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Abstract

EXODUS is a prototype egress model designed to simulate the evacuation of large numbers of individuals from an enclosure. The model tracks the trajectory of each individual as they make their way out of the enclosure, or are overcome by fire hazards such as heat and toxic gases. The software is expert system-based, the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. EXODUS is intended, primarily, for use in mass transport vehicles such as aircraft or trains, but it also has application to cinemas, theatres and lecture halls.

EXODUS comprises five core interacting components – the movement, behaviour, passenger, hazard and toxicity submodels.

The movement model controls the physical movement of individual passengers from their current position to the most suitable neighbouring location, or supervises the waiting period if one does not exist.

The behaviour model determines an individual's response to the current prevailing situation on the basis of his or her personal attributes, and passes its decision on to the movement model. In the current prototype implementation of EXODUS all passengers employ an escape strategy which dictates that they must head for their nearest serviceable or assigned exit.

The passenger model describes an individual as a collection of 22 defining attributes and variables such as name, sex, age, running speed, dead/alive, etc. Some of these are fixed throughout the simulation, while others change as a result of inputs from the other submodels.

The hazard model controls the atmospheric and physical environment. It distributes fire hazards such as heat and toxic products throughout the atmosphere and controls the opening and closing of exits.

The toxicity model determines the effects on an individual exposed to toxic products distributed by the hazard model. These effects are communicated to the behaviour model which, in turn, feeds through to the movement of the individual.

The capabilities of the EXODUS model are demonstrated through a series of hypothetical evacuation scenarios involving a wide body aircraft. Using 'best guess' values for the passenger attributes, the model was then applied to a selection of the CRANFIELD TRIDENT THREE experimental data, and it was successful in reproducing most of the identified trends.

Contents

1 INTRODUCTION

Over the past 20 years considerable effort has been expended in developing mathematical models capable of predicting the generation of hazardous conditions within aircraft and, indeed, any enclosure subjected to fire (1–5). These models are extremely useful in predicting the spread of fire hazards such as heat, smoke and toxic products within a structure, and in determining the impact of physical or environmental parameters on the developing fire atmosphere.

The information produced by such models, combined with a prediction of the likelihood of the scenario occurring, provides a means of assessing the risk such an incident poses to property. Of greater importance, however, must be the determination of the risk to human life, and to estimate this it is essential to predict the occupants' physical, psychological and physiological responses to the emergency, in addition to the above information.

While physical experimentation provides a means of obtaining this information, it can prove to be excessively expensive. For example, a full-scale evacuation trial of an aircraft can cost several millions of dollars. Of more importance is the risk of personal injury the participants are subjected to during the course of the trials. Even where physical experimentation proves to be practical, the relevance of the exercise may be called into question because – for obvious ethical reasons – the tests are not performed under realistic life-threatening or hazardous conditions.

Nevertheless, under international regulations (6) aircraft manufacturers must demonstrate that their aircraft layout (number, type, and distribution of seats, cabin partitioning, etc.) allows for a full load of passengers and crew to evacuate the aircraft within 90 seconds. This must be accomplished through half the number of exits normally available, in darkness and with a passenger load made up of a representative cross-section of the travelling public.

While such tests provide a benchmark for evacuation performance comparisons, they provide little useful information regarding the suitability of the cabin layout and design in the event of a real emergency. The Manchester disaster of 1985, in which 55 people lost their lives, serves as a recent tragic example. The last passenger to escape from the burning Boeing 737 aircraft emerged 5.5 minutes after the aircraft stopped, while 15 years earlier during U.K. certification trials the entire load of passengers and crew managed to evacuate the aircraft in 75 seconds (7).

Furthermore, following recent serious accidents resulting from 90 second certification trials in the United States, there is a growing call to reduce the number of such trials (8).

The practical, financial and ethical constraints on full scale physical experimentation suggests a need for the development of computer-based mathematical models of the evacuation process, and their application to aircraft evacuation studies. A number of such models have been developed for simulating evacuation from buildings.

Mathematical models simulating the egress process fall into two basic categories; those concerned with predicting the optimal time and route for evacuation (9 – 11), and those concerned with simulating likely evacuation times and routes for a particular scenario (12,13). They can be further categorised into models which track the trajectory of individuals (9,12,13) and those which treat the evacuees as a homogenous ensemble (10,11).

The evacuation model EVACNET+ (10) uses a network description of a building and linear programming techniques to arrive at an optimal evacuation time for the initial distribution of building occupants. In order to arrive at optimal evacuation times, the model uses global rather than local information relating to paths. It does not track individuals, neither does it take into consideration spreading fire and smoke and, as a result, people-fire interaction is not modelled.

The network model of Kostreva et al (9) is similar to EVACNET+. But, using dynamic programming techniques which can facilitate time-dependent network attributes and networks with multiple attributes on each link, it is capable of simulating the consequences of spreading fires. By considering each individual separately and in turn, the model is also able to optimize the escape route for individual occupants. But to simulate realistic fire evacuation scenarios, the type and quality of the defining network attributes must be specified, and in their paper, Kostreva et al do not address this point.

Takahashi et al (11) present a network model in which the key assumption is that the evacuees move in a similar way to a homogenous fluid. Here, as in EVACNET+, individuals are not considered and, furthermore, it is assumed that the evacuation paths are kept clear of fire hazards such as smoke and toxic gases.

The optimal egress time models described above fail to consider people-people and/or people-fire interaction and so the realism of the simulations may be questioned. However, the optimal solutions generated by these models may provide insight into the evacuation characteristics of the building design.

In EXITT (12) the evacuation of individuals trapped in a residential fire is simulated. Individuals are characterised by their age, sex, walking speeds, and whether they are awake or asleep when the emergency occurs. People-people interactions, such as alerting and rescuing others and, people-fire interactions such as investigating the fire and avoiding dense smoke regions are incorporated within the model. EXITT uses smoke density data generated by a two-layer zone model, but temperatures and toxic products are not considered. As with the other models discussed here, it uses a network representation of the building – the nodes and links representing rooms and distances between rooms respectively. The behaviourial model used by EXITT is structured around a rule-base which determines what action an individual will take when faced with a set of conditions (eg smoke concentration) and options.

The EXIT89 (13) model is designed to handle large populations evacuating from high rise buildings. Like EXITT, it tracks individuals and is based on a network description of the building, but unlike EXITT, does not include detailed behaviourial considerations. EXIT89 differs from the optimal route finding models by having a local rather than global perspective of the building environment. This feature makes EXIT89 more realistic, as individuals base their decisions on information gathered from their immediate surroundings.

As with EXITT, EXIT89 uses smoke density data generated from a two-layer zone model. This information is used to determine which rooms and passageways are off-limits to the evacuees. The model does not have a facility to allow evacuees to crawl under a smoke layer, neither does it explicitly use temperature or toxic gas data. When used in conjunction with the HAZARD 1 code (14), data generated from an evacuation trial can be post processed by the TENAB toxicity model in order to calculate time to incapacitation and death. However, as this is performed subsequent to the evacuation, the presence of the toxic products does not influence the evacuation process.

Only two of the papers discussed have reported any attempt at model validation: the model by Takahashi (11) and EXIT89 (13). Takahashi has compared model-generated total egress time for various buildings with the measured egress times. Both models generally underestimated the egress times by as much as 41%. The EXIT89 model was used to predict the egress time for a multi-storey building containing 700 occupants. The model predicted an egress time of 5.6 minutes compared to the 7 minutes achieved in an evacuation drill.

In the remainder of this report a prototype mathematical egress model called EXODUS will be presented, and its application to aircraft evacuation scenarios discussed.

2 EXODUS MODEL AIMS

The aim of the EXODUS project is to develop a software tool to assist the safety engineer, design engineer, or regulatory authorities in evaluating the suitability of a given environment in coping with large numbers of individuals under emergency evacuation situations.

The model is intended to aid in the resolution of 'what if' questions such as if an aircraft develops problems with one of its doors while at a stop over, how many passengers could be carried on the next leg 'safely' with this door inoperative? Is there a preferred seating arrangement which should be enforced in this situation? The model could also be used in post mortuum accident investigations to suggest possible contributory mechanisms responsible for a particular accident.

The EXODUS software is expert-system based, the motion and behaviour of each individual being determined by a set of heuristics, or rules (see figure 1). The model tracks the trajectory of individuals through the enclosure until they reach the safety of the exterior, or are overcome by the effects of the hostile fire atmosphere, and perish.

The current prototype version of EXODUS is intended primarily for use with air and rail mass-transport vehicle environments. While specific rail and air emergency scenarios will undoubtably differ, the basic geometries of aircraft and trains are sufficiently alike to allow similar basic treatments. In addition, the software structure of EXODUS allows application-specific sub-components such as behaviourial models to be interchanged easily with more appropriate models. This flexibility allows the package to be adapted for use in other application areas such as cinemas, lecture theatres, etc.

Ultimately, the software will incorporate a wide range of passenger behaviour traits and escape route planing capabilities, but in the current prototype implementation, this is limited to seeking the nearest serviceable or assigned exit.

Whenever any person P ceases to be occupying any grid-point G then conclude that the previous position of P = the id of G and conclude that the wait-counter of P = 0 and conclude that the waiting of P is false.

Figure 1 Typical rule from the EXODUS rule base. This rule acknowledges that a person is leaving a grid point, it also resets the 'waiting' counter

A considerable amount of information exists concerning human behaviour in emergency situations (see for example references 15,16). However, the majority of this data concerns human responses to emergencies within the built environment, and it is not clear to what extent this information is applicable to aircraft incidents. Reliable data relating specifically to human responses to aircraft emergencies is much more rare. For this reason, EXODUS allows the user easy access to the rule base in order to alter or replace system rules in light of new theories and data.

3 SOFTWARE AND HARDWARE REQUIREMENTS

The current prototype version of EXODUS is built within the software environment supplied by G2 (17). G2 is a tool for developing and running real-time expert systems for complex applications that require continuous and intelligent monitoring, diagnosis, and control. The current computer platform which hosts G2 is a SUN SPARC-1 workstation. EXODUS execution times are dependent on the nature of the scenario being simulated and vary from several minutes to several hours.

4 EXODUS MODEL DESCRIPTION

4.1 Introduction

EXODUS simulates the evacuation of large populations of individuals from mass-transport vehicles such as aircraft. Individuals are modelled as if they were solid objects, ignoring their 'squashiness' potential. The model follows their trajectories as they make their way to the exits, and includes various aspects of people-people and people-fire interaction. The evacuation strategy adopted by each individual is to exit via their nearest serviceable exit.

EXODUS comprises five core interacting components – the movement, behaviour, passenger, hazard and toxicity submodels. As its name implies, the movement model controls the physical movement of individual passengers from their current position to the most suitable neighbouring location, or supervises the waiting period if one does not exist. On the basis of an individual's personal attributes, the behaviour model determines an his or her response to the current prevailing situation, and passes its decision on to the movement model.

The passenger model describes an individual as a collection of defining attributes such as name, sex, age, running speed, dead/alive, etc. Some of these attributes are fixed throughout the simulation, while others change as a result of inputs from the other submodels.

The hazard model controls the atmospheric and physical environment. It distributes fire hazards such as heat and toxic products throughout the atmosphere and controls the opening and closing of exits. Finally, the toxicity model determines the effects on an individual exposed to toxic products distributed by the hazard model. These effects are communicated to the behaviour model which, in turn, feeds through to the movement of the individual.

All attributes which have default values may have these values reset by the user.

In addition to the components related to model description, EXODUS possesses various tools which allow interactive construction of the geometry, specification of passenger profiles, simulation interrogation tools, and a colour display capability which enables the user to observe the progress of the evacuation as it is being simulated.

4.2 Space and Time discretisation

The spatial and temporal dimensions within EXODUS are spanned by a two-dimensional spatial grid (see figure 2) and a simulation clock (SC). The spatial grid maps out the geometry of the enclosure, locating exits, internal doors, seats, aisles, bulkheads, etc. Geometries with multilevels can be made up of multiple grids connected by passage ways (eg. stairs).

The simulation clock is the master control of the model. Decisions and actions can only occur with each tick of the SC. The accumulation of ticks to exit or expiration for each individual is a measure of the Personal Elapsed Time (PET) taken to exit or perish.

The enclosure layout is constructed interactively and can be stored in a geometry library for later use. The grid is made up of nodes and arcs, individuals travelling from node to node along the arcs. There is no limit to the number of arcs emanating from a node and all nodes need not possess the same number of arcs. Impassable obstacles such as walls, bulkheads, internal compartments etc, are formed by simply removing the connecting arcs. An arc is assigned a length attribute which represents the actual physical distance spanning the nodes.

Nodes which have distinguishing features may be assigned to special node classes. For example, nodes which correspond to stairs, seats or aisles share certain terrain features and so make up three different types of classes. In the prototype version of EXODUS there are two types of node, aisle and seat. The movement submodel identifies the type of node being traversed by the passenger and then flags the passenger submodel for the appropriate travel speed.

The position of each node is identified by a set of unique co-ordinates which pin point its location. Associated with each node is a set of attributes which define the state of the node. These state attributes are assigned and updated by the hazard submodel.

In addition to these, each node possesses two additional attributes, the 'potential' and 'obstacle' attributes. The former represents an integer measure of its distance from the nearest exit, while the latter is an integer measure of the degree of difficulty in passing over the node. As with the state attributes, the potential attribute may be modified by the hazard model (see table 1).

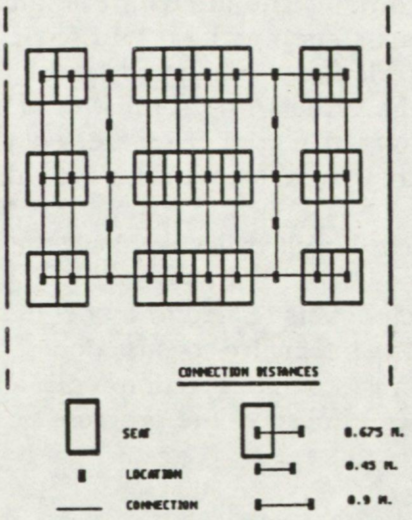

Figure 2 Example of an EXODUS grid showing seat and aisle nodes

The initial obstacle attribute for all aisle nodes is set to 1, while seat nodes assume the value **5** (for motion over seat backs). When a passenger is overcome by fumes and collapses, the passenger submodel increases the obstacle value of the passengers current node by **1**.

To aid in the visual identification of high obstacle node locations, the arcs associated with a node are colour-coded. Arcs associated with an obstacle value of 5 are coloured blue, while those corresponding to a value of 1 are coloured yellow. As the obstacle value of a node is increased, say by the presence of a body, the arcs associated with that node change colour.

Table 1 List of node attributes used in EXODUS. * indicates attribute which is implemented but not activated in the current version

Label
Co-ordinates
Potential
Obstacle value
Upper/Lower Temperature
Upper/Lower HCN
Upper/Lower CO
Upper/Lower CO_2
Upper/Lower O_2
Upper/Lower smoke*

4.3 Movement submodel

Individual passengers in the EXODUS model move under the influence of a potential well. This is achieved by assigning a potential value to each nodal point. Nodal values are set in a systematic manner in order to achieve a predetermined global evacuation strategy.

Passengers assume the potential of the node they are currently occupying and the movement submodel then attempts to move them in a manner which minimizes their current potential, subject to the constraint that only a single conscious passenger may occupy a node at any instant. The movement of passengers is further limited by their personal physical and behaviourial constraints.

If, for example, the strategy employed involves passengers emerging from their nearest exits, setting exit nodes to an arbitrary value and successively increasing the potential of a node the further removed it is from the exit, will ensure that passengers employ this strategy.

In the current version of EXODUS the movement submodel is made up of six main rules. These are concerned with selecting the most desirable neighbouring node, moving the person to the selected node, allowing the person to wait at the current node and moving the person out through the exit.

The movement rules are fired on even ticks of the SC, while selection rules are fired on odd ticks. The wait rules are fired continuously, as the passenger should always have the option to wait. Movement decisions and actions will only take place if the SC shows a time which is at least as large as the individual's PET.

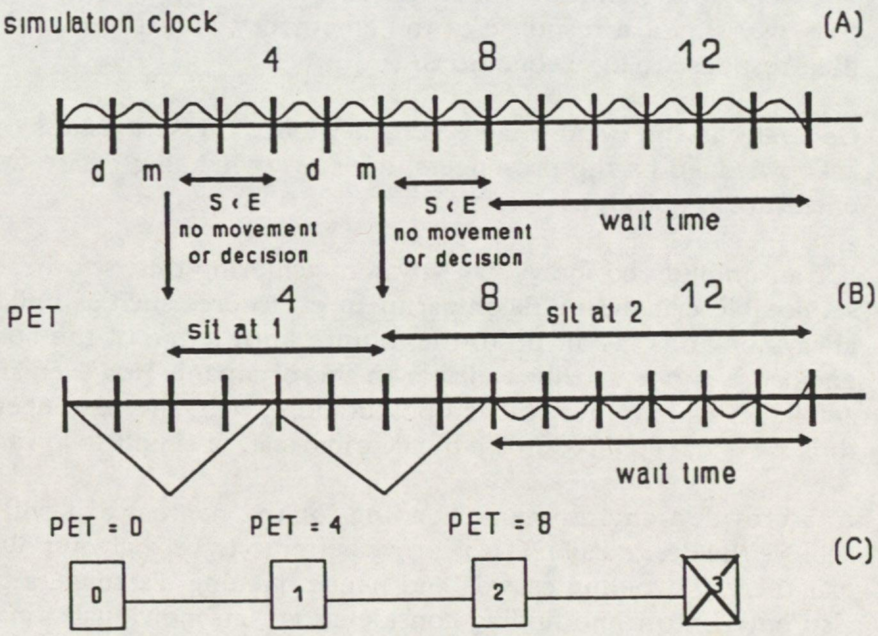

Figure 3 Depicts the relationship between the Simulation Clock (SC) and the PET

On the second tick of the SC (A), the passenger moves from node 0 to 1 (C) and his PET moves to 4 (B). For the next 2 ticks of the SC, no decision or movement is made as PET > SC. On the 4th tick of the SC, the passenger is able to continue moving, on the 5th tick he has selected his move, and by the 6th tick of the SC (A) he moves from node 1 to 2 (C) and his PET advances to 8 (B). As node 3 is occupied, he cannot advance further and so he enters wait mode, his SC and PET advancing with each tick.

