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Computer modelling of human behaviour in aircraft fire accidents

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Abstract

The mathematical simulation of the evacuation process has a wide and largely untapped scope of application within the aircraft industry. The function of the mathematical model is to provide insight into complex behaviour by allowing designers, legislators, and investigators to ask 'what if' questions. Such a model, EXODUS, is currently under development, and this paper describes its evolution and potential applications. EXODUS is an egress model designed to simulate the evacuation of large numbers of individuals from an enclosure, such as an aircraft. 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 comprises five core interacting components: (i) the Movement Submodel — controls the physical movement of individual passengers from their current position to the most suitable neighbouring location; (ii) the Behaviour Submodel — determines an individual's response to the current prevailing situation; (iii) the Passenger Submodel — describes an individual as a collection of 22 defining attributes and variables; (iv) the Hazard Submodel — controls the atmospheric and physical environment; and (v) the Toxicity Submodel — determines the effects on an individual exposed to the fire products, heat, and narcotic gases through the Fractional Effective Dose calculations. These components are briefly described and their capabilities and limitations are demonstrated through comparison with experimental data and several hypothetical evacuation scenarios.

Keywords: Evacuation; Simulation; Model; Fractional effective dose; Expert-system

1. Introduction

The ability to unload passengers quickly is not only important to the efficient day to day operation of air, sea, and rail mass transport vehicles, it is essential in emergency situations resulting from accidents. The layout of the passenger compartment and the nature of the passenger population mix are essential ingredients in the search for optimal configurations. Considerations, such as

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number of seats; number, type, and location of exits; presence of seat obstructions in the vicinity of exits; width of aisles; internal compartments; number of elderly and disabled passengers; nature of passenger disability; presence of luggage, etc.; must be taken into account.

Computer based mathematical simulation of the evacuation process, while still in its infancy, offers the potential to efficiently address these issues. The function of the mathematical model is to provide insight into complex behaviour by enabling designers, legislators, and ultimately accident investigators, to ask 'what if' questions. The use of evacuation models allows the critical examination of these issues at the design phase, while the proposed vehicle is still on the drawing board.

In this paper, several sample aircraft evacuation simulations produced using the EXODUS model will be discussed in order to demonstrate the capabilities and limitations of the model and to highlight the dependence of evacuation models on reliable human performance and behaviour data. In particular, the assumptions inherent in the Toxicity Submodel used to calculate the incapacitating effects of fire hazards will be investigated.

1.1. Reasons for developing evacuation models

Over the past 20 years, considerable effort has been expended in developing mathematical models capable of predicting the generation of hazardous conditions within enclosures subjected to fire (Yang et al., 1984; Galea, 1989; Galea and Markatos, 1991). 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 — with human volunteers — provides a means of obtaining some of this information, it poses considerable ethical, practical, and financial problems which bring into question the value of its overall contribution to passenger safety.

Nevertheless, full-scale evacuation trials are mandatory throughout the aviation industry. Since 1965, international regulations stipulate that aircraft manufacturers must demonstrate that their aircraft layout will allow a full load of passengers and crew to evacuate the aircraft within 90 s. 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. Since 1969, more than 20 full-scale evacuation certification demonstrations have been performed in the USA involving over 7000 volunteers (OTA, 1993).

The ethical problems concern the threat of injury to the participants and the lack of realism inherent in the 90-s evacuation scenario. Between 1972 and 1991, a total of 378 volunteers (or 6% of participants) sustained injuries ranging from cuts and bruises to broken bones (OTA, 1993). During the October 1991 McDonnell Douglas (MD) evacuation certification trial for the MD-11, a female volunteer sustained injuries leading to permanent paralysis. Furthermore, as volunteers are not subject to trauma or panic nor to the physical ramifications of a real emergency situation, such as smoke, fire, and debris, the certification trial provides 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 min after the aircraft stopped, while 15 years earlier during UK certification trials, the entire load of passengers and crew managed to evacuate the aircraft in 75 s (King, 1988).

On a practical level, as only a single evacuation trial is necessary for certification requirements, there can be limited confidence that the test — whether successful or not — truly represents the evacuation capability of the aircraft. In addition, from a design point of view, a single test does not provide sufficient information to arrange the cabin layout for optimal evacuation efficiency. Finally, each full-scale evacuation demonstration can be extremely expensive. For instance, an evacuation trial from a wide-body aircraft costs in the vicinity of US$2 million (OTA, 1993). While the cost may be small in comparison to development costs, it remains a sizeable quantity.

The difficulties faced by the current range of wide-body civil aircraft will be greatly amplified with the proposed next generation of passenger jet transport termed 'ultra-high capacity aircraft' (UHCA). Designs currently being considered are capable of carrying 800 + passengers, consist of 3 or possibly 4 aisles, and may possess 2 or 3 main decks.

Validated computer-based mathematical models describing the aircraft evacuation process together with targeted full- and small-scale experimentation offer an efficient means of addressing these issues. Furthermore, with the aid of these models, safety issues such as the introduction of passenger smoke hoods or cabin water mist systems could be examined in a more realistic manner than current practise allows. In addition, models could also be used in postmortem accident investigations to suggest possible contributory mechanisms responsible for particular incidents and to assist in the training of cabin crews.

The practical, financial, and ethical constraints on full scale physical experimentation suggest a need for the development of computer-based mathematical models of the evacuation process, and their application to aircraft-specific evacuation studies. While a number of such models have been developed and are being used for simulating evacuation from buildings (Kisko and Francis, 1985; Levin, 1989; Takahashi et al., 1989; Fahy, 1991; Kostreva et al., 1991), little mention of specific models addressing transport systems appears in the open literature.

