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The assessment of fire hazards, tenability and human evacuation behaviour for fire safety engineering design
Erasmus Mundus Programme

Design Behavioural Scenarios – A simple but Effective Design Method for Assessing Escape Time

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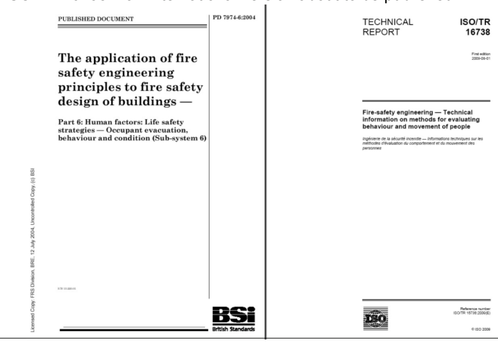
About British Standard PD7974-6

This lecture centres on PD7974-6 which contains a method developed for RSET design calculations applicable to a range of different premises. Also: ISO/TR 16738 – an international version about to be published



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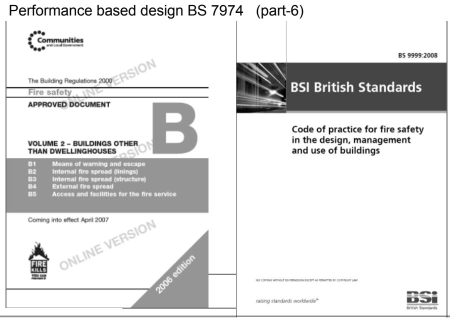
Three methods for Means of Escape Design

Design for means of escape can use one of three approaches:

- Prescriptive guidance (Approved Document B)
- Prescriptive guidance with some flexibility for trade-offs (BS9999)
- Performance based design BS 7974 (part-6)



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Calculation of time to evacuate any occupied enclosure

So basically that is all AD B does to control horizontal means of escape:

- Floor space factors – Exit widths – Travel distances to exits/protected escape routes
- Control of fire spread of linings.
- Fire resisting construction

For shopping malls still calls up BS5588 Part 10 for travel distances

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Principles of approach used in BS9999 and BS7974

For both BS9999 and BS7974 design for means of escape is depends upon a performance-based comparison between Available Safe Escape Time (ASET) and Required Safe Escape Time (RSET)

ASET > RSET + safety margin

For BS7974 guidance is presented in the PDs to enable an engineer to perform these calculations for any specific performance-based design for an individual building. The engineer can in principle use any legitimate means to achieve this including trade-offs between travel distance and sprinklers for example.

For BS9999 a set of such fire engineering calculations were performed for generic buildings with different occupancy types and different fire risks. The results were used to develop a prescriptive guidance set to enable a designer to achieve an acceptable level of performance for different building types.

The basic concept is that means of escape provisions can be traded off against predicted fire performance – if the fire performance is good with low fire risk or active protection, then the means of escape provisions (e.g. travel distances, exit and stair numbers and widths) can be less stringent

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Principles of approach used in BS9999

- The main criteria in BS9999 are the fire risk and the occupancy categories
- These occupancy categories have implications for RSET times

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BS 9999: Fire Growth Rates

- ASET then depends upon the predicted fire growth rates for different types of fuel loads
- Fire engineers classify fires in tow 4 categories with different t^2 growth rates

6.3 Fire growth rate

The fire growth rate is the rate at which it is estimated that a fire will grow. Fire growth rates should be categorized in accordance with Table 3.

NOTE A building with a high fire load density will not necessarily have a rapid fire growth rate, and low fire load density will not necessarily have a slow fire growth rate.

Table 3 **Fire growth rates**

Category	Fire growth rate	Examples	Fire growth parameter [A] kJ/s^3
1	Slow	Banking hall, limited combustible materials	0.002 9
2	Medium	Stacked cardboard boxes, wooden pallets	0.012
3	Fast	Baled thermoplastic chips, stacked plastic products, baled clothing	0.047
4	Ultra-fast	Flammable liquids, expanded cellular plastics and foam	0.188

[A] This is discussed in PD 7974-1.

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BS7974 fire growth rate curves

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Principles of approach used in BS9999

- The main criteria in BS9999 are the fire risk and the occupancy categories

Table 4 **Risk profiles**

Occupancy characteristic (from Table 2)	Fire growth rate		Risk profile
A (Occupants who are awake and familiar with the building)	1	Slow	A1
	2	Medium	A2
	3	Fast	A3
	4	Ultra-fast	A4 [A]
B (Occupants who are awake and unfamiliar with the building)	1	Slow	B1
	2	Medium	B2
	3	Fast	B3
	4	Ultra-fast	B4 [A]
C (Occupants who are likely to be asleep)	1	Slow	C1 [B]
	2	Medium	C2 [B]
	3	Fast	C3 [B, C]
	4	Ultra-fast	C4 [A, B]

[A] These categories are unacceptable within the scope of BS 9999. Addition of an effective localized suppression system or sprinklers will reduce the fire growth rate and consequently change the category (see 6.5).

[B] Risk profile C may be divided into sub-categories, viz. Ci1, Cii1, Ciii1, etc.

[C] Risk profile C3 will be unacceptable under many circumstances unless special precautions are taken.

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About British Standard PD7974-6

Life Safety Strategies – Occupant Evacuation, Behaviour and Condition

- PD6: life safety aspects of FSE design for evacuation
- Covers all aspects of people and life safety: behaviour in emergencies, evacuation and what happens when people are confronted by, or exposed to, heat and toxic smoke.
- Prescriptive codes concentrate on physical aspects of means of escape: warning systems, horizontal and vertical escape routes and compartmentation.
- Performance-based design uses these and other aspects to make a time-based comparison of fire hazard and evacuation. The principle is:

  Available Safe Escape Times (ASET) > Required Safe Escape Time (RSET) by an appropriate safety margin

  ASET Available Safe Escape Time = time from ignition to loss of tenability
  RSET Required Safe Escape Time = time from ignition to escape

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Topics

Performance-based design principle:

Available Safe Escape Time > Required Safe Escape Time by an appropriate safety margin

ASET = time from ignition to loss of tenability
RSET = time from ignition to escape

- Both time lines have a number of stages, all of which need to be addressed to obtain a realistic design outcome
- Some are well understood and quantified while others are often oversimplified or ignored.
- Considerable efforts and expense are directed at research, testing and data collection for different features affecting ASET, very little is directed at features affecting escape behaviour, although this can be equally important in terms of life-safety outcomes

●This presentation is aimed at the identification of:
  - Methods that can be used for the evaluation of escape time (RSET) in a range of building types
  - Data needs for the application of these methods in engineering design and research priorities for obtaining the necessary data

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Escape time formula

RSET (Δt_{esc}) $= \Delta t_{det} + \Delta t_{a} + \Delta t_{pre} + \Delta t_{trav}$

(Evacuation time $\Delta t_{evac} = \Delta t_{pre} + \Delta t_{trav}$)

$\Delta t_{pre} = \Delta t_{pre(first\ occupants)} + \Delta t_{pre(occupant\ distibution)}$

- For each occupant pre-movement time depends upon recognition and response behaviours

Δt_{trav} depends upon:

- time to walk to an exit (walking time) time to flow through exits into protected escape routes
- merging flows antd time to flow through horizontal and vertical escape routes
- for populations of occupants there are considerable interactions between the different phases

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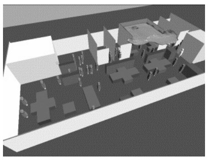
Pre-movement time characteristics

What is meant by pre-movement time and how is it determined?



