carried out sequentially with one person performing the evacuation whilst the other completed the questionnaire relating to the previous evacuation.

3.2 Equipment - Individual Tests

The research facility (see plan in Appendix A) constructed for the initial series of evacuation tests (Bottomley, Muir and Garry, 1991) was used. The only modification to the original design was the reduction of the aperture width from 2.1 to 1.8 metres. Analysis of calibrations performed after this modification showed that the aerodynamic characteristics of the corridor remained constant within the limits of the experimental technique. However, additional calibrations needed to be performed to assess the effects of the presence of a group of people in the exit aperture upon the air flow rates. These will be described in Section 5 of this report. For safety purposes, all participants were requested to wear ear protectors, provided by the researchers, throughout the tests.

3.3 Volunteers - Individual Tests

All volunteers were members of the public recruited through local radio and posters placed in the locality and around the Cranfield Institute of Technology campus and each was paid an attendance fee of £10. All were asked to arrive wearing the type of clothing they would normally expect to use when shopping in a mall. Prior to participation in the test programme, each volunteer was required to complete a brief medical consent form indicating that they did not satisfy any of the criteria which the Applied Psychology Unit's Medical Adviser felt should preclude them from participation. A copy of this form may be found by referring to Appendix A.

It was intended to recruit 12 volunteers for each of the five classes of individuals to be tested. These classes of people were identified as classes of regular shopping centre users and it was felt that any recommendations made as a result of this research should account for the full range of people and that non-consideration of any of these groups would minimise the applicability of the overall programme of research. The classifications were defined as in each of the following sections.

3.3.1 Adults Accompanied by Young Children in a Pushchair

One of the primary concerns with this group of participants was that by allowing adults to provide their own push-chairs, a wide range of different push-chair designs would be used in the tests. It was felt that the different degrees of mobility, stability and weight would introduce too many additional variables into the equation and render any results unreliable. Therefore, a standard push-chair was used throughout the trials for this group of respondents. The particular model was selected on the basis of its lightweight design (so as to maximise the chances of a pronounced effect caused by the wind velocities) and its' ability to accommodate children of as wide an age range as possible. Nevertheless, it was necessary to restrict the age range of the children tested in this group to between 1 and 5 years.

No restrictions were made concerning the adult participants in this group other than the requirement that the adult must be an experienced push-chair user.

3.3.2 Adults Aged Over 60 years

Participants in this section could be of either sex and had to be aged over 60. No other restrictions were felt to be necessary as any potential participants with health problems were screened out during the recruitment phase.

3.3.3 Children Aged Between 12 and 14

This age-band was included in the programme to represent the stage at which children begin to use facilities such as shopping centres without the supervision of adults. All sixteen children within this age range were recruited from a local school.

3.3.4 Wheelchair Pushers

Although it would have been preferable to have included people genuinely restricted to a wheelchair in this series of tests, the facilities at the Institute were deemed to be unsuitable for people with such disabilities. It was therefore decided to restrict the tests to those people who are experienced wheelchair pushers, either as a consequence of having a friend or relative confined to a wheelchair or through their employment. Indeed, a brief observation of a local shopping centre revealed that the vast majority (over 90%) of wheelchair-bound people were pushed by another person rather than being self-propelled. It was argued that in a true emergency situation it would be these pushers that would be responsible for evacuating in the vast majority of cases and therefore that these tests would be more effective if this group of people were studied.

In order to retain a degree of consistency throughout these tests, all volunteers pushed the same wheelchair on all test runs.1 In addition, a member of the research tem sat in the wheelchair on test runs to ensure that the task performed by the wheelchair pushers resembled the true situation as accurately as possible.

3.3.5 Adults with Mobility Restrictions

This category was chosen to represent people with a wide range of mobility problems. Volunteers were included in this group if they suffered from a condition which prevented them from moving as efficiently as would otherwise be expected, either as a consequence of illness or an accident. Therefore, volunteers in this category ranged from those restricted by severe back injury but not requiring any form of stabilising device to those requiring the use of methods of support such as a walking stick or a walking frame.

3.4 Data Collection - Individual Tests

The progress of all volunteers along the corridor was monitored using four video cameras with timebase facilities in an identical arrangement to that adopted for the first phase of the research. Once again, omnidirectional microphones situated in the ante-room enabled the elapsed time for volunteers to negotiate sections of the course to be recorded by relaying the start signal to each video recorder. For the purposes of the analysis, the corridor was divided into three sections so that any effects caused by alterations to the air flow rates on escape performance in specific sub-sections of the corridor could be monitored.

The volunteers' subjective assessment of the effects of the wind were recorded on questionnaires completed after each experimental trial. Therefore, each volunteer completed a total of five separate yet identical questionnaires.

3.5 Experimental Procedure - Individual Tests

The experimental procedure for these individual tests conformed to that adopted for the previous series of evacuations. Upon arrival at the Applied Psychology Unit, volunteers were each given a briefing concerning the nature of the tests and were asked to complete a brief medical consent form, which also requested approximate height and weight details. Due to the noise levels in the research facility, volunteers were given the option of wearing a pair of ear protectors for the duration of the tests. After being given a clipboard containing the questionnaires and a pair of ear protectors (if required) they were escorted to the test facility.

The volunteers were shown the corridor and then led to the ante-room where they were able to deposit their clipboards. The main components of the task were then reiterated by a member of the research team and each participant was then shown to the start line for the practice test using an intermediate wind speed not used in the main body of tests. On occasions when more than one volunteer was used during a session, the volunteer running order was pre-determined and held constant throughout the test procedure.

In tests involving parents with young children, the child was placed in the pushchair at this point and strapped in by the parent. It was advised that all parents should ensure that their child wore a part of ear protectors at all times. In the "wheelchair" tests, the member of the research teams sat in the chair at this point from where they were also able to give the signal to begin each run.

A whistle was used to begin each test run, and upon hearing this, volunteers in all conditions made their way along the corridor staying within the boundaries outlined by the centre track. Another member of the research team was located at the open end of the corridor to monitor the progress of individuals along the track and also to accompany them back to the administration point in the ante-room after each test. Further monitoring of volunteers' progress was achieved via a television placed in the ante-room which was linked to one of the video recorders.

Upon returning to the ante-room, volunteers were asked if the practice run had given them any cause for concern and, if not, asked to repeat the exercise at each of the five test wind speeds. After each of these remaining tests, participants were asked to complete a copy of the questionnaire during which time the wind speed was altered according to the predetermined randomised design by a member of the research team. After completing the five experimental runs, each volunteer was paid the £10 fee and thanked for their participation.

4. METHODOLOGY FOR GROUP TESTS

The equipment and data collection methods used for the group tests were virtually identical to those described in Sections 3.2 and 3.4 respectively. The only slight difference was the addition of an item to the questionnaire which recorded the participants' perceptions of the interference effects of other group members upon their own progress.

4.1 Volunteers for Group Tests

Although it would have been preferable to have studied the behaviour of larger groups of people in order to resemble a real-world evacuation scenario more closely, it was found by trial and error that the maximum number of participants that could he handled at any one time was eight. This was mainly due to the restricted amount of room available in the ante-room.

It was felt that the group tests would be more appropriate if the same groups themselves reflected the population of shopping centre users and it was therefore decided to base the constitution of the groups upon such a population. In order to do this, a survey of shoppers at the Milton Keynes shopping mall was carried out. It was found that, during the study period, roughly equivalent numbers of males and females were observed. The researcher also made age estimates and it was found that the most highly-represented age category was for people between 41 and 60, whilst there were fairly equal proportions of 17-25, 26-40 and over 60 year olds. It was therefore decided that the groups of eight should aim to include four females and four males from a wide variety of age bands. However, due to volunteers available, a higher proportion of the younger age band was represented in favour of the over 60s.

4.2 Experimental Design - Group tests

The five wind speeds used for the group tests were identical to those used for the individual tests (see Section 3.1). Each group was subjected to each of the five test speeds on two occasion, these being presented in a previously-arranged random order as before. Additionally, it was decided to study group evacuations under two distinct conditions, designed to represent two forms of evacuation scenario. It was felt that the nature of a true emergency evacuation would be dependent upon the density of people attempting to pass through an exit at any one time. These differences in density may be a function of more obvious factors such as the actual number of shoppers using the centre at the time of the incident or the number of exits available. However, such differences may also be due to differences in people's ability or willingness to recognise the situation as a true emergency requiring some form of action. Indeed, many such emergencies (e.g. the King's Cross Underground fire of 1987, see Donald and Canter, 1990) have demonstrated that there is often a great deal of ambiguity contained within the situation and response times may vary accordingly. Consequently, it was decided to study the evacuation of groups of eight under high and low density conditions.

As with the individual test, the group members were instructed to imagine that they were involved in a true emergency situation and to evacuate as quickly as they felt comfortable with this scenario in mind.

4.3 Experimental Procedure - Group Tests

The procedure for the group tests had many similarities with that used for the individual tests described in Section 3.5. All participants were randomly assigned a volunteer number (between 1 and 8) to indicate their start position for each of the test runs and were asked to complete a medical consent form before receiving a briefing about the trials. They were also provided with clipboards containing the questionnaires to be completed after each experimental run. Upon arriving at the anteroom, each participant was asked to stand in the appropriate position for their volunteer number, as marked on the floor of the ante-room (see Figure 1 below).

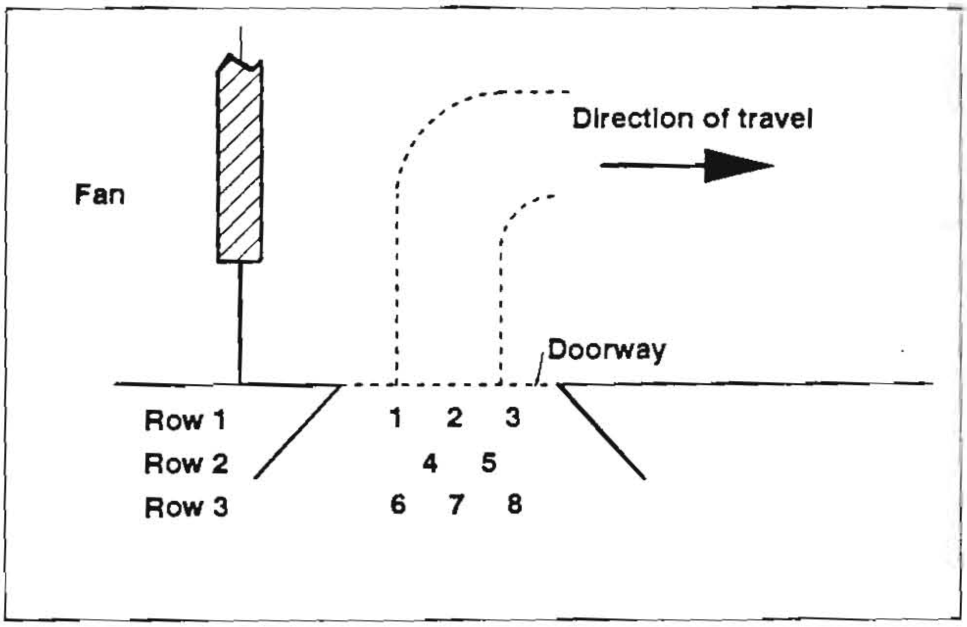


Figure 1: Start Positions for Group Tests

As with previous tests, the signal to begin the evacuation was given on a whistle by a member of the research team. However, the "high-density" and "low-density" conditions were differentiated by the method in which the start signals were given. In the case of the "high-density" conditions, a single blast of the whistle was used to indicate the start point for all eight group members. For the "low-density" conditions, the more dispersed arrangement of volunteers was achieved by starting the three rows of participants separately, requiring three blasts of the whistle, each two seconds apart. Therefore for the first blast, participants 1, 2 and 3 were to begin the evacuation. Referring to a stopwatch, the experimenter then gave a second blast two seconds later for volunteers 4 and 5 to move off. Finally, a further two seconds later, the final blast indicated the moment that the final three volunteers (6, 7 and 8) were to evacuate the corridor.

All groups performed evacuations under each of the five test wind speeds along with a single practice run for both the "high-density" and "low-density" conditions. The total of six runs under each condition (ie. "high" or "low-density") were performed in a block for ease of operation, although the order with which the five wind speeds were arranged within a block and the order of the blocks themselves (ie. six "high-density" runs followed by six "low-density" runs or vice versa) were randomised to counteract effects due to practice or fatigue. Although all group members were informed beforehand as to which order they would be expected to perform the "high-density" and "low-density" tests, at no point were they told which particular wind speeds were being used.

Having successfully completed the practice run, the participants were then asked if they had any queries about the tests. They were then asked to perform the same form of evacuation under each of the five experimental wind speeds, completing a questionnaire after each one. Prior to carrying out the second block of five experimental evacuations, each group was given another practice run to ensure that all participants understood what the change in evacuation style required of them. Once again, for each of the five remaining test runs, volunteers were asked to complete an identical questionnaire. After completion of the session, all volunteers were debriefed, presented with an opportunity to ask questions, paid for their participation and thanked for their involvement.

5. INTERFERENCE EFFECT OF PEOPLE IN THE CORRIDOR

The corridor velocity calibration tests (see Bottomley, Muir and Garry, 1991) ware carried out with the test section of the corridor empty. In order to assess the likely effect on the local flow velocity of the "blockage" caused by a number of people standing in the corridor, a series of measurements was made at specific locations both in the plane of the aperture and in a plane 1.0 metres downstream of the aperture for the range of pre-set throttle positions.

Measurements were made using a Pitot-static tube mounted in the plane of the aperture, at locations around the extremes of an echelon of eight people standing in the working section as shown in Figures 5 to 9 (inclusive) in Appendix B. A summary of the results is given in Table 1 (below).