The EXODUS (Galea and Galparsoro, 1993, 1994) model attempts to address these issues by simulating the evacuation of large populations of individuals from mass-transport vehicles under hazardous (fire conditions) and non-hazardous (non-fire, drill, or certification) conditions. The model follows individual passenger trajectories as they make their way to the exits and includes various aspects of people-people and people-fire interaction. In addition to EXODUS, there are several other aircraft evacuation models currently under development (Gourary, 1994; Marcus, 1994).

2. EXODUS model description

2.1. Introduction

The EXODUS model is only briefly described here as details may be found in other publications (Galea and Galparsoro, 1993, 1994). EXODUS is an 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. There are three generations of EXODUS, namely, V.G2.1, V.G2.2, and V.1. EXODUS versions V.G2.2 and V.1 are currently under development.

The prototype version of EXODUS (V.G2.1) was built within the environment provided by the GENSYM software, G2 (G2, 1987). G2 is a tool for developing and running real-time expert systems. This version of EXODUS was produced utilising version 2.0 of G2 and run on a SUN SPARC 1 workstation. Using this version of EXODUS, execution times — which are strongly scenario dependent — may require several hours.

The next version of EXODUS (V.G2.2) was developed using a more recent version of the G2 software (version 3.0, rev. 3); it incorporated modified movement and conflict resolution rules. Run on a SUN SPARC 10 workstation, simulations require ~ 40 min CPU time.

EXODUS V.1 is a C+ + version of V.G2.2 and as such uses the same rule base. EXODUS V.1 is not dependent on the G2 software and is portable across platform types from PC to work-

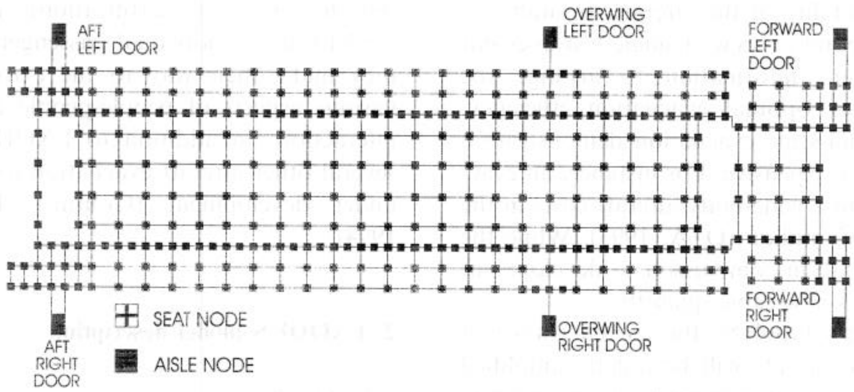

Fig. 1. EXODUS grid used to represent a wide-body aircraft.

station. The recommended minimum computer platform comprises a 25 MHz 486 based PC with 8 Mbytes of memory. Run on this platform, a simulation of a wide-body aircraft evacuation requires ~2 min CPU time.

2.2. Space and time description

A considerable amount of information exists concerning human behaviour in emergency situations (Tadahisa and Tokiyoshi, 1989; Canter, 1990). However, the majority of these data concern human responses to emergencies within the built environment, and it is not clear to what extent this information is applicable to transport-related incidents. Reliable data relating specifically to human responses to transport emergencies are much more rare. For this reason, EXODUS allows the user easy access to the rule base in order to simply alter or replace system rules in light of new theories and data. In more conventional programming environments, this would require the user to rewrite and/or restructure part of the program.

The spatial and temporal dimensions within EXODUS are spanned by a two-dimensional spatial grid 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 (e.g. multi-decked UHCA) can be made up of multiple grids connected by passage ways (e.g. stairs). Fig. 1 depicts an EXODUS grid used to represent the passenger compartment of a wide-body aircraft. The SC 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 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. 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. The Movement Submodel identifies the type of node being traversed by the passenger and then flags the Passenger Submodel for the appropriate travel speed.

Associated with each node is a set of attributes which defines the state of the node. These attributes are temperature (°C), hydrogen cyanide (HCN, ppm), carbon monoxide (CO, ppm), carbon dioxide (CO_2, %), oxygen depletion (O_2, %), and smoke concentration. For each of these variables, two values are stored representing the values at head height and at seat height. These stated attributes are assigned and updated by the Hazard Submodel and used by the Toxicity Submodel.

2.3. Submodel description

The EXODUS software comprises five core interacting components — the Movement, Behaviour, Passenger, Hazard, and Toxicity submodels (Fig. 2). Individual passengers are defined in the Passenger Submodel by ascribing values to a set of distinguishing attributes. By assigning a set of unique values to a passenger, we create an individual who will have unique performance capabilities. In this way, a population of passengers with differing capabilities is created. The Passenger Submodel describes an individual as a collection of 22 attributes defining their physical and psychological state, as well as, their progress through the environment. These are made up of 13 defining attributes and 9 progress variables. In the current implementation of EXODUS, the defining attributes are: name (seat location), gender, age, weight, condition, mobility, agility, travel speed, volume of air breathed (RMV), incapacitation dose (D), response time, drive, and patience. Of the 9 progress variables, 7 represent a measure of a passenger's degree of exposure to narcotic fire gases and convected heat. The dose D is a measure of the carboxyhaemoglobin (COHb) concentration linked to incapacitation. It is used by the Toxicity Submodel to calculate the effects of the gas CO. Some of these attributes are fixed

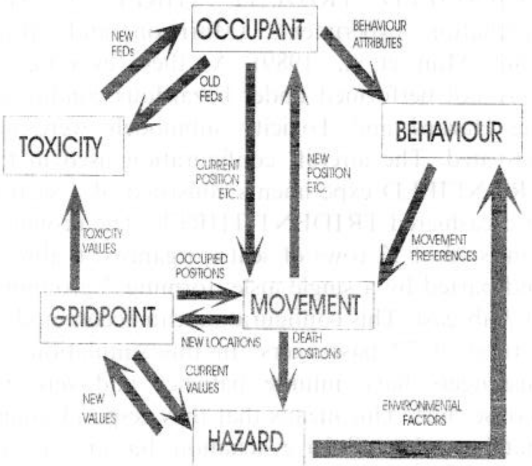

Fig. 2. Logical interaction between EXODUS submodels.

throughout the simulation, while others, such as travel speed, agility, and mobility, change as a result of inputs from the other submodels.

