COMPUTER BASED SIMULATION OF AIRCRAFT EVACUATION AND ITS APPLICATION TO AIRCRAFT SAFETY

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1. ABSTRACT

Computer based mathematical models describing the aircraft evacuation process have a vital role to play in the design and development of safer aircraft, the implementation of safer and more rigorous certification criteria, in cabin crew training and post-mortem accident investigation. As the risk of personal injury and the costs involved in performing large-scale evacuation experiments are high, the development and use of these evacuation modelling tools are essential. Furthermore, these computer models may in fact be the only viable route for certifying the next generation Very Large Aircraft. This paper describes the capabilities of the airEXODUS evacuation model and some attempts at validation, including its successful application to the prediction of a recent certification trial, *prior* to the actual trial taking place.

2. INTRODUCTION

When modifying an existing aircraft or designing a new aircraft, how do we ensure that the proposed design is safe, and how do we demonstrate that it is safe? 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 series of full-scale trials using the passenger compartments 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 are that it poses considerable ethical, practical and financial problems that 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 participants) sustained injuries ranging from cuts and bruises to broken bones [1]. In October 1991 during the McDonnell Douglas evacuation certification trial for the MD-11, a female volunteer sustained injuries leading to permanent paralysis. Furthermore, as volunteers are subject neither to trauma 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 tragic example. The last passenger to escape from the burning B737 aircraft emerged 5.5 minutes after the aircraft had ceased moving, while 15 years earlier in a UK certification trial, the entire load of passengers and crew evacuated 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 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, and does not even necessarily match the types of configuration 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 mathematical models describing the aircraft evacuation process have the potential of addressing all these shortfalls. If evacuation models are to fulfil their promise, they must address the configurational, environmental, behavioural and procedural aspects of the evacuation process [3]. Configurational considerations are those generally covered by conventional methods and involve cabin layout, number of exits, exit type, 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.

The airEXODUS evacuation model [4-7] attempts to address all four of the contributory aspects controlling the evacuation process. A brief description of the airEXODUS evacuation model follows, a fuller account may be found in [7].

3.0 THE airEXODUS EVACUATION MODEL: AN 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, buildingEXODUS [8] and airEXODUS. buildingEXODUS is designed for applications in the built environment and is suitable for application to complex structures such as airport terminal buildings and rail stations. airEXODUS 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 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 utilises rule-based software technology to control the simulation. In this way, the behaviour and movement of each individual is determined by a set of heuristics or rules. The user can view and interact with a simulation as it unfolds. A number of controls are provided so that a simulation can be paused, replayed, jogged, etc. enabling the evacuation to be studied in detail. Graphical output is also provided allowing the user to monitor certain aspects of the simulation. The data produced by a simulation may also be dumped into an output file for subsequent analysis and for later replay.

For additional flexibility, the airEXODUS rule base has been categorised into five interacting submodels, the OCCUPANT, MOVEMENT, BEHAVIOUR, TOXICITY and HAZARD submodels (see Figure 1). These submodels operate on a region of space defined by the GEOMETRY of the enclosure.

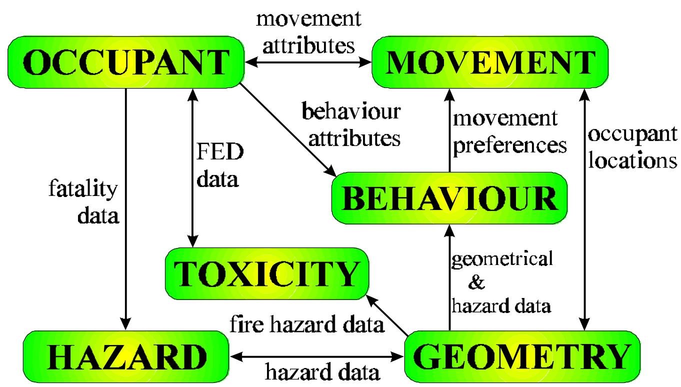

Figure 1: airEXODUS Submodel Interaction

The **OCCUPANT** submodel defines each individual as a collection of 20+ attributes which broadly fall into four categories, *physical* (such as age, gender etc), *psychological* (such as patience, drive etc), *positional* (such as distance travelled, etc) and *hazard effects* (such as fractional incapacitating dose of narcotic gases (FIN), 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, (e.g. age, gender, etc) while others are dynamic, changing as a result of inputs from the other submodels (e.g. distance travelled, travel speed, etc).

