THE ROLE OF EVACUATION MODELLING IN THE DEVELOPMENT OF SAFER AIR TRAVEL.

E. R. Galea, M.Owen and P.Lawrence.
Fire Safety Engineering Group
University of Greenwich
Wellington Street
London SE18 6PF
UK.

1. SUMMARY

Computer based mathematical models describing the aircraft evacuation process have a vital role to play in the design and development of safer aircraft, in the implementation of safer and more rigorous certification criteria and in post mortum accident investigation. As the risk of personal injury and costs involved in performing large-scale evacuation experiments for the next generation 'Ultra High Capacity Aircraft' (UHCA) are expected to be high, the development and use of these evacuation modelling tools may become essential if these aircraft are to prove a viable reality. In this paper the capabilities and limitations of the air-EXODUS evacuation model are described. Its successful application to the prediction of a recent certification trial, prior to the actual trial taking place, is described. Also described is a newly defined parameter known as OPS which can be used as a measure of evacuation trial optimality. Finally, the data requirements of aircraft evacuation models is discussed along with several projects currently underway at the University of Greenwich designed to obtain this data. Included in this discussion is a description of the AASK - Aircraft Accident Statistics and Knowledge - data base which contains detailed information from aircraft accident survivors.

2. INTRODUCTION

When modifying an existing aircraft or designing a new aircraft, how do we ensure that the proposed design is safe, and how we demonstrate that it is safe? As a real but extreme example of this problem consider the proposed next generation UHCA.

Designs currently being considered are capable of carrying 800+ passengers with interiors consisting of two aisles and possessing two full length passenger decks. Questions concerning seating arrangement; design of recreational space; number and location of internal staircases; number, location and type of exits; number of required flight attendants and flight attendant emergency procedures are just some of the issues that need to be addressed. The quantum leap in passenger capacity being suggested should also challenge some of our preconceptions in equipment design and operating procedures. For instance, in order to efficiently complete an evacuation, will it be necessary to extend emergency procedures to the marshalling of those passengers already on the ground? Should evacuation procedures allow passengers to travel between decks before exiting the aircraft? Do we need to consider a new type of exit design?

Quite apart from questions of emergency evacuation, issues concerning the appropriateness of proposed designs in allowing the rapid and efficient movement of passengers during boarding and disembarkation are a further essential design consideration. Furthermore, these requirements may potentially be in conflict with the requirements for emergency egress. Ultimately, the practical limits on passenger capacity are not based on technological constraints concerned with aircraft aerodynamics but on the ability to evacuate the entire complement of passengers within agreed safety limits.

Under current regulations set by national and international certification authorities, aircraft manufacturers must demonstrate that new aircraft designs or seating configurations will allow a full load of passengers and crew to safely evacuate from the aircraft within 90 seconds. The accepted way of demonstrating this capability is to perform a full-scale trial using the passenger compartment under question and an appropriate mix of passengers. Since 1969 more than 20 full-scale evacuation certification demonstrations have been performed involving over 7000 volunteers [1].

The difficulties with this approach is that it poses considerable ethical, practical and financial problems which bring into question the value of their overall contribution to passenger safety. The ethical problems concern the threat of injury to the participants and the lack of realism inherent in the 90 second evacuation scenario. Between 1972 and 1991 a total of 378 volunteers (or 6% of participates) sustained injuries ranging from cuts and bruises to broken bones [1]. During the October 1991 McDonnell Douglas 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 limited 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 B737 aircraft emerged 5.5 minutes 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 seconds [2]

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

Presented at PEP 88th Meeting on Aircraft Fire Safety. Dresden, Germany 14-18 Oct 1996.

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 lay out for optimal evacuation efficiency nor can it match all the different configurations flown by all the potential carriers. 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 $US2 million [1]. While the cost may be small in comparison to development costs it remains a sizeable quantity.

Computer based egress/evacuation models have the potential of addressing all these shortfalls. Computer based mathematical models describing the aircraft evacuation process have a role to play in the design and development of safer aircraft and improved crew procedures, bringing safety matters to the design phase while the proposed aircraft is still on the drawing board. These models also have a role to play in the implementation of safer and more rigorous certification criteria. Finally, evacuation models can also be used to help optimise the efficient movement of passengers during loading and disembarkation.

If evacuation models are to fulfil their promise, they must address the configurational, environmental, behavioural and procedural aspects (see figure 1) of the evacuation process [3]. Configurational considerations are those generally covered by conventional methods and involve cabin layout, number of exits, exit width, travel distance etc. In the event of fire, environmental aspects need to be considered. These include the likely debilitating effects on the passengers of heat, toxic and irritant gases and the impact of increasing smoke density on travel speeds and way-finding abilities. Procedural aspects cover the actions of staff, passenger prior knowledge of the cabin, emergency signage etc. Finally, and possibly most importantly, the likely behavioural responses of the passengers must be considered. These include aspects such as the passengers initial response to the call to evacuate, likely travel directions, family/group interactions etc.

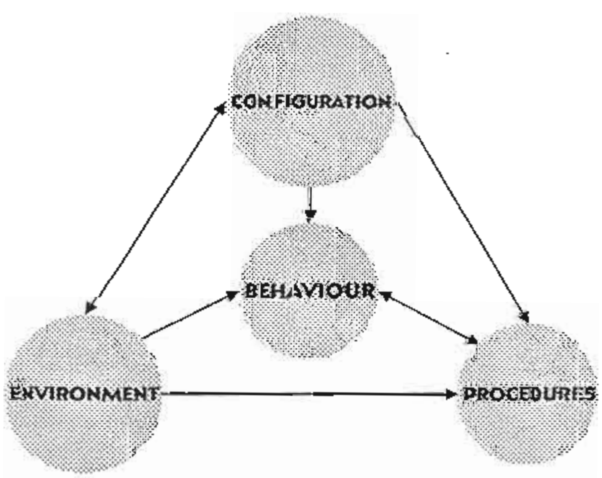

FIGURE 1: The Four Main Interacting Aspects To Be Considered In The Optimal Design Of An Enclosure For Evacuation.