As its name implies, the Movement Submodel controls the physical movement of individual passengers from their current position to the most suitable neighbouring location. If a suitable position does not exist, the Movement Submodel allows the passenger to wait until an opportunity develops for movement to occur.

On the basis of an individual's personal attributes, the Behaviour Submodel determines his or her response to the current prevailing situation and passes its decision on to the Movement Submodel (Fig. 2). The Behaviour Submodel functions on two levels, the first is concerned with the passengers' global response to the emergency. This involves implementing an escape strategy which leads passengers to exit via their nearest serviceable (or assigned) exit. The second level concerns the passengers' response to local situations. This includes such behaviour as determining the passengers initial response to the call to evacuate, i.e. will the passenger react immediately or after a short period of time or display behavioural inaction, conflict resolution, and the selection of possible detouring routes. As certain behaviour rules (e.g. conflict resolution) are probabilistic in nature, it is unlikely that the model will yield identical results if a simulation is repeated.

The Hazard Submodel controls the atmospheric and physical environment. It controls the opening and closing of exits and determines the spread of fire hazards, such as heat and toxic products, throughout the atmosphere. The data used to specify the hazard values may originate from laboratory tests, actual aircraft accidents, artificial data, or be produced by fire models.

Finally, the Fractional Effective Dose (FED) toxicity model of Purser (1989) is implemented: this model determines the effects on an individual exposed to various fire hazards. In FED models, it is assumed that the effects of certain fire hazards are related to the dose received rather than the exposure concentration. The model calculates, for these hazards, 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. These effects are communicated to the behaviour model which, in turn, feeds through to the movement of the individual. As the FED approaches unity, the passengers' agility, mobility, and travel rates can be downgraded making it more difficult for the affected passenger to escape.

The modular approach adopted within EXODUS allows each submodel to be easily updated or replaced by a more appropriate model if necessary. For instance, in moving from an aircraft to ship application, the Behaviour Submodel would need to be modified in such a way as to reflect the types of behaviour appropriate to shipping scenarios. Finally, in order to demonstrate that a particular level of safety has been achieved through a particular enclosure design, it is essential to perform a number of simulations with different population mixes and a variety of personal attributes.

3. Sample simulations

The validation phase of any model development is crucial. Before the model can be implemented to make reliable predictions, it must be thoroughly tested against real data. This usually results in comparisons against specially contrived experiments. While the EXODUS model has not been thoroughly validated, model predictions have been compared with experimental data (Galea and Galparsoro, 1993, 1994) derived from evacuation trials from a narrow-body aircraft under competitive and non-hazardous conditions (Marrison and Muir, 1989; Muir et al., 1989). In these comparisons, the EXODUS model was able to correctly predict observed experimental trends. In the remainder of this section, several sample aircraft evacuation simulations will be discussed in order to demonstrate the capabilities and limitations of the EXODUS model and highlight the dependence of evacuation models on reliable human performance and behaviour data.

3.1. Travel speed and exit availability sensitivity study

The first simulations are intended to demonstrate the sensitivity of the model to the passenger travel speed attribute and number of exits available. The travel speed attribute is a measure of the maximum speed at which the passenger is capable of moving 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 intended for use when the smoke level exceeds a critical value). The Movement Submodel determines the appropriate maximum travel speed to select on the basis of the terrain through which the passenger is passing. Furthermore, 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. These quantities may assume default values or be assigned by the user. In order to achieve realistic results, it is essential that this variable be set to values which are representative of the travelling public.

To demonstrate the importance of this variable, EXODUS predictions made with various distributions of travel speed are compared with the CRANFIELD TRIDENT THREE overwing evacuation experiments (Marrison and Muir, 1989; Muir et al., 1989). As these experiments were not performed under hazardous conditions, the Hazard and Toxicity submodels were not activated. The aircraft configuration used in the CRANFIELD experiments consisted of a section of a cashiered TRIDENT THREE. The geometry consisted of 12 rows of seats, organised 6 abreast and parted by a single aisle, forming 2 groupings of 3 abreast. This configuration can accommodate a total of 72 passengers. In this simulation, all passengers have infinite patience and zero response time. This means that they respond immediately to the call for evacuation, but are obliged to queue rather than jump over seat backs. Fig. 3 displays a graph of evacuation flow for the over-

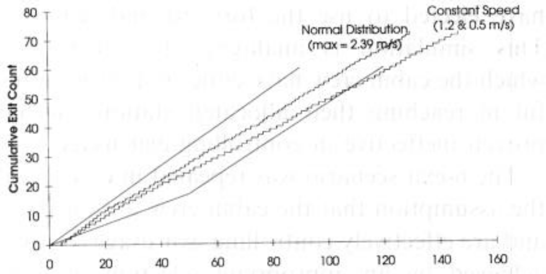

Fig. 3. EXODUS generated egress performance for TRIDENT Type-III trials with two passenger travel speed distributions.

wing case. Plotted are the EXODUS results and an envelope representing the spread of experimental results derived from eight experimental evacuations.