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.

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 predict the generation of fire hazards, it has the capability to use input from complex fire field models or zone models and experimental data.

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 (CO, CO_2, HCN and low O_2), heat and smoke. The effect of the narcotic gases and heat are modelled using various Fractional Effective Dose (FED) models [9]. During a simulation, smoke is considered to reduce an occupant's egress capability by decreasing their travel speed, ultimately causing them to crawl at a critical smoke density. The decrease in travel speed is based on the work of Jin and Yamada [10].

The **BEHAVIOUR** submodel determines an occupant's response to the current prevailing situation and 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 their responses to their current situation. While attempting to implement the global strategy, an individual's behaviour can be significantly modified by the dictates of their local behaviour.

The outcome of aircraft evacuations is highly dependent upon the presence and behaviour of cabin crew. While cabin crew are not modelled explicitly in the current version of airEXODUS, the varying effects produced by their actions may be simulated. These effects may be simply classified into two categories, Passenger Exit Selection and Exit Performance.

- **Effect of Cabin Crew on Passenger Exit Selection:** The effect of cabin crew on passenger exit choice can be profound. Data from aircraft accident reports, 90 second tests and full scale experimentation, suggests that sufficiently assertive cabin crew can redirect passengers from their nearest exits to others, thereby increasing their travel distance dramatically. The overall effect of this behaviour is to change the number of passengers using each exit. This effect is modelled in airEXODUS through the use of exit potentials.

- **Effect of Cabin Crew on Exit Performance:** It has been shown that the flow performance through various aircraft exits may be enhanced by cabin crew displaying assertive behaviour, i.e. encouraging passengers to travel through the exit with more speed [11,12]. Initial analysis performed by the authors suggests that the degree of assertiveness influences the number of passengers displaying slower delay times [12]. Thus it is possible to model this effect by altering the upper limit for the delay time distribution. To aid this process, airEXODUS supplies a range of default values based on the assertiveness level of the cabin attendant. It should be noted that the list of defaults supplied is not definitive, as the research providing the values is still in the early stages.

The nature of the exit can have a profound impact on passenger behaviour as they pass through the exit. There are three main types of exits used on commercial civil aircraft: Type-I, Type-III and Type-A exits (see [7]). One of the most significant behaviour factors is the exit delay time. The delay time attribute reflects the time each passenger spends traversing an exit. In reality, the majority of this time is generally spent hesitating at the exit, the remainder being the time taken to travel across the exit. Within airEXODUS, each passenger is randomly assigned a delay time as they pass through the exit. The delay time is assigned using a uniform random distribution with the maximum and minimum delay times being specified as scenario parameters. These values may be specified from the analysis of actual evacuation certification demonstrations or full-scale experimentation [11-13]. The hesitation time is dependent upon a number of factors, for example, *Exit type*, *Exiting behaviour*, *Passenger physical attributes*, *Presence of cabin attendants*, and *Behaviour of cabin attendants* represent the most prevalent of these factors.

Associated with the development of airEXODUS is the need for comprehensive data collection/generation related to human performance under evacuation conditions. Three forms of existing data are being used as the source of the required information. Aircraft accident human factors reports produced by for example the NTSB and the AAIB [14], 90-second certification data held by the aircraft manufacturers [12], and large-scale experimentation devised to answer operational questions [11].

4.0 airEXODUS SAMPLE SIMULATIONS

To demonstrate the capabilities of the airEXODUS evacuation model several sample simulations will be presented. The following examples involve a simulation of one of the CRANFIELD trials involving two exits in the B737 simulator (see Section 4.1) and predictive calculations of several 90 second certification results (see Section 4.2).