Table 1: Interference Effects Due to Presence of Group in the Aperture

Speed Setting	**Velocity (m/s) at 1500mm on centre line of empty section**	**Mean local velocity measurements**	**% change relative to empty section**
1	4.10	7.19	+ 75
2	5.89	11.25	+ 91
3	8.91	14.78	+ 65
4	10.92	18.04	+ 65
5	14.11	21.06	+ 49

In view of the acceleration of the flow downstream of the plane of the aperture, a similar series of tests were made 1.0 metres downstream of the aperture. The results of these tests are shown in Table 2 (below) and are represented in figures 10 to 13 in Appendix B.

Speed Setting	**Velocity (m/s) at 1500mm on centre line of empty section**	**Mean local velocity measurements**	**% change relative to empty section**
1	5.25	6.18	+ 17
2	7.54	8.46	+ 12
3	11.42	12.37	+ 8
4	13.77	13.70	0

The aerodynamic data for the velocity increase around the group of people standing in the working section is in the form of point measurements in a dynamic flow field in close proximity to an essentially moving body of people. Consequently, the data would be expected to show considerable scatter and this is indeed the case. It should be noted that some measurements were considered to be unreliable and have been omitted from the "grid" of data presented in the figures in Appendix B.

In general, the trend was found to be for the local velocity to increase in close proximity to the group as would be expected due to the constraining effects of the corridor walls. The increase is seen to be greater in the plane of the aperture due to the nature of the flow in this region.

6. RESULTS FROM INDIVIDUAL EVACUATIONS

6.1 Demographics Details for all Volunteer Groups

Table 3 (below) outlines the main demographic details for each of the five classes of individuals studied in the second phase of the research programme, including the female-to-male ratio and the mean age, height and weight of participants in each category. Also presented are the equivalent figures for all volunteers from the first phase. In each case, the first figure in parenthesis represents the standard deviation associated with the accompanying mean whilst the second figure gives the relevant number of cases.

Table 3: Main Demographic Details of Individual Participants

Volunteer Category:	Number of Cases	Female/ Male Ratio	Mean Age (years)	Mean Height (cms)	Mean Weight (kgs)
Adults aged 20-54:	48	24/24	37.00 (9.84)	170.19 (10.39)	69.15 (12.33)
Adults with infant in pushchair:	12	9/3	31.50 (5.32) (12)	165.75 (9.31) (12)	64.08 (11.48) (12)
Adults aged over 60 years:	12	4/8	65.83 (4.11) (12)	171.08 (9.82) (12)	76.50 (15.47) (12)
Children aged 12-14 years:	16	8/8	13.31 (0.48) (16)	166.00 (9.07) (7)	51.85 (8.91) (13)
Wheelchair pushers:	12	5/7	51.33 (18.40) (12)	167.33 (8.82) (12)	70.58 (10.57) (12)
Adults with restricted mobility:	10	7/3	56.10 (14.64) (10)	162.80 (13.00) (10)	73.00 (9.75) (10)

6.2 Evacuation Times for each Experimental Group of Individual Participants

As the primary purpose of the research was to study the effects of different wind speeds upon people's progress in the simulated shopping precinct, the main focus of attention should be placed upon the times to complete the task and evacuate from the research facility. Therefore, Table 4 (below) shows the mean evacuation times, with standard deviations shown in parentheses, for each experimental group under the five test air flow rates. These are also represented graphically in Figure 2 (over), plotting times taken for each experimental group to complete the whole evacuation. For comparative purposes, the equivalent figures from the first phase of the research (see Bottomley, Muir and Garry, 1991) are also given. For each group, the number of cases are as shown in Table 3.

Table 4 Mean Evacuation Times for each Experimental Group

Experimental Group:	**Mean Escape Times (secs.): Air Flow Rate: 1**	**2**	**3**	**4**	**5**
Adults aged 20-54 - Walking:	5.72 (0.68)	5.78 (0.76)	5.74 (0.72)	5.86 (0.75)	6.09 (0.76)
Adults aged 20-54 - Running:	3.58 (0.56)	3.56 (0.58)	3.59 (0.61)	3.68 (0.55)	3.85 (0.70)
Adult with infant in pushchair:	6.19 (1.29)	6.46 (1.76)	6.57 (1.82)	6.73 (1.77)	7.00 (1.98)
Adults aged over 60 years:	7.32 (2.69)	7.26 (2.49)	7.52 (2.64)	7.66 (2.76)	8.54 (3.15)
Children aged 12-14 years:	3.32 (0.31)	3.40 (0.24)	3.47 (0.31)	3.54 (0.28)	3.75 (0.28)
Wheelchair pushers:	8.10 (1.98)	8.40 (2.32)	8.59 (2.56)	8.76 (2.27)	9.27 (2.72)
Adults with restricted mobility:	9.30 (3.94)	9.46 (4.46)	9.95 (4.55)	10.06 (4.28)	10.78 (4.11)

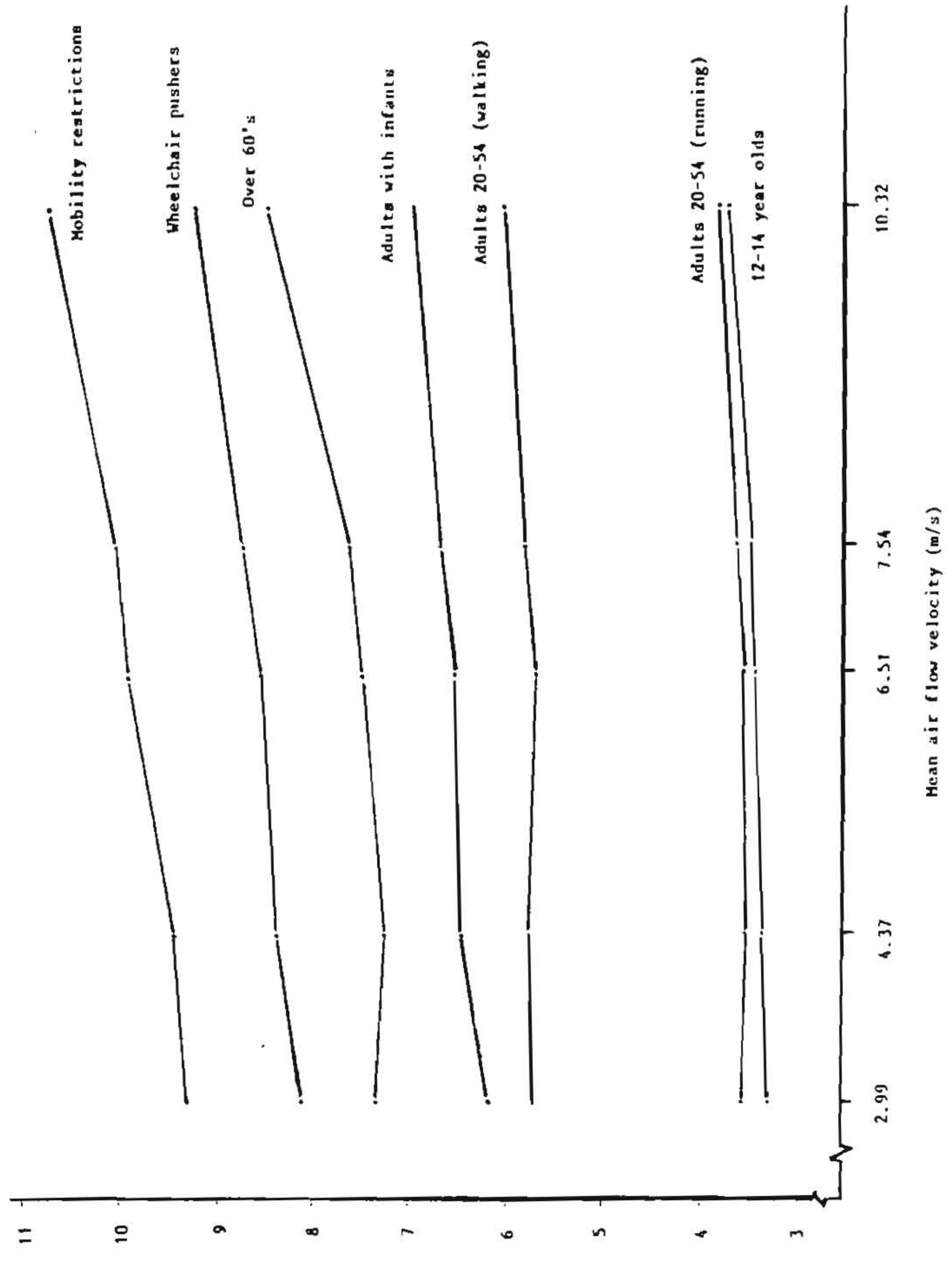


Figure 2: Mean Times to Complete Evacuation Task for all Classes of Individual Participants at each Air Flow Velocity

In the vast majority of cases, it can be seen that an increase in air flow rate was accompanied by an increase in mean escape times. For the second phase volunteers, the only exception to this trend was found for the over 60 year olds, who took slightly longer to evacuate under the lowest wind speed (2.99 m/s) than under the second lowest (4.37 m/s) speed. The actual rates of evacuation can be found in Appendix C.

In order to isolate the effects of air flow rate under different conditions (ie. when entering the main air stream, when walking in the main air stream and when passing through a narrow aperture), the corridor was subdivided into three sections, as shown in the diagram in Appendix A. For each experimental group, the mean times taken to negotiate each of these sections are presented in Appendix D.

In order to assess whether certain air flow rates produced significantly different evacuation times than others, repeated measures analyses of variance (ANOVAS) were performed on the data from each experimental group. These tests, performed on times to complete the whole task as well as the three individual task components, are summarised in Table 5 (over). For each test, the first line shows the degrees of freedom, the second row the test statistic F, and the final row shows the probability of time differences being due to chance factors alone. For each case, the null hypothesis is that the alternative air flow rates do not produce significantly different evacuation rates and the rejection level for these set at 5% ($p = 0.05$).

Table 5 reveals a highly consistent pattern for each volunteer grouping. The tests on escape times for all sectors combined and Section B each produced highly significant results. This was also true of all bar one of the tests performed on times taken to negotiate Sector C (the aperture), this being the over 60's grouping. However, a consistent pattern was also found for the Sector A tests, none of which produced a result significant at the 5% level.

Table 5: Significance Tests for Individual Evacuation Rates

	Sector A:	Sector B:	Sector C:	All Sectors:
Adults with infant in pushchair:	$F_{(4,44)}$ = 0.22 (p=.925)	$F_{(4,44)}$ = 2.80 (p=.037)	$F_{(4,44)}$ = 9.38 (p=.000)	$F_{(4,44)}$ = 6.17 (p=.000)
Adults aged over 60= years:	$F_{(4,44)}$ = .064 (p=.064)	$F_{(4,44)}$ =13.54 (p=.000)	$F_{(4,44)}$ = 2.21 (p=.083)	$F_{(4,44)}$ =10.31 (p=.000)
Children aged 12-14 years:	$F_{(4,60)}$ = 1.79 (p=.143)	$F_{(4,60)}$ =10.59 (p=.000)	$F_{(4,60)}$ = 7.42 (p=.000)	$F_{(4,60)}$ =20.4 (p=.000)
Wheelchair pushers:	$F_{(4,44)}$ = 1.86 (p=.135)	$F_{(4,44)}$ =10.49 (p=.000)	$F_{(4,44)}$ = 6.93 (p=.000)	$F_{(4,44)}$ = 8.31 (p=.000)
Adults restricted mobility:	$F_{(4,36)}$ = 1.48 (p=.228)	$F_{(4,36)}$ = 9.51 (p=.000)	$F_{(4,36)}$ = 6.68 (p=.000)	$F_{(4,36)}$ =17.23 (p=.000)

In order to determine which flow rates were primarily responsible for these significant differences in escape times, post-hoc Newman-Keuls tests (see Winer, 1971) were performed on the data. The tables for these tests are presented in Appendix E (Tables 15 to 28). Analysis of these tables again reveals a fairly clear and consistent pattern with the highest wind speed (10.54 m/s) shown to produce significantly slower evacuation times than each of the four other speeds in 10 out of the 14 tables presented in Appendix E. However, in a number of examples, the second highest flow rate (7.54 m/s) was also shown to significantly impede progress. These cases include: adults with infants in pushchairs passing through the exit aperture; 12-14 year old children when the whole task was considered; wheelchair pushers overall and through the exit aperture; and finally, people with mobility restrictions when negotiating the main section of the corridor and for the complete task. It should also be noted that there are a small number of examples (both 12-14 year olds and mobility-restricted people when the complete evacuation was considered along with wheelchair pushers when passing through the exit aperture) in which the mid-range air flow rate significantly impeded progress.

6.3 Safety Rating for each Experimental Group

As in the first phase of the research, the volunteers' perceptions of their own personal safety whilst evacuating under each of the five test air flow rates was also felt to be an important consideration. Table 6 (below) presents the mean safety ratings (with standard deviations in parentheses) given by participants in each of the five experimental groups from the current phase of the research, along with the equivalent F-ratios and probabilities from the repeated measures analysis of variance tests performed on these figures. The equivalent figures from the first phase are also included for comparative purposes. It may be remembered that a rating of 10 represented "Completely Safe" whilst at the opposite end of the scale, 1 was classified as "Not At All Safe".