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Pre-movement process

- Pre-movement process
  - Starts at alarm or cue - ends when travel to exit begins.
  - Has two components:
    - Recognition - starts at alarm or cue ends with first response
    - Response - starts at first response - ends with travel to exit

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Pre-movement processes

Recognition: occupants continue with pre-alarm activities
- e.g. Working, Shopping, sitting, eating, watching football

Response: occupants carry out a range of activities:
- Investigative behaviour to find source of fire
- Stopping machinery, securing money or other risks
- Gathering children and other family members
- Wayfinding
- Alerting others
- Fighting fire

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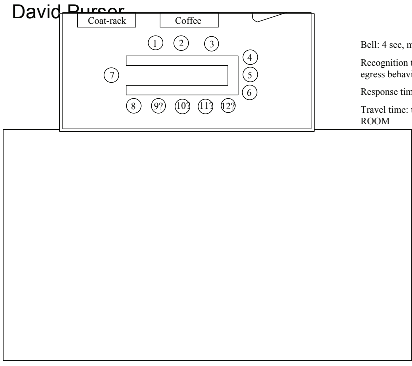

Bell: 4 sec, message: 13s, Total: 17s

Recognition time: time until first movement of egress behaviour

Response time: time to prepare to leave

Travel time: time to turn to face exit and leave ROOM

? Location out of view of camera. Occupant position guessed
* Re-enters to collect jacket. Leaves again at 84 sec

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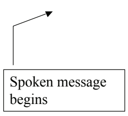
Shopping centre evacuation behaviour measurements



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Pre-movement time

Although understanding recognition and response processes is important in understanding pre-movement behaviours and why time is required to complete them, they are difficult to quantify

Also, while each individual occupant has a recognition and response time, it is the overall pre-movement time distribution of the occupant population that is important in terms of escape time

It is more useful in terms of calculating evacuation times to consider pre-movement time in terms of two time components:

- The time between the alarm sounding and the response of the first few occupants $\Delta t_{pre\ first\ occupants}$
- The pre-movement time distribution of the occupants $\Delta t_{pre\ distribution}$

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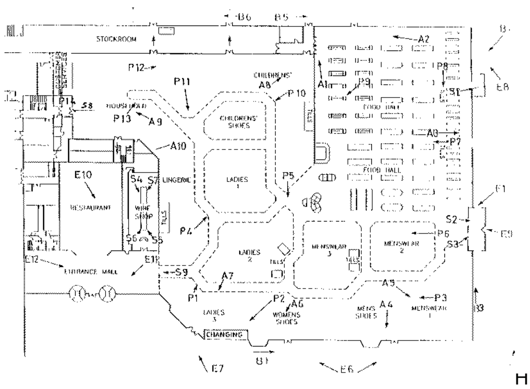
Store with foodhall



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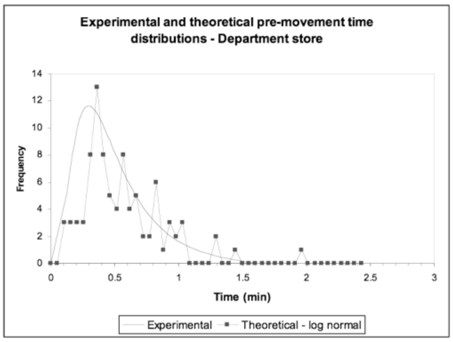
Distribution of pre-movement times



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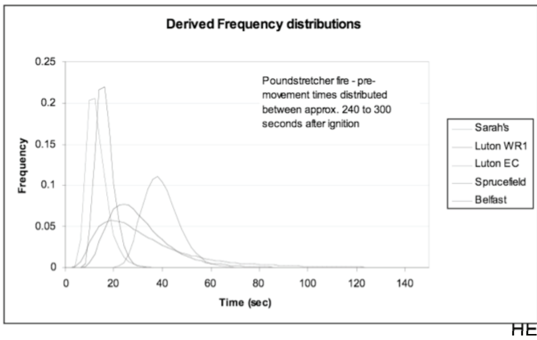
Pre-movement time distributions



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Pre-movement time

How should the pre-movement time distribution be represented in an escape time calculation?

Is it possible to use a single time to represent that of the whole population?

- Pre-movement time of first occupants to move? – over optimistic
- Mean or mode? – may still not allow for survival of slower movers
- Pre-movement time of last occupants to move ? – say 95th or 99th percentile or last to move? – perhaps too conservative
- Another problem is that pre-movement times interact with travel times, while some occupants are still in their pre-movement phase others are in their travel phase, so what effect does this have on overall escape or evacuation time?

Using a computer simulation in which each individual is represented it is possible to take into account all individual pre-movement times and all individual travel times.

It is then possible to determine how they interact in different situations. It is also possible to determine the errors likely in using a single number to represent pre-movement time in simple evacuation calculations

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Pre-movement and travel times

- Calculation outcomes are time-dependent.
- Methods are needed to quantify these processes, their probability distributions and the interactions between them for different scenarios
- Data are needed for the main variables and functions to provide outputs in terms of calculated escape times

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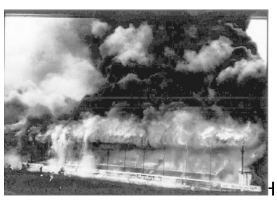

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Bottom up and top down approaches

- All terms in escape time calculation involve human cognition and behaviour as well as physical processes
- Two possible methods for calculation or computer simulations:
  - Bottom up approach - Detailed data on individual occupants, their cognitive processes and behaviours in response to a range of cues as the emergency develops. Detailed behaviours assembled into predictive computational evacuation models for specific scenarios
  - Top down approach - Identify the main stages of an evacuation and obtain experimental data on the times required to complete these stages in different situations (from fire incidents or experimental evacuations). Use these data and distributions as input to evacuation time calculations

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Bottom up approach

Problems:

- Most research on human behaviour has been qualitative
- Number and range of variables rapidly becomes very large, especially as the number of occupants increases
- Data seldom available for even the simpler variables, let alone the more complex ones

Uses:

- Have demonstrated the complexity of evacuation behaviours
- Provide fruitful interaction between behavioural scientists and modellers
- Identification of important aspects can be used to design systems to optimise emergency response
- Identification of qualitative features most important to behavioural outcomes.

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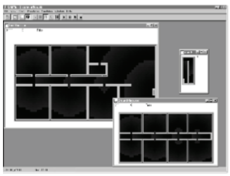
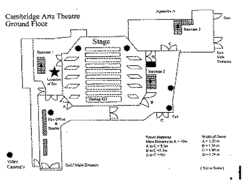
Top down approach

Advantages:

- Simple and empirical, based upon a small range of readily identified qualitative features, simple calculation algorithms and measured data
- Easily verified and validated
- Sensitivity and complexity can be increased as more aspects are developed but simple models can provide valid results





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Basis of a top down method

Main requirements are:

- Good physical movement model.
  - Major components of movement and flow have been measured and developed into validated calculation and computational models
  - Further experimental research is required to provide data and improved algorithms for
    - *Merging flows in different building geometries*
    - *wayfinding and exit choice behaviour*
    - *Distributions of unimpeded walking speeds*
- Data on warning times for different scenarios
- Data on times required for different behaviours involved in pre-movement time distributions in different situations.
- Data on effects of exposure to irritant smoke and heat on escape behaviour and movement speed

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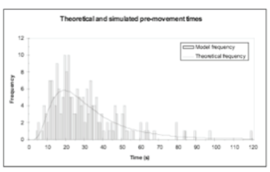
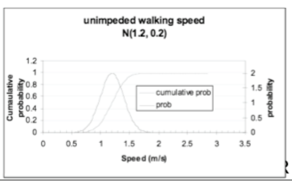
Basis of a top down method

Main considerations are:

- What are most important quantifiable aspects ?
- What are most important qualitative aspects ?
- How can these be combined to obtain data usable in evacuation calculations ?