When a move decision has been made, EXODUS waits till the next tick of the SC, and then moves the passenger to the location. Using the passenger's speed and distance travelled, EXODUS calculates the travel time and advances his or her PET by the appropriate amount. The passenger now sits on the selected node until the SC catches up with the PET, at which time another movement decision may be taken (see figure 3). If the passenger is forced to wait at the current location, then the PET is updated with each tick of the SC (see figure 3).

A tick of the SC is the smallest unit of measured time. Fractions of a tick are not permitted, so if the travel time involves less than a tick, EXODUS rounds this figure up or down. The length of a tick, which is set by the user, is usually a fraction of a second. In the current version of EXODUS, this is set at 1/12th of a second.

In the current version of EXODUS there is no provision for passengers to push past other passengers in queues. The passenger can wait for his/her turn to move, or if their patience has expired, take a detour round the obstruction (see section 4.4).

4.4 Behaviour Submodel

The behaviour submodel functions on two levels, the first concerned with the passengers' global response to the emergency, and the second concerned with their response to local conditions.

Generally, in the event of an emergency, once the seriousness of the situation is acknowledged by the passengers, their overwhelming desire will be to exit the enclosure as quickly as possible.

For an unhindered individual, a way of achieving this is to head for the closest serviceable exit. In multi-compartment enclosures such as buildings, this is not always obvious, as an up-to-the-minute knowledge of the state of the entire enclosure is not usually available to the occupant. However, in aircraft, where smoke levels have not reached obscuration levels, the passenger can usually see the exit, is directed towards it by the cabin staff or simply follows the crowd.

In a crowded environment, heading for the nearest exit will not necessarily achieve the desired aim. It may prove better to travel a greater distance to another exit thereby avoiding crowds and hence queuing. Passengers personal phobias also enter into route finding considerations, an individual's final decision being dependent on many factors such as crowd densities, distance, fire hazard densities, prior knowledge, etc. Based on information (or lack of information) of this type, a passenger may even head in completely the wrong direction.

In the prototype implementation of EXODUS, the escape strategy employed by all the passengers is to exit via the nearest serviceable or assigned exit. While simplistic, this approach should offer a reasonable approximation to minimum expected evacuation times under hazardous conditions. (More thorough route planning capabilities are planned for later versions of EXODUS – see section 7 for details).

As described in section 4.3, this is accomplished through the potential well facility. To ensure that passengers will head for their nearest exit, node potentials at the exit are set at an arbitrary value, and increased successively, the further removed the node is from the exit.

In this way, passengers will naturally and irrevocably gravitate to their nearest exits.

By increasing or decreasing a door's exit potential, it is possible to decrease or increase respectively the number of passengers in its catchment area. This is equivalent to blocks of passengers being assigned doors by the cabin crew, and, in this way, passengers will move towards their **assigned exit** rather than their nearest exit.

During actual evacuations it is possible for exits to become unserviceable. This may be due to fire spread to the exit, damaged slides, blockages etc. Under such circumstances, passengers will normally be directed away from the exit by crew, other passengers or their own observations. In EXODUS this behaviour is simulated by severing the link to the door, and, when this occurs, the entire set of mesh potentials is recalculated and the passengers are redirected. In actual situations, passengers towards the rear of the queue may not necessarily react with such speed.

No-go areas such as fire regions can also be treated by increasing the local potential in the vicinity of the disturbance. The development of no-go areas or the closing of exits can be controlled by the hazard submodel. When either of these instances occurs, passengers will respond by changing direction, preferring to move away from the hazard or closed door.

The second level of behaviour submodel function concerns the passengers' response to local situations.

Conflicts may result when passengers compete for the same node. The movement submodel resolves this situation easily by considering which passenger is the first to arrive at the desired location. However, difficulties arise when two or more passengers are capable of arriving at the same time. This conflict is resolved using the passengers' drive which is a behaviourial attribute assigned to an individual at the commencement of the simulation. It is intended to be a measure of their survival instincts, and the individual with the larger drive wins possession of the node. If competing passengers have identical drives then the node is allocated randomly.

As in real evacuation situations, some passengers within the EXODUS model will find themselves waiting to get into a moving queue. The waiting is a result of there being no other available move which will decrease their potential. However, if they were permitted to make a move which increased their potential, thus taking them further away from the exit, they might find this a more successful strategy than waiting.

To facilitate this behaviour, each passenger is assigned a behavioural attribute called patience. A passenger will wait for a period of time equal their patience. When this is exceeded they will be permitted two alternative courses of action.

If they are caught between seat rows and their agility exceeds the obstacle value associated with travel over seat backs, then they will be permitted to jump over.

Alternatively, the passenger will be permitted to select a node which leads to the minimum increase in potential. Once the patience is exceeded, the passenger will continue with the selected action until able to resume normal travel. In the latter case, it is possible for a passenger to oscillate between two neighbouring nodes. In order to avoid this situation passengers are prevented from visiting the same node twice within a fixed period of time.

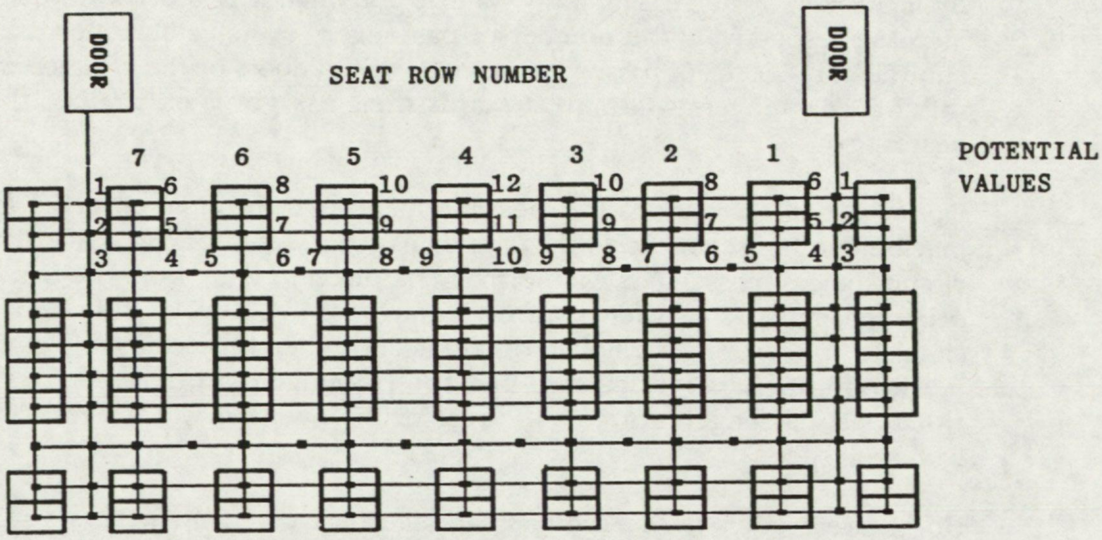

Figure 4A

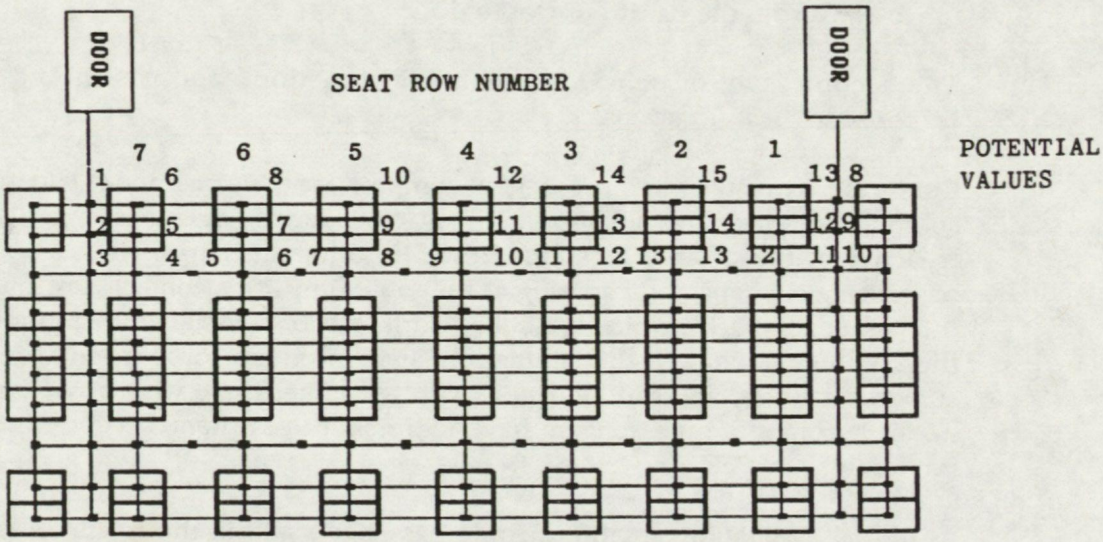

Figure 4B

FIGURE 4: In figure 4A both door potentials are set to 1; here seats 1 to 3 are in the catchment area of the forward door, seats 5 to 7 are in the catchment area of the aft door, and seat 4 is randomly associated with either door. In figure 4B, the forward door potential is set to 8 and the aft door is set to 1. Here seats 1 and 2 are associated with the forward door while seats 3 to 7 are in the catchment area of the aft door.

Passengers do not respond with the same speed to the call to evacuate. This characteristic is simulated by assigning each passenger a behaviourial attribute called response time. It is intended to be a measure of the passenger's initial time to recognise that evacuation is required, and to release the restraint harness. Behaviourial inaction (18) – a condition which sometimes arises in passengers who cannot decide what is the best course of action to take -is simulated by simply increasing the response time to a sufficiently large value.

When passengers expire, the presence of their body contributes to the nodes obstacle value. Other passengers will be able to pass over the fatality only if their agility exceeds the new obstacle value. In addition, the passengers travel speed will be reduced by a fixed proportion to represent the difficulty in passing over the body.

The sensory depravation effects of smoke are thought to have a major effect on passengers' ability to escape (16,17). While the present version of EXODUS accommodates the spread of smoke, this facility is not yet activated. When fully functional, a passenger's response to smoke will be to modify their travel speed and ultimately resort to the crawl mode of movement.

The irratant effects caused by the acid gases HCL and HF, and their contribution to sensory depravation, while thought to be important, are not included in this version of EXODUS.

4.5 **Passenger submodel**

4.5.1 *Introduction*

Passengers are distinguished by a unique identification number corresponding to their assigned seat location and a set of defining physical and psychological characteristics. In the present implementation of EXODUS, there are 12 such attributes: sex, age, weight, condition, mobility, agility, travel speed, volume of air breathed (RMV), incapacitation dose, response time, drive and patience (see appendix 5).

The number, type and default settings of these attributes are not intended to be definitive. They have been chosen as a reasonable basis for demonstration purposes only.

In addition to the defining attributes each passenger has nine progress variables: the Personal Elapsed Time (PET), distance travelled, FIN, FICO, FICN, FIO, FICO2, FIH and VCO2 variables.

4.5.2 *Sex, age and weight attributes*

The sex attribute is used to distinguish male from female passengers. This distinction is necessary because, on average, values for the defining characteristics are sex dependent. The population of evacuees fall into three age and weight bands as described in table 2. Note children are not represented in this version of EXODUS.

Table 2 Age and weight distribution accommodated within the current version of EXODUS

Age (years)–Weight (kg)	*Band*
19–57	1
19–75	1
19–86	1
36–57	1
36–75	1
36–86	1
47–57	2
47–75	2
47–86	3

4.5.3 *Cumulative hazard variables and condition attribute*

The progress variables FIN, FICO, FICN, FIO, FICO2, VCO2, and FIH are a measure of a passenger's degree of exposure to narcotic gases and convected heat. They represent the fraction of an incapacitating dose (FID) of all narcotic gases (CO, HCN, CO_2 and low oxygen hypoxia), FID of CO, FID of HCN, FID of low oxygen hypoxia, FID of CO_2, CO_2 induced hyperventilation, and FID of convective heat respectively. These variables are initially set to zero and are subsequently calculated by the toxicity model.

When either of FIN, FICO2 or FIH attain or exceed the value one, the passenger is terminated and their condition attribute changes from alive (the default value) to dead.

4.5.4 *Mobility attribute*

The mobility attribute is a multiplicative factor used in conjunction with the travel speed and agility attributes. It has two functions: initially, it is intended to allow the introduction of physical disability into the passenger description. A passenger not suffering from any disability will have an initial mobility of one, while a passenger with a minor disability, such as an arm in plaster, will have a slightly reduced mobility value of 0.9. A major disability, such as blindness or a broken leg, will result in a considerable reduction in mobility to say 0.2.

The second function of the mobility attribute is to reduce the passengers' travel speed and agility in response to their growing exposure to the narcotic agents. The mobility may vary from its initial value (no detrimental effects), to zero (individual has expired). The mobility decreases as FIN – determined by the toxicity submodel – increases. Table 3 represents the reduction in mobility as a function of FIN adopted in the current version of EXODUS.

Table 3 Relationship between toxicity submodel generated FIN and passenger attribute Mobility

FIN level	*Mobility*
0.00 – 0.29	1.0
0.291 – 0.30	0.9
0.31 – 0.50	0.80
0.51 – 0.60	0.50
0.61 – 0.80	0.30
0.81 – 0.99	0.10
1 +	0.0

4.5.5 *Agility attribute*

Agility is intended to represent the physical prowess of the individual in tackling physical obstacles such as movement over seat backs. A passenger's agility at any point in time is determined by the relation,

$$\text{agility} = \text{initial agility} * \text{mobility}. \tag{1}$$

4.5.6 *Travel speed attribute*

The travel speed attribute is a measure of the speed at which the passenger moves within the aircraft. Within EXODUS an individual has four levels of travel speed. These may be described as run – maximum travel speed along aisle, walk – reduced travel speed between seats, leap – travel speed over seat backs, and crawl – greatly reduced travel speed.

Table 4 Motion type selected by EXODUS when passenger encounters certain terrain types

Terrain	*Motion Type*
AISLE – AISLE	RUN
ALONG SEATS	WALK
OVER SEATS	LEAP
SEAT – AISLE	WALK
AISLE – SEAT	RUN

The movement submodel determines the appropriate travel speed to select on the basis of the terrain through which the passenger is passing (see table 4 for details). The crawl speed is intended for use when the smoke level exceeds a critical value. This feature, while implemented, has not been activated for the simulations presented in this report.

These quantities may assume default values or be assigned by the user. The default settings are depicted in table 5 and are assigned on the basis of age, sex and weight. Note that the female values are 15% lower than the corresponding male values.

Reductions in an individual's mobility will have a knock-on effect on their travel speed. A passenger's travel speed at any point in time is determined by the relation,

$$\text{travel speed} = \text{initial travel speed} * \text{mobility}. \tag{2}$$

Table 5 Run, Walk and Crawl speeds for males and females in the three age-weight bands. * Indicates that CRAWL has not been activated in the current version of EXODUS

Band	*Run/Leap (M/S)*		*Walk (M/S)*		*Crawl * (M/S)*	
	M	*F*	*M*	*F*	*M*	*F*
1	1.35	1.15	0.98	0.77	0.23	0.19
2	1.22	1.04	0.81	0.69	0.20	0.17
3	1.15	0.98	0.77	0.65	0.19	0.16

It is not necessary to regulate an individual's travel speed for motion in crowds as this is self regulating. A fast individual trapped in the middle of a crowd or an exit queue will automatically move with the speed of the crowd or queue.

Normally each node will only accommodate a single active individual. However, it will be possible for an active individual to occupy the same node as an expired individual. In such cases, the active individual's travel speed will be reduced.

4.5.7 Volume of Air Breathed Attribute

The volume of air breathed (or respiratory minute volume RMV) is a measure of the volume of air taken into the lungs by the passenger (litres/min). It is used by the toxicity submodel to calculate the FICO. The RMV is dependent on age, weight, sex and type of activity the individual is involved in, for example a 70kg male involved in light work has an RMV of 25 l/min, while at rest, it falls to 8.5 l/min (19). The default values used by EXODUS are depicted in table 6 (with the exception of the 25 l/min value, all other values are estimated by the author). In the current implementation of EXODUS the RMV shows no age or activity-dependence, and a value indicative of light work is used.

Table 6 Default RMV values for males and females used by EXODUS

Weight (kg)	*Male RMV (L/Min)*	*Female RMV (L/Min)*
57	22.5	20.5
75	25.0	22.5
86	27.5	24.75

4.5.8 *Incapacitation dose*

The incapacitation dose (D) is a measure of the carboxyhaemoglobin (COHb) concentration necessary to cause incapacitation. It is used by the toxicity submodel to calculate the FICO. The incapacitation dose is dependent on age, sex and level of activity. In the present implementation of EXODUS, only sex and activity dependence is incorporated. The default values used by the model are depicted in table 7 (the male values are taken from reference 19, while the female values are estimated by the author).