Table 6: Safety Ratings and ANOVA Summaries for each Experimental Group

Mean Safety Ratings:

Experimental Group:	**Air Flow Rate:** 1	2	3	4	5	**F-Ratio**
Adults aged 20-54 - Walking:	9.52 (0.85)	9.50 (1.03)	9.19 (1.27)	9.13 (1.27)	8.46 (1.68)	19.77 (p=.000)
Adults aged 20 to 54 - Running:	9.55 (0.78)	9.55 (0.95)	9.17 (1.24)	8.98 (1.34)	8.47 (1.61)	17.19 (p=.000)
Adult with infant in pushchair:	9.58 (0.79)	9.58 (1.00)	8.50 (1.88)	8.33 (1.97)	7.83 (2.04)	8.64 (p=.000)
Adults aged over 60 years:	9.08 (2.28)	9.25 (2.30)	9.25 (2.01)	9.17 (1.47)	8.50 (1.93)	2.57 (p=.051)
Children aged 12-14 years:	9.19 (0.75)	9.25 (0.86)	8.63 (1.26)	8.69 (0.95)	8.25 (0.86)	6.54 (p=.000)
Wheelchair pushers:	9.92 (0.29)	9.75 (0.62)	9.50 (0.91)	9.42 (1.00)	9.17 (2.04)	1.35 (p=.268)
Adults with restricted mobility:	9.50 (0.71)	9.50 (0.71)	9.20 (0.92)	9.20 (1.32)	8.20 (2.70)	1.85 (p=.140)

Table 6 reveals a general trend with the stronger wind speeds usually provoking more "unsafe ratings". However, the statistical analyses of the safety figures for the five classes of participant from the second phase of the research produced only two results significant at the 5% level when subjected to post-hoc analyses (see Tables 29 and 30 in Appendix E), it was found that participants in both the "adults with children" and "12-14 year olds" categories felt significantly more safe when evacuating under the lower two wind speeds than under the three higher rates.

6.4 Comparison of all Classes of Individual Participants

By comparing the effects of alternative air flow rates on different members of the shopping precinct user population, it was felt that people who may be put more at risk by increasing air flow rates could be identified. Therefore, a measure of susceptibility was calculated by expressing participants' evacuation times under the highest flow rate (T_5) as a function of their times under the lowest flow rate (T_1). These figures are presented in Table 7 (over), with all standard deviations being shown in parentheses. It should be noted that, for statistical reasons (ie. retention of independent data when comparing between groups), only one set of escape times for volunteers from the first phase of the research could be included. The times for "walking" escapes were selected for the adults aged between 20 and 54 as it was felt that these evacuations more closely resembled those by the majority of the remaining experimental groups, as reflected in the evacuation times (see Table 4).

Table 7 shows that adults aged between 20 and 54 were the group least affected by the top air flow rate, with this producing a 6% increase in escape times over the lowest rate. In addition, the over-60s and those with mobility restrictions were found to be most affected with a mean increase of around 17%. These figures were subjected to a one-way analysis of variance technique. This produced an F-ratio of 5.48 (degrees of freedom = 5,104), significant beyond the 0.1% level. The Newman-Keuls post-hoc test to identify the specific areas of significance (see Appendix E - Table 31) reveals the "over 60s" and "restricted mobility" participants to be significantly more affected than the 20 to 54 year old adults. No other significant differences were noted.

Table 7: Ratio of Evacuation Times Under Highest and Lowest Air Flow Rates for each Grouping of Individual Participants

Group:	Number of cases:	Mean Evacuation Times (Secs): T_1	T_5	Mean Ratio (T_5/T_1):
Adults aged 20-54 - Walking:	48	5.72 (0.68)	6.09 (0.76)	1.07 (0.07)
Adult with infant in pushchair	12	6.19 (1.29)	7.00 (1.98)	1.12 (0.11)
Adults aged over 60 years:	12	7.32 (2.69)	8.54 (3.15)	1.17 (0.07)
Children aged 12-14 years:	16	3.32 (0.31)	3.75 (0.28)	1.13 (0.11)
Wheelchair pushers:	12	8.10 (1.98)	9.27 (2.72)	1.13 (0.11)
Adults with restricted mobility:	10	9.30 (3.94)	10.78 (4.11)	1.17 (0.09)

Brief analyses were also performed to ascertain whether there were any sex differences within these experimental groups. However, males and females belonging to each grouping were found to be similarly affected and no significant differences were noted.

6.5 Additional Information

The final item on each questionnaire asked which, if any, factors other than the air flow had impeded the individual's progress along the corridor. The only problems in this respect were noted by two of the wheelchair pushers who both reported their progress to be impeded by "lift" under the wheelchair, one at each of the two higher flow rates.

7. RESULTS OF GROUP EVACUATIONS

7.1 Demographic Description of Groups

Twelve groups each with eight members were involved in the study making a total of 96 participants. All bar 2 groups had equal number female and male members. The exceptions contained 5 males and 3 females, on both occasions resulting from last-minute cancellations by female volunteers. The mean age of participants was 31.95 years (standard deviation, SD = 9.43), ranging from 20 to 56, mean height was 169.28 cms (SD = 9.15) and mean weight 64.29 kgs (SD = 10.68). One female member of Group 9 required the use of a walking stick.

7.2 Total Evacuation Times - Group Tests

7.2.1 Evacuation Times for the Whole Group

As with the individual tests, it was felt that times taken to evacuate from the shopping precinct were the most relevant points for consideration. Firstly, it was decided to analyse the times for the whole group to escape, treating the "high-density" and "low-density" evacuations separately. Table 8 (over) shows the mean times taken for all 96 participants to negotiate each of the three sub-sections of the corridor (see Appendix A) as well as the total times for each of the five test air flow rates. Following on, the equivalent data for the "low-density" evacuations are presented in Table 9 (over). In both cases, the data were subjected to analyses of variance tests and the F-ratios and associated probabilities ware also given in Tables 8 and 9. For all analyses, the degrees of freedom for the ANOVA tests are 4,380. In the case of the "low-density" conditions, it should be noted that the escape times for participants in the second and third rows were recorded from the second and third (respectively) start cues rather than from the initial cue. A plot of these escape times is presented in Figure 3 (over).

The overall times presented in Tables 8 and 9 reveal a generally consistent trend in line with that noted for the individual tests: an increase in wind speed producing slower mean evacuation rates. This trend is not universal when the individual corridor sectors are considered, although the highest wind speed produced consistently slower times.

Table 8: Mean Escape Times for all Volunteers - High-Density Conditions

Sector:	Mean Evacuation Times (Secs.): Air Flow Rate: 1	2	3	4	5	F-Ratio
A	1.98 (0.70)	2.0 (0.72)	2.01 (0.69)	2.02 (0.68)	2.06 (0.75)	5.07 (p=.001)
B	2.11 (0.79)	2.16 (0.79)	2.20 (0.75)	2.18 (0.71)	2.31 (0.76)	19.85 (p=.000)
C	0.81 (0.36)	0.87 (0.42)	0.86 (0.37)	0.97 (0.37)	0.99 (0.44)	24.41 (p=.000)
Overall	4.90 (1.67)	5.03 (1.79)	5.07 (1.66)	5.16 (1.63)	5.36 (1.79)	27.72 (p=.000)

Table 9: Mean Escape Times for all Volunteers - Low-Density Conditions

Sector:	Mean Evacuation Times (Secs.): Air Flow Rate: 1	2	3	4	5	F-Ratio
A	1.71 (0.47)	1.71 (0.48)	1.71 (0.53)	1.68 (0.46)	1.74 (0.48)	1.67 (p=.155)
B	2.10 (0.73)	2.06 (0.74)	2.17 (0.76)	2.17 (0.68)	2.25 (0.76)	22.86 (p=.000)
C	0.72 (0.34)	0.71 (0.35)	0.78 (0.32)	0.78 (0.34)	0.88 (0.36)	23.04 (p=.000)
Overall	4.53 (1.43)	4.48 (1.44)	4.66 (1.50)	4.63 (1.37)	4.87 (1.50)	25.88 (p=.000)

The ANOVA tests carried out on these times were all significant beyond the 0.1% level with one exception (the Sector A test for the "low-density" evacuations). The Newman-Keuls post-hoc tests of significance contained in Appendix F reveal that virtually all air flow rates produced significantly different evacuation rates than each of the other rates when the whole evacuation task was considered. The equivalent analyses for Sectors B and C produced similar patterns for both density conditions, although only the highest flow rate was found to differ from the others during the negotiation of Sector A under "high-density" conditions.

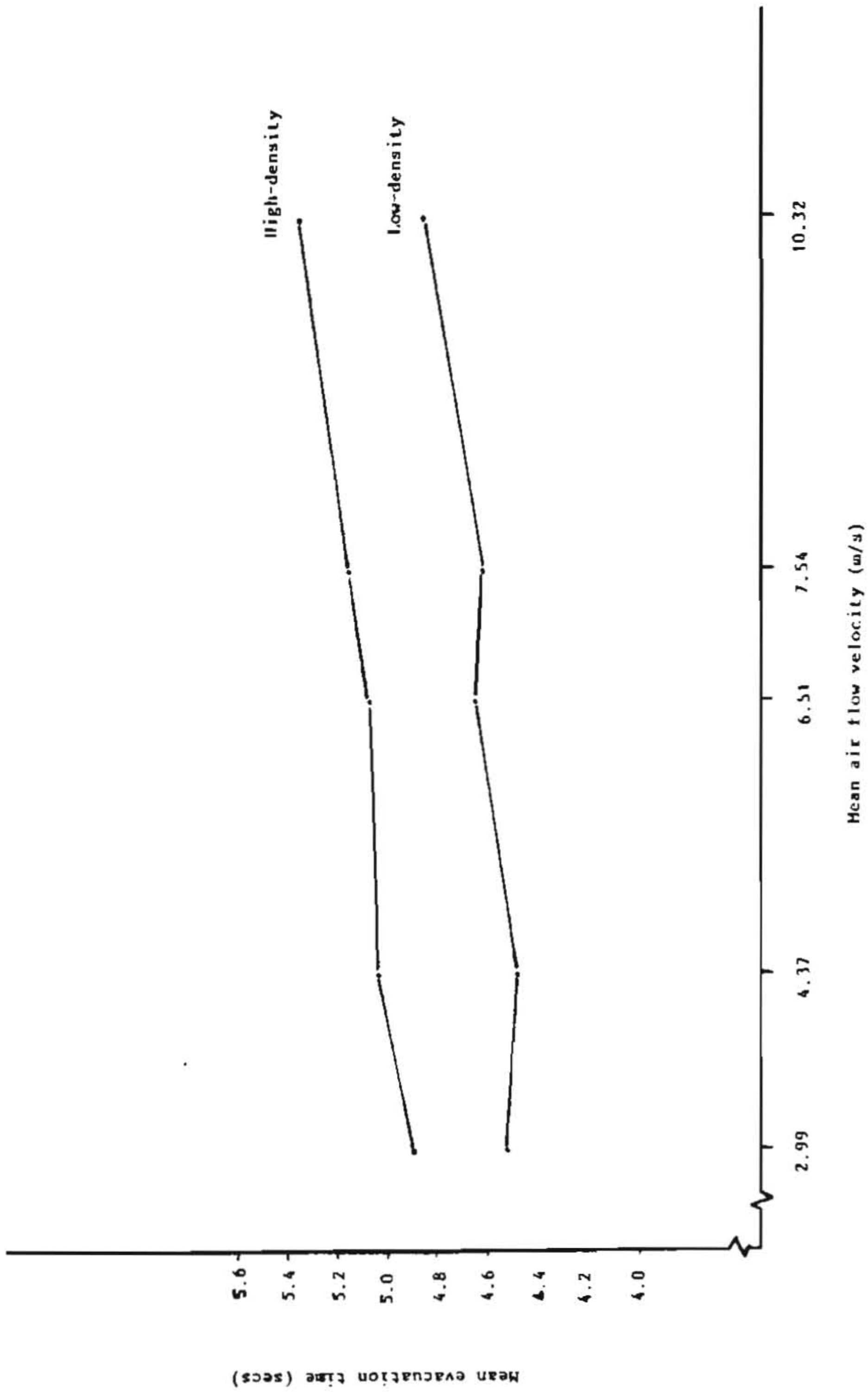


Figure 3: Mean Times to Complete Evacuation Task for Groups in High and Low-Density Conditions

7.2.2 Evacuation Times by Start Position

It may be argued that, by combining the data for all participants, the analyses described in the previous section may be obscuring some important effects. Therefore, it was decided to perform similar analyses for individuals occupying each of the eight "start" positions under both density conditions. The tables (41 and 42) in Appendix G give the times taken to complete the whole evacuation task under each of the five test air flow rates in addition to the accompanying statistics for the ANOVA tests performed on the data. The "high-density" tests showed that the alternative air flow rates produced significantly different evacuation rates from those occupying start positions 1, 4, 6, 7 and 8 (see Section 4.3). Similarly, those beginning the evacuations in start positions 1, 3, 4, 5, 6 and 7 were found to have significantly different evacuation rates in the "low-density" conditions. The post-hoc tests (detailed in Tables 43 to 53 in Appendix H) performed to assess the specific areas of significance each show virtually identical patterns with the highest wind speed found to significantly increase escape times in every case. However, in only one example (for those occupying position 4 in the "high-density" tests) did the second highest rate significantly affect progress.

7.3 Safety Perceptions of Group Members

As for the individual, it was also felt to be of importance to consider the participants' subjective perceptions of their own personal safety under each of the five air flow rates. Table 10 (below) gives the mean safety ratings associated with exact rate for both "high density" and "low density" escapes, along with summaries of the repeated measures ANOVA tests of significance (degrees of freedom = 4,372).