Two sets of model predictions are presented. In the first case, the predicted evacuation performance falls just outside the experimental envelope after the 50th passenger has exited. This suggests that the tail of our distribution is taking too long to exit the aircraft compared with the experimental values. In this simulation, each passenger had identical maximum run and walk speeds of 1.2 and 0.5 m/s, respectively.

In the second simulation, the passenger population had a range of run and walk abilities. The maximum run speeds ranged from 0.8–2.4 m/s, while the corresponding maximum walk speeds ranged from 0.3–1.0 m/s. Using this travel speed distribution, the evacuation curve has shifted so that it falls well within the envelope of observed performance behaviour. This suggests, as is to be expected, that the model is sensitive to individual travel rates associated with each passenger. The exiting procedure followed by each passenger is also of considerable importance to the overall predicted evacuation times. The current version of EXODUS uses an exiting procedure which delays each passenger as they pass through the Type-III exit. Exiting passengers are delayed at the exit by a time given by:

$$\textit{Type III exit delay}\ (s) = (age \times 0.0286) + 0.2147 \quad (1)$$

where, the age variable measures the age in years of the passenger attempting to pass through the Type-III exit. Eq. (1) is a regression formula generated from data produced by the US Federal Aviation Administration's Civil Aeromedical Institute (McLean et al., 1993; McLean and George, 1995). For the population used in the simulation, Eq. (1) produces exit delay times of between 0.79 and 1.36 s. During the experimental trials, the Type-III overwing exits were observed to jam with passengers. On most occasions, the blockages would clear up naturally, but external assistance was necessary at times, and in several cases, trials were terminated because of the severity of the blockage. Clearly, it is essential to represent this effect within the model.

The aircraft geometry used in the next series of simulations relate to a hypothetical wide-body aircraft consisting of 6 exits, 3 located on each side, 2 at the front, 2 over the wings, and 2 in the rear. The internal geometry consisted of 8 rows of seats (abreast) by 27 rows (front to rear). The rows of seats were separated by 2 main aisles and configured 2, 4, and 2 abreast. Bulkheads, toilets, and galleys are represented by missing nodes or broken links (Fig. 1). This geometry is similar in make-up to modern wide-body aircraft. The aircraft can accommodate a full load of 204 passengers. In these simulations, a full load of passengers evacuate from the aircraft under a variety of scenarios involving various combinations of useable exits. The population involves an arbitrary mix of passengers with varying performance capabilities. The maximum run rate varies between 0.98 and 1.35 m/s, while the maximum walk rate varies from 0.65 to 0.98 m/s. As in the previous simulation, the response time is set to zero and the patience is set to a large value for each individual. These attributes result in each passenger reacting immediately to the call to evacuate and essentially prevent passengers from choosing to jump over seat backs. The passenger attributes have been selected for demonstration purposes only and do not necessarily represent the performance capabilities of passengers in evacuation conditions. Each simulation uses an identical population.

The first four simulations concern evacuations involving all 6 exits open (cases 1 and 2), 3 exits on the left side open (case 3), and the 2 over wing exits open (case 4). In these simulations all exits are immediately open and available for use. In case 1, the evacuation time is 92 s; case 2, 62 s; case 3, 91 s; and case 4, 259 s (Fig. 4). These results are intuitively correct as the 2-exit scenario produces the longest evacuation time while the 6-exit scenario produces the shortest egress time. The results from these simulations should be examined with consideration of the comments made in the previous example. Case 1 represents quite a long evacuation time. The reason for this lies in the particular selection of passenger attributes chosen and also in the behaviour of the passengers. The velocity distribution chosen for all four cases was skewed towards the slower end of the spectrum. The maximum run rate in this example was 1.35 m/s, while in the previous example a distribution which peaked at 2.4 m/s was found to produce better agreement with experimental data. Of greater significance, however, is the behaviour exhibited by the passengers in case 1. In case 1, a total of 70 passengers exited via the wing exits requiring a total of 92 s, 44 passengers exited through the forward exits in 24 s, while 90 exited from the aft exits in 52 s. In this simulation, the evacuation rate through the over wing exits has dictated the overall evacuation performance. The Type-III exits proved to be a bottleneck with too many passengers selecting this exit as their means of escape. Considerably more passengers should

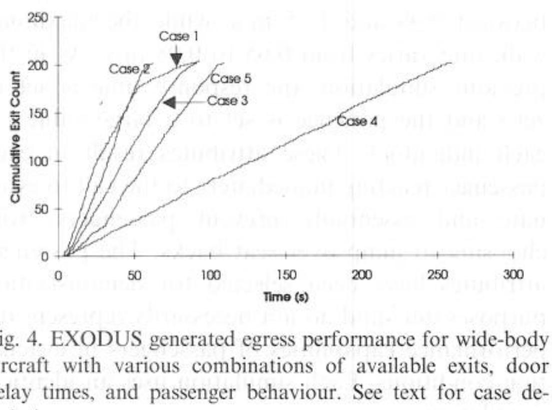

Fig. 4. EXODUS generated egress performance for wide-body aircraft with various combinations of available exits, door delay times, and passenger behaviour. See text for case descriptions.

have elected to use the forward and rear exits. This simulation is analogous to situations in which the cabin crew have either not been successful in reaching their allocated stations or have proven ineffective in controlling exit usage.