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Main qualitative and quantifiable aspects

Occupant escape behaviours depend upon :

- Building characteristics
- Occupant characteristics
- Fire dynamics

Although some aspects are quantifiable those affecting behaviour are essentially qualitative. Although factors affecting individuals are complex, when groups of occupants are considered a range of common situations and scenarios can be identified.

These can be used to predict generic evacuation times for design.

A set of key qualitative building and occupant features is used to specify a small number of "design behavioural scenarios"

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Main qualitative and quantifiable aspects

The main qualitative features used to define the scenarios are :
- Occupant alertness (awake or sleeping)
- Occupant familiarity (familiar or unfamiliar)
- Single or multi-enclosures

Further qualitative features influencing response times in any particular scenario:
- Alarm system
- Spatial complexity
- Fire safety management system

Quantitative features for any particular scenario:

- Pre-movement time distribution
- Occupant numbers
- Building features (dimensions, escape routes)
- (Features of fire and fire dynamics) – behaviour and movement in smoke

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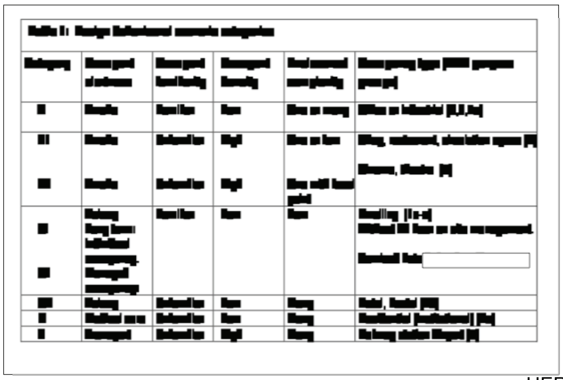

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Factors affecting Pre-movement time

- Pre-movement time (Pre Travel Activity Time) is affected by many variables related to individual occupant and group behavioural characteristics, the nature of the occupancy, the building and its systems. Some of the more important include:
- Alertness (sleeping/waking)
- Occupants familiar or unfamiliar with building and systems
- Fire safety management: extent to which trained staff/floor wardens encourage evacuation
- Warnings: sounder, pre-recorded voice alarm or directed Personal Address
- Activities: commitment to ongoing activities
- Training and previous experience
- Group interactions: extent to which evacuation of a group is influenced by individuals (especially staff trained in emergency evacuation procedures)

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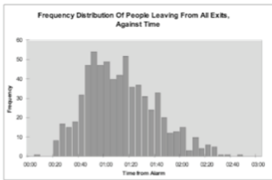
Data needs for scenario classification

- Data-base of pre-movement time distributions from a large sample of buildings in each category
- Pre-movement time distributions for sub-categories and sub-populations (e.g. staff, diners, shoppers, audiences)
- Research to improve scenario definition (also sub-categories and sub-populations)



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Categorization of key semi-quantitative factors affecting escape time

In addition to the major design behavioural categories there are three key variables affecting evacuation performance in each behavioural scenario. Each of these has been classified into three levels of performance.

- **Fire safety management provision**
- **Type of alarm system**
- **Building complexity**

The second two features interact with the management since they comprise part of the fire safety management tools. For example it is easy to obtain a rapid and efficient evacuation when a detector activates an immediate general alarm and the building consists of a simple rectangular single-storey enclosure with many exits and good visual access.

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Major determinants of Escape time

For any particular scenario category evacuation time also depends upon:

- **Fire safety management**
- **Alarm system**
- **Building complexity**

These are each classified into three levels with respect to effects on escape time

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Time to alarm

Level A1 alarm system: Automatic detection activating immediate general alarm

Δt_a = 0 Alarm time effectively zero

Level A2 (two stage) alarm system: Automatic detection providing a pre-alarm to security, manually (or automatic time-out delay) activated general alarm. Alarm time should be taken as the fixed delay. For a voice alarm system add message time x 2

Δt_a = time out delay (usually 2 or 5 minutes)

Level A3 alarm system: Local automatic detection and alarm near the fire or no automatic detection with manually activated general alarm.

Δt_a = likely to be long and unpredictable

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Levels of building complexity

- **Building level B1: - e.g. simple supermarket**
  - **Simple rectangular single storey building**
  - **One or few enclosures**
  - **simple layout, good visual access to exits and outside**
  - **short travel distances good exit provision leading directly to outside**
- **Building level B2 - example simple multi-storey office block**
  - **Simple multi-enclosure and/or multi-storey building**
  - **most features prescriptively designed**
  - **Simple internal layout**
- **Building level B3 - e.g old hotel of department store or modern entertainment complex**
  - **Large complex building:**
    - **formed by integration of a number of existing buildings on the same site -**
    - **modern complex such as a leisure centre, shopping mall or airport**
  - **large and complex spaces so occupants may have wayfinding difficulties and managing an evacuation is challenging**

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Levels of fire safety management

The quality of the fire safety management strategy and its implementation are the most important features for obtaining a rapid and efficient evacuation and are part of the FSE design

- Level M1 : shortest and most reliable escape times. High level of management and staff training, independent certification
- Level M2 designs for an efficient evacuation but with somewhat lower level of provision providing longer times and with wider margins of variability than for a level 1 system
- Level M3 would represent the basic minimum requirements for an efficient evacuation. Efficient management of an evacuation is required, but with significantly longer escape times likely than for level 2 and a wide margin of variability

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Levels of fire safety management

The design escape time would depend upon the level of fire safety management and would be part of the fire safety design strategy

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Levels of fire safety management

The main components of a fire safety management system (tools available to the fire safety manager) are:

- **The familiarity and level of training of the building staff and any other occupants. The staff resources available to manage an evacuation**
- **The detection and warning system. A level A1 warning system with immediate general alarm after detection provides for a more rapid evacuation than a level A2 two stage system**
- **The physical escape routes: building complexity and escape route provision – (It is much easier to manage the evacuation of a single storey supermarket with many exits leading to the outside than a rambling, old fashioned city centre department store or a modern theatre and entertainment complex)**

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Levels of fire safety management

- **Level M1:**
  - **Well designed building with obvious and easy to use escape routes,**
  - **Level 1 The normal occupants (staff or residents) must be trained to a high level of fire safety management with good fire prevention and maintenance practice, floor wardens, a well-developed emergency plan and regular drills.**
  - **For “awake and unfamiliar” there must be a high ratio of trained staff to visitors.**
  - **The system and procedures are subject to independent certification, including a regular audit with monitored evacuations for which the performance must match the assumed design performance. Security videotapes from any incidents or unwanted alarms must me made available for audit under the certification scheme**
  - **This would normally require automatic detection and alarm system to a high level of provision (Level A1) If used by the public a voice alarm system should be provided.**
  - **The building would be well designed with obvious and easy to use escape routes (Building Level B1 or at least B2)**

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Levels of fire safety management

- **Level M2:**
  - **May involve more complex or lower level of building escape routes**
  - **May have, lower staff ratio, cannot guarantee that floor wardens always present.**
  - **May not include independent audit.**
  - **The assumed or design escape and evacuation times will be more conservative than for a Level 1 system, with longer times to general alarm, wider pre-movement time distributions and longer travel times.**
  - **May use a level A2 (two stage) alarm system**
  - **The building features may not be as simple to use (Level B2 or B3)**
- **Level M3:**
  - **Standard facilities, basic minimum fire safety management.**
  - **No independent audit.**
  - **Not suitable for a fire engineered design unless other measures are taken to ensure a high level of safety.**
  - **These might include restrictions on fire performance of contents, high levels of passive protection and/or active systems (e.g a prison).**
  - **Longer and more variable escape times are allowed for in the design**
  - **May not have an automatic detection system (Alarm Level A3)**
  - **The building may be complex (Building Level B3)**