The air-EXODUS evacuation model [4,5,6] attempts to address all four of the contributory aspects controlling the evacuation process. In order to understand how these components are brought together within an evacuation model and highlight their associated data requirements, a brief description of the air-EXODUS evacuation model follows.

3.0 THE air-EXODUS EVACUATION MODEL

3.1 EXODUS Overview.

EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of individuals from complex structures. EXODUS was originally designed for use with aircraft. However, its modular format makes it ideally suited for adaptation to other types of environment. As a result its range of application has grown as has the number of specific EXODUS products. The EXODUS family of evacuation models currently consists of two distinct packages, building-EXODUS [7,8,9] and air-EXODUS.

building-EXODUS is designed for applications in the built environment and is suitable for application to high rise buildings, rail stations, airport terminals, etc. building-EXODUS can be used to demonstrate compliance with building codes and to evaluate the evacuation capabilities of all types of structures.

air-EXODUS is designed for applications in the aviation industry including, aircraft design, compliance with 90 second certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation.

The EXODUS software is portable across platform types from PCs running the WINDOWS environment to UNIX WORKSTATIONS running under MOTIF. The minimum recommended computer platform comprises a 25 MHz 486 PC with 8 Mbytes of memory. Run on this platform a simulation of a wide-body aircraft evacuation involving 400 occupants requires approximately three minutes CPU time.

The EXODUS software takes into consideration people-people, people-fire and people-structure interactions. 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, smoke and toxic gases. The EXODUS software has been written in C++ using Object Orientated techniques and rule-base software technology to control the simulation. Thus, the behaviour and movement of each individual is determined by a set of heuristics or rules.

3.2 air-EXODUS Submodels.

For additional flexibility these rules have been categorised into five interacting submodels, the OCCUPANT, MOVEMENT, BEHAVIOUR, TOXICITY and HAZARD submodels (see figure 2). These submodels operate on a region of space defined by the GEOMETRY of the enclosure.

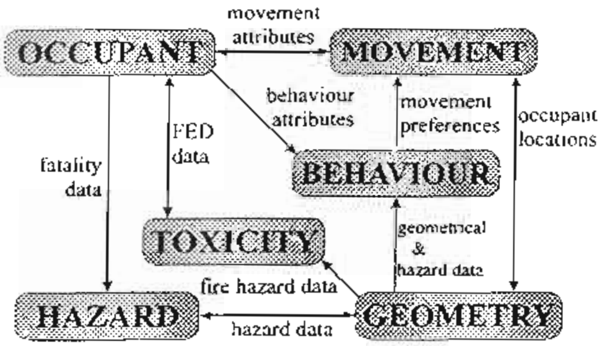

FIGURE 2: air-EXODUS Submodel Interaction.

3.2.1 Enclosure Description
Within air-EXODUS, the enclosure GEOMETRY is made up from two-dimensional grids. The GEOMETRY can be defined in several ways. It can be (i) read from a geometry library, (ii) constructed interactively using the tools provided or (iii) read from a CAD drawing using the DXF format. Internally the entire space of the geometry is covered in a mesh of nodes which are typically spaced at 0.5m intervals. Each node represents a region of space typically occupied by a single occupant. Nodes are linked to their nearest neighbours by a number of arcs, typically four or eight. Nodes which have distinguishing features may be assigned to special node classes for example, *aisle, stair, seat, door* etc. Occupants travelling over specific node types will be assigned attribute values appropriate for that node type, for example different maximum travel speeds and behavioural responses would be appropriate for an individual travelling over an aisle node as opposed to a stair node.

Associated with each node is a set of attributes which define the state of the node. These are, temperature (degree C), HCN (ppm), CO (ppm), CO_2 (%), oxygen depletion (%) and smoke concentration. For each of these variables, two values are stored, representing the value at head height and near floor level. air-EXODUS does not include a component for predicting the generation and spread of fire hazards but simply distributes the hazards generated by fire models.

Each node is also assigned an obstacle value which is a measure of the degree of difficulty in travelling over the node. A node representing an open space may have an obstacle value of one, while a node with debris may have a higher value of four for example.

3.2.2 The Occupant Submodel
The **OCCUPANT** submodel defines each individual as a collection of 20+ attributes which broadly fall into four categories, *physical* (such as age, weight, gender, agility etc), *psychological* (such as patience, drive etc), *positional* (such as distance travelled, PET etc) and *hazard effects* (such as FIN, $FICO_2$, FIH etc). These attributes have the dual purpose of defining each occupant as an individual and allowing their progress through the enclosure to be tracked. Some of the attributes are fixed throughout the simulation while others are dynamic, changing as a result of inputs from the other submodels.

3.2.3 The Movement Submodel
The **MOVEMENT** submodel is concerned with the physical movement of the occupants through the different terrain types. Its main function is to determine the appropriate travel speed for the terrain type, for example - leap speed for jumping over seat backs. In addition it also ensures that the occupant has the capability of performing the requested action, for example - checks if occupant agility is sufficient to allow travel over node with particular obstacle value. The direction of travel is determined by the behaviour submodel.

3.2.4 The Hazard Submodel
The **HAZARD** submodel controls the enclosure environment and allows the user to specify the specific *simulation scenario*. The environmental aspects comprise the spread of fire hazards CO_2, CO, HCN, O_2 depletion, heat and smoke. The values for these are set at two heights, head height and knee height. Although EXODUS contains no specific component to generate the fire hazards, it has the capability to use input from fire models [10] and experimental data. Scenario specific factors which are controlled by the Hazard model include aspects such as door opening/closing times.

3.2.5 The Toxicity Submodel
The **TOXICITY** submodel functions only when fire hazards are present. Its' function is to determine the effect of fire hazards upon the occupants The TOXICITY submodel currently models the effects of the narcotic fire gases, heat and smoke. The effect of the narcotic gases and heat are modelled using various Fractional Effective Dose (FED) models [11,12]. During a simulation smoke is considered to reduce an occupants egress capability by decreasing their travel speed. The decrease in travel speed is based on the work of Jin and Yamada [13]. Furthermore, at a critical smoke density the occupants are forced to crawl. When this occurs the occupants are exposed to the fire hazards located at the lower level.