The 6-exit scenario was repeated in case 2, with the assumption that the cabin crew are on station and are effectively controlling exit usage — this is achieved by an appropriate selection of model parameters. This results in the majority of passengers being directed to more advantageous exits. In this case, we now find that a total of 34 passengers exited via the wing exits requiring a total of 50 s, 88 passengers exited through the forward exits in 62 s, while 82 exited from the aft exits in 53 s. In this simulation, the passengers who previously elected to use the wing exits have elected to use the forward exits, thereby reducing the overall evacuation time.

In case 5, the 3-exit simulation was repeated with the introduction of a door opening delay time. In this case, the forward exit was activated 30 s after the wing and rear doors are opened. This results in the evacuation time increasing to 109 s. While the evacuation time has increased by 18 s, several of the passengers who previously elected to use the forward exit have chosen either the rear exits or the wing exits.

Simulations of this type could be used in cabin crew training sessions to graphically demonstrate the importance of crew getting to their allocated station as soon as possible, rapid exit deployment, and the effective control of exit usage.

3.2. Evacuations under hazardous conditions

The next set of demonstration simulations involves an evacuation with a hostile fire atmosphere. These simulations are intended to demonstrate the sensitivity of model predictions to the assumptions inherent in the Toxicity Submodel and its precise formulation. Unlike the previous simulation, only the rear part of the wide-body aircraft is utilised. The rear two doors are the only exits available to the passengers.

The cabin section comprises the rear 15 rows of seats and involves 120 passengers. The passenger population mix and their initial seating locations are identical in each of the simulations presented below. Within EXODUS, each passenger's respiratory minute volume (RMV) may be set individually and may vary according to whether the passenger is at rest or involved in light or heavy work. For simplicity, the RMV for each passenger is set to a value representative of a light work load, typically 25 l/min.

In order to represent a developing fire atmosphere, the aircraft fuselage was divided into three zones, each with a set of fixed temperature (200, 160, and 50°C), HCN (6, 12, and 9 ppm), CO (10 000, 8000, and 4000 ppm), CO_2 (5, 3.6, and 0.9%), and O_2 (14.8, 16.1, and 19.9%) data. While the EXODUS model is capable of representing a layered atmosphere in which the concentration of the various species varies with height and is changing over time, for reasons of simplicity, the hazard data were held constant throughout each zone.

The severest conditions occur furthest from the exits and gradually ease towards the rear exits. The 200°C-zone encompasses the five seat rows furthest from the exit, the 160°C-zone the next five seat rows, and the 60°C-zone the remainder of the cabin. While this may appear a reasonable assumption, recent results from an aircraft cabin fire field model suggest that this intuitive assumption may not always be correct (Galea and Hoffmann, 1995). The model simulated a fire originating in the rear of a B737 aircraft. The model predicts that conditions in the vicinity of the forward bulkhead — remote from the fire source — become severe as the ceiling jets carrying hot combustion products impact the bulkhead obstruction and descend into the seat region. The atmosphere used in this example can be considered extreme. In a simulated post-crash fuel fire, Sarkos et al. (1982) measured a 295°C temperature, 15 ppm HCN, 10 816 ppm CO, 5% CO_2, and 15.1% O_2, at ceiling height. These data were measured 3 min after ignition at a location towards the rear of the aircraft — remote from the fire which was located towards the front of the aircraft by an open doorway. These conditions are more extreme than the severest conditions in the model demonstration.

Within the EXODUS model, passengers are considered incapacitated if FIN (fraction of an incapacitating dose of all narcotic gases), $FICO_2$ (fraction of an incapacitating dose of CO_2), or FIH (fraction of an incapacitating dose of heat) exceeds unity. While the Purser model (Purser, 1989) is typical of FED models, other formulations have been suggested. For example, Speitel (1995) has developed a model specifically for postcrash aircraft fire applications. In addition to the quantities specified in the Purser model, Speitel considers the gases, hydrogen fluoride (HF), hydrogen chloride (HCl), hydrogen bromide (HBr), nitrogen dioxide (NO_2), and acrolein. Furthermore, expressions for the CO and heat contribution to the FED calculation are significantly different from those specified in the Purser model. Consider the heat expression.

In Purser's model, the FIH acquired each min,

$$FIH = \exp(0.0273 \times T°C - 5.1849) \quad (2)$$

is based on data using naked men at rest (Blockley, 1973), while in the Speitel model the FIH calculation,

$$FIH = 2.4 \times 10^{-09} \times (T°C)^{3.61} \quad (3)$$

is based on data using clothed subjects (Crane, 1978). The Purser model predicts incapacitation at significantly lower temperatures than the Speitel model. For example, according to Eq. (2), a 1-min exposure to 190°C results in incapacitation, whereas using Eq. (3) temperatures in excess of 240°C are required to produce the same result.

To demonstrate the influences these two formulations may have on the outcome, two simulations were run with the fire atmosphere described above. The first (identified as Model 1) used Eq. (2) and the second (identified as Model 2) used Eq. (3) to represent the incapacitating effect of heat exposure. In Model 1, a total of 30 passengers are incapacitated compared with 20 passengers in Model 2. Furthermore, while 22 passengers are predicted to be overcome from heat exposure in Model 1, no passengers are incapacitated due to heat exposure in Model 2 (Table 1). Note that a total of 40 passengers are initially exposed to the high temperature region and that the last passenger to emerge from this

Table 1
Classification of incapacitated passengers[a] using Models 1 to 6

Model	Number of PAX with FIN > 1 or FIH > 1	Number of PAX with FIN > 1 and FIH < 1	Number of PAX with FIH > 1 and FIN < 1	Maximum/Average FIN for PAX with FIN < 1	Number of active PAX with FIN or FIH > 0.9
Model 1	30	8	22	0.99/0.33	6
Model 2	20	20	0	0.99/0.39	12
Model 3	27	0	27	0.30/0.15	8
Model 4	27	0	27	0.94/0.30	8
Model 5	9	9	0	0.97/0.39	4
Model 6	27	0	27	0.08/0.02	8

[a]PAX, passengers; FIN, fraction of an incapacitating dose of all narcotic gases; FIH, fraction of an incapacitating dose of heat.

zone was exposed for 30 s. It should be emphasised that these predictions are dependent on the nature of the fire atmosphere imposed on the simulation.