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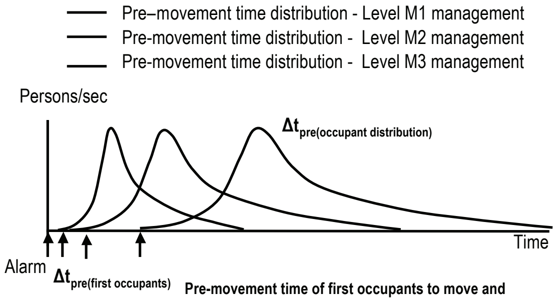
Effect of fire safety management level on pre-movement time



Pre-movement time of first occupants to move and subsequent pre-movement time distribution is lengthened by progressively lower levels of fire safety management

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Data needs for fire safety management

- This simple 3 level scheme recognises that pre-movement time distributions are very dependent upon the implementation of the fire safety management strategy – some data are available but much more are needed
- Research is needed to developed a quantified basis for fire safety management.
- One approach might be to develop a scoring system for management features.
- Data on warning times, pre-movement time distributions and exit choice behaviour for different occupancies could then be collected for different measured levels of fire safety management competence
- For existing buildings the extent to which escape time targets are achieved can be monitored – these data should be made available to the research community
- For large and complex buildings research is needed on the efficacy of different management strategies appropriate for different types of emergencies (fire, explosion, CBRN)

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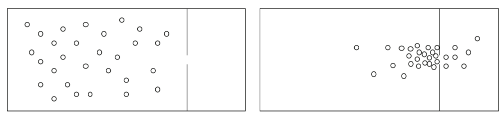
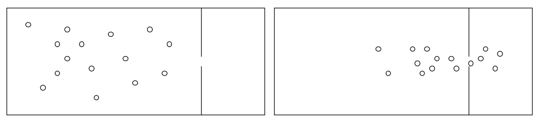


Rate of emptying of a crowded space determined by pre-movement time of *quickest* to respond, establishment of maximum flow and doorway flow capacity



Rate of emptying of a sparsely occupied space determined principally by the pre-movement and travel speed of the *slowest* occupants

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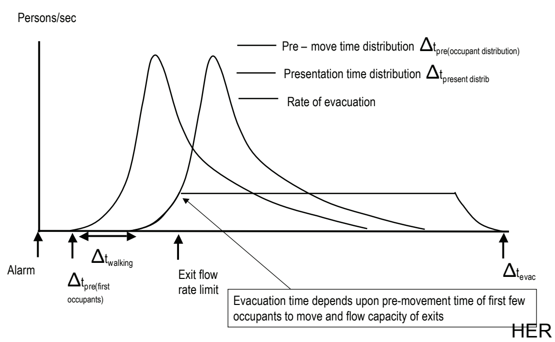
Determinants of evacuation time from a crowded enclosure



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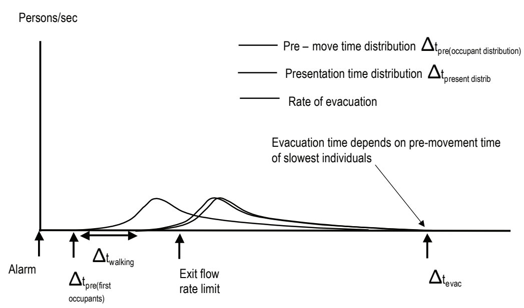
Determinants of evacuation time from a sparsely occupied enclosure



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Data needs for pre-movement time distributions

- Computer simulations need data for pre-movement time of each occupant, sampled from distributions such as those shown, for a range of specified design behavioural scenarios
- An adequate estimation of evacuation times can be made for most situations by considering two main criteria:
  - Pre-movement time of 1st percentile (which determines time to queue formation for crowded cases). This represents the period before anybody moves.
  - Pre-movement time of 99th percentile (which determine time for last few occupants to leave in sparsely occupied spaces). This represents the time before anybody moves **plus** the 99th percentile time for the pre-movement distribution

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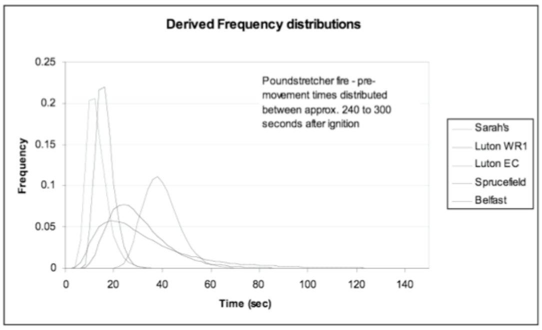
Pre-movement time distributions



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Methods for single retail enclosure

- For a crowded case - evacuation time for an enclosure (Δt_{evac}) is given by:

$$\Delta t_{evac} = \Delta t_{pre(1st\ percentile)} + \Delta t_{trav\ (walking)} + \Delta t_{trav\ (flow)} \qquad (1)$$

$\Delta t_{pre(1st\ percentile)}$ = time from alarm to movement of first few occupants

$\Delta t_{trav\ (walking)}$ = walking time (unimpeded average walking speed x average travel distance to exits).

$\Delta t_{trav\ (flow)}$ = time of total occupant population to flow though available exits.

- For a sparsely occupied case - Evacuation time from an enclosure is then given by:

$$\Delta t_{evac} = \Delta t_{pre(99th\ percentile)} + \Delta t_{trav\ (walking)} \qquad (2)$$

$\Delta t_{pre(99th\ percentile)}$ = time from alarm to movement to time of movement of last few occupants

(= time to first percentile plus time from first to 99th percentile)

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Category A: worked examples for Level M1 office

For situations where occupant densities in the building are low and building is of simple design with mainly open plan areas: minutes

Level 1: Automatic detection with immediate activation of general alarm sounder (or voice).

High standard of training, floor warden provision and fire safety management, independent audit and certification.

Time to detection: depends on fire and system

- Time to alarm: 0 seconds 0.00
- Pre-movement time of first few occupants: 0.50
- Pre-movement time to to 99% occupants (0.50 first + 1.0 99% distribution) 1.50
- Average walking time to protected escape route: 0.25
- Total evacuation time to protected escape route: 2.25
- Total escape time to protected escape route detection + alarm+ 2.25

Time to travel through protected escape routes depends upon building area or height but no points of queuing are anticipated

If high occupant densities are anticipated Level 1 performance cannot be obtained

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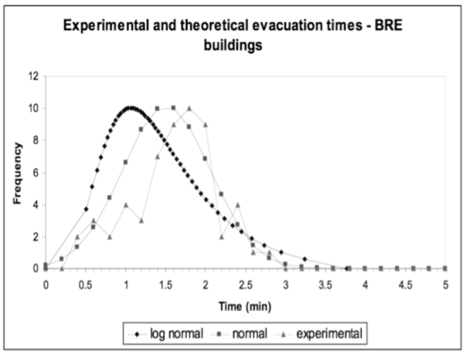
Category A: worked examples for offices



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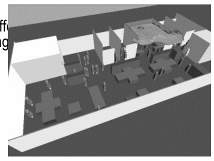
Evacuation times for well-managed offices and workplaces

- The data in the previous slide are for total evacuation times of all different buildings on the BRE site
- Most buildings are less than 4 storeys so travel time within protected escape routes is seldom more than one minute
- The results show that pre-movement times are very short < ~ 30 seconds, although there are sometimes a few stragglers
- The data illustrate an import point: Not only do individual pre-movement and evacuation times within a population show a distribution during a single evacuation event, but total evacuation times for a building follow a distribution when trial evacuations are repeated over a period.
- For the BRE site, where behavioural scenarios are all the same, the distribution is approximately normal between repeated evacuations.
- When data for total evacuation times for a variety of diffe behavioural scenarios), with different qualities of manag distribution was more logarithmic.