4.1 airEXODUS Predictions of Cranfield B737 Evacuation Trials

As part of an on-going validation exercise, airEXODUS is being used to simulate the evacuation trials conducted at Cranfield University in their B737 cabin simulator [11]. A fuller account of these simulations may be found in [7]. The cabin section consists of the front two Type-I exits and the first 10 rows of seats (60 seats in total). The volunteers used in the trials were aged between 20 and 50 years and were limited to a maximum weight of 95 kg for males and 76 kg for females. The specific trials presented here involved co-operative evacuations through two forward Type-I exits and two assertive cabin crew [11].

The co-operative behaviour exhibited by the participants in the Cranfield trials reflects the type of behaviour observed in industry standard 90 second certification trials, in particular, very little seat jumping occurs. The experimental trials were repeated four times, each trial producing different evacuation histories - as measured by the number of people out as a function of time. The extremes in evacuation performance, i.e. the minimum and maximum number of people out at each time-step of 0.1 seconds, were used to define an *experimental window* of results.

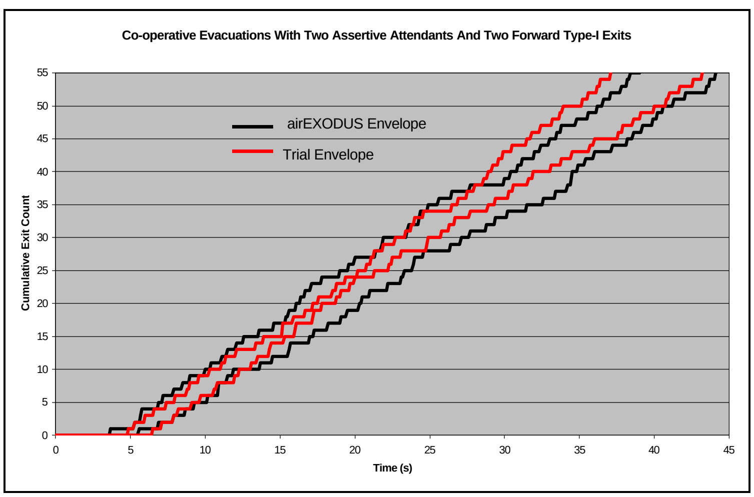

Figure 2: Window of results for numerical simulations (dark lines) and experimental trials (light lines)

In order to model the above scenario, airEXODUS was run with the competitive behaviour options deactivated. The population used within the airEXODUS simulations consisted of 38 males and 22 females. The exit hesitation time distribution used in these simulations was derived from 90 second trial data for Type-I exits with assertive cabin crew. The extremes in evacuation performance were used to define the numerical window of results using an identical process to that described for the experimental results.

A total of twelve airEXODUS simulations were conducted involving four repeats of three different seating arrangements. Figure 2 depicts the window of results for both the numerical simulations and the experimental trials. While there appears to be quite good agreement between the numerical and experimental results, the numerical predictions appear to produce a slightly wider distribution in evacuation times between 15 and 28 seconds into the evacuation. In making these comparisons it should be noted that the numerical predictions are the result of 12 simulations while the experimental data is based on only four repeat trials. Thus the experimental trials may fail to record the full range of variability. In addition, the mean numerical evacuation curves (generated by determining the mean number of passengers out of the simulator at each point in time) for the numerical and experimental results are almost identical, showing very little variation.

Table 1: Comparison between numerical and experimental spread in evacuation times for 55 passengers

Time for 55 passengers (s)	airEXODUS	Cranfield
Minimum	38.4	37.1
Mean	41.2	42.7
Maximum	44.1	43.2

4.2 airEXODUS Predictions of A 90-Second Certification Trial

While airEXODUS has successfully been used to predict the certification performance of several aircraft, the outcome of these trials was known to the authors before the simulations were performed. A more challenging validation exercise was requested by the UK CAA, requiring airEXODUS to predict the performance of a modified Boeing B767 aircraft, (designated the B767-304ER), *prior to the actual test*, in order to establish the predictive capabilities of airEXODUS for 90 second certification trials. A confidential report [15] containing details of the model formulation and results of the simulations was produced by FSEG and distributed to the UK CAA and US FAA prior to the trial, and Boeing after the trial. In this paper, a brief description of the results for the B767-304ER are presented, a fuller account may be found in [7].