A possible deficiency in both models concerns the exclusion of the thermal effects due to humid rather than dry air. Recent research concerning the use of cabin water misting systems has suggested that the concentration of water vapour in the atmosphere of aircraft cabins subjected to simulated large post-crash fuel fires can reach levels of 17% (Speitel, 1993). This reported water vapour concentration is a result of the combustion of cabin interior materials and jet fuel. The incapacitating effects of air with a high water vapour content are more severe than dry air as it reduces heat loss through sweat and delivers more heat to exposed skin. Because of the relatively short exposures typically encountered in aircraft evacuation situations, this effect may not be of great significance. However, due to its higher heat capacity, inhaled hot air with a high water vapour content can cause more severe damage to the respiratory tract than dry air at the same temperature (Purser, 1988). Thus, this effect may assume greater significance in aircraft evacuation scenarios. It is unclear if water vapour concentrations at the levels recorded in simulated aircraft fires are sufficiently high to have a contributory effect on the thermal hazard calculation. It is also unclear if the thermal hazard regression equations used in the Purser and Speitel models (Eqs. (2) and (3)) correctly incorporate the effects of air with a significant water vapour content. These considerations could become more significant in situations where cabin water misting systems are deployed.

Both the Purser and Speitel models incorporate a factor which takes into account the increased respiration rate which results from the presence of CO_2. The hyperventilation factor, VCO2,

$$VCO2 = \exp(0.2496 \times \%CO_2 + 1.9086)/6.8 \quad (4)$$

has an identical formulation in both models. It is used in the Purser model to represent the increase in uptake of CO and HCN and, in the Speitel model, it serves a similar function for CO, HCN, HF, HCl, HBr, NO_2, and acrolein. Using Eq. (4), a 5% atmosphere of CO_2 will increase the RMV by 3.45. This will have a significant effect on the FIN calculation in both models. To demonstrate the significance of this factor, Model 1 was altered so that VCO2 was set to 1 irrespective of the CO_2 concentration (identified as Model 3), thus ignoring the hyperventilation effects of CO_2. In this case, 27 passengers succumb to heat while none are overcome by the toxic atmosphere. Furthermore, the largest FIN recorded was 0.30 (average FIN = 0.15), well below the value necessary to cause incapacitation.

A modified version of the VCO2 equation has been suggested by Purser (1995) of the form,

$$VCO2 = \exp(0.1903 \times \%CO_2 + 2.004)/7.1 \quad (5)$$

The modified form of the VCO2 equation is intended to represent the difference between the volume of CO_2 inhaled and the actual amount of CO_2 uptake.

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For a given concentration of CO_2, Eq. (5) generates smaller values for VCO2 than Eq. (4) (Table 2). Model 1 was altered so that Eq. (5) replaced the original VCO2 equation (identified as Model 4). In this case, 3 fewer passengers are predicted to become incapacitated. Model 4 produced a similar outcome to Model 3 in that no passengers are overcome by the gaseous atmosphere. However, unlike Model 3, 1 passenger has an FIN in excess of 0.90, suggesting that at least 1 passenger is near incapacitation.

Model 5 incorporates Purser's modified VCO2 formulation and the FIH equation used in the Speitel model. This combination produces a dramatic change in model predictions with only 9 passengers — as opposed to 30 — succumbing to the fire atmosphere. As found in Model 2, no passengers are predicted to become incapacitated due to heat exposure.

While CO_2-induced hyperventilation has a measurable effect under laboratory conditions and possibly in circumstances where the subject is unaware of the fire (such as a sleeping victim of a domestic fire), it is unclear if it is appropriate that it should be factored into aircraft evacuation models in its present form. This is particularly true if the RMV used in the CO equation is already set to a large value appropriate to heavy work. Clearly, the VCO2 factor has a dramatic impact on the outcome of the simulation and may lead to a severe over estimation of the number of fatalities.

A related issue concerns the breathing rate of passengers in the presence of smoke irritants.

Table 2
Comparison of CO_2-induced hyperventilation factors generated by Eqs. (4) and (5)

CO_2 (%)	VCO2 using Eq. (4)	VCO2 using Eq. (5)
1	1.27	1.26
3	2.10	1.85
5	3.45	2.71

The RMV may be altered or passengers may decide to hold their breath during the evacuation. This may occur either as part of a conscious escape strategy or as a reflex response to the painful effects of irritant gases and smoke. To demonstrate the effect this may have on an evacuation simulation, Model 1 was modified to allow passengers to hold their breath for a fixed amount of time (identified as Model 6). The simulation involved passengers who held their breath for periods of 10 s. All FED calculations, with the exception of FIH, were suspended over this period. Once breathing was resumed, the RMV used in the FICO (fraction of an incapacitating dose of CO) equation was increased to twice its normal value. When a breath was taken, the procedure was repeated until the passenger escaped or became incapacitated.

These performance figures are arbitrary and not meant to represent specific human capabilities. The assumptions may be valid if the individual's evacuation time is short, possibly less than 90 s. However, it is possible that passengers may hold their breath for longer periods of time or, upon resuming to breathe, take in greater quantities of air. It is also possible that as a result of taking a deep breath of irritants and smoke, passengers may cough and thereby inhale even greater quantities of air.