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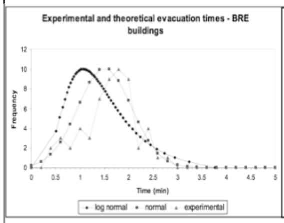
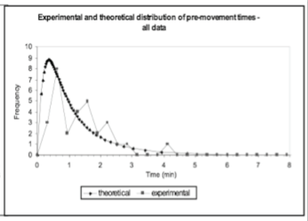
Distributions of evacuation times





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Evacuation data

[illegible]

From Purser and Bensilum

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Category A: worked examples for Level M2 office

For situations where occupant densities in the building are low but building may contain cellular offices: minutes

- Time to detection: depends on fire and system
- Time to alarm: 0 seconds (if level A1 or 5 minutes if level A2)[1] 0.00 – 5.00
  [1]or time-out default
- Pre-movement time of first few occupants: 1.00
- Pre-movement time of 99% occupants (1.00 first + 2.00 99% distribution) 3.00
- Average walking time to protected escape route (30 m maximum): 0.25
- Total evacuation time to protected escape route: 3.25
- Total escape time to protected escape route detection + 3.75 - 8.25

Time to travel through protected escape routes depends upon building area or height but no points of queuing are anticipated

If high occupant densities are anticipated then calculations of queuing time at storey exits and in escape routes will be necessary and escape time will be flow dominated

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Category B1: worked examples for Level M1 retail enclosure

For situations where occupant densities in the building may be high. Automatic detection with a level 1 single stage alarm with voice message is used (a sounder may be sufficient if backed by immediate staff sweep, in which case alarm time would be 0.00):

minutes

- Time to detection: depends on fire and system
- Time to alarm: Level A1 alarm system 15 s message (+ 1 repeat) 0.50
- Pre-movement time of first few occupants: 0.50
- Time to queue formation after first few occupants move 0.50
- (Pre-movement distribution time of last few occupants (0.5 + 2.0) 2.50)
- Walking time to protected escape route (assuming 30 metres maximum) 0.25
- Flow time ADB: 2.50
- Flow time Nelson and Mowrer (SFPE): 3.50
- Evacuation time (flow controlled N&M [ADB]) 4.5 [3.5]
- Escape time (flow controlled N&M [ADB]) Detection + 5.0 [4.0]
- Evacuation time (unrestricted for low population) N&M [ADB] 3.25 [3.25]
- Escape time (unrestricted for low population Detection + 3.75 [3.75]

Times assume adequate number of well trained staff sweep shoppers to nearest exits immediately when alarm sounds

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Office and workplace notes

- The following times might be added for other variables:
  - Open plan office 0 min
  - Compact/small office area 0 min
  - Cellular offices +0.25 min
  - Large floor area +0.25 min
  - If > 20% of occupants are likely to be outside visitors unfamiliar with the building systems, add 0.5 min

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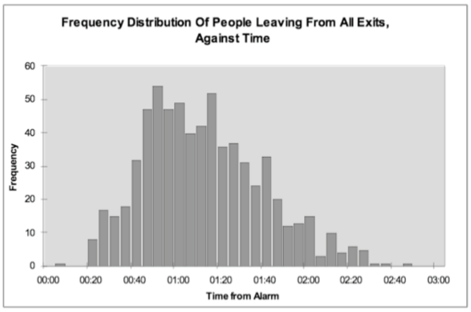

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Category B1: worked examples for Level M2 retail enclosure

For situations where occupant densities in the building may be high and a level 2 two stage alarm with voice message is used and staff response is less efficient than for Level 1 management system:

		minutes
• Time to detection: depends on fire and system		
• Time to alarm: Level 2 with 2 minutes pre-alarm time and 15 s message		2.50
• Pre-movement time of first few occupants:		1.00
• Time to queue formation after first few occupants move		0.50
• (Pre-movement distribution time of last few occupants (1.00 + 3.00)		4.00)
• Average walking time to protected escape route		0.25
• Flow time ADB:		2.50
• Flow time Nelson and MacLennan:		3.50
• Evacuation time (flow controlled N&M [ADB])		5.0 [4.0]
• Escape time (flow controlled N&M [ADB])	Detection +	7.5 [6.5]
• Evacuation time (unrestricted for low population) N&M [ADB]		5.25 [4.25]
• Escape time (unrestricted for low population	Detection +	7.75 [7.75]

NB If pre-movement distribution time is 4 minutes then a few occupants will remain for 15 seconds after end of the flow controlled evacuation. Flow controlled evacuation times assume equal use of all exits except the largest (discounted). It is also assumed that staff are well trained and reasonably efficient in "sweeping up" shoppers

Times assume adequate number of well trained staff sweep shoppers to nearest exits immediately when alarm sounds

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Category B1: worked examples for Level 3 retail enclosure

For situations where occupant densities in the building may be high and a level 3 alarm with sounder and staff response is less efficient than for Level 2 management system:

		minutes
• Time to detection: depends on fire and system		
• Time to alarm: Indeterminate		a few minutes to 1 hour
• Pre-movement time of first few occupants:		a few minutes to 15
• Time to queue formation after first few occupants move		0.50
• (Pre-movement distribution time of last few occupants		a few minutes to 20
• Average walking time to protected escape route		0.25
• Flow time ADB:		2.50
• Flow time Nelson and MacLennan:		3.50
• Evacuation time (flow controlled N&M [ADB])		> 20 minutes
• Escape time (flow controlled N&M [ADB])	Detection +	Alarm + > 20

Evacuation and escape times difficult to predict since they are so dependent on staff behaviour which cannot be relied on at Level 3.

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SEQUENCE OF EVENTS IN CLOTHING STORE FIRE	
Time from ignition (min.sec)	Occupant behaviour
0.19	Fire visible on camera approximately half metre flame height. Customer sees fire and warns shop assistant who investigates and goes to fetch fire extinguisher
1.19	Assistant fighting fire with extinguisher, flame height approximately 1 metre, fire quite large, fails to extinguish and moves away
0.19-3.30	All this time people are entering the shop, passing the fire, shopping, and waiting at the checkout to pay for goods.
3.30	Shop filling with smoke, people reluctant to leave shopping
4.00	People evacuating through thick smoke
4.15	Staff evacuating
4.00-5.00	A few people occasionally re-enter near doorway
6.00	Front doors shut from outside

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Retail notes

- The following times might be added for other variables:
  - If staff number small compared to customers and size of store +0.5 min
  - Large floor area and complex layout +0.5 min
  - Voice alarm system +0.5 min
  - If fire or smoke are visible and threatening to the majority of occupants this may curtail the pre-movement time distribution. Subsequent evacuation time is likely to be ~ 4 minutes (depending upon the layout of the building and available escape routes).

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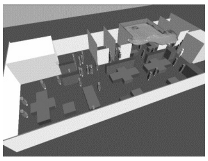
Pre-movement time – travel time interactions

- Since pre-movement and travel time follow distributions they interact
- For detailed analysis each individual occupant modelled with respect to:
  - location, pre-movement, walking time, density effects and flow time through exits and escape routes
- In practice these can be reduced to simple calculations without serious error for any building enclosure by considering two cases:
  - Sparsely populated (< 1/3 design population)
  - Maximum design population



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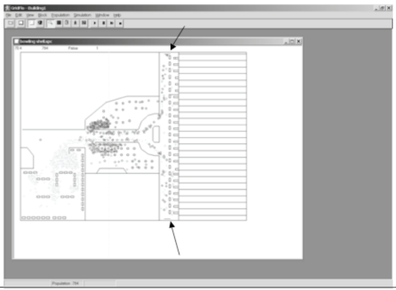
MODEL OVERVIEW - GridFlow

BUILDING REPRESENTATION

- Each space "fine network" of 2D rectangular cells (0.5 m x 0.5 m)
- Each cell can represent free-floor space, a wall or obstruction, or an exit
- GUI enables spaces to be constructed as a series of lines. Each space in a separate window which can be zoomed or panned, copied and pasted or stored.
- Building can be represented as a single space – containing one or more enclosures separated by walls, or as a series of spaces linked by doorway elements



Example:

Bowling alley represented as a single space with obstacles (walls, games machines, bowling stations, tables etc.)