Table 10: Safety Ratings and ANOVA Summaries for Group Evacuations

Mean Safety Ratings:

	Air Flow Rate:					
Condition:	**1**	**2**	**3**	**4**	**5**	**F-Ratio**
High-Density:	8.44 (2.01)	8.50 (1.81)	8.05 (1.87)	7.78 (2.08)	7.39 (1.93)	21.92 (p=.000)
Low-Density:	8.75 (1.83)	8.64 (1.92)	8.23 (1.85)	7.96 (1.83)	7.44 (1.94)	28.55 (p=.000)

It may be remembered that the high end of this scale was labelled "completely safe", and therefore Table 10 clearly demonstrates that the higher wind speeds generally produced more "unsafe" ratings, corresponding to the findings of the individual tests. The post-hoc tests for the ANOVAs given in Appendix F show that the pattern of significant differences is virtually identical for the "high-density" and low-density" evacuations with every flow rate above "2" found to produce significantly different safety perceptions to every other rate.

7.4 Effects of the Presence of Other People

The questionnaire used in the group tests contained an additional item to that used for the individual tests as participants were asked to indicate the extent to which other group members had impeded their own progress. No significant differences were found when the ratings produced for each test flow rate were compared for the "high-density" evacuations. However, the equivalent test for the "low-density" conditions was found to be significant at the 1% level, with the most disruption reported during the evacuations at flow rates "3" and "5". Of greater interest were the comparisons between the occupiers of the eight start positions. When a composite score for each of the five evacuations under each density condition was calculated, significant differences due to start position were found ($F_{(7,87)}=6.43$, $p=.000$ for "high-density" conditions and $F_{(7,86)}=3.28$, $p=.004$ for "low-density" evacuations). Not surprisingly, participants beginning the evacuations in the front row were less affected by others, higher scores indicating increased disruption due to others. The three positions produced a mean "disruption" score per evacuation of 2.37 in the "high-density" evacuations in comparison with 3.74 for those in the middle row and 5.41 for back-row members. Similarly, these back-row participants reported more disturbances due to the presence of others in the "low-density" conditions (mean=3.86), although members of the first two rows reported more similar mean "disruption" scores (2.11 for the first row, 1.98 for the second).

7.5 Other Information

Volunteers were also asked to note any other factors which had caused them to be impeded whilst evacuating from the corridor. Several people reiterated items included elsewhere on the questionnaire (eg. "other people") but the most common suggestions included: "hitting the doorframe whilst turning into the corridor" (suggested by 3 people under "high-density" conditions, 5 people under "low-density" evacuations) "hitting the aperture frame near the end of the corridor" (2 participants - "high-density", 4 "low-density"); and "wearing inadequate shoes" (2 participants - "low-density").

It was also felt to be of interest to investigate briefly which factors, if any, contributed to good individual "performances" within the groups. This was achieved by calculating a "performance index" based upon individuals' relative performances in each of the ten test evacuations. An "expected" finish position was given to each of the eight start positions according to start row and position within a row (those on the "inside" of the bend expected to finish before those on the outside etc.) and these were compared to actual finish positions. Therefore, an "expected" performance (ie. in which the participant finished in the expected position each time) would achieve a score of 0. Positive scores indicated a better-than-expectation performance whilst negative scores indicated a worse-than-expectation performance. Several demographic factors were found to be significantly linked to this performance index, most notably: **sex** (mean male score = 2.40, mean female score = -2.11, producing a value of t = 2.55, significant at the 5% level); **height** (producing a significant positive correlation of 0.305, p = .001); **age** (correlation coefficient = -0.237, p = .01); **shoe-type** ("flat shoes" mean = 0.95, high-heeled shoes mean = -6.67, t = 2.51, p = .014); and finally presence or absence of a **handbag** ("handbag" mean = -10.00, "no handbag" mean = 0.80, t = 2.73, p = .008). All other demographic factors tested produced non-significant results. These indicated that better performances were more likely to be achieved by males, taller people, younger people, those wearing flat shoes and those not carrying a handbag.

8. DISCUSSION

8.1 Individual Tests

8.1.1 Participants

Although the target number of individuals required for each category of participants was achieved, some of these displayed an imbalance in terms of the sex ratio of the volunteers. In some cases, such as the nine females to three males ratio in the parent/infant in pushchair category, this was not considered to be a cause for concern as these imbalances were more likely to be a reflection of the population sex ratios of such people than a result of a selection bias. This is certainly not true of the " over 60s" and "restricted mobility" categories, which contained excessively high male and female members respectively. Although this was a direct result of a sampling bias, it should be pointed out that very few persons fitting into these categories could be persuaded to participate in the research programme and consequently it was felt that any volunteers had to be accepted, regardless of their sex. It should also be noted that, when the effect of the higher wind speed upon progress was investigated (see Section 6.4) no significant sex differences were found thereby suggesting that this slight sampling bias may be inconsequential.

8.1.2 Evacuation Times

The times to evacuate not surprisingly indicated that, with the exception of the 12-14 year-olds who produced the fastest escape times of all, the escape times of each of the individual categories used in the investigation reported in this paper were slower than those of the adult 20-54 year olds tested in the first phase of the research. Although the instructions given to participants in this phase of the research differed from those given previously in that they were simply asked to progress as quickly as they felt comfortable, it is of note that a wide range of approaches were taken and it was felt that those volunteers who were able to run did so.

The pattern of those wind speeds significantly impeding progress showed considerable consistency between study groups. Analysing progress for the whole evacuation task (ie. through all three corridor sectors), the highest flow rate (10.32 m/s) significantly impeded the progress of all classes of participants. If recommended air flow rates in shopping centres are to be altered, it is clear that setting the new criterion at this level would lead to seriously delayed evacuations for these people. However, progress at the second highest speed (7.54 m/s) was also significantly reduced for most participants and the 12-14 year-old children and the people with restricted mobility were also found to be hampered by the third wind speed (6.51 m/s) and it could be argued that a more conservative estimate would have to place the flow rate criterion somewhere between 4.37 and 6.51 metres per second.

The current recommended flow rate refers to air flow through an exit aperture and therefore it may be that the most important results are those relating to progress along Sector C of the corridor. Although the top speed still impeded participants of all classifications during this sector, the second highest was found to impeded the progress of members of two groups: adults accompanied by young children in pushchairs and wheelchair pushers.

8.1.3 Safety Assessments

Members of three of the five participant groups did not report the different air flow rates affecting their perceived level of safety whilst evacuating from the corridor. However, both the adults pushing pushchairs and the 12-14 year-old children reported feeling more unsafe under each of three higher wind conditions. Despite this, it should be noted that the lowest mean "safety rating" (ie. that indicating the lowest level of perceived safety) recorded at the third flow rate was 8.50 (by the adults with children) which is still considerably nearer the "totally safe" (ie. 10) end of the scale than the "not at all safe" end (ie. 1). Furthermore, even at the highest air flow rate, no class of respondents gave a mean lower than 7.83, suggesting that perceived levels of safety are not a major consideration at speeds as flow as those studied in this research programme.

8.1.4 Additional Considerations

Some additional points are worth noting at this stage. The course deviations of each of the individual participants were recorded by noting the number of occasions upon which each person deviated from the central track. Confirming the findings of the first phase of the research, where no course deviations beyond the limits of the track occurred, the vast majority of participants in this phase did likewise. Only two participants did make any course deviations beyond these limits, both wheelchair pushers, and on all of their evacuations. As these were also the producers of the two fastest sets of escape times in this category, it was concluded that the deviations were a result of evacuation style rather than being due to the air flow and therefore of limited interest to the aims and objectives of this research.

The other point of interest regarding the wheelchair pushers concerned the additional causes of impeded progress as noted in Section 6.5. The problems associated with the wheelchair all occurred when the two higher wind speeds were in use and, although this may be a problem unique to the particular wheelchair used, it may be argued that this lends additional support to the argument that the air flow criterion should be placed between the third and fourth levels.

Finally, the participants aged over 60 and those with restricted mobility were found to be more heavily affected by the highest wind speed suggesting that these people would be more vulnerable in a true emergency. However, this was based upon the ratio of escape times under the highest flow rate to those under the lowest rate and as it is suggested elsewhere that this highest wind speed should not be adopted, the evidence presented cannot be used to suggest that these people would be more vulnerable than others should a new criterion be selected somewhere below this highest speed.

8.2 Group Tests

8.2.1 Participants

The 96 volunteers recruited for the group tests represented a fairly wide range of ages although it would have been preferable to have included several people aged over 60 years. Indeed, the mean age of just under 32 indicates that the sample was slightly biased towards the younger end of the spectrum. However, it could be argued that the main aim of the research was to investigate for differences between the experimental air flow rates and therefore the exact constitution of the groups is of lesser importance. Despite this, it would clearly have been preferable to have obtained a truly representative sample although recruitment difficulties rendered this impossible. In addition, the groups would have been more representative had they incorporated individuals falling into the classifications studied in the individual tests described in this report. However, it was felt that the nature of these tests may have put some of these people at risk. Nevertheless, one female participant with restricted mobility was included in the tests, although in this case the random placement of volunteers within the group gave her a position at the rear of the group and consequently she was in no danger from the other group members nor did she impede the progress of the others.

8.2.2 Evacuation Times

Mean evacuation rates during the "low-density" conditions were faster than for "high-density" evacuations, implying that the air flow under the former conditions had less of an effect upon individuals. However, it is argued that these differences are more likely to result from the disruptive influences of the close proximity of the group members to each other.

The analysis of group evacuation times under both high and low density conditions produced a somewhat confusing picture when the data from all members were grouped together, with all flow rates found to produce significantly different evacuation rates from each other. It was felt that this relatively crude combination of data may have produced some spurious results and therefore the escape times of individuals occupying each of the eight starting positions were subjected to individual analysis. This revealed that the alternative flow rates did not affect the escape times of people occupying three of the positions for the "high-density" evacuations and two during the "low-density" evacuations. In the vast majority of cases where significant differences were found, the highest air flow rate was the only one which produced significantly slower evacuation rates. The only exception to this was for those group members beginning the evacuations in position "4" (middle row, on the "outside") in the high-density conditions, in which the second highest flow rate was also found to produce significantly slower times than the slowest wind speed.

8.2.3 Safety Assessments

The safety perceptions of group members were subjected to analysis, revealing that all flow rates above the second

4.37 m/s) were perceived to be more unsafe than the two lowest speeds. The air flow rates during the "high-density" evacuations were found to be perceived to be more unsafe than those during the "low-density" evacuations for each distinct flow rate suggesting that their perceptions of the wind's influence was more marked when participants were grouped together. However, it is again suggested that they may have felt more "unsafe" under the "high-density" conditions more as a result of the presence of other people rather than an effect attributable to the air flow, lending support to Saegart's (1974) assertion that the presence of large numbers of people within a confined space increases arousal within those individuals. As with the individual tests described in this report, it should be noted that the actual "safety ratings" under both conditions were relatively high (ie. safe) at 7.39 ("high-density") and 7.44 ("low-density") where 10 was labelled "Completely safe".

8.2.4 Additional Information

The findings of the assessment of the influence of other group members on progress did not produce any unexpected results. When the group members were more dispersed, disruption ratings were lower and those occupying front row positions also reported less interference from others. Clearly, it might be expected that those occupying back row positions would be more prone to interference effects from other people, and this was indeed borne out by the responses to these items.

Perhaps of more interest was the "performance index"; a method of highlighting those individuals who evacuated more effectively in comparison with their compatriots. Males and younger volunteers were found to be significantly more successful at getting ahead of other group members, confirming the findings of Muir, Marrison and Evans (1989) that males tend to be more competitive in such situations. Height was also found to be significantly related to the performance index, as was wearing of high-heeled shoes and possession of a handbag, but it is argued that these differences are probably largely a function of the sex differences already noted and therefore of limited interest.

8.3 Selection of an Optimum Wind Speed

The tests conducted in the first phase of the research studying adults aged between 20 and 54 suggested that the air flow rates through shopping centre exits could be increased to a point not exceeding the fourth wind speed used (7.54 metres per second) without impeding the progress of shoppers walking to evacuate. If evacuations whilst running were considered, it was suggested that this criterion would need to be lowered to exclude all above the third rate used (6.51 m/s). Similarly, if the part of the task involving passing through the exit aperture was considered in isolation, only the fifth air flow rate (10.32 m/s) could be said to impede progress.

The findings from the research described in this report largely confirm these initial findings. There is overwhelming evidence to suggest that the highest wind speed significantly impedes the progress of all volunteers and in many cases, the second highest wind speed was also found to affect progress. Although the case against the latter was less relevant when progress through the exit aperture was considered in isolation, it is argued that all potential shopping centre users must be considered when reaching a decision regarding a new air flow rate criterion. The fact that some people (eg. adults with young children in pushchairs) were impeded by this fourth rate when passing through the aperture suggests that a more conservative criterion should be adopted. This is even more important when considering the entire evacuation task as, in these cases, more people were found to be significantly affected by the fourth speed. This would suggest that a criterion should be placed so that their air flow rate does not exceed 6.51 metres per second. However, it may be argued that the occasional example of the third air flow rate impeding progress (eg. for wheelchair pushers during Sector C) implies that an even more conservative criterion (ie. not exceeding 4.37 m/s) would be more appropriate.

8.4 Recommendations for Further Research

One aspect of the research not taken into consideration is the effect upon evacuation rates and safety perceptions of a number of alternative floor surfaces found in shopping malls, particularly with reference to the types of shoes worn by shoppers. In the group tests, there was evidence to suggest that those participants wearing high-heeled shoes were less able to perform well in comparison with their fellow group members.

In addition, the ability to evacuate rapidly from a shopping centre in an emergency is dependent upon several factors,including the time to perceive and interpret the cues (ie. fire alarms or announcements over public address systems) used to announce the emergency (see Canter, 1990). Some people (eg. those with impaired hearing or sight) may have severe problems in recognising those cues and it is therefore recommended that research be carried out to uncover methods by which the evacuation potential of these shoppers may be enhanced.