3.2.6 The Behaviour Submodel
The **BEHAVIOUR** submodel determines an occupants response to the current prevailing situation. It is the most complex of the submodels. The behaviour submodel operates on two levels, *global* and *local*. The global behaviour provides an overall escape strategy for the occupants while the local behaviour governs the occupants' responses to their current situation. While attempting to implement the global strategy, an individuals behaviour can be significantly modified by the dictates of their local behaviour.

In the current implementation of EXODUS the global behaviour is fairly simple. This involves implementing an escape strategy which leads occupants to exit via their nearest serviceable exit or the exit to which they have been directed to by cabin staff.

The second level of Behaviour Submodel function concerns the occupants' response to local situations. This includes such behaviour as determining the occupants initial response to the call to evacuate i.e. will the occupant react immediately or after a short period of time or display behavioural inaction, conflict resolution, overtaking and the selection of possible detouring routes. The local behaviour is determined by the occupants attributes and as certain behaviour rules (e.g. conflict resolution) are probabilistic in nature, the model is unlikely to produce identical results if a simulation is repeated. There are two operational regimes under which local behaviour rules function, these are known as, *EXTREME* and *NORMAL* behaviour. Under *NORMAL* behaviour conditions, the occupants will behave in an orderly manner and for the most part attempt to adhere to the global behaviour rules. This is the preferred mode of operation when attempting to simulate 90 second certification trials. Under *EXTREME* behaviour occupants are given a wider range of options such as jumping over seats, moving away from a exit, heading for an exit which is not necessarily their closest exit, etc. This is the preferred mode of operation when attempting to simulate realistic evacuation scenarios. Some of the local behaviour typically observed in air-EXODUS simulations will be discussed.

(i) Response time - this is a measure of the time an occupant requires before they have moved out of their seat It can involve a representation of an individuals reaction time, time to release seat restraint and time to stand upright. An individuals response time is part of the occupant attribute parameter set.

(ii) Conflict resolution - when two or more occupants via for space (usually in crowds) conflicts arise which must be resolved. Conflict resolution is the procedure by which this occurs within air-EXODUS.

air-EXODUS utilises a fine network of nodes to describe an enclosure. Each node is intended to represent the smallest amount of free space available for occupancy, essentially it is the space that a single individual can occupy. Thus only one occupant can occupy a node at a time. However, the situation often arises where two or more occupants may wish to occupy a particular node. An example to illustrate this is shown in figure 3 where three occupants wish to occupy the same node, two occupants are attempting to enter the aisle from their seats, while a third occupant, already in the aisle, is attempting to proceed The three occupants (labelled 1,2 and 3) are attempting to occupy the indicated node and thus a three-way conflict arises.

Given that the travel distances and speeds associated with each of the conflicting occupants are such that there is no clear winner, the outcome of such a conflict would depend on the *drive* psychological attribute for each of the occupants. The *drive* is a measure of the assertiveness of an occupant and is part of the occupant attribute parameter set.

(iii) Direction changes - occur as a result of three factors, cabin crew influence, queuing/crowding and hazard concentration. Whenever an occupant is forced to remain stationary, for example due to crowding, the amount of time they remain stationary - known as wait time - is recorded. When an individuals wait time exceeds a critical level - defined by their patience attribute - the occupant attempts either to go around the blockage or move away, possibly towards another exit.

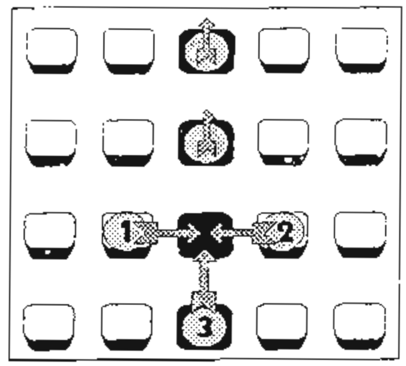

FIGURE 3: air-EXODUS Conflict Resolution.

(iv) Overtaking - occurs as a natural consequence of the movement rules, specific overtaking algorithms are not required. An occupant blocked by a slower moving occupant will attempt to find an alternative neighbouring empty nodal position within the direction of travel.

(v) Obstacle jumping - in the form of seat or debris jumping occurs when an occupant's wait time exceeds their patience and their agility attribute will allow them to do so. It is behaviour usually displayed by occupants caught between seats while aisles are blocked.

(vi) Exiting procedure - is dependent on two factors, exit width and exit hesitation time. The exit width determines the maximum number of people which can pass through the exit simultaneously. The exit hesitation time is used to determine the delay each occupant is likely to experience in passing through the exit. The exit hesitation time may be obtained using one of three methods, the software can predict the hesitation time on the basis of its rules, it can be prescribed through the use of historical or experimental data and finally, a combination of rules and experimental data can be used. Access to exits and congestion around exits while exerting a strong influence on overall exit flow rates are handled by features of the model previously described.

4.0 FACTUAL DATA RELATING TO EVACUATION MODELS

Associated with the development of computer based aircraft evacuation models is the need for comprehensive data collection/generation related to human performance under evacuation conditions.

Factual data regarding the evacuation process is essential to the development of computer egress models. While specifically addressing the data requirements of air-EXODUS, other aircraft evacuation models [14] have a similar reliance on data. Every component of the evacuation model just described relies on input from the real world in order to,

a) identify the physical, physiological and psychological processes which contribute/influence the evacuation process and hence formulate the appropriate rules,

b) quantify attributes/variables associated with the identified processes and finally,

c) provide data for model validation purposes.

The following is a list of data/information which is necessary for the development of aircraft evacuation models. While it is not definitive it addresses each of the three areas listed above.

1) **Exiting Procedures:** Develop relationships describing measured exit delay times for particular exit types related to gender/size/age and nature of exiting method i.e. slide or platform.

2) **Occupant Behaviour:** Observation and characterisation of occupant behaviour, in particular, (a) route planning, (b) exit path recommitment, (c) influence of travel companions on behaviour and (c) change in behaviour dynamics as a function of increasing smoke density, reduced lighting, single or multiple aisled geometries.