Several occupant populations from different starting locations coded with different colours

Two exits shown as red bars (arrowed)

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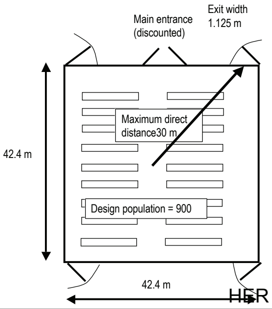
SAMPLE APPLICATION AND HIGHER LEVEL VALIDATION OF A BUILDING CASE

- Interactions between pre-movement time, walking time, exit flow capacity and travel time for simple retail enclosure layouts.
- An important aspect has been the sensitivity of total evacuation time to the distributions of these variables

- Simple prescriptive design case with main entrance discounted,
- Design population 900
- 4 available exits 1.125 m width
- Maximum direct distance 30 m (using 2/3 guidance for cases when layout unknown)
- What are main limitations on evacuation time?
- What are effects of occupant population on evacuation time?
- What are effects of pre-movement time distribution on evacuation time?
- Can simple guidance be given on expected evacuation times – fully taking into account pre-movement times and interactions?



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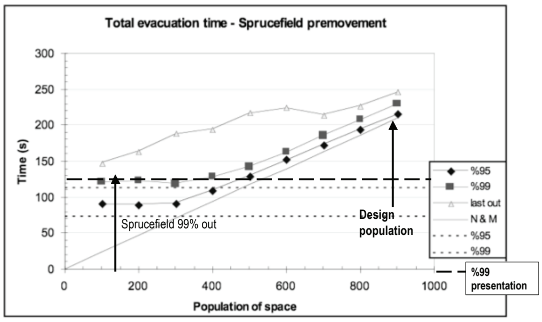
Interactions between pre-movement, presentation and flow times and effects on evacuation times



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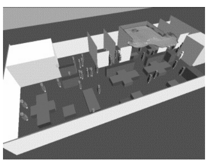
Pre-movement time – travel time interactions

Detailed breakdown of validation case for evacuation times for a single large enclosure



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Interactions between pre-movement and travel time

- Pre-movement time determines time to start to evacuate
- Presentation time = time to travel to exits
- Flow time = determines times to flow through exits
- In shops containing a design population, what is interaction between pre-movement time distribution, presentation time, exit flow and overall evacuation times?
- How important is time to queue formation when crowded and travel when sparsely occupied?

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Pre-movement time

How should the pre-movement time distribution be represented in an escape time calculation?

Is it possible to use a single time to represent that of the whole population?

- Pre-movement time of first occupants to move? – over optimistic
- Mean or mode? – may still not allow for survival of slower movers
- Pre-movement time of last occupants to move ? – say 95th or 99th percentile or last to move? – perhaps too conservative
- Another problem is that pre-movement times interact with travel times, while some occupants are still in their pre-movement phase others are in their travel phase, so what effect does this have on overall escape or evacuation time?

Using a computer simulation in which each individual is represented it is possible to take into account all individual pre-movement times and all individual travel times.

It is then possible to determine how they interact in different situations. It is also possible to determine the errors likely in using a single number to represent pre-movement time in simple evacuation calculations

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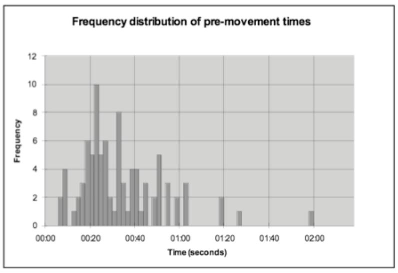
Pre-movement time – travel time interactions

- Pre-movement time distribution taken as that obtained from Sprucefield



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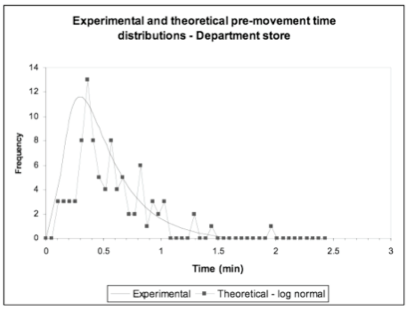
Distribution of pre-movement times

- Log-normal distribution fitted. Each occupant in simulation randomly assigned a pre-movement time sampled from this distribution



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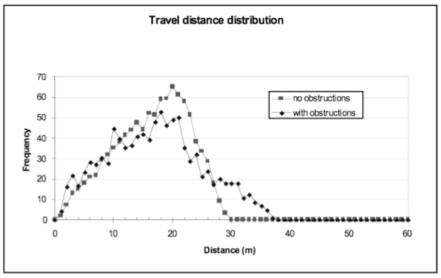
Simple enclosure with 4 exits and 30 m maximum travel distance



Mean actual distance:
unobstructed = 16.5 m
obstructed = 17.0 m

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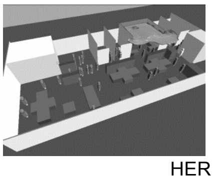
Travel distances

For the performance-based calculation the distribution of actual travel distances is used, with a mean of only 17 m when the maximum is 30 m (for a randomly dispersed population).



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Travel speeds - Horizontal

- Average unobstructed horizontal travel speed typically quoted as ~ 1.2 m/s in buildings.
  - Pauls 1.25 m/s SFPE Handbook
  - Nelson and Mowrer 1.19 (derived from Fuin, Pauls and Predtechenskii and Milinskii) SFPE Handbook
  - Ando et al. male 1.6, female 1.3 m/s max at 20 years of age (in railway stations)
  - Thompson and Marchant: median 1.4 m/s unimpeded, with an interference threshold of 1.6 metres to person in front after which slowing occurs
- Relationship between speed and density (Nelson and Mowrer SFPE Handbook)
  - As unobstructed below 0.54 persons/m^2 and movement ceases > 3.8 persons/m^2
  - Between limits:

$$S = k - akd$$

where:

S = speed m/s

D = density persons/m^2

k = 1.4 for horizontal travel

a = 0.266

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Travel speeds - Vertical

- Average unobstructed vertical travel speed typically quoted as ~ 1 m/s
  - Ando et al. 0.8 m/s down and 0.7 m/s up
  - Fruin range from 1.01 for males < 30 years to 0.595 for females > 50
  - Nelson and Mowrer SFPE Handbook

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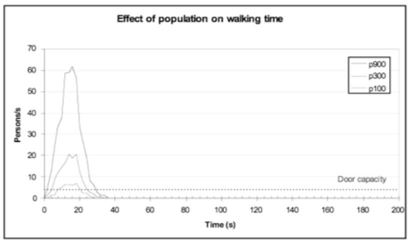
Travel speed distribution and walking time

Default unobstructed mean travel speed used 1.2 m/s S.D., 0.2 and a minimum of 0.3 m/s to allow for variations in individual walking speeds.