9. CONCLUSIONS

1. The evacuation rates for individual participants were found to be significantly slower at the highest air flow rate (10.32 m/s), although some categories of individual participants were also found to be restricted by the second highest flow rate (7.54 m/s). In some cases, the middle range flow rate (6.51 m/s) restricted people, but only when the whole evacuation task was considered. When considering only passages through the exit aperture, only the two higher flow rates were found to impede progress.

2. When asked how safe they felt when evacuating in each of the test air flow rates, individuals reported feeling more unsafe at each of the rates above 4.37 m/s. However, these ratings were not felt to be sufficiently high, even at the highest speed, to prevent people from progressing on safety grounds alone.

3. The behaviour of individuals in small groups was also investigated. These group members were also found to be significantly impeded by the highest wind speed, with some also restricted by the second highest speed.

4. In a similar manner to the individual tests, the safety perceptions of group members were found to be significantly affected by the higher wind speeds, although the ratings were again not felt to be sufficient to prevent progress in a true emergency.

5. Within the group tests, males and younger participants were found to be more successful evacuees than their counterparts.

6. When compared with the results from the initial phase of this research, the results of the research described in this report suggest that air flow rates through the exit apertures of shopping centres in excess of 6.51 metres per second would impede the progress of escaping shoppers. However, there was also evidence to suggest that some individuals would be significantly impeded by wind speeds above 4.37 m/s.

10. REFERENCES

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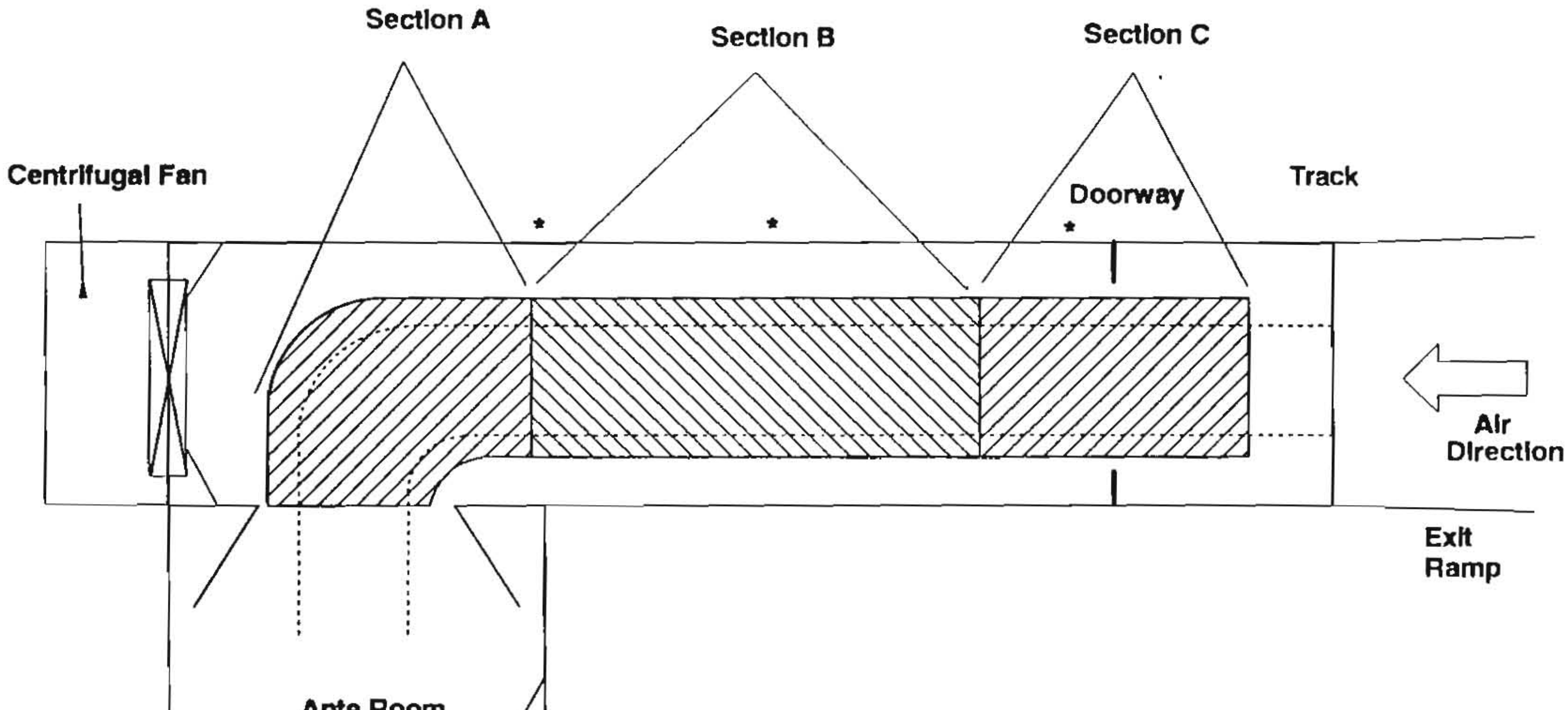


INTERNAL DIMENSIONS

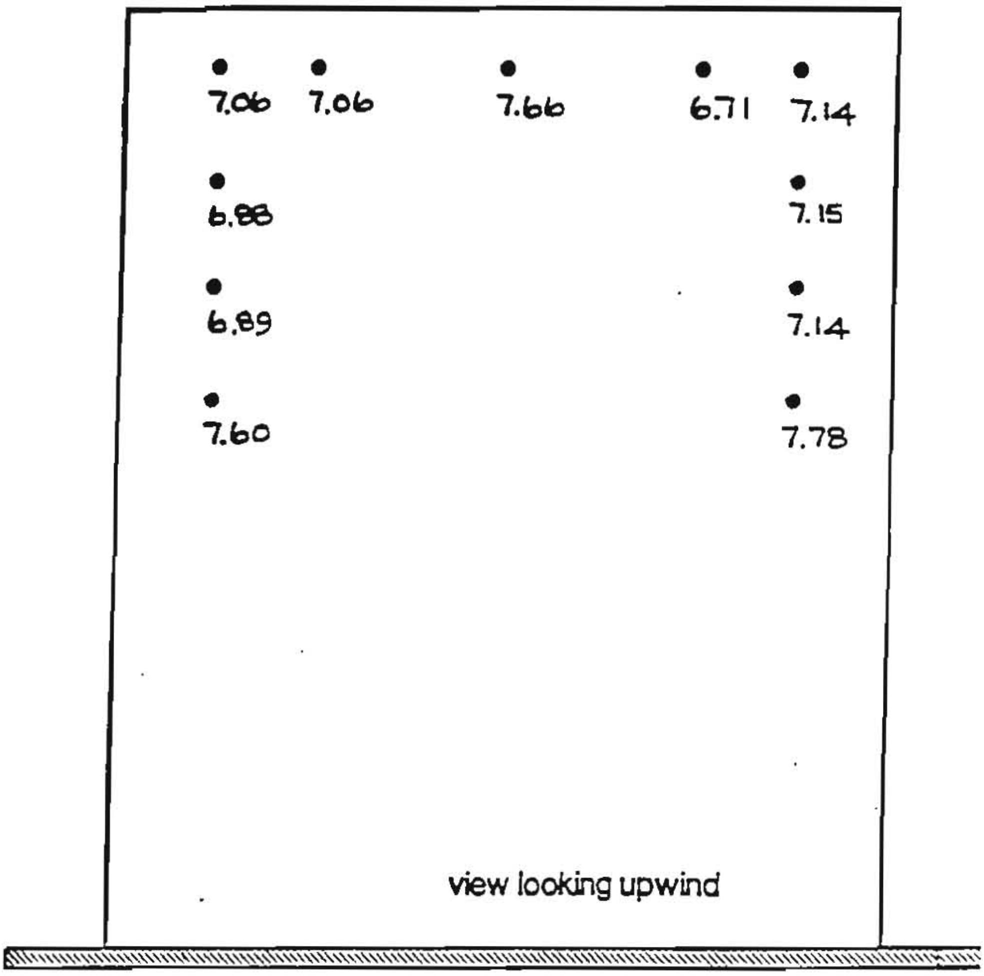
Length of corridor = 14.4 m
Height of corridor = 2.5 m
Width of corridor = 2.7 m
Width of track = 0.6 m

Height of aperture = 2.1 m
Width of aperture = 1.8 m
Length of ante room = 2.8 m
Width of ante room = 3.4 m

Camera Positions - *

Figure 4: Plan of the research facility

SPEED SETTING NUMBER 1

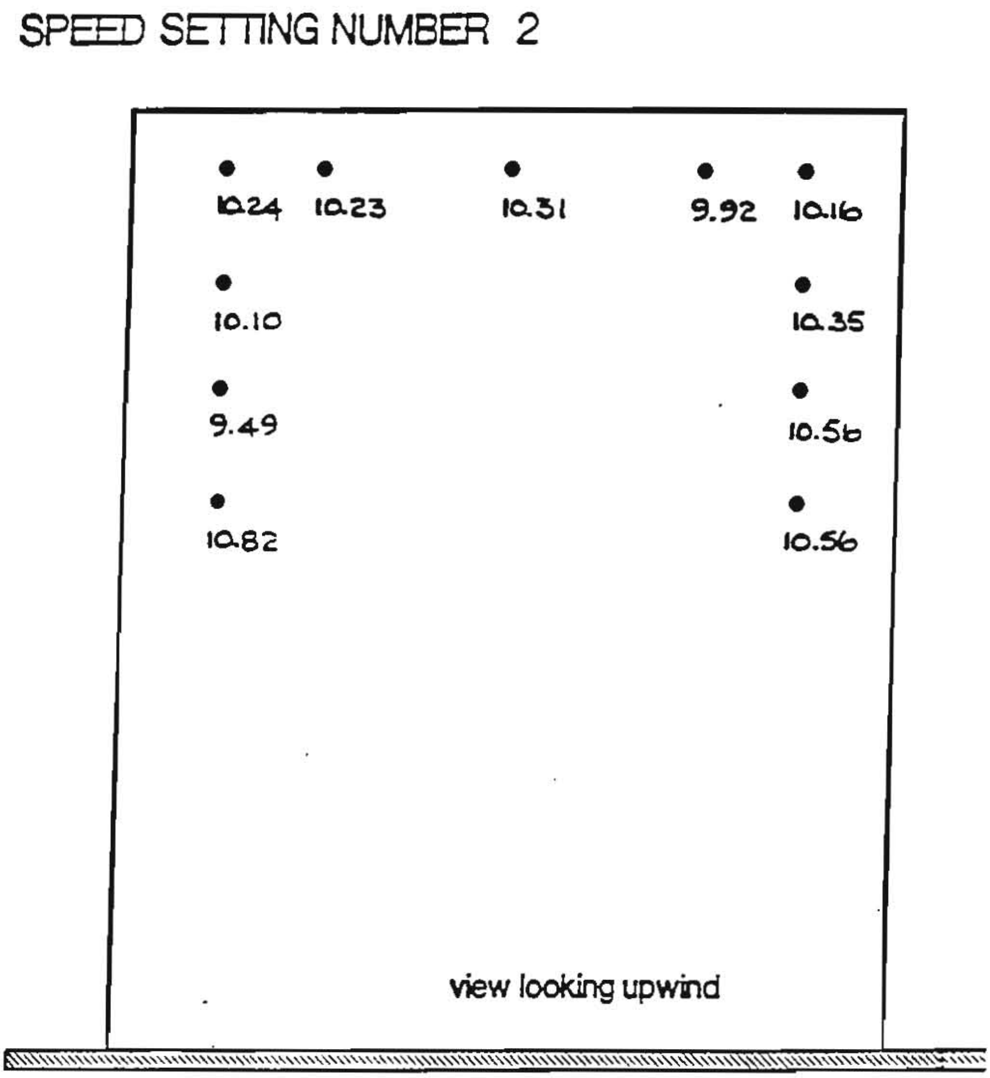


Measurements in plane of aperture.
Number of people in working section area = 8

(local velocity shown in metres/second)

Figure 5: Interference effects due to presence of group in aperture - Wind speed 1