The geometry of the B767-304ER was constructed within airEXODUS using the interactive tools available, based on plans supplied by Boeing. The aircraft seats 351 passengers and has four pairs of exits 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. In all the airEXODUS simulations conducted the four exits on the right side of the aircraft were assumed to be available.

A total of 321 evacuation simulations for the B767-304ER were conducted using the airEXODUS evacuation model. All the times quoted are for passengers only and do not include passenger slide or crew evacuation times. In the results presented in this paper, the exits were made ready after a delay of 10 seconds. Two types of scenario were investigated. The first scenario involved passengers heading towards the exit deemed optimal. Such a strategy necessitates some passengers using an exit that is not necessarily their closest exit and gives 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 scenarios were also conducted in order to give an indication of times that may be achieved if problems occurred during the trial. The sub-optimal cases investigated included late opening of exits and inefficient crew performance resulting in poor passenger distribution between the available exits. In both types of scenario, each case examined was repeated at least four times, each group of repeats being associated with a random re-seating of the passengers.

Table 2: airEXODUS predictions for B767-304ER
(Note: times exclude slide times and crew times)

AR		MAR		MFR		FR		Overall	
#pax	Time(s)	#pax	Time(s)	#pax	Time(s)	#pax	Time(s)	TET(s)	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

The results presented in Table 2 represent a selection of the optimal predictions.

These results suggest,

(1) The B767-304ER is capable of producing evacuation times in the range from 69.5 to 74.4 seconds with an average of 71.8 seconds.
(2) The average exit usage is distributed as follows:
Aft Right Exit (AR) 98 passengers, Mid-Aft Right Exit (MAR) 62 passengers, Mid-Front right Exit (MFR) 95 passengers and Front Right Exit (FR) 93 passengers.
(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 has not yet been extracted from the video. The evacuation times (seconds) and flow rates (persons per minute) reported for each exit in the trial are shown in Table 3.

Table 3: Exit evacuation times and flow rates reported for the certification trial of the B767-304ER

Exit	Evacuation Time (s)	Flow Rate (ppm)
AL	73.2	113.3
MAR	72.5	62.9
MFR	68.5	109.6
FR	75.0	89.0

The times shown in Table 3 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. However, estimates of the times can be made 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 estimated evacuation times (seconds) for the exits shown in Table 4.

Table 4: Estimated exit evacuation times derived from Table 3

Exit	Estimated Time (s)
AL	70.1
MAR	68.6
MFR	65.4
FR	70.3

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

4.3 Predicting the impact of cabin fires on evacuation performance

airEXODUS has the capability to include the impact of smoke, heat and toxic gases on an evacuation and to consider passengers with movement disabilities. In the following set of demonstration simulations, airEXODUS is used to examine the effect a passenger with severely restricted movement capabilities may have on several evacuation scenarios, including cases with fire. The geometry used in this demonstration represents the rear section (eleven seat rows) of a hypothetical narrow-body aircraft. In the scenarios considered, 66 passengers evacuate through an arbitrary Type-I exit, located behind seat row 11. Row 11 is the exit row, row 1 is the row furthest from the exit, while seats A and F are the window seats and seats C and D are the aisle seats.

The population involves an **arbitrary** mix of passengers with varying performance capabilities. The maximum movement rates vary between 0.65 m/s and 1.35 m/s (excluding the disabled passenger) and the passengers' response time and patience are set to zero and a large value respectively. 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.

In the control case, the geometry is populated with 66 passengers with the characteristics described above. For the control case airEXODUS predicts that the passengers require 62.9 seconds to vacate the aircraft. In the next three simulations a passenger with a maximum movement rate of 0.1 m/s (designated PAX A) is inserted in the passenger population and placed in three different seat locations. In SCENARIO 1, PAX A is seated in the seat nearest to the exit (row 11, position C); in SCENARIO 2, in the seat row furthest away from the exit (row 1), also in position C, and finally in SCENARIO 3 in the seat most remote from the exit, (row 1, position A).