Table 7 Default incapacitation dose for male and females involved in walking and running activities

Activity	*Male*	*Female*
WALKING	30	27
RUNNING	20	18

4.5.9 *Response time attribute*

The response time is intended to be a measure of the time taken by the passenger to recognise that evacuation is required and to release the restraint harness. The default response time is set to zero. EXODUS uses the response time to delay the passenger's initial response to the call to evacuate.

4.5.10 *Drive attribute*

The drive is a measure of a passenger's survival instincts. In situations where passengers compete to occupy a node, the passengers drive will resolve possible conflicts. The drive attribute is assigned values from 1 (low drive) to 20 (high drive).

4.5.11 *Patience attribute*

The patience attribute is a measure of the time a passenger is likely to wait before they deviate from normal behaviour. This is defined as selection of possible moves which minimise the passenger's potential, while abnormal behaviour consists of travel over seat backs or travel which increases the potential. If the wait time exceeds the patience, then the passenger is able to behave abnormally. The default setting for patience is set to a very large number.

4.5.12 *Personal elapsed time variable*

The PET variable is a measure of the time (seconds) required by the passenger to arrive at a particular point. At the end of the simulation, it measures the time to exit or incapacitation. PET is initially set to zero.

4.5.13 *Distance travelled variable*

The distance travelled variable is a measure of the total distance travelled by the passenger at any point in time. At the end of the simulation, it measures the distance travelled to exit, or the point of death. The distance travelled variable is initially set to zero.

4.5.14 *Passenger initialisation*

To simplify the initiation of passenger attributes, EXODUS allows the creation of passenger classes. The physical attributes of sex, age and weight define a class, and the remaining attributes and variables are assigned on the basis of the passengers' class. In the current implementation of EXODUS, there are 18 classes, each one associated with a band from 1 to 3. Travel speeds and agility are then assigned according to the individual's band. Passengers are colour-coded according to their class, allowing for easy identification through the simulation..

All personal attributes and variables may be edited after the initialisation procedure.

4.6 Hazard submodel

The hazard submodel controls the development of the atmospheric and physical environment. In the context of the current implementation of EXODUS, the control of the physical environment extends to opening and closing aircraft exits, and the creation of no-go areas.

During the course of an evacuation the status of exits may alter as a result of the progress of the fire or equipment malfunction. Some exits may not be open throughout the evacuation due to difficulties with the equipment, or inability of the cabin crew or passengers to reach the door. Exits also become unserviceable due to the spread of fire inside or outside the cabin. Likewise, certain areas in the cabin may become no-go areas due to the presence of the fire or structural damage.

These sequences of events may be specified in the hazard submodel which notifies the movement submodel when/which door is opened/closed and where/when no-go areas occur. At the specified time, (as measured by the SC) the movement submodel then recalculates the potential well, enforcing the change in physical environment.

The hazard submodel also controls the spread of fire hazards such as heat and toxic products throughout the atmosphere. The fire hazards incorporated in the current implementation of EXODUS are those required by the toxicity model ie. temperature (degree C), HCN (ppm), CO (ppm), CO_2 (%) and oxygen depletion (%).

The initial concentration of all hazards is zero, with the exception of temperature and O_2. The temperature is set to the ambient value, by default 21°C while the O_2 value is set to the default 20.9%.

The values of these hazards are set at each node at two different heights, one representing head height (2m) and the other, seat base height (1m). These locations may be altered and additional hazard height locations included if necessary. The values may also be time dependent. The data used to specify the hazard values may originate from actual aircraft accidents, artificial data or be produced by fire models.

EXODUS will potentially accept data from either zone or field models. As hazard data can be stored and utilised at each spatial node within EXODUS, the use of data produced by fire field models is possible. The superior resolution of field model data over that produced by zone models, makes this an extremely desirable option.

If data for each node is not available, it is possible to set values over entire regions of the aircraft.

Other important fire hazards are smoke and the acid gases HCL and HF. While no provision has been made for the acid gases, a facility has been provided for the inclusion of smoke data within the EXODUS model.

4.7 Toxicity submodel

The toxicity model implemented within EXODUS is the Fractional Effective Dose (FED) model of Purser (19). This model considers the toxic and physical hazards associated with elevated temperature, HCN, CO, CO_2 and low O_2 and estimates the time to incapacitation and death.

The FED model assumes that the effects of certain fire hazards are related to the dose received rather than the exposure concentration. The model calculates, for these agents, the ratio of the dose received over time to the effective dose which causes incapacitation or death, and sums these ratios during the exposure. When the total reaches unity, the toxic effect is predicted to occur.

The fractional incapacitating dose (FID) for each of the agents is calculated as follows:

$$FICO = 3.317E{-}5 * CO^{1.036} * RMV * t / D \qquad (3)$$

where t is the exposure time (minutes) and RMV is the volume of air breathed (litres/minute)

Equation (3) is unreliable for small adults or children.

$$FICN = t / EXP(5.396 - 0.023 * HCN) \qquad (4)$$

The equation for FICN is unreliable outside the range 80 – 180 ppm HCN.

$$FIO = t / EXP(8.13 - 0.54*(20.9 - O_2)) \qquad (5)$$

$$FICO2 = t / EXP(6.1623 - 0.5189 * CO_2) \qquad (6)$$

and finally,

$$FIH = t / EXP(5.1849 - 0.0273 * T) \qquad (7)$$

where T is the temperature (degree C).

Another effect that CO_2 has is to increase an exposed person's RMV and thus increase their rate of uptake of other toxic gases.

The FED model considers the combined effect of these agents in the following way,

$$FIN = (FICO + FICN) * VCO2 + FIO \qquad (8)$$

where,

$$VCO2 = EXP(0.2496 * CO2 + 1.9086) / 6.8 \qquad (9)$$

is a multiplicative factor which measures the increased uptake of CO and HCN due to CO_2-induced hyperventilation.

When FIN or FICO2 or FIH equal or exceed unity, the passenger is assumed to be incapacitated.

The EXODUS model considers fire hazard data (in the form of concentrations or temperatures) located at several heights. In the current version, only two heights are implemented: head and seat height. As the crawl facility has not been activated for the demonstrations described in this report, only data at head height is considered.

4.8 Run time analysis

EXODUS compiles statistics relating to global evacuation and individual passengers. The global statistics concern the exit rates corresponding to various doors, total exit rate and – when the toxicity model is activated – the casualty rate.

The total number of successful evacuees at any point in time is represented on a graph displayed in the control panel. In addition to this graph, the simulation clock is depicted along with the running total of successful evacuees. If the simulation includes the toxicity model, data relating to the number of casualties is presented in a similar manner.

A detailed account of the traffic through each door is also available. This is presented as a set of graphs displaying the number of evacuees versus time for each door, as well as the total number of escapees and the time of the last exit.

As passengers exit the aircraft or perish, they are assembled in areas associated with their exit location or the mortuary. This allows for an easy visual check on the progress of the evacuation.

Data relating to individual passengers may also be examined. Any passenger, whether in the process of evacuation, at a door assembly point or in the mortuary may have their current state examined. The passenger is selected by the use of a mouse driven pointer, and once this has taken place, a table displaying the values of all the person's attributes and progress variables is displayed (see appendix 5). This information is useful in determining why a passenger has taken a particular course of action. The pointer may also be used to examine the status of a particular node.

For specially-selected passengers, it is possible to display graphically their progress through the aircraft. Information which can be displayed includes distance travelled, FIN, FIH and FCO2 as functions of time. This information, along with the elapsed time, distance travelled and distance to nearest exit is displayed in the passenger window.

5 EVACUATION SIMULATIONS

5.1 Introduction

Before the EXODUS software can be applied to realistic evacuation scenarios it is essential to test the basic components of the model. Furthermore, the parameter list defining passenger characteristics incorporated within the prototype version of EXODUS is not yet complete, neither have the existing characteristics been tuned to appropriate realistic values. The tuning process requires input from experimental data not currently available to the author and until the tuning process is carried out, the person attributes assume 'best guess' data. Therefore results generated by the model should be viewed with a measure of scepticism.

In the following sections, the model capabilities are demonstrated on hypothetical evacuation scenarios from a hypothetical wide body aircraft using default data settings. The model is then applied to test data from CRANFIELD evacuation experiments performed in a section of a Trident Three aircraft (20).

5.2 Demonstration data

The aircraft geometry used in the demonstration relates to a hypothetical wide body aircraft consisting of six exits, three located on each side, two at the front, two over the wings and two in the rear. The internal geometry consisted of 8 rows of seats labelled A (right) to H (left) and 27 rows numbered 1 (front) to 27 (rear). The rows of seats were separated by two main aisles and configured 2, 4 and 2 abreast. Seat rows 1 to 3 contained 6 seats, while row 4 had only 4 seats. The A and H seats in row 10, opposite the overwing exits, were removed. Bulkheads, toilets and galleys are represented by missing nodes or broken links (see figure 5).

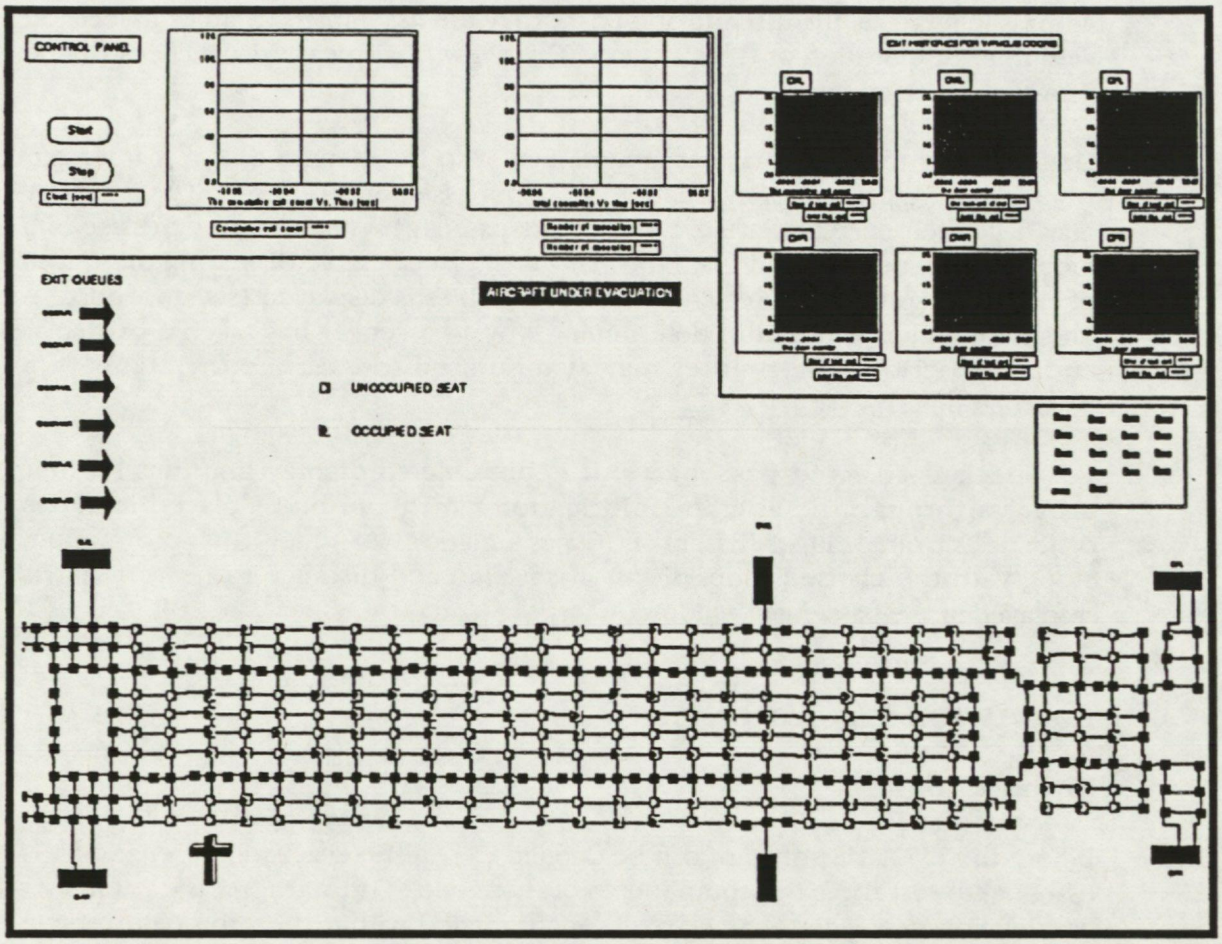

Figure 5 Figure 5 depicts the wide body layout used in the EXODUS simulations. Also depicted is the EXODUS work space

The width of the aircraft as measured by the distance from the centre of seat A to the centre of seat H is 4.95m while the length of the cabin is 28.35m.

The aircraft can accommodate a full load of 206 passengers. The demonstrations presented here were performed with 112 passengers, 54 women and 58 men. The passengers were distributed in the nine categories according to table 8.

The passengers agility, mobility, response times and travel speeds are set to the default values. With regard to the response time, this means all passengers will react immediately. In order to demonstrate the seat jumping facility, certain passengers have their patience reduced from the default value to a small practical value.

The passengers are distributed randomly through the left half of the aircraft. The passenger mixture in the right portion represents a mirror image of the left (see figure 6). For demonstrations involving the toxicity submodel, hypothetical data is distributed by the hazard submodel (see table 12 and appendix 3).

Table 8 Age/weight distribution of passengers in demonstration simulations

Age/Weight (kg)	*Number of Males*	*Number of Females*
19–57	8	8
19–75	6	6
19–86	4	6
36–57	8	6
36–75	6	4
36–86	8	8
47–57	8	4
47–75	6	6
47–86	4	6

5.3 Demonstration scenarios

5.3.1 *Introduction*

Two series of demonstration simulations are presented involving 112 passengers. In the first series, comprising 11 test cases, the passengers are not subject to the effects of toxic fire hazards. Here the basic movement and behaviourial submodels are demonstrated. The second series, comprising 4 test cases, utilises the toxic and hazard submodels as well as the movement and behaviourial components. Similar scenarios are run in both cases allowing the influence of the hostile environment on the passengers' progress to be gauged.

5.3.2 *Evacuation under non-hostile environmental conditions*

To check the accuracy of the basic movement submodel a 19–57 (age-weight) male was placed in two locations and his model-determined egress time was compared with his expected travel time. Both starting positions where located in the rear of the aircraft, the first in the aisle, and the second in seat 27H. In both cases, only the front exits were opened, requiring the passenger to travel the entire length of the aircraft.

The first passenger travelled a total distance of 29.48m and as only aisle nodes were occupied a constant speed of 1.35m/s was maintained. This results in an expected egress time of 21.8 seconds and a measured egress time of 21.8 seconds.

The second passenger travelled a distance of 1.125m from seat to aisle and 26.1m along the aisle to the exit. His travel speed along the seat row was 0.9m/s and 1.35m/s along the aisle. This corresponds to an expected egress time of 20.6 seconds and a measured egress time of 20.6 seconds.

A total of eleven demonstration experiments were performed with a complement of 112 passengers representing a 54% occupancy. A summary of the results may be found in table 9; for more details refer to Appendix 1.

Table 9 Summary of evacuation times for the 11 scenarios without toxicity data

Configuration	*Potential 1 Evacuation Time (sec)*	*Potential 10 Evacuation Time (sec)*
6 open doors	24.5 (Demo1)	15 (Demo2)
4 open doors (DWL,DWR closed)	22.9 (Demo11)	22.9 (Demo11)
4 open doors (DFL,DFR closed)	29.5 (Demo7)	25.5 (Demo8)
4 open doors (DAL,DAR closed)	34.2 (Demo9)	29.4 (Demo10)
3 open doors (DFL,DFR,DAL closed)	30.4 (Demo5)	27.4 (Demo6)
3 open doors (DFL,DWL,DAL closed)	46.0 (Demo3)	32.1 (Demo4)

For demonstration 1 (demo1) all six doors are functioning and the potential on each of the exits is arbitrarily fixed to the value 1. A summary of the evacuation history may be found in table A1.1. The evacuation time for this scenario was 24.5 seconds, with the majority of passengers (67) exiting via the wing doors (DWL/R door wing left/right) and the front doors (DFL/R door front left/right) being used by the least number of passengers. The catchment area for the front doors encompassed 14 passengers and extended through the first class area (seat rows 1 to 3) past the cabin partition and into the first row of economy class (seat row 4). The catchment area for the aft doors (DAL/R door aft left/right) extended from row 19 to the last row and included 31 passengers.

This uneven distribution of passengers results in widely varying last exit times for the various doors. The last person to exit via the front doors emerged after 6.98 seconds, the aft doors after 15.1 seconds and the wing doors after 24.5 seconds.

By increasing the potential on wing exits, it is possible to alter the catchment area associated with each door. In demo2, (table A1.2) the exit potential on the wing doors is increased to 10, resulting in an evacuation time of 18.3 seconds. In this case the wing and aft doors service similar numbers of passengers. Also, the number of evacuees exiting from the forward doors has increased from 14 to 31 passengers.