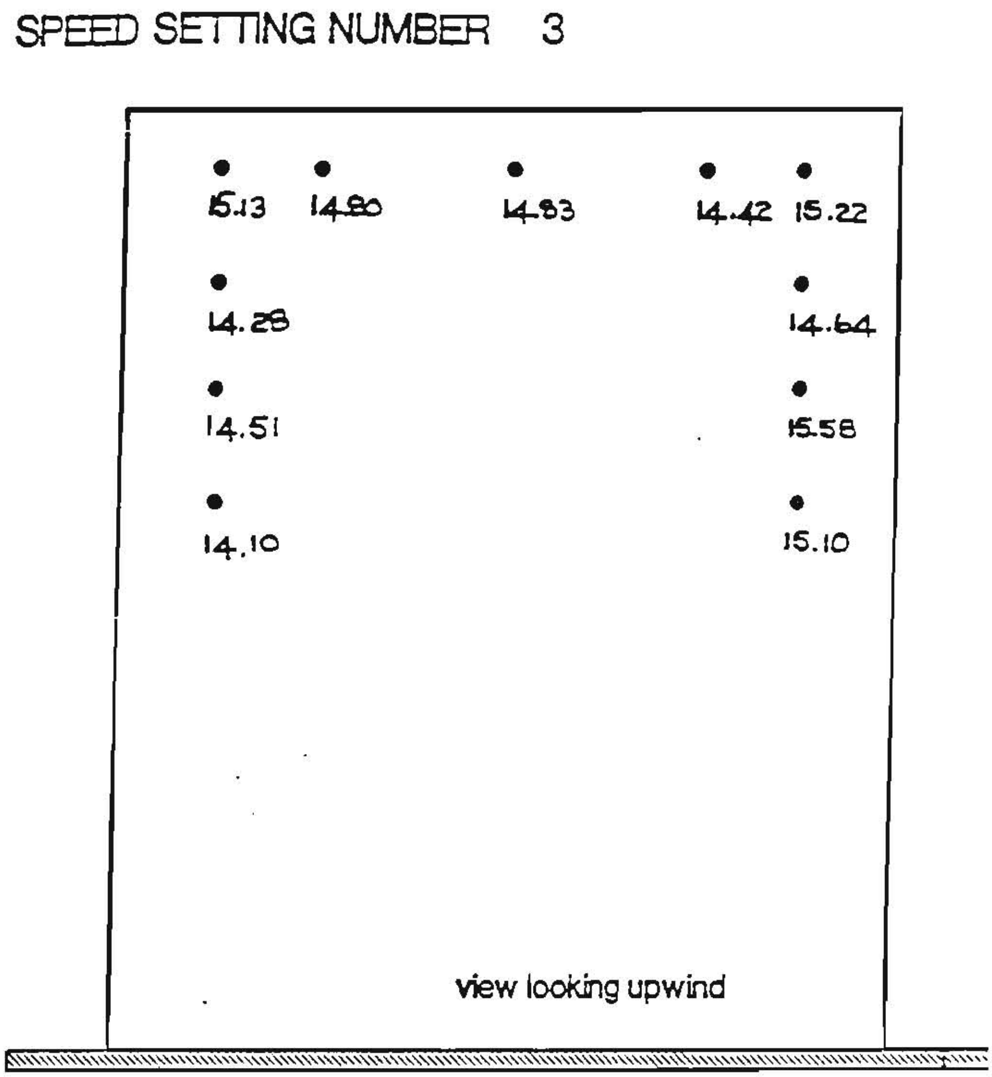
APPENDIX B:



Measurements in plane of aperture.
Number of people in working section area = 8

(local velocity shown in metres/second)

Figure 6: Interference effects due to presence of group in aperture - Wind speed 2



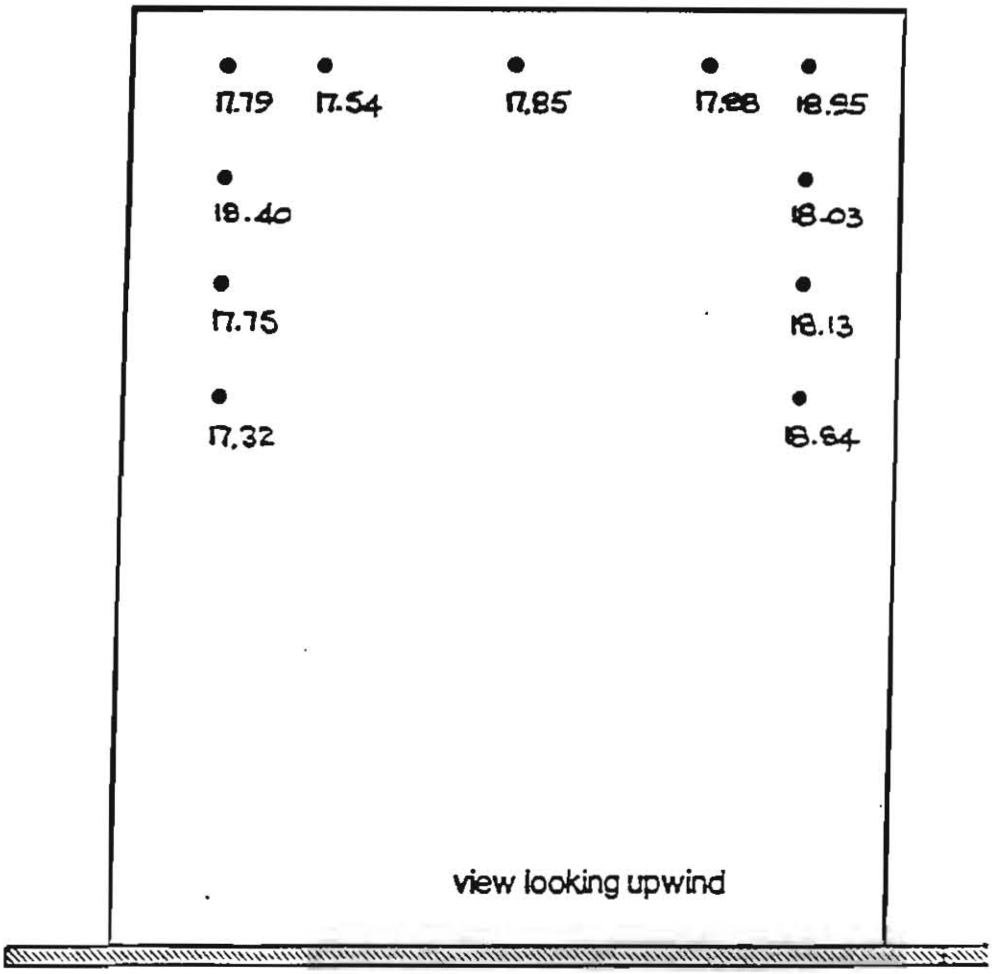
Measurements in plane of aperture.
Number of people in working section area = 8

(local velocity shown in metres/second)

Figure 7: Interference effects due to presence of group in aperture - Wind speed 3

APPENDIX B:

SPEED SETTING NUMBER 4



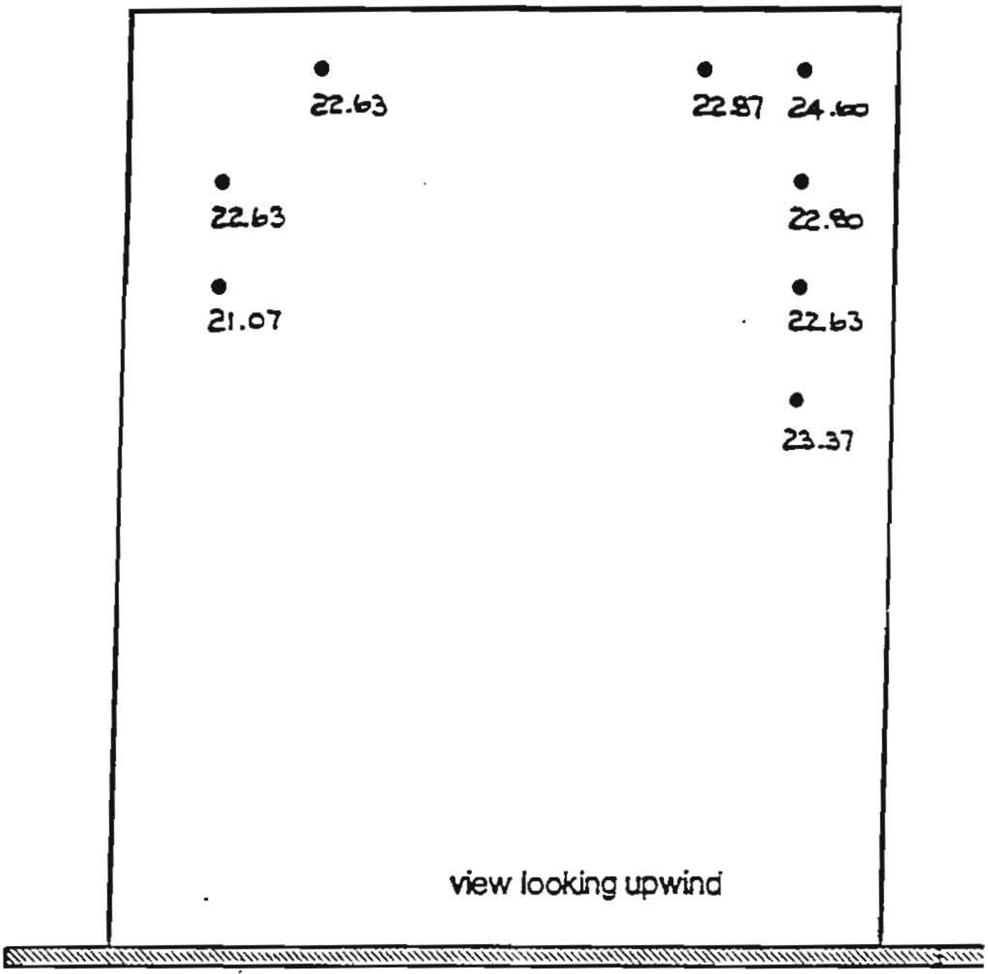
Measurements in plane of aperture.
Number of people in working section area = 8

(local velocity shown in metres/second)

Figure 8: Interference effects due to presence of group in aperture - Wind speed 4

APPENDIX B:

SPEED SETTING NUMBER 5

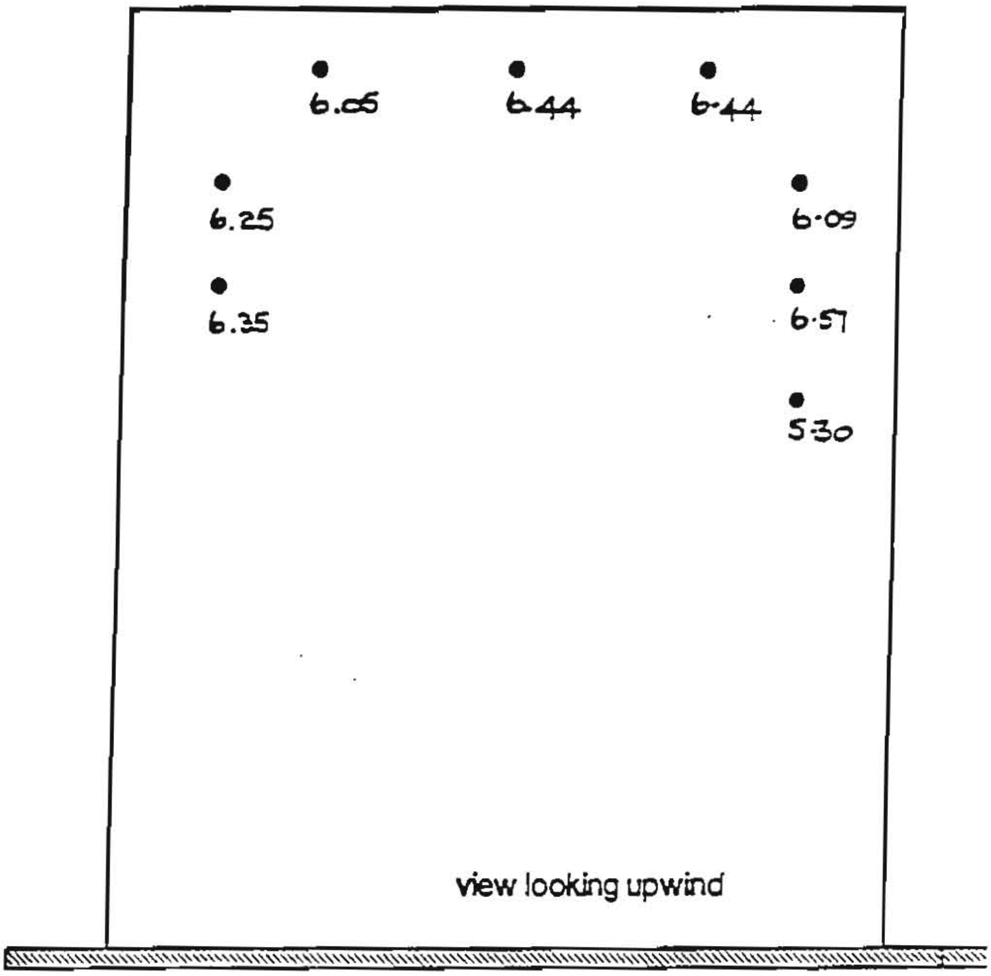


Measurements in plane of aperture.
Number of people in working section area = 8

(local velocity shown in metres/second)

Figure 9: Interference effects due to presence of group in aperture - Wind speed 5

SPEED SETTING NUMBER 1

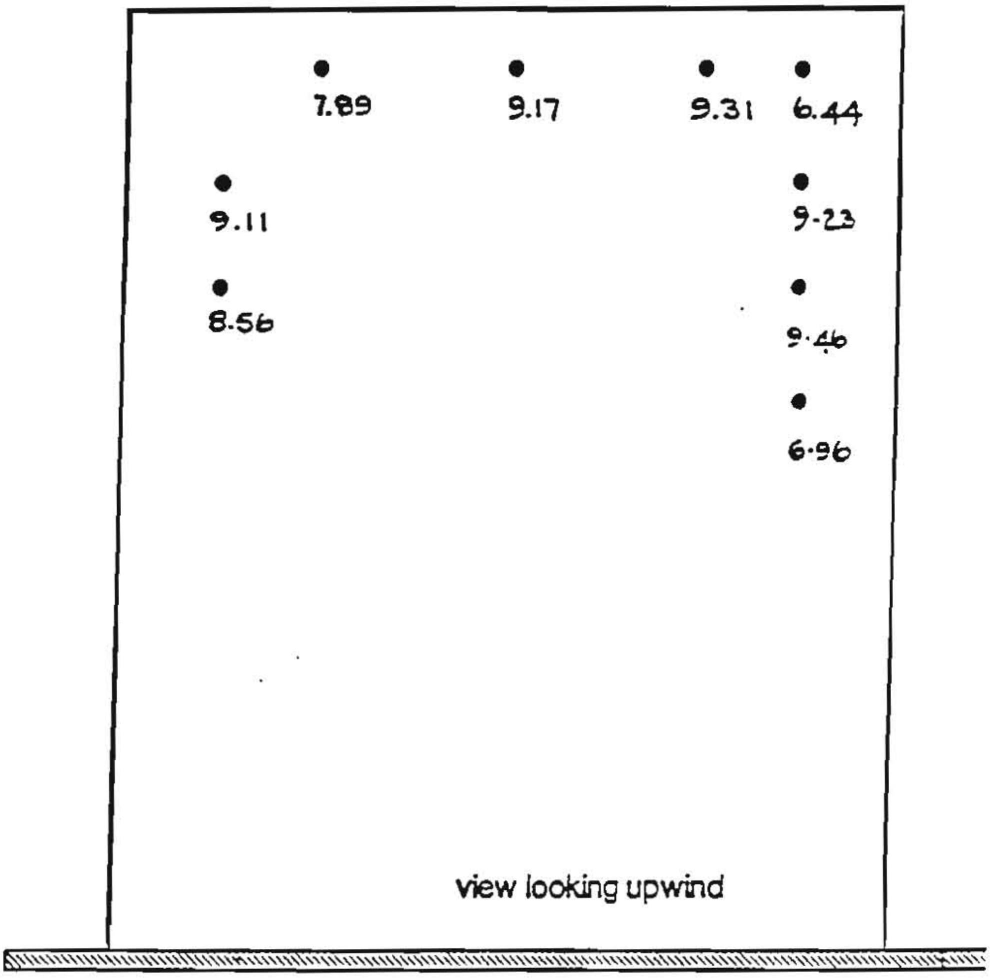


Measurements in a plane 1 metre downstream of aperture.
Number of people in working section area = 8