The results for Model 6 are presented in Table 1. In Model 6, there are 3 fewer fatalities than are found in the base case and no passengers succumb to the narcotic gases. This model produces a similar outcome to the previous two cases in which VCO2 was modified; however, the maximum and average FINs recorded in the breath-holding cases are considerably less than those recorded in all the previous models. This simplistic model suggests that significant differences in model predictions can result by changing the breathing strategy of the evacuating occupants. These results should be viewed in light of the assumptions inherent in the model. Further fundamental work concerning the physiology and psychology of breathing rates of people exposed to irritant gases is essential before more realistic assumptions can be imposed on the model.

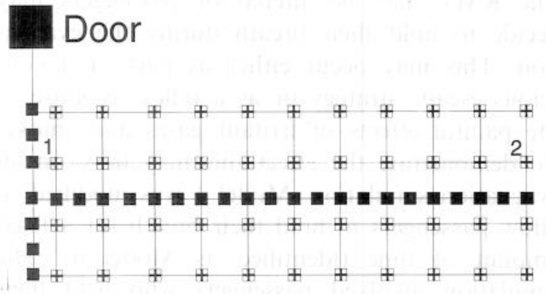

Fig. 5. Wide-body aircraft cabin section used in simulations for passenger with restricted movement capability. Starting location of passenger is indicated by the numbers 1 and 2.

These six examples demonstrate that differences in the precise formulation and application of the FED models can lead to quite different predicted outcomes. A more subtle problem concerns the assumptions inherent in these models. Implicit in the application of the FED model is the assumption that the work load of the exposed individual remains constant throughout the exposure. This is because, with the exception of CO, the RMV does not explicitly appear in any of the expressions. As RMV values may vary from about 10 l/min at rest to in excess of 50 l/min while involved in heavy work, this is expected to have a pronounced impact on the dose inhaled and, hence, the time to incapacitation. Furthermore, while it may be valid to assume that the effort involved in participating in a life threatening aircraft evacuation is the equivalent of light to heavy activity, this may not be equivalent to the level of activity used in the derivation of the FED regression equations.

3.3. Predicting the impact on evacuation performance of passengers with severely restricted movement capabilities

In the final set of simulations, the model is used to demonstrate the effect that a passenger with severely restricted movement capabilities may have on a hypothetical evacuation scenario. These simulations are intended to demonstrate a potential area of model application and do not constitute a set of definitive conclusions upon which to base optimal seating strategies. For it to be feasible to apply a modelling tool to this type of application, considerable research into the behaviour of passengers under these conditions is required and appropriate rules built into the Behaviour Submodel.

The geometry used (Fig. 5) represents that portion of the previously described wide-body aircraft which may be serviced by a single rear exit. The region under consideration includes 44 passengers and 11 rows of seats (seats A, B, C and D).

In the control case, passengers with the previously defined range of run and walk rates (see Section 3.1) require 88 s to vacate the aircraft. In the next two simulations, a passenger with a maximum movement rate of 0.1 m/s (PAX A) is inserted in the passenger population and placed in one of two aisle-seat locations, first seat row ahead of exit (Scenario 1) and furthest away from the exit (Scenario 2). It is important that the assumptions inherent in this demonstration are clearly understood. In these simulations, it is assumed that all passengers react immediately to the call to evacuate, PAX A moves unaided and those behind PAX A do not attempt to push him over or overtake. The movement rate of 0.1 m/s was arbitrarily selected to represent a slow passenger; however, there is some evidence to suggest that this is not an unreasonable estimate (Blethrow et al., 1977). It should be remembered that in realistic life-threatening evacuations, PAX A may be aided by crew or other passengers, be pushed over or circumvented in some other way, or PAX A may remain in his seat until the aisle is clear. With PAX A included, the total evacuation times be-

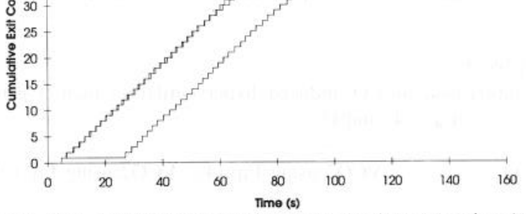

Fig. 6. Exit performance for three evacuation scenarios (see text): CONTROL — excludes passenger A; FRONT — passenger A is located immediately in front of exit; BACK — passenger A is located in rear of cabin section.

Table 3
Summary of results for evacuation simulations with mobility impaired passenger[a]

Parameter	Control (no fire atmosphere)	Control	Scenario 1	Scenario 2
Evacuation time (s)	88	108	141	159
Average wait time (s)/PAX	36	31	49	33
Average FIN/PAX	—	0.15	0.31	0.17

[a]Also, refer to Fig. 7 and the Table 1 footnote.

come 108 s for Scenario 1 and 148 s for Scenario 2. The evacuation curves for the various scenarios are depicted in Fig. 6.

In the control case, the total wait time (determined by summing the wait time incurred by each passenger as a result of queuing and conflicts, etc.) is ~27 min. The additional wait time incurred by the passengers in the other scenarios as a result of PAX A are 14 min for Scenario 1 and 1 min for Scenario 2. This suggests that Scenario 2 incurring the maximum evacuation time results in the minimum delay for the majority of passengers, while Scenario 1 causes the maximum delay but results in the minimum evacuation time.