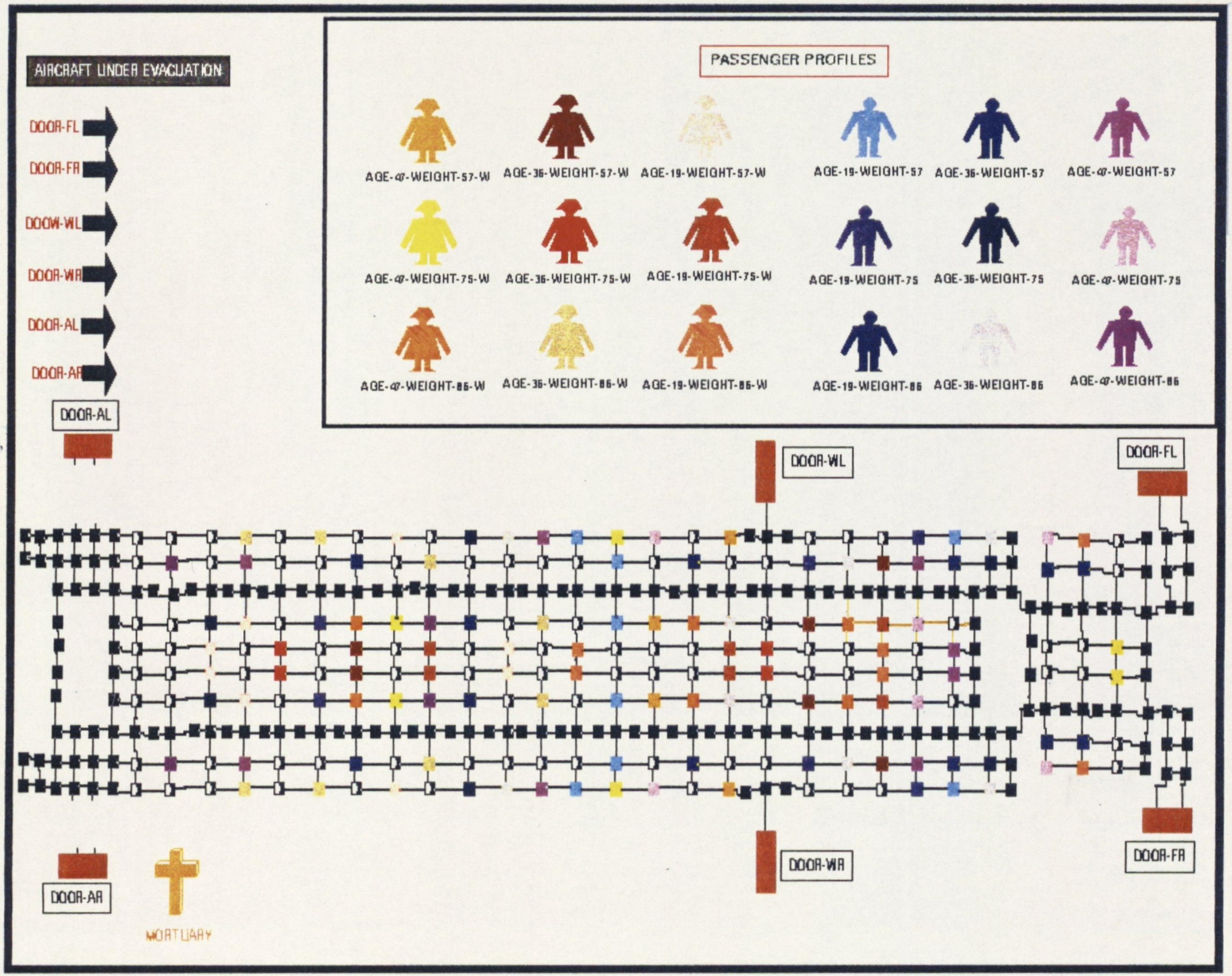

Figure 6

Wide body aircraft and passenger distribution used in demonstration simulations

Each wing door must service at least two streams of competing passengers. The competition is resolved by a combination of who would cover the distance in the least amount of time, their drive and finally by random choice. Passenger 7G travelled a total distance of 4.9m and required 14.9 seconds to exit via DWL. Unhindered, this passenger should have exited in 4.3 seconds. This difference reflects the wait time associated with her queue, her reduced travel speed resulting from travelling within a queue and her response time (which is this case is set to the default, 0 seconds).

The passengers in these simulations display most of the behaviour described in earlier sections. Figures 7 through to 10 depict demo2 through various stages of development. To illustrate this range of behaviour consider the initial moves made by passengers in seat rows 21, 22 and 23 (tables 9 and 10 and figures 7 and 8).

Figure 7 shows the initial seating position for all the passengers, while figure 8 depicts the situation 0.5 seconds after the passengers have started to move. As can be seen from figure 8 and tables 10 and 11, passengers in seat 23D and 23E have moved towards the aisle and are occupying seats 23C and 23F respectively. In row 22 passengers in the window seats (22A and 22H) have moved across to locations 22B and 22G respectively, bringing them closer to the aisle, while passengers located in the aisle seats (22C and 22F) have moved into the aisle.

The passengers in row 21 display a set of complicated manoeuvres. Both aisle seated passengers (ie 21B–21C and 21G–21F) wish to move into the aisle. As the males (21B and 21G) are in the highest band their travel speeds and drive are greater than the females (21C and 21F) who are members of the lowest band, and so the males move into the aisle and the females wait in their seats. The females located in seats 21D and 21E are also forced to wait, however as their patience has expired, and they have a high agility (band 1 females), they choose to climb over the seat backs and find themselves located in seats 22D and 22E (see table 11).

Table 10 Initial seating position for passengers in rows 21 to 23

Seat	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*
21		M 19–86	F 47–86	F 36–57	F 36–57	F 47–86	M 19–86	
22	F 36–86		M 19–75			M 19–75		F 36–86
23				F 36–75	F 36–75			

Figure 9 depicts the situation 11.34 seconds into the simulation. Some 79 passengers have evacuated by this time. Also depicted are the exit graphs for each door and the accumulation of escapees by their exit locations. These passengers may be interrogated to find their escape history. Figure 10 depicts the situation after all the passengers have evacuated.

Table 11 Seating position for passengers in rows 21 to 23 after first movement round

Seat	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*
21			F 47–86			F 47–86		
22		F 36–86		F 36–57	F 36–57		F 36–86	
23			F 36–75			F 36–75		

The remaining 10 demonstration simulations illustrate situations in which some of the exits are not available. In the industry standard 90 second evacuation, the entire load of passengers must vacate the aircraft within 90 seconds with only half the exits operational. Demo3 (table A1.3) and demo4 (table A1.4) simulates this situation. In these cases the three doors on the left side of the aircraft are inoperative, demo3 has a potential of 1 on all operating exits, while demo4 has a potential of 10 on DWR and a value of 1 on DFR and DAR.

The evacuation time for demo3 has increased from 24.5 (demo1) to 46.0 seconds and for demo4, from 18.3 (demo2) to 32.1 seconds. In these cases the passengers on the left side of the aircraft make their way to the right side either by crossing through the middle rows of seats or moving down the aisle, or a combination of both.

The next two demonstrations also involve three inoperative doors. In demo5 (table A1.5) and demo6 (table A1.6) the forward doors and DAL were closed, the former had a wing exit potential of 1, and the latter a wing exit potential of 10. For demo5, the evacuation time was 30.4 seconds and for demo6, 33.7 seconds.

The catchment area for the wing doors is large when their exit potential is set to 1, and so they tend to attract a large number of passengers. Thus, by taking one of these doors out of service, as in demo3, most of the demand is shifted to the remaining wing door, resulting in a long evacuation time (46 seconds). As the forward doors service a small number of passengers, when they are made inoperative, as in demo5, both wing doors share the load, resulting in a shorter evacuation time (30.37 seconds) than for demo3.

With the wing door potentials set to 10, a more even distribution of passenger door preferences is achieved. This results in little differential in the total evacuation time for demo4 (32.1 seconds) and demo6 (33.6 seconds).

Three scenarios were simulated with two doors inoperative. These were with the forward doors closed (demo7 and demo8, potential 1 and 10 respectively), the aft two doors closed (demo9 and demo10, potential 1 and 10 respectively) and the two wing doors closed (demo11, see tables A1.7 to A1.11).

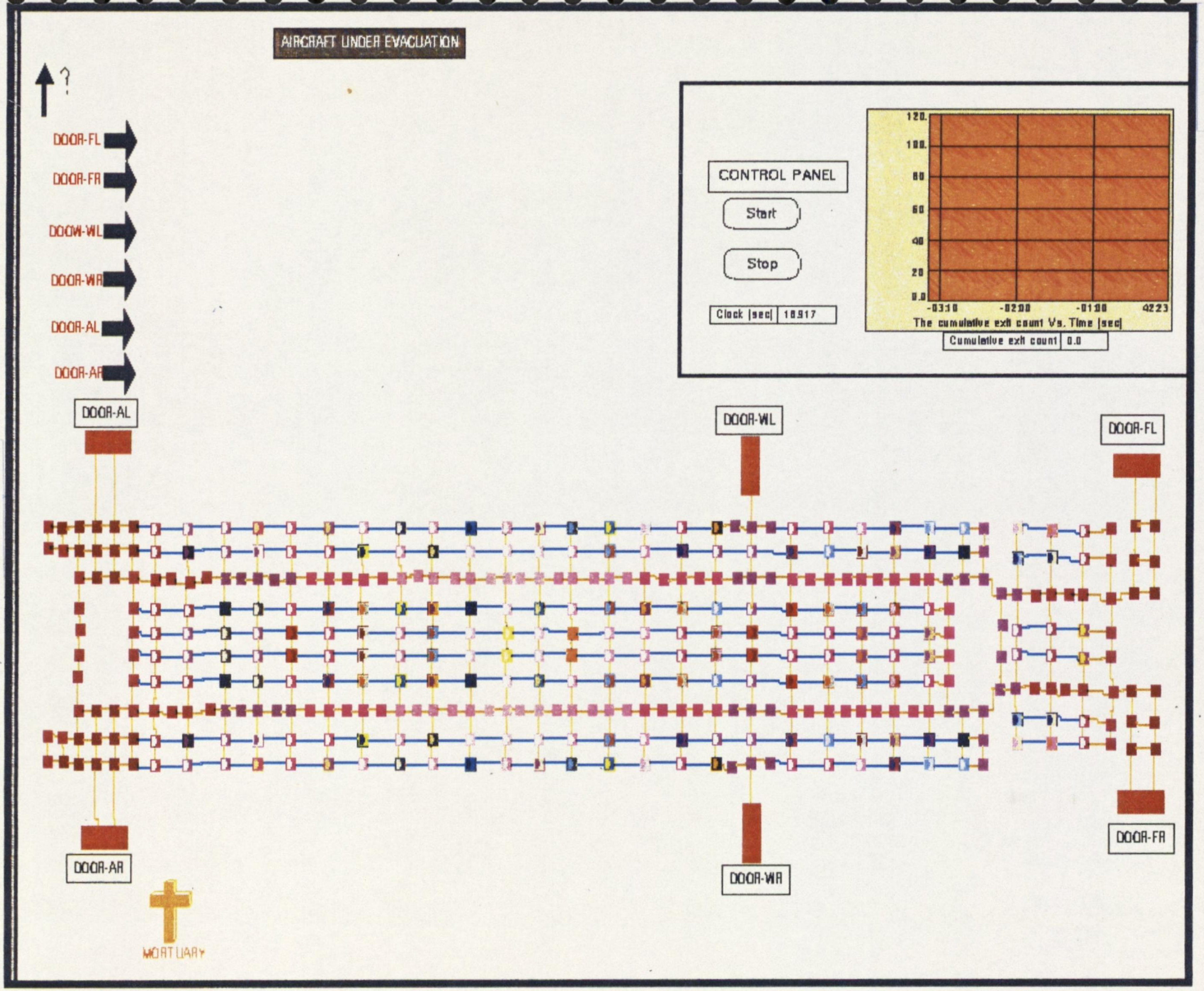

Figure 7

Initial set up for demo2

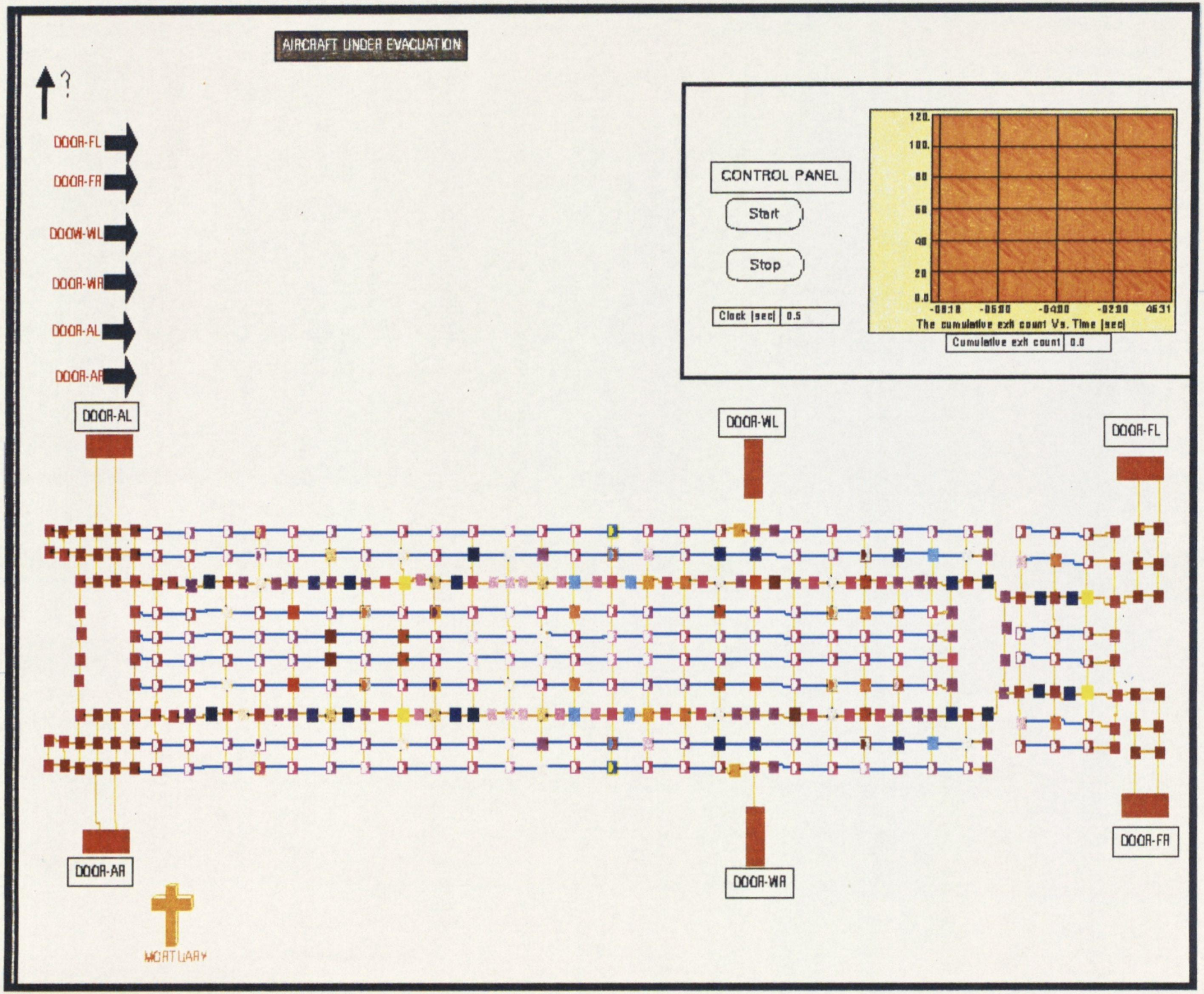

Figure 8

0.5 seconds into demo2.
A number of passengers have moved out of their seats and the aisles are becoming crowded