3) **Physiological Response:** Establish which - if any - of the existing narcosis and irritant gas models is appropriate for use in aircraft fire situations and develop a linkage between passenger attributes and level of exposure to irritant and narcotic gases.

4) **Response Times:** Data which characterises the range of occupant response times for a variety of age/gender/agility groups. In particular need to consider, (a) time to release seat belts, (b) time required to assist others and (c) effect of smoke/darkness.

5) **Travel Speeds:** Data which characterises the range of occupant travel speeds for a variety of age/gender/agility groups. In particular need to consider travel speeds, (a) from window seat to aisle, (b) along aisle, (c) over seats, (d) over obstructions. This data can be characterised for level cabin floors, sloped cabin floors, as a function of smoke density (similar to the work of Jin and Yamada 1988) and in reduced light conditions.

6) **Validation Data:** Provide full-scale evacuation data from single and twin aisled configurations suitable for the validation of evacuation models

Three forms of existing data are expected to provide some of the required information. Aircraft accident human factors reports produced by for example the NTSB and the AAIB (see 4.1), 90 second certification data held by the aircraft manufacturers (see 4.2), and large-scale experimentation devised to answer operational questions (see 4.3). Gaps in the knowledge this information provides can be filled by a combination of large- and small-scale targeted experimentation.

4.1 The AASK Data Base of Survivor Statistics

Information from the first source is currently being collected by researchers from the Fire Safety Engineering Group (FSEG) at the University of Greenwich. The information is being collated into a database known as AASK which is an acronym for Aircraft Accident Statistics and Knowledge. At present, detailed information from NTSB and AAIB reports are being loaded into the database. This information is being collected from documented accounts of survivor interviews and factual reports.

Two types of passenger information is being collected. These involve:

(1) Simple factual information, for example,
- which exit passengers used,
- location of fatalities and where they started from,
- location and nature of cabin debris.

(2) Passenger/Crew accounts of behaviour, for example,
- how quickly occupants responded,
- difficulty with seat restraints,
- path taken to exit,
- did they encounter difficulty entering aisle?
- did they go over seat backs?
- did they recommit after selecting a particular exit,
- did they experience difficulty seeing or breathing.

The database can be used to analyse a single accident or a collection of accidents. As an example of the type of analysis which can be performed consider the following exit usage analysis performed on several of the accidents currently in the database.

Consider the B727 accident at Dallas on 31 August 1988 [15]. The aircraft crashed shortly after takeoff and was eventually destroyed by a postcrash fuel fire. The passengers and crew used two serviceable exits and three fuselage ruptures to make their escape.

Of the 89 survivors 81 passengers or 91% filled in a report. Of the 81 passengers reporting their exit usage only 18 passengers failed to use their nearest serviceable exit/opening. Of these passengers, nine passengers supplied reasons for this action. Three passengers were not aware of their nearest exit, two passengers decided that the congestion at the exit was too great and decided to try another, and four passengers were following someone else.

A similar analysis was performed over 16 accidents since 1982 and involved responses from 616 passengers or 49% of the survivors. The 16 accidents involved incidents during take-off (7) landing (5), post take-off (1), mid-flight (2) and parked (1). The aircraft involved in these accidents ranged from small commuter aircraft to wide-body aircraft. Of the 616 passengers who reported their exit usage 125 (20%) passengers failed to use their nearest serviceable exit. Of these, 77 (12.5%) passengers failed to supply any reason for their actions. The remaining 48 passengers gave the following reasons for not using their nearest exits, 22 reported following the Flight Attendants instructions (i.e. re-direction), 11 simply followed other passengers, 5 reported congestion at the nearest exit, 1 reported a fire in the vicinity of the exit, 6 thought that the nearest exit was blocked and 3 were not aware of the nearest exit.

While not complete, this analysis suggests that 98% of those reporting their behaviour used or had a good reason for not using their nearest serviceable exit.

This type of analysis is extremely valuable in aiding our understanding of the behaviour of people in real accidents and as such addresses the requirements of item (a) listed above and to a lesser extent item (b). It also provides essential insight to modellers attempting to simulate the evacuation process. While not yet complete, the analysis just described provides some justification for adopting the global behaviour described in air-EXODUS and the nature of the local behaviour override. Detailed investigation of this type may also highlight behaviour which can be further examined through experimentation.

4.2 Manufacturers 90 Second Certification Trial Data.

A further source of potentially useful data has been collected by the aircraft manufacturers through the certification process. While the relevance of certification data to the development of models attempting to simulate evacuations under 'real' conditions may be questionable, its relevance to the development of evacuation models capable of simulating certification conditions is obvious. Furthermore, in the absence of more relevant data this information is vital. However, access to this data is difficult due to its propriety nature. The FSEG in conjunction with the UK CAA have undertaken a study of the manufacturers 90 second certification data. To date, BOEING, MDC, BAe and deHavilland have made all their 90 second data available for study. AIRBUS INDUSTRIE have agreed in principle to make their data available.

The data being extracted from this information is useful for all three of the above areas. For example, by studying video footage of certification demonstrations it is possible to collect information describing human behaviour such as,

- do passengers encounter difficulty entering aisle from seat?
- do passengers queue in aisles? if so for how long and where did the congestion occur? What is the nature of the congestion? What was the cause of the congestion?
- do passengers go over seat backs? If so, why? exit and entry points noted.
- do passengers recommit after selecting a particular exit,
- do exits become congested?
- quantify passenger hesitation at various exit types,
- is the behaviour of passengers under reduced lighting conditions significantly different to that expected under normal lighting conditions?

This information partially addresses item (a). Detailed analysis of video footage is also useful in quantifying attributes/variables used in the evacuation model thereby providing input to item (b) identified above. For example it is possible to extract information relating to,

- how quickly passenger's respond to evacuation call,
- estimates of passenger maximum travel speeds,
- estimates of delay times at exits.

Finally detailed information concerning exit usage and evacuation times is useful for validation purposes thereby addressing item (c). While the study has only just begun, the information is proving extremely valuable.