Scenario 1 may be considered the optimal situation as it results in minimum evacuation times, but under fire conditions, it may in fact result in the least desirable outcome as the majority of passengers are forced to wait for the maximum amount of additional time. This will, therefore, result in the majority of passengers being exposed to the fire atmosphere for longer than would be expected in the other scenario. To examine this possibility, the simulations were repeated with a contrived fire atmosphere. The aircraft fuselage was divided into three zones, with maximum values of temperature (130, 90 and 60°C), HCN (6, 4 and 1 ppm), CO (7000, 2000 and 500 ppm), CO_2 (4, 3 and 1.5%), and O_2 (17, 18.4 and 19.5%) data. Unlike the previous examples, these quantities vary with time, following a simple linear change law achieving their maximum (or minimum) value after 30 s. The severest conditions occur furthest from the exit and gradually ease towards the rear exit. The 130°C-zone encompasses the four seat rows furthest from the exit, the 90°C-zone the next four seat rows, and the 60°C-zone the remainder of the cabin.

In addition to the fire hazards mentioned above, smoke was included in the simulation. The maximum smoke density in each zone was 0.6, 0.5 and 0.5 l/m, where smoke density is expressed in extinction coefficient. As with the other fire hazards, the smoke density was increased in a linear manner achieving a maximum value after 50 s. Smoke has the effect of obscuring vision and irritating the eyes, thus impairing the ability of an individual to escape. Several studies (Jin, 1978; Jin and Yamada, 1989) have suggested that a victim's walk rate decreases as the smoke concentration increases. This effect is thought to be concentration related and does not increase with prolonged exposure.

Within the model, the smoke density is linked to the passenger attribute mobility. The mobility attribute is linked in turn to the travel speed attribute and decreases the travel speed as the mobility decreases according to Eq. (6),

$$\textit{Travel speed} = \textit{initial travel speed} \times \textit{mobility} \quad (6)$$

The mobility attribute is kept constant up to smoke concentrations of 0.1 l/m, after which, it decreases to half its original value at a smoke concentration of 0.5 l/m. For smoke concentrations above 0.5 l/m, passengers' escape abilities are severely limited, and the model assumes a maximum travel speed equivalent to the crawl rate of 0.2 m/s.

Here again, it is important that the assumptions inherent in this demonstration are clearly understood. In addition to the assumptions made in the previous simulation, it is further assumed that the Purser FED model is valid and, with the exception of travel speed, passenger defining attributes are not affected by exposure to the fire atmosphere. The results are also dependent on the nature of the fire atmosphere imposed.

The results from this simulation are summarised in Table 3 and Fig. 7. The effect of increasing smoke density on passenger escape ability can be seen in Fig. 7. As the smoke density increases, the movement rates of the exposed passengers begin to decrease and egress times increase. This is depicted by the curve for the control case with fire atmosphere departing from that for the control case without fire atmosphere at ~50 s. While no passengers are predicted to become incapacitated due to the imposed fire atmosphere, the average FIN per passenger is 80% larger in the case where PAX A is located near the exit compared to when the passenger is furthest away from the exit. This difference is due to the additional wait time experienced by the passengers in Scenario 1. With PAX A located furthest from the exit, the average FIN per passenger becomes 0.17, only marginally greater than the corresponding value in the control case. This model attempts to incorporate the impairing effects of smoke on the ability of a victim to escape by reducing the run/walk rates as the smoke density increases. In a similar fashion, within the evacuation model, it is possible to link a degradation in passenger attributes, such as run/walk rates, to increasing exposure to narcotic gases (FIN) and elevated temperatures (FIH). In order to make these links meaningful, guidelines as to appropriate thresholds and degree of incurred degradation are essential.

Fig. 7. Exit performance for three evacuation scenarios (see text): CONTROL — excludes passenger A; FRONT — passenger A is located immediately in front of exit; BACK — passenger A is located in rear of cabin section. Also, refer to Table 3.

The effect of the irritant fire gases on the escape capabilities of individuals has not been included in the above discussions. These gases include HF, HCl, HBr, sulphur dioxide (SO_2), and NO_2 amongst some estimated 20 others (Purser, 1988). These gases cause sensory irritation to the eyes, nose, throat, and lungs ranging from mild irritation to severe pain. As the degree of irritancy increases, the occupants' escape abilities are degraded. As with the effects of smoke concentration, these effects are considered to be proportional to the concentration of exposure rather than the accumulated dose. By using the concept of Fractional Irritant Concentration (Purser, 1993), it is possible to incorporate the effects of these gases into the evacuation model. However, as stated above, in order to make these links meaningful, guidelines as to appropriate exposure thresholds and associated degree of performance degradation are essential.

4. Conclusions

An evacuation model for aircraft has been developed. The escape strategy employed by each of the individuals is to leave the passenger compartment 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 predicts a lower bound for the expected evacuation time.

The evacuation model incorporates a Toxicity Submodel which considers each passenger's response to their accumulated dose of CO, HCN, and CO_2, as well as the effects of O_2 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.

When run with an artificially contrived fire atmosphere, a significant number of passengers were found to become incapacitated. However, the number of incapacitated passengers and the nature of the incapacitation were shown to be acutely linked to the precise expression of the FED model and the assumptions inherent in its formulation.

Finally, associated with the development of computer-based, life-threat hazard analysis models is the need for comprehensive data collection/generation. This is essential in order to: (i) identify the physical, physiological, and psychological processes which contribute to, or influence, the evacuation process; (ii) quantify attributes/variables associated with the identified processes; and finally, (iii) provide data for model validation purposes.

All sectors of the industry have expressed a desire to use evacuation models in the design of aircraft, their certification, and in aircraft accident investigation. Before this desire can become a reality, it is essential that the industry cooperate to generate the necessary data.

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