When taken with the distribution of actual travel distances for our example case, this enables the walking time distribution of the occupants to be calculated



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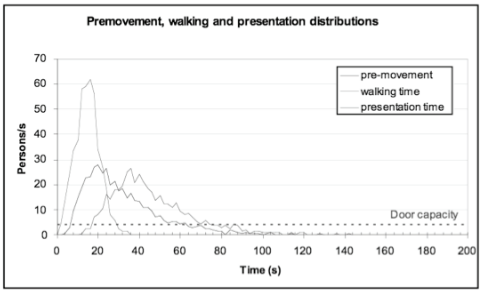
Effect of pre-movement and travel distance and walking speed distributions on presentation time at the exits



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Flow rates horizontal and vertical

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Summary of maximum flow rates (reproduced from Thompson and Marchant)

Source	Maximum design flow (persons/m/s)	Ultimate flow capacity (persons/m/s)	Comments
UK regulations Approved Document B	1·33[a]		Standard British code for buildings
SCICON report	1·37		Data from football crowds
Guide to Safety at Sports Grounds	1·82[b]		Based on Japanese data and derived from 60 persons/0·55m/min unit exit width calculation
Hankin & Wright	1·48	1·92	Commuters on the London Underground
Fruin	1·37	4·37	Max. flow is a peak regimented, 'funnelled' flow under pressure
Daly	1·43		For underground stations
Ando et al		1·7 – 1·8	Japanese commuters at railway stations
Fire and Buildings, The Aqua Group	1·5		General design text
Predtechenskii & Milinskii		1·83	'emergency conditions' for adults in mid-season dress
SFPE handbook [Nelson & MacLennan]	1·3[c]		2 × 0·15m boundary layers deducted from width of exit
Polus et al	1·25 – 1·58	1·58	Pedestrian movement on sidewalks in Israel

[a] derived from exit capacities

[b] unit exit width method

[c] effective width method

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Effective exit flow rates in ADB assuming 2.5 minutes clearance time

Maximum number of persons	Minimum width (mm)	Maximum flow capacity (persons/s/m)
50	750	0·44
110	850	0·86
220	1050	1·40
More than 220	5 per person	1·33

Flow rates in ADB are reasonably conservative for smaller exit widths, generous for 220 occupant case and about average for >220. method

However failure to allow for effective width makes flow rate assumptions generous

Also, no allowance is made for slower progress down stairs (SFPE = 0.94 – 1.01 persons/s/m effective width)

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Flow rates horizontal and vertical

- Horizontal maximum flow rates through doors and stairs = 1.3 persons/s/metre effective width
- Vertical maximum flow rates on stairs = 1.0 persons/s/metre effective width
- Effective width = clear width – (0.15 m x 2)

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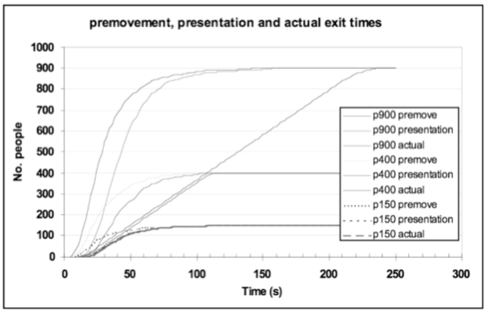
Interactions between pre-movement, presentation and flow times and effects on evacuation times



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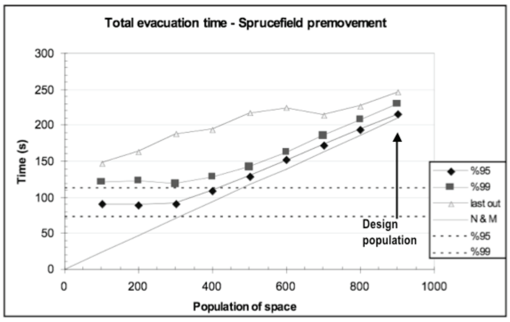
Interactions between pre-movement, presentation and flow times and effects on evacuation times



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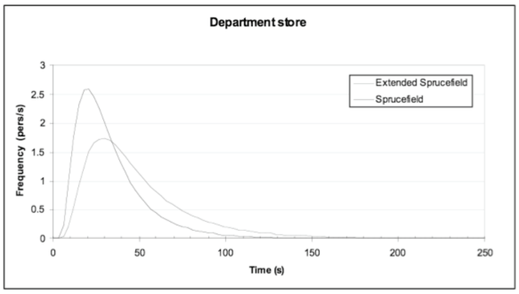
Extended pre-movement time distributions



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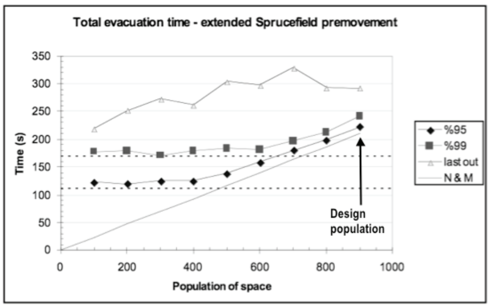
Interactions between pre-movement, presentation and flow times and effects on evacuation times



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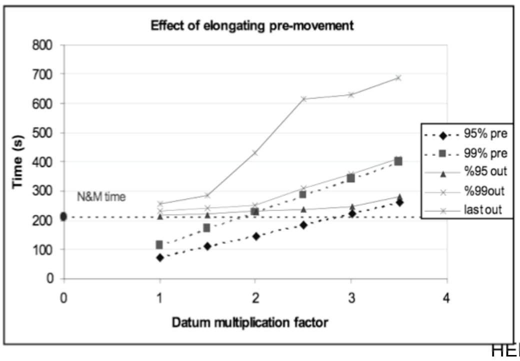
Interactions between elongated pre-movement times, presentation and flow times and effects on evacuation times



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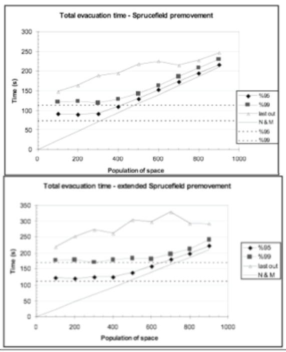
Interactions between pre-movement, presentation and flow times and effects on evacuation times



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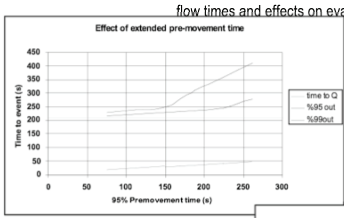
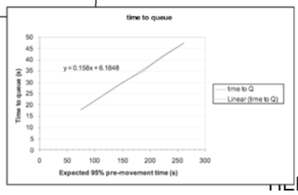
Interactions between elongated pre-movement times, presentation and flow times and effects on evacuation times



This work shows that we can use the detailed computer simulations to develop simple hand calculation tools to predict key effects



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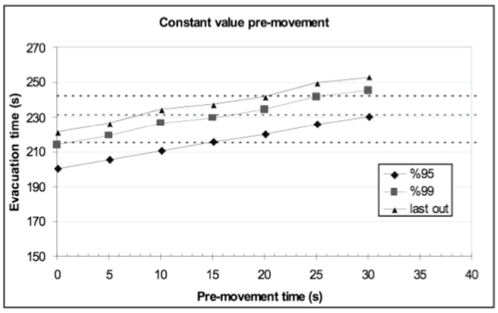
Effect of using a simple constant to represent pre-movement time compared to using the full distribution



Constant to represent pre-movement time of fist percentile

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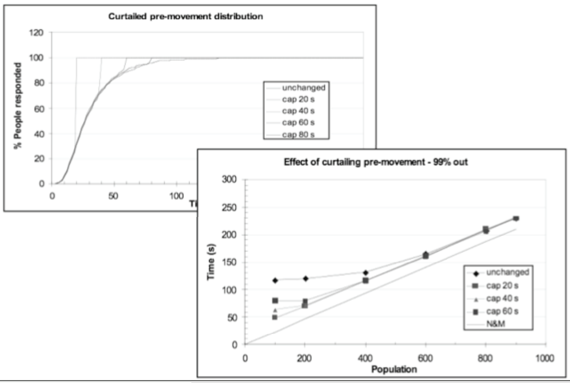
Interactions between elongated pre-movement times, presentation and flow times and effects on evacuation times



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Conclusions from detailed modelling

For evacuation from a single enclosure:

- Detailed modelling confirms that for prescriptively designed situations containing a design population based upon floor space factors, the time required to clear the enclosure depends upon the "presentation" time of the first few occupants forming the queues at the exits plus the "flow time" of the exits.
- If time to queue formation is known, then accurate predictions of 99th percentile evacuation time is possible.
- Time for last person out is inherently unpredictable, but it is possible to predict if last few persons have the "means to escape" by comparison with the ASET time line calculation (i.e. if conditions are still tenable after the 99th percentile time, then exits are clear, enabling the last few occupants to leave immediately should they choose to do so.
- If exit choice is less than perfectly even, then the pre-movement time distribution has even less effect. Exit flow capacity becomes an even more important factor. Since occupants are known to favour particular exits over others, it is important to exercise a conservative view of exit choice. UK prescriptive guidance recommends discounting of the largest exit.