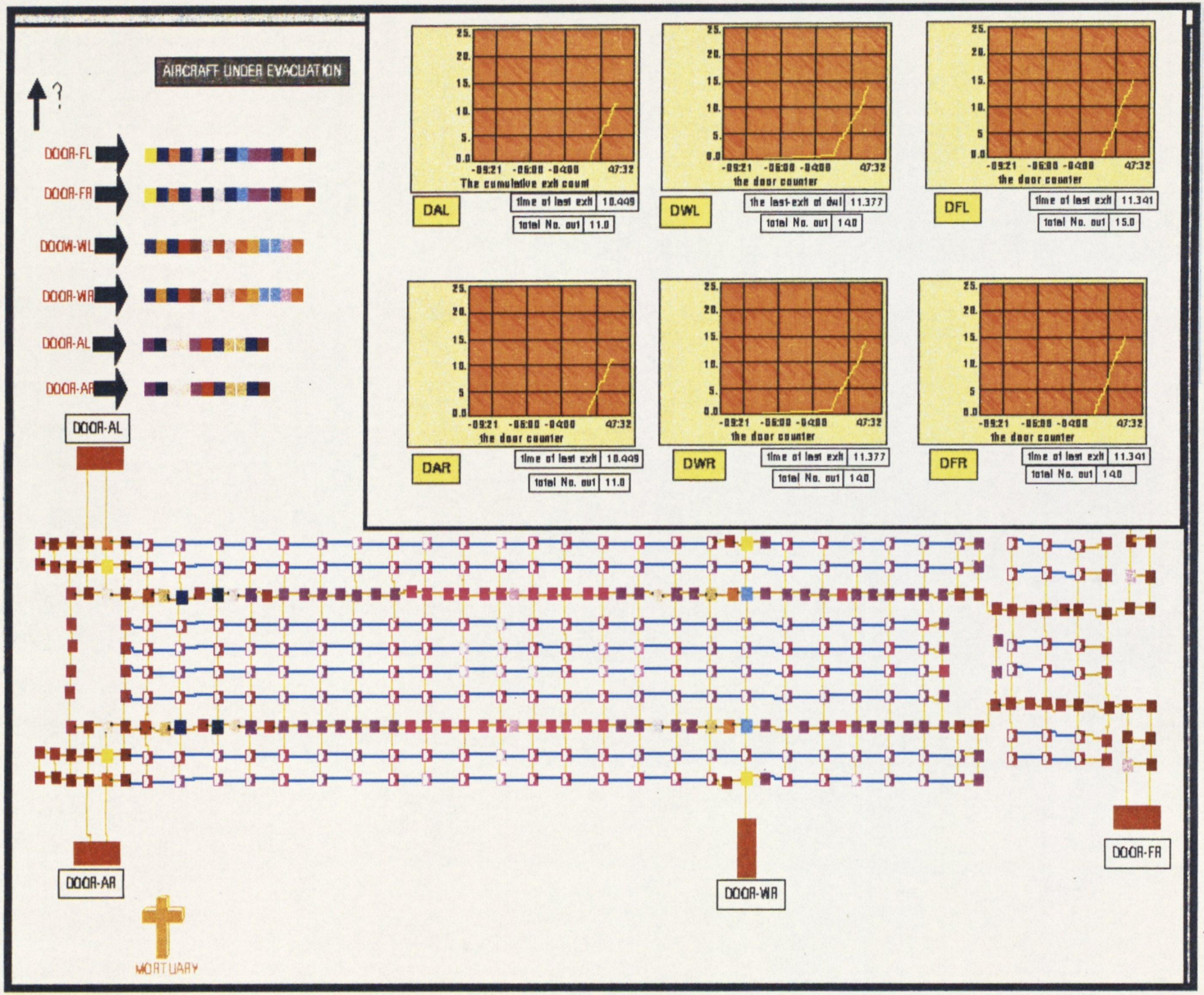

Figure 9

11.5 seconds into demo2.
79 passengers (70%) have exitec the aircraft. The majority of the remaining passengers are exiting via the aft doors. Also depicted are the passenger flow graphs for each door

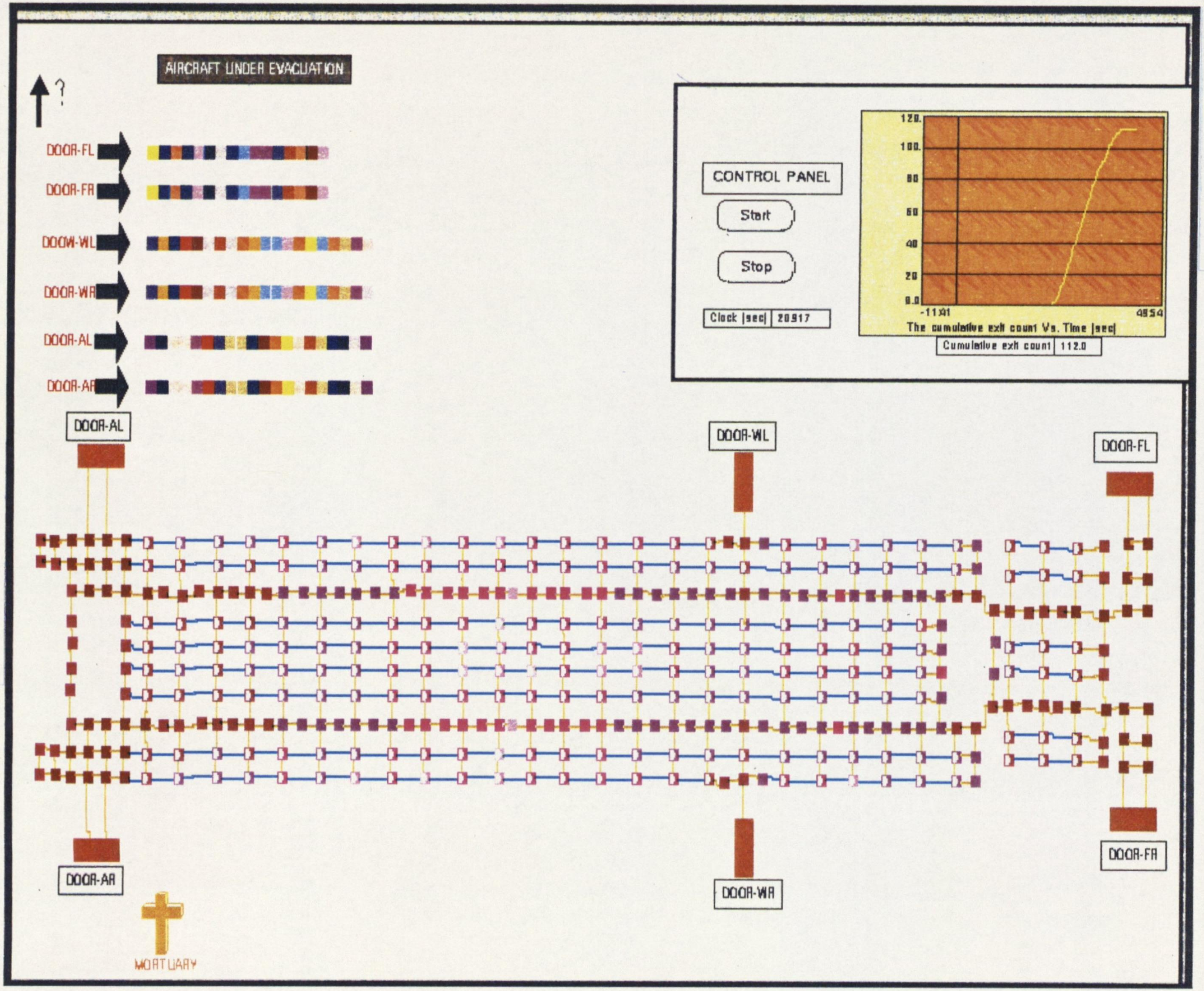

Figure 10

Demo2 after the last passenger has exited the aircraft (18.3 seconds). Also depicted is the cumulative exit count

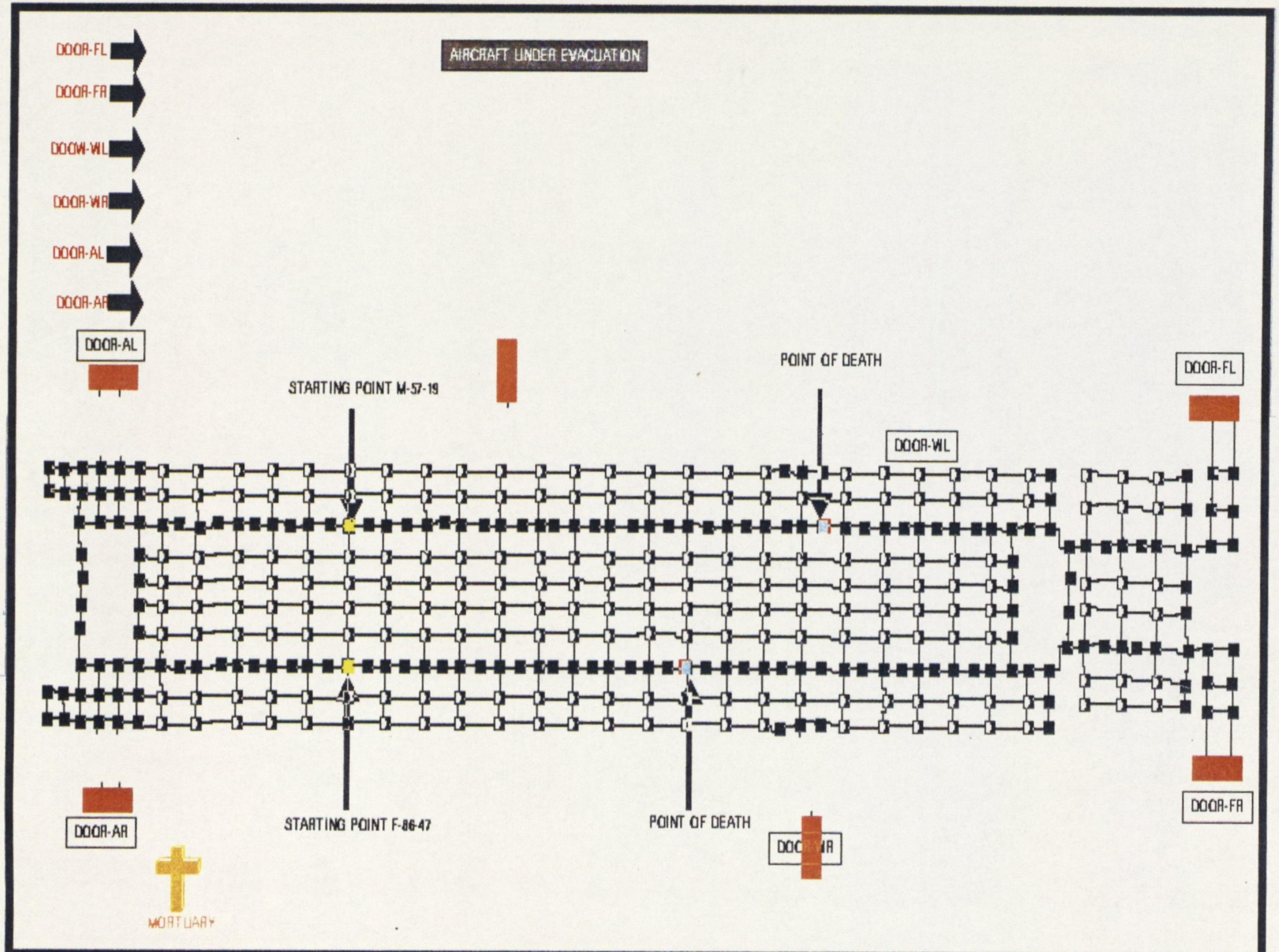

Figure 11

Fastest male and slowest female passengers making their way out of the aircraft while exposed to toxic products. Both passengers expire, the male travels a total distance of 11.25 m while the female travels 8.1 m

With the wing exit potentials set to 1, the evacuation times become 22.9 seconds with the wing doors closed (demo11), 29.5 seconds with the forward doors closed (demo7), and 34.2 seconds with the aft doors closed (demo9). Setting the wing potentials to 10, the evacuation times for these cases become 22.9 seconds (demo11), 25.5 seconds (demo8) and 29.4 seconds (demo10). The worst case scenario occurs when both aft doors are shut.

5.3.3 *Evacuation under hostile environmental conditions*

To check the accuracy of the toxicity submodel a single passenger was placed in the aircraft fuselage and subjected to various levels of toxic hazards. Their progress was recorded and the model predicted outcomes compared with expected results.

The selected passenger was a 19–57 male (RMV = 22.5 L/min, D = 20). The aircraft fuselage was divided into four zones, each with a set of fixed temperature, HCN, CO, CO2 and O2 data (see table 12). For reasons of simplicity, the hazard data was not transient in nature. The severest conditions occur in the rear of the aircraft and gradually ease towards the front of the aircraft. The passenger was placed in the rear of each zone on an aisle node and allowed to move. In these cases, all doors, with the exception of the forward doors were closed.

Table 12 Distribution of fire hazards for passenger trials

Fire hazard	*A*	*B*	*C*	*D*
Temperature (C)	300	80	35	30
CO(ppm)	20,000	15,000	6,000	4,000
HCN(ppm)	30	20	10	5
CO_2 %	20	15	10	5
O_2 %	15	19	20	21
Extent (seat #)	rear – 27+	27 – 21	20 – 8	7 – front

For the first case, the passenger was placed in the rear of zone A, the most hostile region in the aircraft. As expected the passenger expires after 0.667 seconds (see table 13) having travelled only 0.9 m. The cause of incapacitation is the relatively large value for the FICO (0.012) coupled with a large value of the VCO2 (146.01).

Table 13 Exodus calculated and expected results for passenger placed in zone A

Quantity	*Exodus results*	*Expected results*
TIME (sec)	0.667	0.667
FIN	1.744	1.745
FIH	0.224	0.224
FICO2	0.753	0.753
Distance (m) travelled	0.90	0.90
Distance (m) to Exit	28.55	28.55

For the second case the passenger was subjected to the milder conditions of zone B. In this he remains conscious for 2 seconds and travels a distance of 2.7 m. The lower temperature experienced in this zone results in a negligible value for FIH (see table 14).

Table 14 Exodus calculated and expected results for passenger placed in zone B

Quantity	*Exodus results*	*Expected results*
TIME (sec)	2.0	2.0
FIN	1.116	1.116
FIH	$1.658e^{-3}$	$1.658e^{-3}$
FICO2	0.169	0.169
Distance (m) travelled	2.7	2.7
Distance (m) to Exit	24.075	24.075

In the third case the passenger, who is placed in the rear of zone C, succeeds in escaping from the aircraft in 15 seconds. The vast majority of the hazard accumulation occurs during the 8.3 seconds that they are travelling through zone C (tables 15 and 16).

Table 15 FIN and exposure times for passenger at cross over from zone C to D

Quantity	*Exodus results*	*Expected results*
FIN to end of 35° zone	0.521	0.519
FIN at start of 30° zone	0.525	0.523
Time (sec) in 35°C	8.3	–
Time (sec) in 30°C	6.7	–

Table 16 Exodus calculated and expected results for passenger placed in zone C and exiting the aircraft through zone D

Quantity	*Exodus results*	*Expected results*
TIME (sec)	15.0	15.0
FIN	0.601	0.599
FIH	$3.343e^{-3}$	$3.343e^{-3}$
$FICO_2$	$5.561e^{-2}$	$5.561e^{-2}$
Distance (m) travelled	20.25	20.25
Distance (m) to exit	–	–

The fourth elementary test involved a passenger placed in the rear of zone D. This is the least hazardous zone and, as expected he escapes the aircraft with minimal accumulation of toxic products.

The final elementary test involved two passengers racing each other across the aircraft from the last node in zone B to the forward exits. They were a 19–57 male (maximum speed 1.35 m/s, RMV = 22.5, D = 20) and a 47–86 female (maximum speed 0.98 m/s, RMV = 24.75, D= 18). As expected (figure 11), the male travels (11.25 m) a greater distance than the female (8.1 m) and remains conscious for longer; however eventually both become incapacitated.

Table 17 Exodus calculated and expected results for passenger placed in zone D

Quantity	*Exodus results*	*Expected results*
Time(sec)	6.667	6.667
FIN	0.0792	0.0792
FIH	$1.41147e^{-3}$	$1.41147e^{-3}$
FICO2	$3.13532e^{-3}$	$3.13532e^{-3}$

With the successful completion of these experiments, four additional simulations were performed with a complement of 112 passengers representing a 54% occupancy. This passenger distribution is identical to that used in the last section. Throughout these simulations, the rear doors were closed and the potential of the forward exits set to the value 1, while those of the wing exits were set to the value 10. These simulations are thus similar to Demo10 of the last section. A summary of the results may be found in table 18, for more details refer to Appendix 2 (tables A2.1 to A2.4).

Table 18 Summary of evacuation times for the 4 scenarios including toxicity data

Scenario	*Evacuation time (sec)*	*Number of fatalities*
Demo12 Fixed toxicity	16.81	41
Demo13 Fixed toxicity speed=speed*mobility	12.3	62
Demo14 Fixed toxicity agility=agility*mobility	10.3	50
Demo15 Variable toxicity	14.42	52

The first simulation incorporated the fixed hazard data described in table 12. Figure 12 depicts the starting and finishing location for each of the passengers which were overcome by the fire hazards. The numbering indicates the order in which the passengers succumb.

As can be seen in figure 12, a number of aisle nodes have two fatalities. This increases the obstacle value of these nodes from 1 to 3. In this simulation the minimum agility of the passengers is 4; in addition, the agility is not affected by the FIN and so the passengers have no difficulty in overcoming these obstacles.

The majority of the fatalities (59%) occurred in the high temperature/toxicity zone (B) where these passengers were also the first to succumb. A total of five passengers were overcome in the immediate vicinity of the exits. The 39th casualty, a 36–57 male travelled over 9.2 m and survived for 16.3 seconds before passing out in the right wing exit.

To understand the order and location of incapacitation it is necessary to follow in detail the passengers' movements. To illustrate this, consider passengers in seat rows 21, 20 and 19 (table 19). Note that the 80°C zone ends and the 35°C begins between seat rows 21 and 20.

Consider the passengers in seats 21F and 21G. Both compete for the aisle, but because the male is in band 1 he beats the female in seat 21F, forcing her to wait. The male thus spends less time in zone B than the female, survives for longer and travels further before being overcome. Similarly, the passenger in seat 21E has an agility and patience which allows her to jump over the seat back (into location 20E) rather than wait for a path to the aisle to become clear.

Table 19 Initial seating position for passengers in rows 19 to 21. Numbers in brackets indicate the order in which the fatalities occurred. This data relates to Demo12

Seat	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*
21		M (21) 19–86	F (15) 47–86	F (23) 36–57	F (24) 36–57	F (16) 47–86	M (22) 19–86	
20	F (37) 19–57		F (33) 47–75			F (34) 47–75		F(38) 19–57
19		F (26) 36–86	M (29) 47–86	F (36) 19–75	F (35) 19–75	M (30) 47–86	F (25) 36–86	

Passengers in seats 19F and 19G also compete for an aisle position. The passenger in seat 19G is a band 1 female while the passenger in seat 19F is a band 3 male. As both these passengers have the same travel speed, possession of the aisle is determined by the individuals drive. As the female has the higher drive she wins the aisle node, forcing the male in location 19F to wait. As this is occurring, the passenger in location 20F, a band 2 female, also moves into the aisle. While both these passengers take their next step along the aisle, the passenger in location 19F enters the aisle just ahead of passenger 20F.