4.3 Large- and Small-Scale Evacuation Experiments.

The third source of existing data is provided by large- and small-scale evacuation experiments. Over the past six years, the UK CAA has sponsored a series of large-scale competitive evacuation trials from a single aisled aircraft using a single exit [16]. These trials were designed to answer specific operational questions concerning passenger behaviour relating to exit width and seat spacing at exits. This work has recently been extended to include competitive evacuations through multiple exits and the role of cabin crew intervention [17]. This research is on-going and forms part of an international collaboration between the UK CAA and the USA FAA. Unfortunately, no detailed information of this type currently exists concerning competitive evacuations from wide-body aircraft.

To date most - if not all - the experimental effort in human evacuation research has been directed towards answering specific operational questions. Wherever possible this data has also been used to assist in the development of computer based evacuation models by providing insight into competitive human behaviour, more importantly however, they contribute to the general pool of data for model validation purposes. Thus, the data from this type of experimentation provides information which partially addresses item (c) above and to a lesser extent item (a). Information from the Cranfield trials for example is being used as part of the EXODUS validation procedure (see figure 4). Other experimental research involving large-scale evacuation can provide detailed information to quantify essential model parameters and thereby address the requirements of item (b) listed above. For instance, recent work conducted by FAA CAMI has correlated the delay time associated with passengers of various weights, heights and genders, on passing through Type III exits [18]. This data has been included within the EXODUS model as part of the exiting procedure options.

5.0 air-EXODUS SAMPLE SIMULATIONS

To demonstrate the capabilities of the air-EXODUS evacuation model several sample simulations will be presented. These simulations are not intended to demonstrate the hazard or toxicity submodel and so the scenarios simulated will be free of fire hazards. Sample simulations of air-EXODUS including the effects of fire hazards may be found in references [4,5,6]. The following examples involve a simulation of one of the CRANFIELD trials involving two exits in the B737 simulator (see 5.1) and the predictive calculations of several 90 second certification results (see 5.2).

5.1 air-EXODUS Predictions of Cranfield B737 Evacuation Trial

air-EXODUS is being used to simulate the evacuation trials conducted by CRANFIELD in their B737 simulator. The cabin section consists of the front two Type I exits, and 60 passengers distributed over the first 10 rows of seats. The specific trials presented here involved competitive evacuations with both Type I exits and two assertive cabin crew [17]. The experimental trials were repeated four times with the experimental results producing a spread in evacuation times (see figure 4).

The extremes in evacuation performance were used to define an experimental window of acceptable results, denoted by the solid straight lines in figure 4. The situation was then modelled using air-EXODUS. The results from four repeats of air-EXODUS are also shown in figure 4 and are denoted by the stepped curves. Clearly, the air-EXODUS simulations fall within the variation observed in the experiment.

5.2 air-EXODUS Predictions of Boeing 767 Certification Trials.

On April 13 1996 Boeing successfully performed a 90 second certification trial on a modified B767 aircraft, designated the B767-304ER. This aircraft was configured with three pairs of Type A exits similar to those found on existing B767 aircraft and one pair of Type I exits similar to those found on B757 aircraft. The UK CAA requested that FSEG perform a series of predictive simulations using the air-EXODUS model for this aircraft prior to the actual test inorder to establish whether or not air-EXODUS was capable of accurately predicting the outcome of 90 second certification trials. Three confidential reports [19,20,21] containing details of the model formulation and results of the simulations were produced by FSEG and distributed to the UK CAA and US FAA prior to the trials, and Boeing after the trials. Here we briefly present some of the preparatory simulations and a description of the results for the B767-304ER.

5.2.1 Preparatory Analysis

In order to make air-EXODUS model predictions for the B767-304ER meaningful, a considerable amount of data analysis was performed prior to the test. Prior B767 (B767-200 and B767-346) and B757 certification data - including video footage of the actual trials - was analysed (as part of the project described in 4.2). This analysis included such aspects

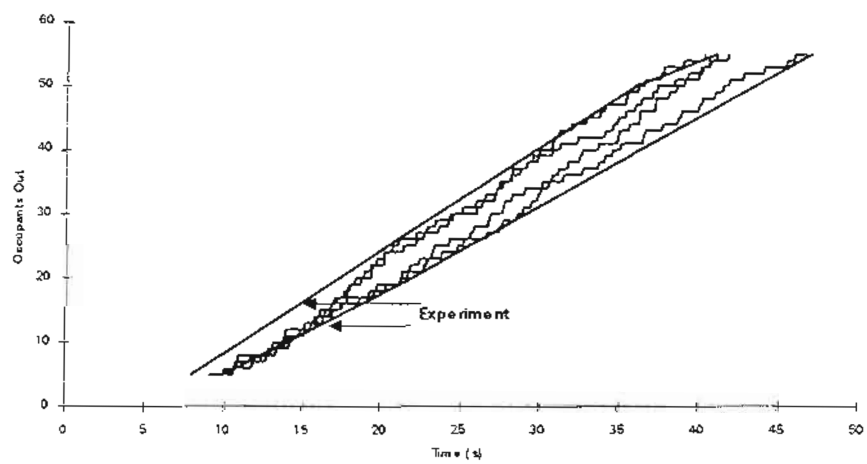

FIGURE 4: Evacuation curves depicting air-EXODUS predictions (stepped curves) and experimental envelope derived from Cranfield trials (B737 simulator) involving two forward exits and two assertive cabin crew.

Table 1: air-EXODUS evacuation times using optimal exit distribution for the 767 series 346.

	Aft (A)		Fwd O/W (III)		Aft O/W (III)		Fwd (A)	
	No	Time	No	Time	No	Time	No	Time
min	106	69.9	41	66.9	47	67 6	91	64.1
max	106	76.9	40	67.3	48	67.8	91	69 1

as crew performance (i.e. level of assertiveness), door opening times, slide times, etc. The primary purpose of this analysis was to establish a range of approximate exit hesitation times suitable for Type A, Type I and Type III exits [19].