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Sequence of fire hazards

ACUTE SURVIVAL HAZARDS DURING FIRES AND EFFECTS ON RSET AND ASET

- Effects on escape behaviour of seeing smoke *(may inhibit from entering a smoke-filled escape route or stimulate evacuation from a fire enclosure - RSET)*
- Impaired vision from smoke obscuration once in the smoke *(affects evacuation behaviour and reduces speed– RSET, may prevent escape - ASET)*
- Impaired vision, pain and breathing difficulties from effects of smoke irritants on eyes and respiratory tract *(at low concentrations affects evacuation behaviour and speed– RSET, at high concentrations causes incapacitation - ASET)*
- Asphyxiation from toxic gases leading to confusion and loss consciousness *(endpoint of collapse – ASET)*
- Pain to exposed skin and respiratory tract followed by burns from exposure to radiant and convected heat leading to collapse – *(endpoint collapse from heat – ASET)*

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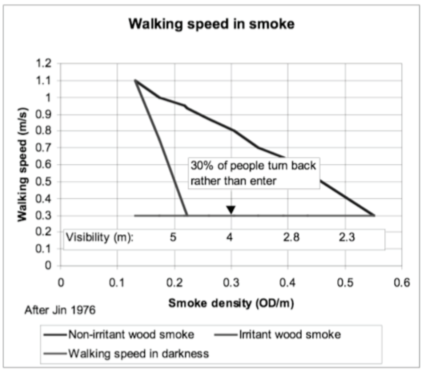
Hazards from smoke



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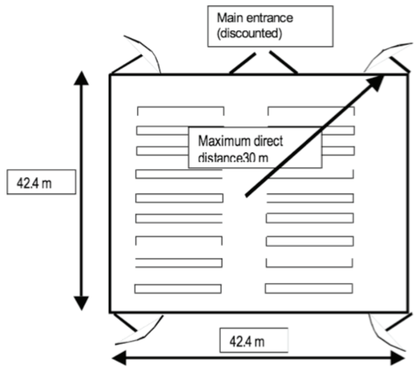
Retail enclosure (2000 m^2 – ceiling height 3 m)



A simple retail enclosure with four exits available for evacuation of a design population of 900 occupants

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ASET- RSET comparison for retail store case

- Evacuation time - well managed case:
  - 3.8 minutes for 99% of occupants, which is almost the minimum possible based upon the flow capacity of the exits and approximately 20 seconds to queue formation.
  - For less well managed case with the pre-movement time distribution x 3 (level 2 management), then the evacuation time increases to approximately 6 minutes.
- For a generic example approximately 0.5 minutes allowed for the pre-movement time of the first few occupants to move, plus 0.5 minutes for queue formation (Level M1) and 1 minute plus 0.5 minutes for level M2. The generic evacuation times were 4.5 and 5 minutes respectively.
- To this must be added the detection time (assume 1.5 minutes) and the alarm time. For the Level M1 case and A1 alarm system was assumed giving an alarm time of 0 minutes, and for the M2 case a two- stage (A2) alarm with an alarm time of 2.5 minutes.
- These therefore give escape times of 6.5 and 9 minutes for the Level M1 and M2 cases.

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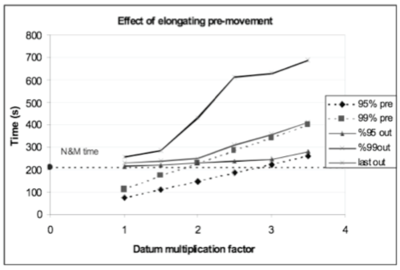
Evacuation times for retail store



Calculated evacuation times from an 1800 m^2 retail store, assuming different levels of management producing different pre-movement time distributions.

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ASET- RSET comparison for retail store case

ASET times:

- Charity shop fire tests: time to loss of tenability due to smoke would be approximately 3 minutes for an unsprinklered case and 4 minutes for a sprinklered case.
- Open calorimeter using an unsprinklered fire approximated to a medium t^2 growth curve during the first 3 minutes of the fire followed by a very rapid rate of growth that was much more rapid than the ultrafast curve. Tenability was lost at 3.5 minutes.
- A number of incidents in unsprinklered retail stores have produced very rapid fire growth resulting in occupants being unable to escape before being enveloped in dense smoke.
- Simple ASET calculations for a 1800 m^2 3 m high retail space were carried out using simple tenability criteria consisting of a 2 metre smoke layer height or 200°C upper layer temperature. Two methods were used, that in DD240 (BS7974) and that in the SFPE Handbook For a fast fire growth curve, this gave an ASET time of approximately 4 minutes (SFPE method) and 4.5 minutes (BS7974 method).
- Based simple calculations, the test results and incidents reports - time required for escape from a retail store filled to design capacity with occupants is uncomfortably close to estimated times to loss of tenability.
- For sprinkler case, possibility that occupants may be exposed to some smoke (due to sprinkler down-drag and loss of plume buoyancy), results showed that smoke would not be dense, with low concentrations of toxic products, so conditions should remain tenable for sufficient time for a safe evacuation.

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Conclusions: benefits of BS PD7974-6

For the first time:

- Provides practical overall guidance on solving all terms in the RSET (escape time) equation for any purpose group (occupancy type)
- Concept of “design behavioural scenarios” provides a rational basis for the classification of occupant evacuation characteristics (particularly pre-movement behaviour), into a small number of types for which quantitative (time-based) data can be measured or modelled
- Provides a method for quantifying the effects of Fire Safety Management on escape time, together with effects of alarm type and building complexity
- Provides a method for assessing interactions between pre-movement and travel time
- Highlights importance of exit choice behaviour and merging flows on travel time
- Proves methods of the evaluation of effects of heat and smoke on movement speed
- Provides methods for determination of ASET endpoints using Fractional Effective Dose methodology
- Enables ASET and RSET comparisons and determination of safety margins

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Also detailed in PD6: determination of occupant condition

Occupant condition is considered in PD6 in terms of three criteria:

- Psychological effects of exposure to heat and smoke (for example on exit choice behaviour)
- Psychological and physiological effects of direct heat and smoke exposure on evacuation behaviour and travel speeds (provides methods of the evaluation of effects of heat and smoke on movement speed)
- Physiological effects of direct heat and smoke exposure on tenability (provides methods for determination of ASET endpoints using Fractional Effective Dose methodology (further detailed in BS7899 Part 1 [1997] and Part 2 [1999]).

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Cases where a long period of maintained structural performance is required

- **Any sleeping risk (residential domestic, institutional or other [e.g. hotel or HMO]), health care.**
- **Hotels and hostels an immediate simultaneous evacuation strategy may be used, but long periods are needed and some occupants may not evacuate. (one hour or more)**
- **Each room or suite needs to be a compartment, at least in relation to the common escape routes**
- **For apartment blocks of flats or maisonettes the main strategy is to defend in place. Only the affected unit and adjacent areas are evacuated.**
- **The structure thus needs to withstand burnout of any particular unit**

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