As all three passengers are exposed to the same concentrations of toxins, the order in which they succumb is determined by their respective values for the RMV/D ratio in the FICO formula (equation 3). The RMV/D ratio for passenger 19F is 27.5/20, while for passenger 19G it is 24.75/18. As the ratio is identical, this results in both these passengers passing out in approximately the same time.

In fact passenger 19G is the 25th passenger to expire, while passenger 19F is the 30th passenger. However, if the actual time to incapacitation is examined it becomes clear that they expired in approximately the same amount of time, 19G in 13.30 seconds and 19F in 13.34 seconds. As they pass out in the same amount of time and, as 19G was ahead of 19F she has managed to travel slightly further (see figure 12).

Passenger 20F, while being slower than 19F and 19G, survives the longest of the three and travels the furthest distance. This is so because she has the smallest RMV/D ratio (22.5/18).

Demo13 involved the same toxicity and passenger data as in the previous example, however in this simulation each passenger's travel speed was modified according to their current mobility value. A passenger's mobility is reduced as the FIN increases (see table 3 and equation 2). Figure 13 depicts the starting and finishing location for each of the passengers which were overcome by toxins. The numbering indicates the order in which the passengers succumb.

The results are very similar to those of Demo12, however the number of fatalities has increased from 41 (36.6%) to 62 (55.4%) passengers. We also note that two passengers in zone C are among the fatalities. The increase in the number of fatalities is expected as a reduction in travel speed increases the passengers' duration of exposure to the toxic products.

It is also interesting to note that in this simulation as many as three passengers have passed out on a single node. This increases the obstacle value of aisle nodes to 4, equivalent to the minimum default agility setting.

In Demo14, once again we have the same toxicity and passenger data as in the previous example, however in this simulation each passengers' agility was modified according to their current mobility value (see table 3 and equation 1). Figure 14 depicts the starting and finishing location for each of the passengers which were overcome by toxins. The numbering indicates the order in which the passengers succumb.

The link between mobility and agility does not have as pronounced an effect as the link between mobility and speed. Here we find the number of fatalities has increased from 41 (36.6%) to 50 (44.6%) passengers and the fatalities are restricted to zone B.

To examine the consequences of this linkage, consider the movements of passengers in seats 20H and 20F; these are the 38th and 42nd passengers to succumb to the hazardous atmosphere.

Passenger 20F travels a distance of 5.2m before coming to a stop. She occupies an aisle node on which another passenger (19F) has died; however, while her agility was sufficient to move her onto the node, by the time she comes to move off, her agility has fallen below the critical value (2) and she is unable to move off. She thus waits, extending her exposure to the toxic products and eventually passes out. In Demo12 the same passenger travelled a distance of 7.4 m.

Passenger 20H also travelled a distance of 5.2m before coming to a stop. She was prevented from travelling further by the blockage (obstacle value = 2) caused by passenger 19F, the 26th passenger to pass out. Her agility was reduced to such a level that passing over the blockage was impossible. As she waited on the spot her exposure to the toxic products increased to the point of incapacitation. In Demo12, the same person (also labelled as 38 in figure 12) travelled a distance of 9.2m before incapacitation.

The final demonstration simulation (Demo15) once again involved the same population distribution, but incorporated fire hazard data which varies in time and space. The values of the various hazards and the extent of the zones were increased in two time steps starting with an initial distribution as described in table 15 (see appendix 3).

This case (see figure 15) is again similar to that of Demo12, with the number of fatalities increased from 41 (36.7%) to 52 (46.4%). As expected, when the concentration of the fire hazards increases the passengers' dose will also increase leading to a greater number of fatalities.

The fire hazard data incorporated in these simulations was artifical and crude. Only single layer values were considered, the interfaces between the zones were sharp and well defined and the zones themselves were regular and block-structured. The nature and location of the resulting fatalities reflect this simplicity. This type of data was used purely for demonstration purposes.

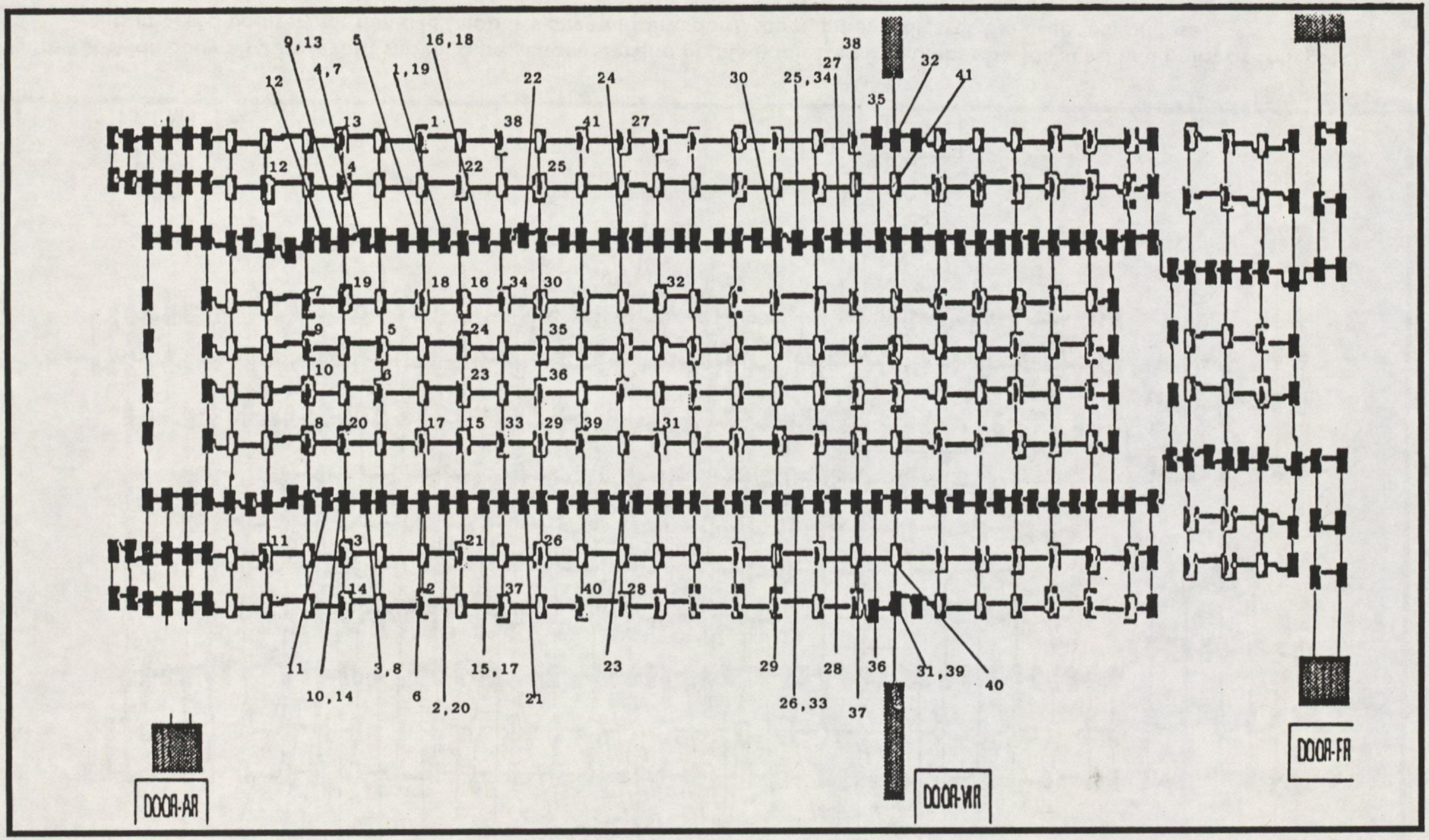

Figure 12 Wide body aircraft layout showing passenger starting points (indicated by number beside seat) and point of collapse (numbered pointer) for demo12 (fixed toxicity data). The number indicates the order of collapse

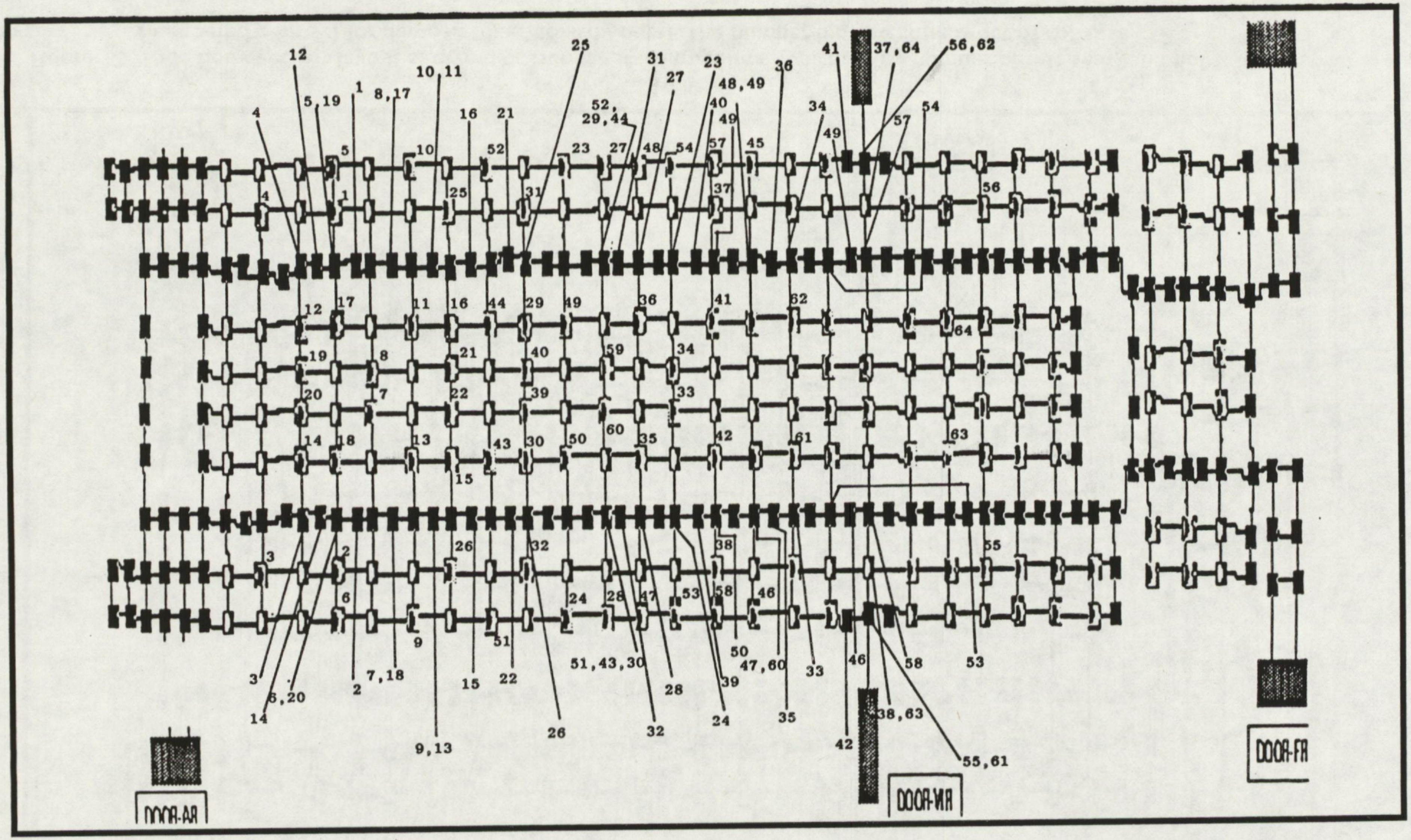

Figure 13 Wide body aircraft layout showing passenger starting points (indicated by number beside seat) and point of collapse (numbered pointer) for demo13 (mobility-speed interaction), the number indicates the order of collapse

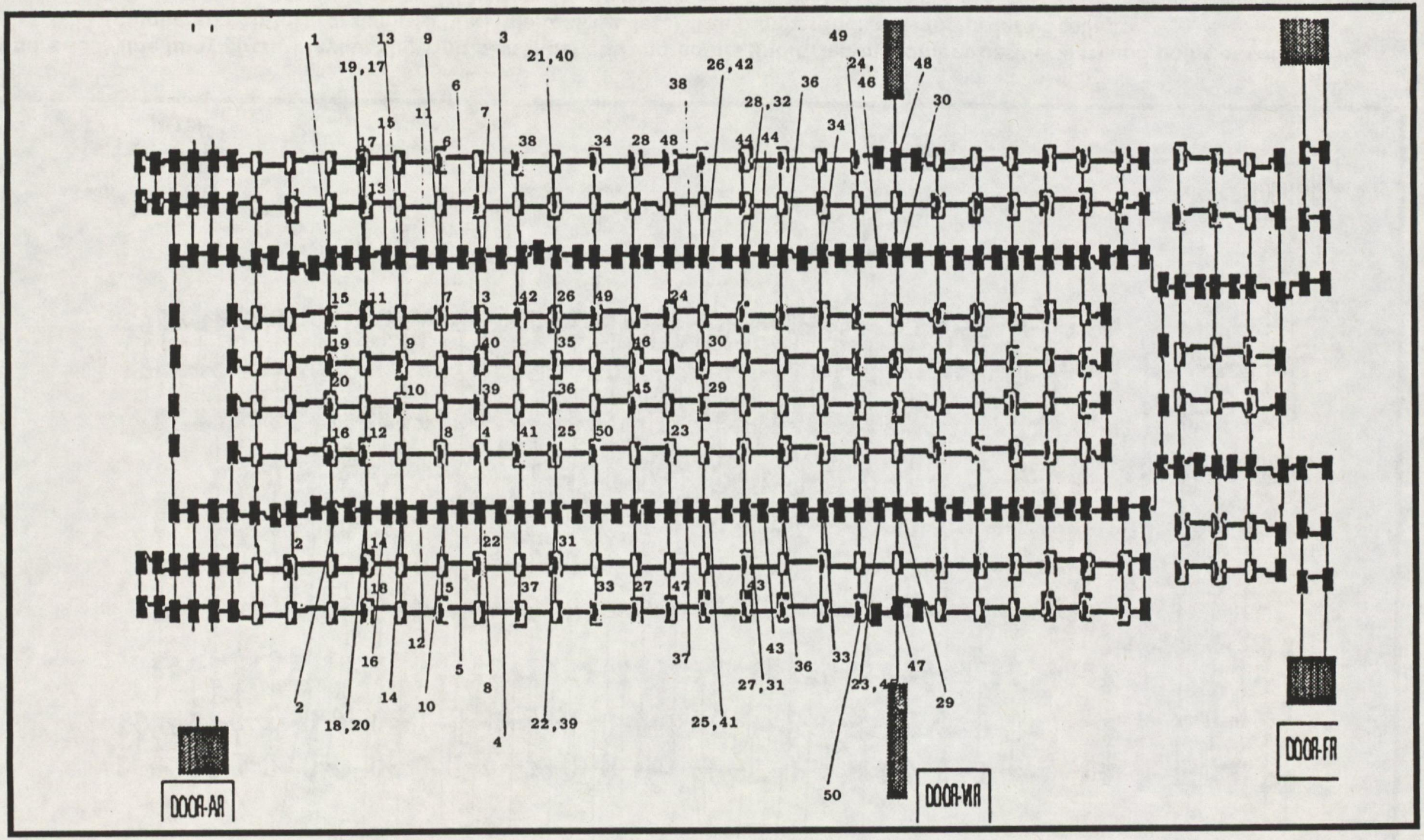

Figure 14 Wide body aircraft layout showing passenger starting points (indicated by number beside seat) and point of collapse (numbered pointer) for demo14 (mobility-agility interaction). The number indicates the order of collapse

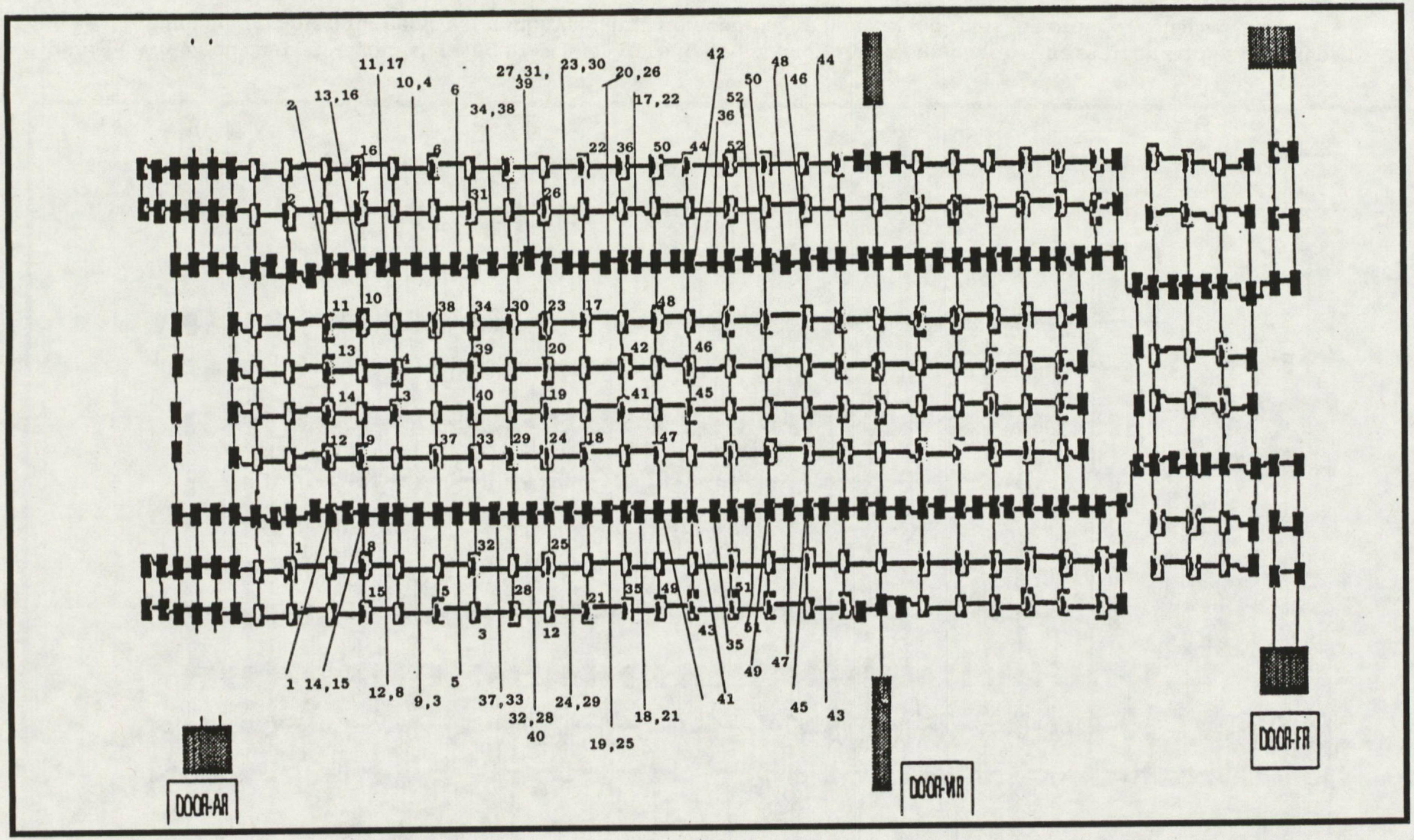

Figure 15 Wide body aircraft layout showing passenger starting points (indicated by number beside seat) and point of collapse (numbered pointer) for demo15 (variable toxicity data). The number indicates the order of collapse

Ideally this information should be derived from actual physical measurements or generated by fire models (1–5). As EXODUS has the capability of differentiating between neighbouring seats, the fire hazard data should also reflect this degree of resolution. Of the fire modelling techniques currently available, only fire field models (3–5) offer this type of resolution.