As described in section 3.2.6 (vi) air-EXODUS requires the exit hesitation time as part of the data entry to characterise an exit. The exit hesitation time for Type I and A exits represents the delay a person experiences between standing on the door sill and transferring onto the slide. Some passengers jump from the sill to the slide in the correct manner - experiencing a small delay - while some passengers sit on the sill before pushing themselves onto the slide - experiencing a longer delay - while others freeze momentarily before moving onto the slide - very long delay. The delay time is dependent on a number of factors including type of exit, height above the ground, size, age, weight and gender of passenger, assertiveness of cabin crew etc. In air-EXODUS it is possible to specify the exit hesitation times in a number of ways depending on the quality of the data. It is possible to specify a minimum and maximum hesitation time for each exit type and randomly assign each passenger with a hesitation time according to the limits. If more data is available a functional form describing the hesitation time distribution is possible. As an indication of the range of hesitation times noted for Type A exits, passengers were observed to hesitate from a few tenths of seconds to several seconds.

This data was extracted from the initial analysis [19] and as a first test applied to the prediction of the previous B767-200 and B767-346 certification trials [20]. A number of different scenarios were performed, these were intended to simulate efficient and inefficient evacuations. Among the options considered were allowing the passengers to head towards their nearest serviceable (inefficient) and allowing passengers to head towards the optimal exit. A summary of the optimal model predictions for the B767-346 are presented here.

The B767-346 has two pairs of Type A exits and a pair of dual Type III exits over the wing. The aircraft seats 285 passengers. The aircraft configuration used in the certification trial was constructed in air-EXODUS using the interactive geometry tools. For each of the simulations, the exit opening times used in the air-EXODUS trials are the actual times recorded for the opening of each particular exit. In the simulations presented here, the exit hesitation times were assigned using a uniform random distribution between the observed maximum and minimum values. Each case examined was repeated a number of times. The repeats were associated with a random re-seating of the passengers. In the results presented note that,

(i) All times refer to evacuation times for passengers only. Crew evacuation times are not included.

(ii) Exit opening times correspond to the actual values achieved in the trial.

(iii) All times refer to the time to exit the aircraft and so do not include slide times i.e. on ground times.

Table 1 shows the minimum and maximum evacuation times achieved for the B767-346 aircraft. The model predicts an evacuation time of between 69.9 and 76.9 seconds, with an average over 12 trials of 72.9 seconds (excluding crew and slide times). The predicted overall evacuation time was within 2% of that achieved in the trial. Results for the B767-200 were predicted to an identical level of accuracy.

5.2.2 Blind Predictions for the B767-304ER

Following the success of the B767-200 and B767-346 predictions, air-EXODUS was used to predict the performance of the new B767-304ER prior to the actual test [21]. The geometry of the B767-304ER was constructed within air-EXODUS using the interactive geometry mode. The geometry is based on dimensions and seating configurations supplied by Boeing. The aircraft seats 351 passengers. The exits are arranged with two pairs of Type A exits forward of the wing, a pair of Type I exits just aft of the wing and a pair of Type A exits in the rear of the aircraft. For the purposes of the simulations, all four exits on the right side of the aircraft are used in the evacuation.

A total of 321 evacuation simulations for the B767-304ER were produced using the air-EXODUS evacuation model. As in the previous cases all times quoted are for passengers only and do not include passenger slide or crew evacuation times. In the results presented here all exits were made ready after a delay of 10 seconds.

Two types of scenario were investigated. Each case examined was repeated at least four times. The repeats were associated with a random re-seating of the passengers. The first scenario involved passengers heading towards the exit which is deemed optimal. An optimal selection of exits may necessitate some passengers using an exit which is not necessarily their closest exit. These cases give an indication of the best times that can be achieved by crew and aircraft during the trial assuming all goes well. A number of sub-optimal cases were also run. These cases give an indication of times which may be achieved if problems are encountered during the trial. Scenarios investigated included late opening of exits and inefficient crew performance resulting in poor passenger distribution between the available exits.

In order to specify various levels of sub-optimal performance it is necessary to define a parameter which measures optimal performance. In aircraft which have more than one exit available for evacuation, the total evacuation time will typically be reduced if the flow through each exit terminates at the same time. Failure to achieve the simultaneous termination of exit flows is usually a result of poor distribution of passengers between exits which in turn results in an unnecessarily prolonged evacuation time. Note that no mention of the number of passengers using each exit is made, simply that the flow through each exit terminates simultaneously.

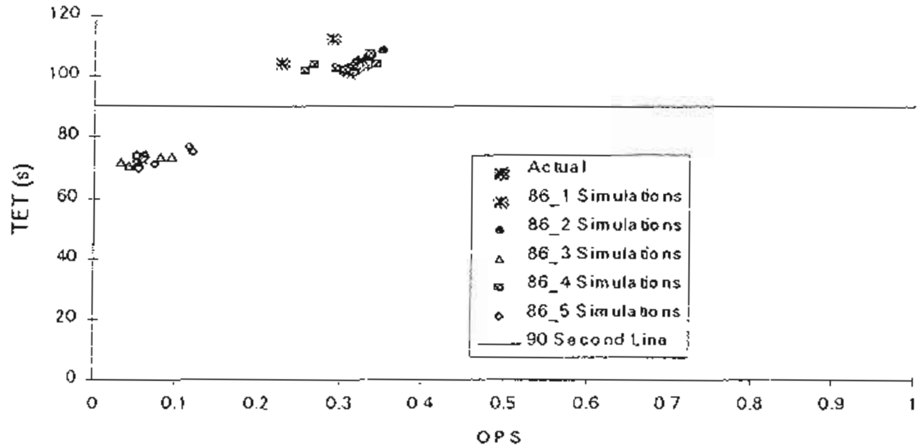

FIGURE 5: air-EXODUS generated evacuation time (seconds) versus OPS graph for the B767-346.

Thus in optimal evacuation situations exit flows will be completed at approximately the same time. Sub-optimal cases occur when one or more exits exhaust their supply of passengers before the remaining exits. Reasons for sub-optimal performance are many and varied and can be due to poor evacuation procedures, poor cabin crew performance, equipment failure, unusual passenger behaviour, poor cabin design and layout or a combination of all these factors.