(local velocity shown in metres/second)

Figure 10: Interference effects due to presence of group 1 metre downstream from aperture - Wind speed 1

SPEED SETTING NUMBER 2

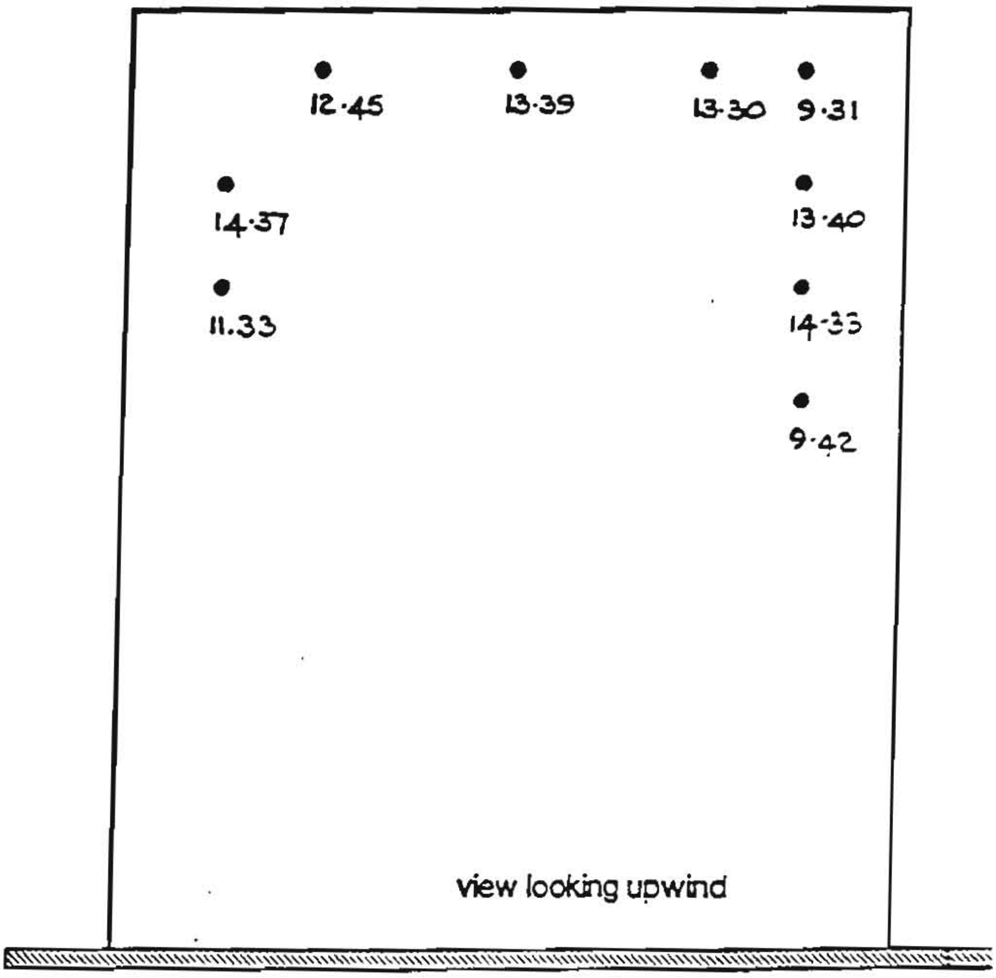


Measurements in a plane 1 metre downstream of aperture.
Number of people in working section area = 8

(local velocity shown in metres/second)

Figure 11: Interference effects due to presence of group 1 metre downstream from aperture - Wind speed 2

SPEED SETTING NUMBER 3

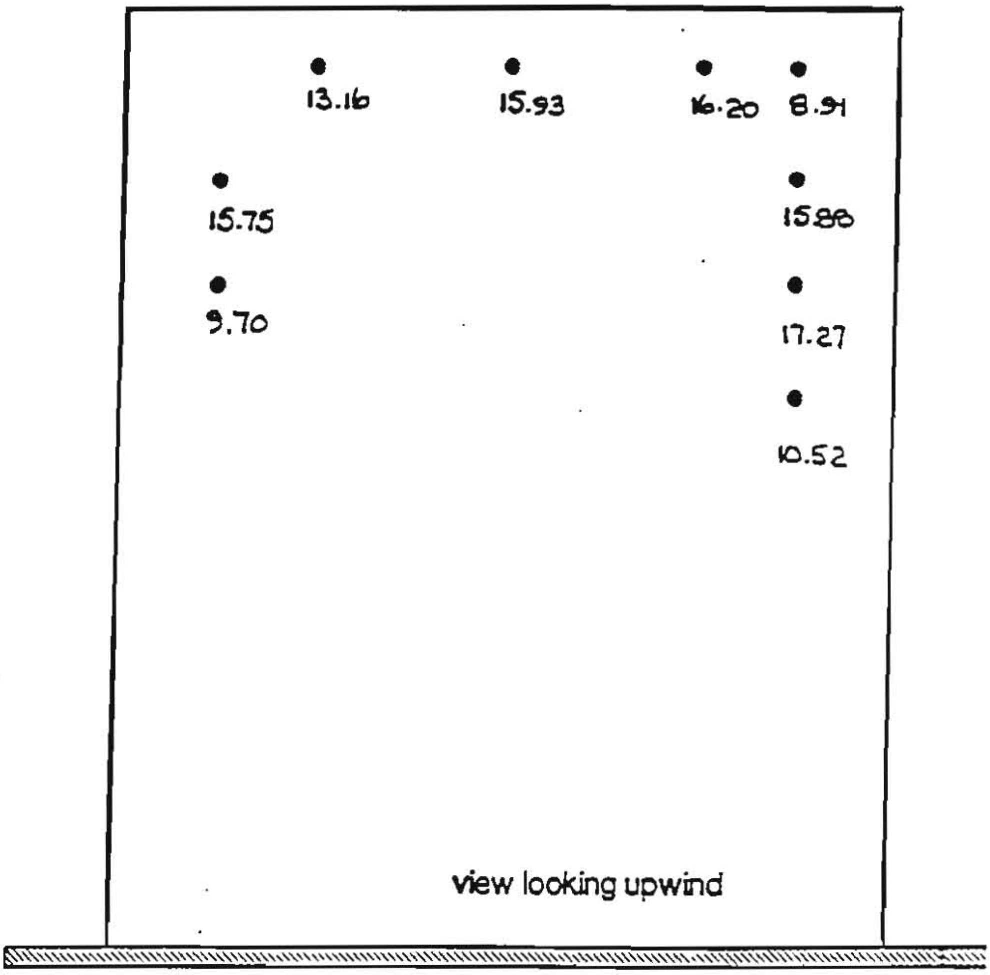


Measurements in a plane 1 metre downstream of aperture.
Number of people in working section area = 8

(local velocity shown in metres/second)

Figure 12: Interference effects due to presence of group 1 metre downstream from aperture - Wind speed 3

SPEED SETTING NUMBER 4



Measurements in a plane 1 metre downstream of aperture.
Number of people in working section area = 8

(local velocity shown in metres/second)

Figure 13: Interference effects due to presence of group 1 metre downstream from aperture - Wind speed 4

APPENDIX C: MEAN EVACUATION RATES - INDIVIDUAL TESTS

Table 11 shows the mean evacuation rates (in metres per second) of each of the experimental groups of individual participants to negotiate the corridor. The total length of the track is 12.661 metres.

Table 11: Mean evacuation rates for each experimental group

Experimental Group:	Mean Escape Rates (m/s): Air Flow Rate: 1	2	3	4	5
Adults aged 20 to 54 - Walking:	2.21	2.19	2.21	2.16	2.08
Adults aged 20 to 54 - Running:	3.54	3.56	3.53	3.44	3.29
Adult with infant in pushchair:	2.05	1.96	1.93	1.88	1.81
Adults aged over 60 years:	1.73	1.74	1.68	1.65	1.48
Children aged 12-14 years:	3.81	3.72	3.65	3.58	3.38
Wheelchair pushers:	1.56	1.51	1.47	1.45	1.37
Adults with restricted mobility:	1.36	1.34	1.27	1.26	1.17

APPENDIX D: MEAN ESCAPE TIMES FOR SECTORS A, B & C - INDIVIDUAL TESTS

Tables 12 to 14 (below and over) give the mean evacuation times for each group of individual participants (including the 20 to 54 year old adults from the initial phase of the research) to negotiate each of the three sub-sections of the shopping precinct.

Table 12: Mean Escape Times for Sector A - Individual Tests

Experimental Group:	Mean Escape Times (secs.): Air Flow Rate: 1	2	3	4	5
Adults aged 20 to 54 Walking:	1.59 (0.29)	1.56 (0.22)	1.56 (0.25)	1.59 (0.24)	1.62 (0.28)
Adults aged 20 to 54 - Running:	1.22 (0.20)	1.21 (0.20)	1.22 (0.21)	1.27 (0.17)	1.26 (0.21)
Adults with infant in pushchair:	2.19 (0.66)	2.23 (0.66)	2.27 (0.72)	2.24 (0.65)	2.23 (0.42)
Adults aged over 60 years:	2.15 (0.62)	2.24 (0.66)	2.26 (0.71)	2.26 (0.69)	2.48 (0.84)
Children aged 12-14 years:	1.15 (0.15)	1.21 (0.09)	1.19 (0.15)	1.26 (0.17)	1.22 (0.15)
Wheelchair pushers:	2.75 (0.53)	2.77 (0.69)	2.91 (0.76)	2.90 (0.66)	2.96 (0.82)
Adults with restricted mobility:	2.52 (1.13)	2.59 (1.14)	2.82 (1.56)	2.67 (1.01)	2.74 (1.07)

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Table 13: Mean Escape Times for Sector B - Individual Tests

Experimental Group:	Mean Escape Times (secs.): Air Flow Rate: 1	2	3	4	5
Adults aged 20 to 54 - Walking:	2.94 (0.39)	2.99 (0.47)	2.97 (0.41)	3.04 (0.46)	3.20 (0.44)
Adults aged 20 to 54 - Running:	1.66 (0.30)	1.65 (0.32)	1.71 (0.31)	1.73 (0.32)	1.83 (0.37)
Adult with infant in pushchair:	2.82 (0.53)	3.05 (0.83)	3.10 (0.80)	3.19 (0.84)	3.38 (1.29)
Adults aged over 60 years:	3.56 (1.31)	3.56 (1.26)	3.74 (1.35)	3.82 (1.40)	4.33 (1.64)
Children aged 12-14 years:	1.56 (0.14)	1.60 (0.13)	1.64 (0.17)	1.63 (0.24)	1.80 (0.12)
Wheelchair pushers:	3.80 (1.00)	3.91 (1.18)	3.97 (1.26)	4.06 (1.17)	4.41 (1.28)
Adults with restricted mobility:	4.77 (1.93)	4.91 (2.36)	5.07 (2.15)	5.15 (1.86)	5.53 (2.05)

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Table 14: Mean Escape Times for Sector C - Individual Tests

Experimental Group:	Mean Escape Times (secs.): Air Flow Rate: 1	2	3	4	5
Adults aged 20 to 54 - Walking:	1.19 (0.17)	1.22 (0.22)	1.21 (0.19)	1.22 (0.18)	1.28 (0.18)
Adults aged 20 to 54 - Running:	0.70 (0.19)	0.70 (0.18)	0.67 (0.18)	0.68 (0.16)	0.76 (0.24)
Adult with infant in pushchair:	1.17 (0.29)	1.19 (0.32)	1.21 (0.37)	1.30 (0.32)	1.39 (0.38)
Adults aged over 60 years:	1.61 (1.03)	1.47 (0.66)	1.53 (0.65)	1.58 (0.76)	1.73 (0.76)
Children aged 12-14 years:	0.60 (0.10)	0.59 (0.11)	0.63 (0.08)	0.65 (0.09)	0.72 (0.10)
Wheelchair pushers:	1.56 (0.51)	1.72 (0.57)	1.71 (0.60)	1.80 (0.60)	1.90 (0.72)
Adults with restricted mobility:	2.01 (0.93)	1.97 (0.98)	2.06 (0.87)	2.23 (1.46)	2.51 (1.05)

APPENDIX E: NEWMAN-KEULS POST-HOC TESTS OF SIGNIFICANCE - INDIVIDUAL TESTS

Tables 15 to 28 (below and over) summarise the Newman-Keuls post-hoc tests of significance performed in conjunction with the ANOVAs to determine which air flow velocities produced significantly different evacuation rates. Summaries are provided for each category of participant in turn, and include analyses of evacuation rates for the whole task and for each of Sector A, B and C in isolation. Following these, the equivalent tables for the post-hoc tests on safety ratings are presented (Tables 29 and 30). Finally, Table 31 shows the post-hoc test performed to compare the various sets of individuals.