5.4 Trident Three Simulations

5.4.1 *Introduction*

The capabilities of the EXODUS evacuation model have been demonstrated through a set of hypothetical evacuation scenarios. In this section results from an attempt to model a selection of the CRANFIELD TRIDENT THREE experiments (20) are presented.

Very few details concerning aircraft dimensions and passenger attributes were available to the authors, and so little attempt was made to tune the model. However, experience gained from the demonstration simulations suggested that passenger travel speeds were in excess of realistic values. The values used in the TRIDENT THREE simulations were therefore arbitrarily reduced to the values shown in Table 20.

Table 20 Running and walking speeds adopted by the passengers in Trident Three application of EXODUS model.

Band	*Run (m/s)*		*Walk (m/s)*	
	Male	*Female*	*Male*	*Female*
1	1.2	1.02	0.5	0.42
2	1.0	0.85	0.41	0.32
3	0.8	0.68	0.33	0.28

The aircraft configuration used in the CRANFIELD experiments was a section of a TRIDENT THREE. The geometry consisted of 12 rows of seats organised 6 abreast and parted by a single aisle forming two groupings of 3 abreast. This configuration could accommodate a total of 72 passengers. The seat rows were numbered from 8 (forward seat) to 19 (aft seat), and from A (left) to F (right).

The CRANFIELD experiments involved competitive evacuations through various sized apertures. Two basic configurations were used, one involving an overwing exit (TYPE III exit) located near seat 14A, and the other, an exit in the forward bulkhead.

The bulkhead series involved 6 different experiments each of which was repeated a number of times. These experiments consisted of progressively widening the bulkhead aperture. The overwing series involved 7 different experiments each of which was repeated a number of times. These experiments involved increasing the seat pitch in the immediate vicinity of the overwing exit.

The experimental means displayed in tables 21 to 24 represent mean evacuation times over all the experiments, whereas the EXODUS means represent a single numerical experiment for a single case. Comparisons based on this data should be made with care. The experimental data used in figures 16 to 19 refer to a single configuration, and so make for more reliable comparisons.

The type of people used in the experiments and their distribution were not known to the authors. For the purposes of the simulation, the standard population mix as specified in the 90 second evacuation trials (6) was used, and the passengers were positioned randomly. This resulted in 22 females and 50 males. The age-weight distribution of the model passengers is detailed in Table A4.1.

The model used the following geometric data: seat pitch 0.737 m (29 inches), seat width 0.432 m and the distance from aisle seat to aisle centre, 0.66 m. The EXODUS model was applied to the two basic exit geometries. These simulations most closely resemble the wing exit experiment with 29 inch seat pitch (ie (ii) in ref 20) and the 20 inch bulkhead aperture experiment. As the CRANFIELD experiments were not performed in hazardous conditions the hazard and toxicity submodels are not implemented in these simulations.

Finally, it must again be emphasised that the EXODUS model has not been tuned to the experimental data and that all attributes assume 'best guess' values.

5.4.2 *Wing exit trials*

For the wing exit simulations the wing exit potential was set to 1. All passengers have infinite patience and zero response time, which means that they respond immediately to the call for evacuation, but are obliged to queue rather than jump over seat backs. The results for this simulation are presented in tables 21 and 22 and figure 16.

Table 21 EXODUS evacuation times and experimental mean evacuation times (16) for overwing exit as a function of row

Number of rows from overwing exit and (actual row)	*EXODUS evacuation time (sec)*	*Experimental mean evacuation time (sec)*
6 (8)	92.79	82.4
5 (9)	81.35	71.6
4 (10)	65.38	66.0
3 (11)	49.39	57.4
2 (12)	33.44	47.7
1 (13)	16.50	37.1
0 (14)	4.38	18.1
1 (15)	18.66	38.4
2 (16)	32.99	46.8
3 (17)	51.59	56.1
4 (18)	65.76	58.0
5 (19)	82.13	68.9

The EXODUS times represent an average for the six seats within a row while the experimental times represent row means determined over several experiments.

Tables 21 and 22 reveal that EXODUS has captured most of the general trends found in the experimental data. From Table 21 it is clear that as the seat row becomes further removed from the exit the evacuation time increases. Experimentally it is clear that the passengers seated in the aisle seats achieve the minimum evacuation times on average and passengers in the window seats achieve the maximum evacuation times on average. Also note, seats A, B and C have shorter evacuation times than their opposite corresponding seats. This is also observed in the EXODUS results (see table 22).

Figure 16 displays a graph of evacuation flow for the overwing case. Plotted are the EXODUS results and an envelope representing the spread of experimental results. The EXODUS prediction falls just outside the experimental envelope and suggests that the model is predicting too rapid an exit flow.

Table 22 EXODUS evacuation times and experimental mean evacuation times (16) for overwing exit as a function of locality

F	*E*	*D*	*Aisle*	*C*	*B*	*A*	
58.9	51.9	44.0		38.4	48.5	55.4	EXODUS (SEC)
66.4	57.8	49.2		48.4	56.5	58.9	Experiment (sec, mean)

The EXODUS times represent an average over 12 seats while the experimental means represent row means determined over several experiments.

5.4.3 *Bulkhead evacuation*

In the bulkhead exit simulations a potential of 1 was set at the exit. The population distribution used in these simulations was identical to that used in the wing exit simulations. A series of three numerical experiments was performed. The first was identical to the single wing simulation (A); the second simulation involved allowing certain passengers to jump over seat backs (B), and in the third simulation, a single travel speed was set for all passengers (C). The results are summarised in tables 23 and 24.

As with the wing exit simulation, bulkhead simulation A correctly predicts the trends found in the experiments. However, the actual evacuation times are over predicted (figure 17). Figure 17 reveals that after the 40th passenger has escaped, EXODUS over-predicts the egress times, resulting in the predicted flow curve falling outside the experimental envelope.

In simulation B, 6 passengers were given the ability to leap over seat backs rather then wait for an opening in the aisle queue. All six passengers availed themselves of the opportunity and of these, five were located in the rear half of the cabin section (18E, 18F, 16A, 15F, 14A, and 11A). The results shown in Figure 18 suggest that the total evacuation time is reduced slightly (from 85 to 81 seconds) by this action and the simulated results move closer to the experimental envelope. However, the evacuation time for the last 50% of the passengers is still over-estimated.

Table 23 EXODUS evacuation times for the three simulations and experimental mean evacuation times (16) for bulkhead exit as a function of locality

F	*E*	*D*	*Aisle*	*C*	*B*	*A*	
							EXODUS (SEC)
46.64	42.84	39.60		36.37	41.12	44.97	A
39.79[3]	45.32	41.71		38.99	42.75[1]	38.80[2]	B
26.35	24.25	21.02		22.67	24.15	27.42	C
21.2	20.3	19.2		17.8	18.6	19.7	Experiment (sec, mean)

The EXODUS times represent an average over 12 seats while the experimental means represent row means determined over several experiments. Superscript indicates number of passengers in row who jumped over seat backs.

Table 24 EXODUS evacuation times for the three simulations and experimental mean evacuation times (16) for bulkhead exit as a function of row

Number of rows from bulkhead exit and (actual row)	*EXODUS evacuation time (sec)*	*Experimental mean evacuation time (sec)*
1 (8)	5.16 5.16 2.97	6.3
2 (9)	11.04 14.38 6.50	9.4
3 (10)	17.08 23.08 10.05	12.9
4 (11)	24.52 27.041 14.50	15.4
5 (12)	31.65 36.01 18.50	17.5
6 (13)	38.57 42.57 22.50	19.4
7 (14)	45.26 43.121 26.50	20.8
8 (15)	52.24 47.051 30.43	24.4
9 (16)	59.46 53.151 34.51	26.1
10 (17)	66.53 67.53 38.31	27.7
11 (18)	71.84 60.262 42.51	28.1
12 (19)	79.81 75.90 46.00	29.8

The EXODUS times represent an average for the six seats within a row while the experimental means represent row means determined over several experiments. Superscript indicates number of passengers in row who jumped over seat backs.

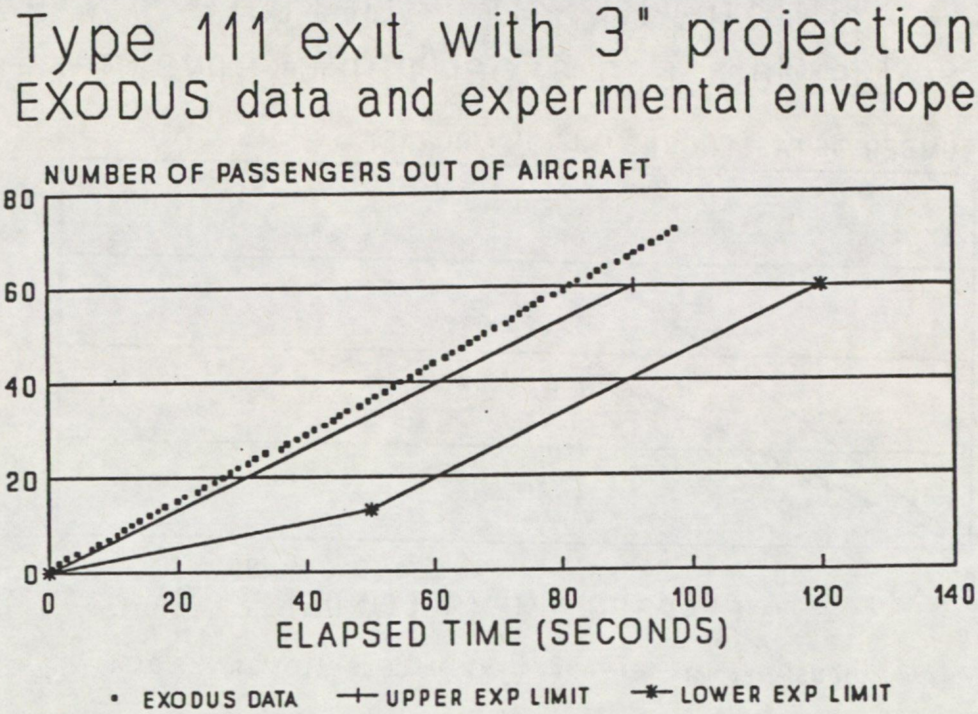

Figure 16 Evacuation flow for the overwing case, EXODUS data and experimental envelope

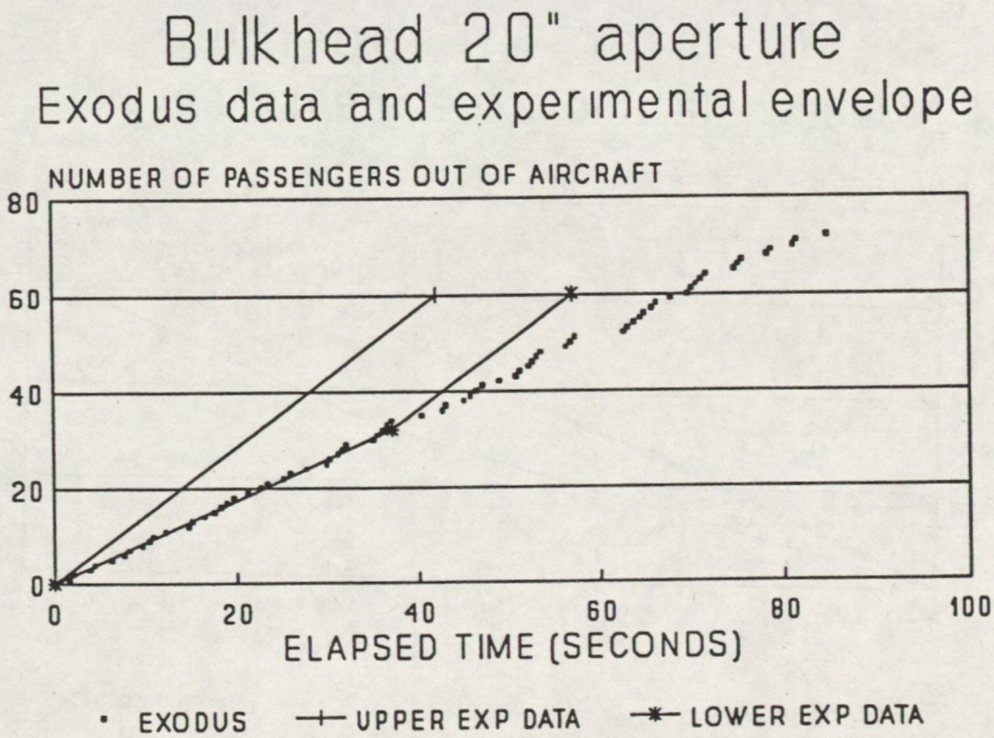

Figure 17 Evacuation flow for bulkhead aperture, EXODUS data and experimental envelope

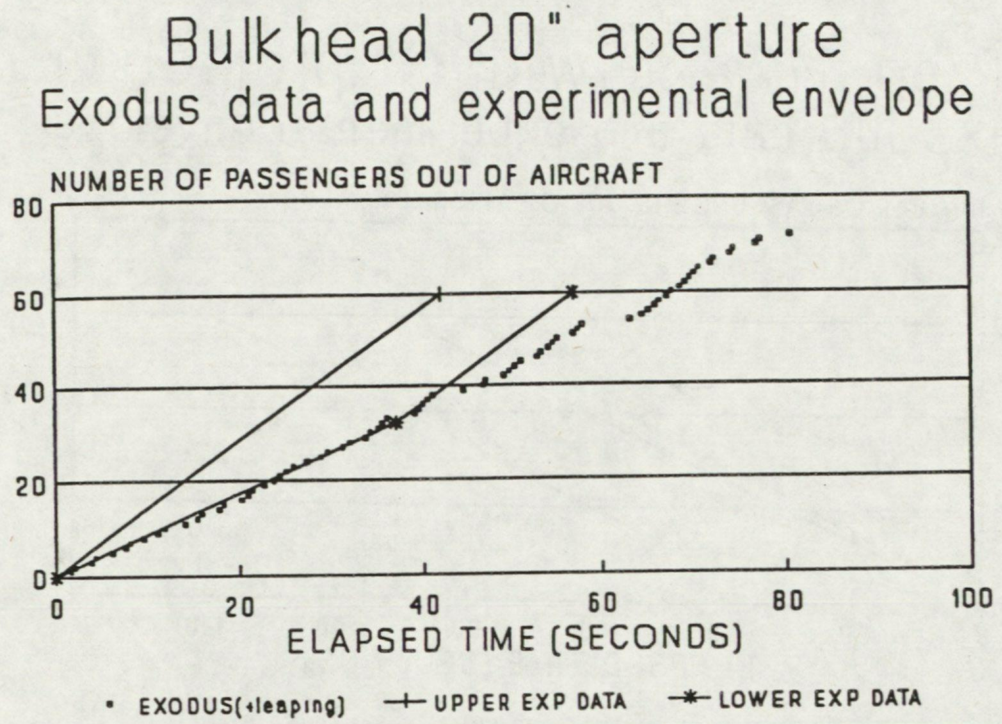

Figure 18 Evacuation flow for bulkhead aperture, EXODS model in which all passengers travel with identical uniform speed and experimental data