As a measure of optimal performance we have developed a statistic known as the OPS or Optimal Performance Statistic. The OPS can be calculated for each evacuation, providing a measure of the degree of performance. The OPS is defined as follows,

$$OPS = \frac{\sum_{i=1}^{n} TET - EET_i}{(n-1) * TET}$$

where,

n = number of exits used in evacuation

EET_n = Exit Evacuation Time (time last passenger out) of Exit n (seconds)

TET = Total Evacuation Time (seconds) = max[EET]

An evacuation in which OPS = 0 indicates an optimal (or perfect) distribution of passengers was achieved.

An evacuation in which OPS = 1 indicates the worst possible distribution of passengers in which every passenger used a single exit thereby ignoring all other exits.

An OPS value greater than zero is sub-optimal indicating that the evacuation time can be improved by achieving a better distribution of passengers or better crew performance etc.

While it is unlikely that an aircraft will achieve an OPS = 0, near optimal performance will be marked by low values of OPS. As an example consider the performance figures for the B767-346 predicted using air-EXODUS. The results reported in table 1 were reported to be optimal.

From table 1 using the minimum set of results,

EET_1 = 66.9s, EET_2 = 67.6s, EET_3 = 64.1s and TET = 69.9s (ignoring crew times and slide times).

Substituting these values into the OPS expression results in,

OPS = [(69.9 - 66.9) + (69.9 - 67.6) + (69.9 - 64.1)]/[69.9*3]
= 0.05

If the calculations are repeated using the maximum times we find OPS = 0.11

Aircraft and crew in both cases achieved OPS values near zero and hence both produced near optimal performance.

A plot of evacuation time versus OPS can suggest how the evacuation performance may be improved. Figure 5 presents a plot of evacuation time versus OPS for the air-EXODUS predictions of the B767-346. Clusters in the bottom left represent desirable outcomes - aircraft and crew achieve sub-90 second evacuation times and an optimal OPS. These aircraft have an efficient cabin layout and crew. An aircraft which fails the 90 second evacuation criteria but achieves a near optimal OPS (clusters in the top left) can not be expected to achieve better evacuation performance through improved passenger distribution. Performance may be improved either through improved aircraft design (e.g. exit capacity or exit approach) or through improved crew performance at the exits (i.e. greater assertiveness). Conversely, an aircraft which fails the 90 second evacuation criteria and achieves a sub-optimal OPS (clusters in the top right) can be expected to achieve better performance through improved passenger distribution. This may require improved crew procedures, improved crew performance, more crew, improved cabin layout etc An aircraft which passes the 90 second evacuation criteria and achieves a sub-optimal OPS (clusters in the bottom right) has excess exit capability and/or a poor distribution of passengers/exits (i.e. cabin layout).

Selecting an acceptable value for OPS is somewhat arbitrary From the B767-200 and B767-346 EXODUS simulations, OPS values less than 0.12 produced efficient evacuations, while in the actual trials each aircraft achieved an OPS value of 0.05. For the purposes of the B767-304ER predictions, OPS values less than to 0.1 are considered optimal.

The results presented in table 2 represent a selection of the optimal (OPS<0.1) predictions.

These results suggest,

(1) The B767-302ER is capable of producing evacuation times in the range from 69.5 to 74.4 seconds with an average of 71.8 seconds. Each case produced an OPS < 0.084, satisfying our optimality criteria.

(2) The average exit usage is distributed as follows,

AR 98 passengers, MAR 62 passengers, MFR 95 passengers and FR 93 passengers.

These times include slide times and the time for the crew to evacuate. In order to make a direct comparison with the model predictions the time for the crew to leave the aircraft and the slide times must be subtracted from the above times This will require an analysis of the video footage of the trial It can however be estimated from the recorded exit flow rate in passengers per minute (ppm), the number of crew to use each exit and allowing 2 seconds for slide times. This produces the following estimated times for the trial, AL 70.1 seconds, MAR 68.6 seconds, MFR 65.4 seconds, and FR 70 3 seconds, and an OPS value of 0.032.

The OPS value achieved in the trial indicates that this evacuation was very efficient and achieved the same level of optimality as achieved in air-EXODUS.

This suggests that the average evacuation time predicted by air-EXODUS is within approximately 2% of the measured time. Furthermore, general trends in passenger flow behaviour predicted by air-EXODUS appear to have been corroborated by actual events, for instance, the passenger split within the cabin predicted by air-EXODUS was achieved in the actual trial.

6. CONCLUSIONS

In this paper we have attempted to describe possible enhancements to the current evacuation certification process. Evacuation models have been suggested as a possible alternative to the current practice of performing a single

TABLE 2: air-EXODUS predictions for B767-304ER (note: times exclude slide times and crew times).

AR		MAR		MFR		FR			
# pax	time (sec)	# pax	time (sec)	# pax	time (sec)	# pax	time (sec)	TET (sec)	OPS
99	68.4	63	69.5	98	70.5	91	65.7	70.5	0.037
98	70.6	63	70.6	99	69.5	91	63.5	70.6	0.039
98	64.8	63	71.4	98	72.2	92	63.6	72.2	0.078
97	72.5	60	66	95	68.7	99	74.4	74.4	0.072
97	67.5	62	69.8	99	73.7	93	73.6	73.7	0.046
97	65.9	63	69.7	97	71.6	94	67 6	71.6	0.054
100	72.7	63	68.7	89	66.7	92	64 6	72.7	0.083
100	67.9	63	70.7	88	68.8	93	66.9	70.7	0.040
100	69.5	62	66.4	90	68.6	92	67.2	69.5	0.030

(3) The last exit to finish was distributed amongst the various exits as follows,

AR 22%, MAR 22%, MFR 45% and FR 11%.