E.1 Adults with Infant in Pushchair

Table 15: Summary of Newman-Keuls Post-Hoc Test on Data from Adults with Infant in Pushchair - All Sectors

Air Flow Rate:

	1	**2**	**3**	**4**	**5**
1	-				
2		-			
3			-		
4	*			-	
5	**	*	*		-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 16: Summary of Newman-Keuls Post-Hoc Test on Data from Adults with Infant in Pushchair - Sector B

Air Flow Rate:

	1	**2**	**3**	**4**	**5**
1	-				
2		-			
3			-		
4				-	
5	*				-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX E:

Table 17: Summary of Newman-Keuls Post-Hoc Test on Data from Adults with Infant in Pushchair - Sector C

Air Flow Rate:

	1	2	3	4	5
1	-				
2		-			
3			-		
4	*	*	*	-	
5	**	**	**	*	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

E.2 Adults Aged Over 60 Years

Table 18: Summary of Newman-Keuls Post-Hoc Test on Data from Adults Aged Over 60 Years - All Sectors

Air Flow Rate:

	2	1	3	4	5
2	-				
1		-			
3			-		
4				-	
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX E:

Table 19: Summary of Newman-Keuls Post-Hoc Test on Data from Adults Aged Over 60 Years - Sector B

Air Flow Rate:

	1	2	3	4	5
1	-				
2		-			
3			-		
4				-	
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

E.3 12-14 Year Old Children

Table 20: Summary of Newman-Keuls Post-Hoc Test on Data from 12 to 14 Year Olds - All Sectors

Air Flow Rate:

	1	2	3	4	5
1	-				
2		-			
3	*		-		
4	**	*		-	
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX E:

Table 21: Summary of Newman-Keuls Post-Hoc Test on Data from 12 to 14 Year Olds - Sector B

Air Flow Rate:

	1	2	3	4	5
1	-				
2		-			
3			-		
4				-	
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 22: Summary of Newman-Keuls Post-Hoc Test on Data from 12 to 14 Year Olds - Sector C

Air Flow Rate:

	2	1	3	4	5
2	-				
1		-			
3			-		
4				-	
5	**	**	*		-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX E:

E.4 Wheelchair Pushers

Table 23: Summary of Newman-Keuls Post-Hoc Test on Data from Wheelchair Pushers - All Sectors

Air Flow Rate:

	1	2	3	4	5
1	-				
2		-			
3			-		
4	*			-	
5	**	**	**	*	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 24: Summary of Newman-Keuls Post-Hoc Test on Data from Wheelchair Pushers - Sector B

Air Flow Rate:

	1	2	3	4	5
1	-				
2		-			
3			-		
4				-	
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX E:

Table 25: Summary of Newman-Keuls Post-Hoc Test on Data from Wheelchair Pushers - Sector C

Air Flow Rate:

	1	3	2	4	5
1	-				
3	*	-			
2			-		
4	**			-	
5	**	*	*		-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

E.5 Adults with Restricted Mobility

Table 26: Summary of Newman-Keuls Post-Hoc Test on Data from Adults with Restricted Mobility - All Sectors

Air Flow Rate:

	1	2	3	4	5
1	-				
2		-			
3	**	*	-		
4	**	*		-	
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX E:

Table 27: Summary of Newman-Keuls Post-Hoc Test on Data from Adults with Restricted Mobility - Sector B

Air Flow Rate:

	1	2	3	4	5
1	-				
2		-			
3			-		
4	*			-	
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 28: Summary of Newman-Keuls Post-Hoc Test on Data from Adults with Restricted Mobility - Sector C

Air Flow Rate:

	2	1	3	4	5
2	-				
1		-			
3			-		
4				-	
5	**	**	**	*	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX E:

E.6 Safety Ratings - Individual Tests

Table 29: Summary of Newman-Keuls Post-Hoc Test on Safety Data from Adults with Infant in Pushchair

Air Flow Rate:

	5	4	3	2	1
5	-				
4		-			
3			-		
2	**	**	**	-	
1	**	**	*		-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 30: Summary of Newman-Keuls Post-Hoc Test on Safety Data from 12 to 14 Year Olds

Air Flow Rate:

	5	3	4	1	2
5	-				
3		-			
4			-		
1	**	*	*	-	
2	**	*	*		-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX E:

E.7 Comparison of Individual Categories

Key to categories:

A - Adults 20-54;
B - Adults with infants;
C - Children 12-14;
D - Wheelchair pushers;
E - Adults 60+;
F - Adults with restricted mobility.

Table 31: Summary of Newman-Keuls Post-Hoc Test on Data to Compare Categories of Individual Participants

	A	B	C	D	E	F
A	-					
B		-				
C			-			
D				-		
E	*				-	
F	*					-

* - Significant difference at the 5% level;
** - Significant difference at the 1% level.

APPENDIX F: NEWMAN- KEULS POST-HOC TESTS OF SIGNIFICANCE - GROUP TESTS

Tables 32-38 (below and over) summarise the Newman-Keuls post-hoc tests performed on the data for group evacuations for both high and low-density conditions. Following on, Tables 39 and 40 summarise the analyses for the analyses concerning perceptions of the safety of group evacuations.

F.1 High-density Evacuations

Table 32: Summary of Newman-Keuls Post-Hoc Test: High-Density Group Evacuations - All Sectors

Air Flow Rate:

	1				
1	-	2			
2	**	-	3		
3	**		-	4	
4	**	*		-	5
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 33: Summary of Newman-Keuls Post-Hoc Test: High-Density Group Evacuations - Sector A

Air Flow Rate:

	1				
1	-	2			
2		-	3		
3			-	4	
4				-	5
5	**	*	*	*	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX F:

Table 34: Summary of Newman-Keuls Post-Hoc Test: High-Density Group Evacuations - Sector B

Air Flow Rate:

	1	2	4	3	5
1	-				
2	*	-			
4	**		-		
3	**			-	
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 35: Summary of Newman-Keuls Post-Hoc Test: High-Density Group Evacuations - Sector C

Air Flow Rate:

	1	3	2	4	5
1	-				
3	*	-			
2	*		-		
4	**	**	**	-	
5	**	**	**		-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX F:

Table 36: Summary of Newman Keuls Post-Hoc Test: Low-Density Group Evacuations - All Sectors

Air Flow Rate:

	2	1	4	3	5
2	-				
1		-			
4	**	*	-		
3	**	**		-	
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 37: Summary of Newman-Keuls Post-Hoc Test: Low-Density Group Evacuations - Sector B

Air Flow Rate:

	2	1	3	4	5
2	-				
1		-			
3	**	**	-		
4	**	**		-	
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX F:

Table 38: Summary of Newman-Keuls Post-Hoc Test: Low-Density Group Evacuations - Sector C

Air Flow Rate:

	2	1	4	3	5
2	-				
1		-			
4	**	**	-		
3	**	**		-	
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 39: Summary of Newman-Keuls Post-Hoc Test Safety Data: High-Density Group Evacuations

Air Flow Rate:

	5	4	3	1	2
5	-				
4	**	-			
3	**		-		
1	**	**	**	-	
2	**	**	**		-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX F:

Table 40: Summary of Newman-Keuls Post-Hoc Test Safety Data: Low-Density Group Evacuations

Air Flow Rate:

	5	4	3	2	1
5	-				
4	**	-			
3	**	*	-		
2	**	**	**	-	
1	**	**	**		-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX G: EVACUATION TIMES BY START POSITION - GROUP TESTS

Tables 41 and 42 (below) present the mean times of each of the twelve occupiers of each start position during the evacuations performed on groups of eight for high-density and low-density evacuations respectively. Also included in these tables are the F-statistics from the ANOVAs performed on the evacuation times for each set of position occupiers. Finally, Tables 43 through to 53 present summaries of the post-hoc tests carried out on these evacuation times.

Table 41: Evacuation Times by Start Position - High Density Conditions

Mean Safety Ratings:

Start Position:	Air Flow Rate: 1	2	3	4	4	F-Ratio
1	4.24 (1.30)	4.44 (1.44)	4.39 (1.38)	4.53 (1.27)	4.76 (1.46)	5.82 (p=.001)
2	4.16 (1.39)	4.25 (1.55)	4.39 (1.39)	4.38 (1.35)	4.52 (1.58)	2.31 (p=.073)
3	3.72 (1.08)	4.10 (1.65)	3.87 (1.15)	4.04 (1.20)	4.18 (1.19)	2.00 (p=.111)
4	4.89 (1.49)	4.96 (1.66)	5.15 (1.59)	5.22 (1.55)	5.38 (1.78)	5.75 (p=.001)
5	5.03 (1.67)	5.15 (1.86)	5.07 (1.51)	5.17 (1.42)	5.28 (1.54)	1.02 (p=.408)
6	6.01 (1.85)	5.98 (1.96)	6.18 (1.86)	6.24 (1.88)	6.62 (2.15)	8.99 (p=.000)
7	5.57 (1.79)	5.62 (1.93)	5.74 (1.70)	5.81 (1.76)	6.09 (1.73)	9.07 (p=.000)
8	5.61 (1.65)	5.73 (1.69)	5.75 (1.59)	5.86 (1.53)	6.01 (1.70)	3.58 (p=.013)

APPENDIX G:

Table 42: Evacuation Times by Start Position - Low Density Conditions

Mean Safety Ratings:

Start Position:	**Air Flow Rate:** 1	2	3	4	4	**F-Ratio**
1	4.29 (1.46)	4.27 (1.38)	4.51 (1.49)	4.35 (1.28)	4.72 (1.55)	3.31 (p=.019)
2	4.32 (1.36)	4.26 (1.35)	4.37 (1.37)	4.27 (1.20)	4.55 (1.32)	2.20 (p=.085)
3	3.79 (1.17)	3.85 (1.14)	3.95 (1.15)	3.86 (1.04)	4.09 (1.08)	4.18 (p=.006)
4	4.62 (1.40)	4.44 (1.44)	4.60 (1.52)	4.70 (1.33)	4.88 (1.43)	4.09 (p=.007)
5	4.52 (1.61)	4.47 (1.56)	4.62 (1.56)	4.69 (1.53)	4.87 (1.56)	6.07 (p=.001)
6	5.23 (1.74)	5.20 (1.86)	5.45 (1.88)	5.42 (1.75)	5.64 (2.03)	3.51 (p=.014)
7	4.82 (1.40)	4.74 (1.49)	4.99 (1.58)	4.97 (1.37)	5.22 (1.52)	4.65 (p=.003)
8	4.65 (1.22)	4.61 (1.30)	4.77 (1.28)	4.78 (1.11)	4.96 (1.24)	1.79 (p=.148)

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Table 43: Summary of Newman-Keuls Post-Hoc Test: High-Density Group Evacuations - Start Position 1

Air Flow Rate:

	1	3	2	4	5
1	-				
3		-			
2			-		
4				-	
5	**	*	*	*	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 44: Summary of Newman-Keuls Post-Hoc Test: High-Density Group Evacuations - Start Position 4

Air Flow Rate:

	1	2	3	4	5
1	-				
2		-			
3			-		
4	*			-	
5	**	**			-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

APPENDIX G:

Table 45: Summary of Newman-Keuls Post-Hoc Test: High-Density Group Evacuations - Start Position 6

Air Flow Rate:

	2				
2	-	**1**			
1		-	**3**		
3			-	**4**	
4				-	**5**
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 46: Summary of Newman-Keuls Post-Hoc Test: High-Density Group Evacuations - Start Position 7

Air Flow Rate:

	1				
1	-	**2**			
2		-	**3**		
3			-	**4**	
4				-	**5**
5	**	**	**	**	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

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Table 47: Summary of Newman-Keuls Post-Hoc Test: High-Density Group Evacuations - Start Position 8

Air Flow Rate:

	1	2	3	4	5
1	-				
2		-			
3			-		
4				-	
5	**				-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 48: Summary of Newman-Keuls Post-Hoc Test: Low-Density Group Evacuations - Start Position 1

Air Flow Rate:

	2	1	4	3	5
2	-				
1		-			
4			-		
3				-	
5	*	*	*		-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

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Table 49: Summary of Newman-Keuls Post-Hoc Test: Low-Density Group Evacuations - Start Position 3

Air Flow Rate:

	1	2	4	3	5
1	-				
2		-			
4			-		
3				-	
5	**	*	*		-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 50: Summary of Newman-Keuls Post-Hoc Test: Low-Density Group Evacuations - Start Position 4

Air Flow Rate:

	2	3	1	4	5
2	-				
3		-			
1			-		
4				-	
5	**				-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

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Table 51: Summary of Newman-Keuls Post-Hoc Test: Low-Density Group Evacuations - Start Position 5

Air Flow Rate:

	2				
2	-	1			
1		-	3		
3			-	4	
4				-	5
5	**	**	*	*	-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

Table 52: Summary of Newman-Keuls Post-Hoc Test: Low-Density Group Evacuations - Start Position 6

Air Flow Rate:

	2				
2	-	1			
1		-	4		
4			-	3	
3				-	5
5	*	*			-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.

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Table 53: Summary of Newman-Keuls Post-Hoc Test: Low-Density Group Evacuations - Start Position 7

Air Flow Rate:

	2	1	4	3	5
2	-				
1		-			
4			-		
3				-	
5	**	**			-

* - Significant difference at the 5% level:
** - Significant difference at the 1% level.