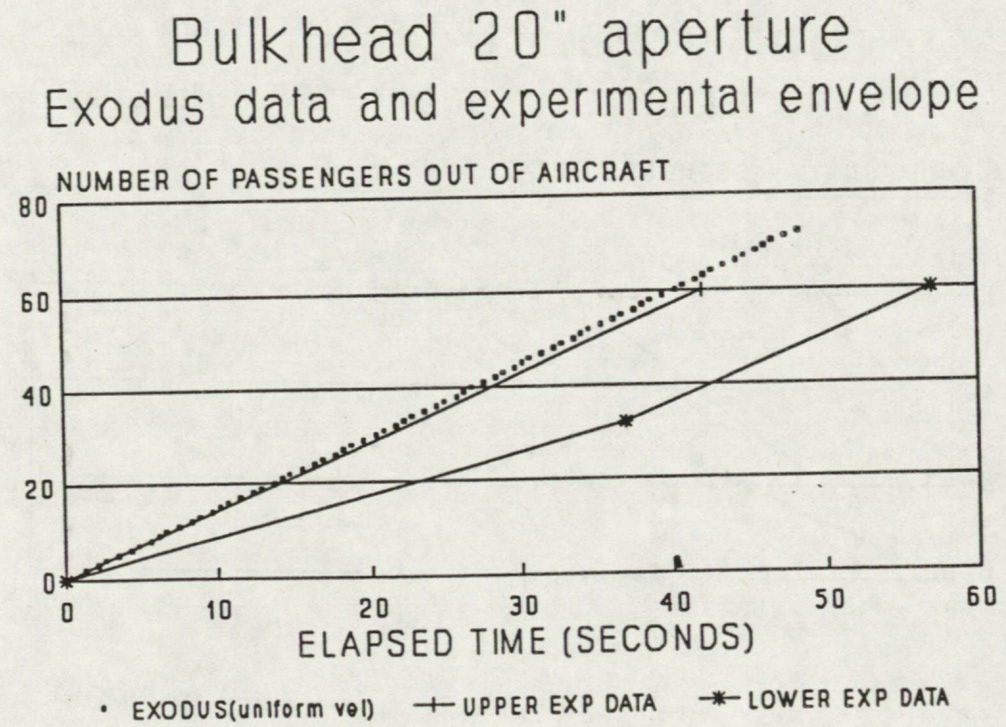

Figure 19 Evacuation flow for bulkhead aperture, EXODUS model data in which 6 passengers jump over seat backs and experimental envelope

Those passengers selecting a route which took them over seat backs ignored the aisle completely. Once they had travelled as far as possible (typically stopping at the bulkhead) using this path, they then attempted to enter the aisle exit queue. Without exception, these passengers exited the aircraft quicker than when they were unable to go over the seats. For example, passenger 16A moved from 55th passenger out (63 seconds) to 16th place (20 seconds), while passenger 18E advanced from 63rd place (71 seconds) to 55th place (65 seconds).

In the final simulation all passengers travel at the same speed and there is no differentiation between walking and running speeds. Here we find that the model results fall just outside the experimental envelope (figure 19), the model passengers fleeing the aircraft more rapidly than suggested by the experiments.

6 CONCLUSIONS

A prototype evacuation model for mass transport vehicles has been developed and hypothetical aircraft emergency scenarios used to demonstrate the model's capabilities. It attempts to simulate the escape trajectory of competing individuals subjected to fire hazards. In comparisons with experimental data derived from competitive trials under non-hazardous conditions, it was able to correctly predict most experimental trends.

The escape strategy employed by each of the individuals is to leave the aircraft via the nearest or assigned exit. This approach assumes that the passengers have access to global information concerning the location and condition of the various exits. Using this strategy, the model (with appropriately tuned attributes) predicts a lower bound for the expected evacuation time.

When run without the toxicity model, EXODUS may have use in predicting the expected outcome of the industry standard 90 second evacuation trials.

The toxicity model incorporated within EXODUS considers each passenger's response to their accumulated dose of CO, HCN, CO2, as well as the effects of O2 depletion and exposure to convective heat. The model has been demonstrated with concentrations of these products located at head height; however, it also has the capability to utilise data at multiple heights thus accommodating the possibility of crawling passengers.

The sensory depravation effects of smoke are thought to have a major effect on the passengers' ability to escape. While the present version of EXODUS accommodates the spread of smoke, it has not been fully activated within the model. The model also does not take into account the acid gases (HCL and HF) and their contribution to sensory depravation. These factors constitute details which can be incorporated within EXODUS in a straight forward manner.

While EXODUS has been specifically designed to simulate evacuation from mass transport vehicles, the software can also be applied to enclosures which have similar features ie rows of seats separated by aisles with little free space. Examples of such enclosures are cinemas, lecture halls, theatres, churches etc.

The modular approach used in the design of the EXODUS software enables alterations and additions to the model to be incorporated relatively easily.

7 FURTHER MODEL DEVELOPMENT:

Two areas which would benefit from further development are the movement and behaviour sub-models. In the current implementation of EXODUS the passengers have limited decision-making capability with regard to route planning. Passengers simply head for their nearest serviceable exit.

As described in section 4.4 this is a simplistic representation of reality. Individuals may change their direction, seeking another exit. This may occur as a result of a calculated decision based, for example, on the size of the crowds at the nearest exits and the predicted travel time to those exits, or the passenger may simply choose to exit via the path taken on entry. In such cases, the potential well alone can not cope with these possibilities as this will necessitate travel in a direction opposed to the local favourable potential. To accommodate these possibilities passengers require a more sophisticated decision making capability.

A decision-making capability which will enable passengers to determine their 'best' (or favoured) or optimal escape route based on environmental, physical and psychological information is proposed. The proposed capability will make use of network analysis to determine the optimal path, and this will require the enclosure geometry to be divided into zones. A zone may involve a number of grid nodes; for example, the nodes within a seat row may comprise a zone, while the grid nodes along an aisle may constitute a number of zones. The zones will be connected by arcs which have attributes of 'cost' associated with that path. The cost attributes may involve travel time, degree of occupancy, smoke density, personal phoebias, etc. The occupant may then choose the travel path which minimises his or her 'cost'.

Another area within the behaviour sub-model which requires further development is the passenger attribute list. For example the current model does not include bonding. Bonding is meant to signify if two (or more) passengers are linked physically (eg parent with baby) or emotionally (eg husband and wife). If bonding occurs an individuals travel speed and agility may be affected. For example, a parent and child bonding would result in a reduced set of movement parameters for the couple, while a husband and wife bonding would result in the couple assuming the lesser set of movement parameters.

Passenger behaviour at the exit also requires further investigation. In the current implementation, once at the door, the passenger exits after an arbitrarily short delay, equivalent to travelling an additional 0.5m. A more thorough approach would involve the introduction of a delay time representative of the time taken to jump onto or sit down on the emergency slide. Also, delays at the exit caused by several passengers attempting to pass through simultaneously could be incorporated.

The module design of EXODUS allows modifications of these types to be made relatively easily.

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9 REFERENCES

1 C.D.MacArthur and J.F.Myers, Dayton aircraft cabin fire model validation. FAA Research Report FAA-RD-78-57, 1978.

2 K.T.Yang, J.R.Lloyd, A.M.Kanury and K.Satoh, Modelling of turbulent buoyant flows in aircraft cabins. Combustion Sci. Tech., 1984, 39, 107–118.

3 E.R.Galea and N.C.Markatos, The mathematical modelling and computer simulation of fire development in aircraft. Int.J.Heat Mass Transfer, 1991, Vol 34. No.1 pp 181–197

4 N.Markatos and G.Cox, Hydrodynamics and heat transfer in enclosures, Physico-Chem. Hydrody. 1984 5 (1), 53–66.

5 E.R.Galea, On the field modelling approach to the simulation of enclosure fires. J. Fire Protection Engng 1 (1), 11–22 1989.

6 FAR part 25.803

7 D.F.King, Report on the accident to Boeing 737-236 series 1, G-BGJL at Manchester International Airport on 22 August 1985. Aircraft Accident Report 8/88. HMSO LONDON. 1988.

8 Flight International p7, 13/10/92.

9 M.M.Kostreva, M.M.Wiecek and T.Getachew, Optimization Models in fire Egress Analysis for Residential Buildings, Fire Safety Science Proceedings of the Third International Symposium, pp 805–814.

10 T.M.Kisko and R.L.Francis, EVACNET+: A computer program to determine optimal building evacuation plans, Fire Safety Journal, 9,1985, pp.211–220.

11 K.Takahashi, T.Tanaka and S.Kose, An evacuation model for use in fire safety design of buildings, Fire Safety Science Proceedings of the Second International Symposium, Tokyo, June 13–17, 1988, Hemisphere Publishing Company, New York, 1989. pp 551–560.

12 B.M.Levin, EXITT – A simulation model of occupant decisions and actions in residential fires, Fire Safety Science Proceedings of the Second International Symposium, Tokyo, June 13–17, 1988, Hemisphere Publishing Company, New York, 1989. pp 561–570.

13 R.F.Fahy, EXIT89: An evacuation model for high-rise buildings, Fire Safety Science Proceedings of the Third International Symposium, pp 815–823.

14 R.W.Bukowski, R.D.Peacock, W.W.Jones and C.L.Forney, Technical Reference Guide for HAZARD 1, Fire Hazard Assessment Method, Handbook 146, Volume 11 U.S. NIST, Gaithersburg Maryland, 1989.

15 Fires and Human Behaviour, edited by D.Canter, David Fulton Publishers Ltd, Second Edition, 1990.

16 J.Tadahisa and Y Tokiyoshi, Experimental Study of Human Behaviour in Smoke filled corridors, Fire Safety Science Proceedings of the Second International Symposium, Tokyo, June 13–17, 1988, Hemisphere Publishing Company, New York, 1989. pp 511–519.

17 G2 Reference Manual, Version 2.0. Gensym Corporation, 125 Cambridge Park Drive Cambridge, MA 02140 USA.

18 C.Marrison, and H.Muir, Passenger behaviour in aircraft emergencies involving smoke and fire. AGARD No 467, pp 35–1 – 35–7, 1989.

19 D.A.Purser, Modelling time to incapacitation and death from toxic and physical hazards in aircraft fires. AGARD No 467, pp 41–1 – 41–12, 1989.

20 H.Muir, C.Marrison and A.Evans, Aircraft evacuations: the effect of passenger motivation and cabin configuration adjacent to the exit. CAA Paper 89019, ISBN 0 86039 406 9, 1989.

Appendix 1 Details of 11 evacuation scenarios without toxic hazards

Table A1.1 Evacuation details for scenario Demo1

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	6.986	7	6.525	H4
DFR	6.986	7	6.525	A4
DWL	24.532	34	10.35	G19
DWR	23.192	33	10.35	B19
DAL	14.558	15	10.35	F19
DAR	15.116	16	10.35	C19

Table A1.2 Evacuation details for scenario Demo2

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	11.844	15	7.875	F6
DFR	12.88	16	7.875	C6
DWL	14.949	21	4.95	G7
DWR	14.281	20	4.05	C8
DAL	18.261	20	10.35	F19
DAR	18.261	20	10.35	C19

Table A1.3 Evacuation details for scenario Demo3

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	–	–	–	–
DFR	15.083	17	8.775	G5
DWL	–	–	–	–
DWR	46.012	67	11.7	F19
DAL	–	–	–	–
DAR	27.25	28	11.25	G21

Table A1.4 Evacuation details for scenario Demo4

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	–	–	–	–
DFR	21.273	31	9.225	F6
DWL	–	–	–	–
DWR	30.667	40	10.8	H16
DAL	–	–	–	–
DAR	32.136	41	13.05	G19

Table A1.5 Evacuation details for scenario Demo5

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	–	–	–	–
DFR	–	–	–	–
DWL	26.449	41	10.575	D1
DWR	30.365	42	10.575	C1
DAL	–	–	–	–
DAR	29.056	29	10.8	F20

Table A1.6 Evacuation details for scenario Demo6

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	–	–	–	–
DFR	–	–	–	–
DWL	27.315	36	10.575	C1
DWR	27.365	36	10.575	D1
DAL	–	–	–	–
DAR	33.6	40	13.35	G19

Table A1.7 Evacuation details for scenario Demo7

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	–	–	–	–
DFR	–	–	–	–
DWL	29.449	41	10.35	F19
DWR	28.616	40	10.35	C19
DAL	14.745	15	10.35	G19
DAR	15.447	16	10.35	B19

Table A1.8 Evacuation details for scenario Demo8

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	–	–	–	–
DFR	–	–	–	–
DWL	25.532	36	10.575	D1
DWR	25.532	36	10.575	C1
DAL	17.659	20	10.35	F19
DAR	17.659	20	10.35	C19

Table A1.9 Evacuation details for scenario Demo9

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	7.522	8	6.525	F6
DFR	7.522	8	6.525	C6
DWL	34.225	48	16.65	G26
DWR	34.225	48	16.65	B26
DAL	–	–	–	–
DAR	–	–	–	–

Table A1.10 Evacuation details for scenario Demo10

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	12.511	16	7.875	F6
DFR	12.511	16	7.875	C6
DWL	29.391	40	16.65	G26
DWR	29.391	40	16.65	B26
DAL	–	–	–	–
DAR	–	–	–	–

Table A1.11 Evacuation details for scenario Demo11

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	21.844	29	14.625	H13
DFR	22.897	30	15.525	A14
DWL	–	–	–	–
DWR	–	–	–	–
DAL	22.725	27	10.35	F19
DAR	21.652	26	10.35	C19

Appendix 2 Details of 4 evacuation scenarios with toxic hazards

Table A2.1 Evacuation details for scenario Demo12, constant toxicity data

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	11.213	15	7.875	F6
DFR	11.213	15	7.875	C6
DWL	16.809	21	4.95	G7
DWR	16.058	20	4.95	B7

Number of fatalities = 41 Number of successful evacuees = 71

Table A2.2 Evacuation details for scenario Demo13, constant toxicity data and mobility-speed relationship

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	12.298	16	7.875	F6
DFR	12.298	16	7.875	C6
DWL	4.95	9	5.175	F13
DWR	4.95	9	5.175	C13

Number of fatalities = 62 Number of successful evacuees = 50

Table A2.3 Evacuation details for scenario Demo14, constant toxicity data and mobility-agility relationship

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	10.273	15	7.875	F6
DFR	10.273	15	7.875	C6
DWL	9.833	16	7.2	H15
DWR	4.95	16	7.2	A15

Number of fatalities = 50 Number of successful evacuees = 62

Table A2.4 Evacuation details for scenario Demo15, three phase toxicity data

Door	*Time of last exit*	*Total out*	*Distance*	*Seat*
DFL	11.63	15	7.875	F6
DFR	11.63	15	7.875	D6
DWL	14.417	17	5.85	F14
DWR	14.417	17	5.85	C14

Number of fatalities = 52 Number of successful evacuees = 60

Appendix 3 Time varying fire hazard data used in Demo15

Demonstration simulation 15 involves fire hazard data which varies in time and space. Table A3.1 describes the range of data for the second time period while Table A3.2 describes the data for the third and final time period. The data used in the first time period may be found in Table 15. The three time zones cover the following periods, 0 – 4 sec, 4 – 8 sec and 8 – end seconds.

Table A3.1 Second component of transient fire hazard data used in Demo 15

Fire hazard	*A*	*B*	*C*	*D*
Temperature (C)	300	110	50	40
CO(ppm)	20,000	15,000	6,000	4,000
HCN(ppm)	30	20	10	5
CO_2 %	20	15	10	5
O_2 %	15	19	20	20
Extent (seat #)	rear – 25	24 – 15	14 – 6	5 – front

Table A3.2 Third component of transient fire hazard data used in Demo 15

Fire hazard	*A*	*B*	*C*	*D*
Temperature (C)	300	150	80	50
CO(ppm)	20,000	15,000	10,000	10,000
HCN(ppm)	30	20	15	10
CO_2 %	20	15	15	10
O_2 %	15	19	20	20
Extent (seat #)	rear – 22	21 – 12	11 – 6	5 – front

Appendix 4 Passenger distribution in Trident Three simulation

TABLE A4.1 Age/weight distribution of passengers in Trident Three simulations

Age/Weight (kg)	*Number of Passengers*
19–57	10
19–75	8
19–86	9
36–57	8
36–75	5
36–86	7
47–57	8
47–75	10
47–86	7

Appendix 5 Passenger personal attributes

Figure A5.1

Notes	*OK*
USER RESTRICTIONS	NONE
NAME	PA5
ID	0.0
SEX	MALE
WEIGHT	57
AGE	19
AGILITY	7
SPEED	1.2
DRIVE	20
MOBILITY	1
RMV	22.5
DISTANCE	1.5
RESPONSE TIME	0.0
WISH TO MOVE	TRUE
PLACING	0.0
PREFERENCE	AN OPTION
OPTIONS	AN ITEM-LIST
PERSONAL ELAPSED TIME	1.25
FID	1.10E-03
FICO2	1.00E-03
FIH	1.00E-03
D	20
UNCONSCIOUSNESS	FALSE
WAITING	FALSE
DEATH X	0.0
DEATH Y	0.0
PATIENCE	10
PREVIOUS	28
WAIT COUNTER	0
START LOCATION	15E

The above figure represents the state of passengers PA5s' personal attributes at an instant during an evacuation. As can be seen from the table passenger PA5 is a 19–57 male who travelled a total distance of 1.5m in 1.25 sec. Mr PA5 started in seat 15E and is currently moving. His current accumulative dose of toxic gases and heat is minimal and as a result he is not showing any detrimental effects.