A thorough comparison of model predictions with actual test results is not yet possible as the detailed information from the trial is not yet available. The evacuation times reported for the trial are,

AL 73.2 seconds, 113.3 ppm, MAL 72.5 seconds, 62.9 ppm, MFR 68.5 seconds, 109.6 ppm and FR 75 seconds, 89.0 ppm.

evacuation demonstration with live people. The demonstrated success of the air-EXODUS evacuation model in predicting the outcome of a recent evacuation trial prior to the actual event is a compelling argument of the use of computer models for evacuation certification - at least for derivative aircraft. For truly 'new' aircraft configurations involving new hardware features such as a new type of exit, it is expected that evacuation models in conjunction with component testing of the new feature will offer a sensible and reliable alternative to full-scale live evacuation trials. However, more validation of evacuation models is required before they can be accepted as a reliable general alternative to evacuation trials. Validation of the air-EXODUS evacuation model is continuing through the simulation of past 90 second certification trials.

While the regulatory authorities may require further evidence of the benefits offered by evacuation models for certification purposes, aircraft manufacturers and aircraft operators should exploit this technology as an aid in the design of new aircraft and in the development of cabin crew procedures and training of cabin crew. In addition, features of the air-EXODUS model not demonstrated in this paper, such as the impact of smoke, heat and toxic fire gases on the passengers, make the model useful as an aid to the investigation of real accidents. Furthermore, these features can also be used for design, bringing issues such as the impact of smoke on the evacuation into the design phase

Work on the air-EXODUS model is continuing with the development of new features such as explicit modelling of cabin crew - including the specification of primary and secondary duties, and the development of a virtual reality visualisation capability Data analysis is also continuing with the further development of the AASK data base and the analysis of aircraft manufacturers 90 second certification data.

7. ACKNOWLEDGEMENTS

Professor E R Galea is indebted to the CAA for their financial support of his personal chair in Mathematical Modelling at the University of Greenwich. The research work described in this paper and originating from the University of Greenwich could not have been achieved without the dedicated efforts of the staff of the Fire Safety Engineering Group and the financial support of our main sponsors the UK CAA and UK EPSRC. Prof Galea is also indebted to the Boeing Commercial Airplane Group for allowing the use of Boeing data and providing access to observe Boeing evacuation certification trials. While the Boeing Company has provided data in support of this research and the UK CAA has funded the research, the opinions expressed in this paper are those of the authors.

8. REFERENCES

1. OTA, 1993, "Aircraft Evacuation Testing: Research and Technology Issues Background Paper," Technical Report OTA-BP-SET-121, Office of Technology Assessment Congress of the United States.

2. King D , 1988, 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.

3. Snow, C , C., Carroll, J., J., and Allgood, M., A., 1970, "Survival in emergency escape from passenger aircraft," Technical Report AM 70-16, FAA Office of Aviation Medicine, Dept of Transport, USA.

4 Galea, E. R., and Galparsoro, J M. P., 1993, "EXODUS: An evacuation model for mass transportvehicles," Technical Report, CAA Paper 93006 ISBN 086039 543X, CAA London

5 Galea, E. R., and Galparsoro, J. M P , 1994, "A Computer Based Simulation Model for the Prediction of Evacuation from Mass Transport Vehicles," *Fire Safety Journal*, 22 pp 341 - 366.

6. Galea, E R., Owen, M , and Lawrence, P , 1996, "Computer Modelling of Human Behaviour in Aircraft Fire Accidents," *Proc of Combustion Toxicology Symposium*, CAMI, Oklahoma City, 1995, To appear in Toxiocology

7. Owen, M., Galea, E.R. and Lawrence, P , 1995, The EXODUS evacuation model applied to building evacuation scenarios. Proc of Fire Safety by Design, Univ of Sunderland, 10-12 July 1995.

8. Galea, E.R., Owen, M., and Lawrence, P., 1996, Emergency Egress from Large Buildings under fire conditions simulated using the EXODUS evacuation model., Proc INTERFLAM'96, Interscience Communications Ltd,. London pp 711-720.

9. Owen, M., Galea, E.R., and Lawrence, P , 1996, The EXODUS Evacuation Model Applied To Building Evacuation Scenarios, To Appear Jounmal of Fire Protection Engg.

10. Galea, E. R., and Hoffmann, N. A., 1995, "The Numerical Simulation of Aircraft Cabin Fires," Technical Report, CAA Paper 95008, CAA London.

11. Purser, D. A., 1988, "Toxicity Assessment of combustion products," In: C.L.Beyler (Ed) *SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, Quincy M.A., 1-200 - 1-245.

12. Speital L. 1996, " Fractional Effective Dose Model for Postcrash Aircraft Survivability"; Proc Int Colloquium on Advances in Combustion Toxicology, FAA CAMI, Oklahoma City, USA, 11-13 April 1995 To appear in Toxicology.

13. Jin, T., and Yamada, T., 1988, "Experimental Study of Human Behaviour in Smoke Filled Corridors," *Proceedings of The Second International Symposium on Fire Safety Science*, pp 511-519.

14. Marcus, J., H., 1994, "A Review of Computer Evacuation Models and their data needs," *Procs 11th Annual Int Aircraft Cabin Safety Symp and Technical Conf*, pp 282-300, SCSI.

15. Hammack, G., 1989, "Survival Factors Group Chairman's Factual Report of Investigation (Boeing 727-232,Delta Airlines, N473DA, Dallas-Fort Worth Int Airport, August 31 1988)," Technical Report National Transport Safety Board, Washington, D.C., Docket No. SA-499, Exhibit No. 6A.

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

17 Muir, H., 1995, Private communication, to appear as a CAA Paper in 1996

18. McLean, G. A., and George, M. H., 1994, "Individual Difference in Efficiency of Emergency Egress from Type-III Overwing Exits," *Aviation, Space and Environmental Medicine*, Vol 64, 5, pp 468-.

19 Galea E.R. and Owen M., 1996, Initial Analysis of B767 and B757 Certification Trial Data, Confidential Report for the U.K. CAA Not for public dissemination

20. Galea E.R. and Owen M., 1996, Initial EXODUS Model Predictions for Certification Evacuation Scenarios of the B767-200 and B767-346 Aircraft., Confidential Report for the U.K. CAA. Not for public dissemination.

21. Galea E.R. and Owen M., 1996, Initial EXODUS Model Predictions for Certification evacuation Scenarios of the B767-304ER Aircraft., Confidential Report for the U.K. CAA. Not for public dissemination.