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 [16]. It should be remembered that in real 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 become 78.7 seconds for Scenario 1, 157.6 seconds for Scenario 2, and 164.1 for Scenario 3. The longer evacuation times in Scenarios 2 and 3 are predominately due to the time PAX A requires to reach and use the exit. The vast majority of other passengers have exited long before. In the control case, the total cumulative wait time (incurred as a result of queuing and conflicts etc) is 26.8 minutes. This increases to 47.0 minutes in Scenario 1, 34.5 minutes in Scenario 2 and 25.1 minutes in Scenario 3. This suggests that for the cases involving PAX A, Scenario 3, while 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.

While Scenario 1 may be considered the preferable situation as it results in minimum evacuation time, 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 scenarios.

To examine this possibility, the simulations were repeated with a contrived fire atmosphere. In the following simulations the fire hazards vary with time, following a simple linear change law achieving their maximum (or minimum) value 30 seconds after simulation commencement. The aircraft fuselage was divided into three zones, with each hazard attaining the maximum values indicated in table 6.

Table 6: Contrived fire hazards used in demonstration scenarios

Hazard	Zone 1	Zone 2	Zone 3
Temperature (°C)	130.0	90.0	60.0
HCN (ppm)	6	4	1
CO (ppm)	7000	2000	500
CO_2 (%)	4.0	3.0	1.5
O_2 (%)	17.0	18.0	19.5

The severest conditions occur furthest from the exit (Zone 1) and gradually ease towards the rear exit. Zone 1 encompasses the four seat rows furthest from the exit, Zone 2 the next four seat rows and Zone 3 the remainder of the cabin.

In addition to the fire hazards above, smoke was included in the simulation. airEXODUS attempts to incorporate the impairing effects of smoke on the ability of a passenger to escape by reducing the movement rates as the smoke density increases. The maximum smoke density in each zone was 0.6 l/m (Zone 1), 0.5 l/m (Zone 2) and 0.5 l/m (Zone 3), where smoke density is expressed as an extinction coefficient. As with the other fire hazards, the smoke density was increased in a linear manner achieving a maximum value 50 seconds after simulation commencement.

Smoke has the effect of obscuring vision and irritating the eyes thus impairing the ability of an individual to escape. Several studies [10] 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.

In airEXODUS, the smoke density is linked to the passenger travel speed attribute, which decreases as the local smoke density increases. The maximum travel speed is unaffected up to smoke concentrations of 0.1 l/m after which point it decreases to half its original value at a smoke concentration of 0.5 1/m. For smoke concentrations above 0.5 1/m passenger's 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 [9] 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.

Within the FED model, a Fractional Incapacitating dose of Narcotic gases (FIN) is calculated per passenger. This is a measure of the ratio of dose received of narcotic gases to the dose required to cause incapacitation. An FIN = 1.0 corresponds to a fatality, i.e. a passenger succumbing to the effects of the narcotic gases. However, the FED model is based on the assumption that all passengers are in good health. In practice, if FIN > 0.9, it is likely that the passenger will be seriously injured and unlikely to survive.

Table 7: Summary of results for evacuation simulations with mobility impaired passenger

Parameter	Control	Control (+ fire)	S1 (+fire)	S2 (+fire)	S3 (+fire)
Evacuation Time (s)	65.8	126.6	161.7	147.9	122.0
Total wait time (min)	27.3	37.4	71.5	40.7	37.6
Average FIN/PAX	-	0.16	0.26	0.19	0.16
Fatalities (FIN > 0.9)	0 (0)	0 (1)	1 (2)	2 (1)	1 (0)

The results from these simulations are summarised in table 7. As the smoke density increases the movement rates of the exposed passengers begin to decrease and egress times increase from 65.8 seconds (Control) to 126.6 seconds (Control + fire). Furthermore, the average FIN per passenger is larger in the case where PAX A is located near the exit (FIN=0.26) compared to when he is furthest away from the exit (FIN=0.16).

The average FIN/passenger is greatest in Scenario 1, while in Scenario 3 it is identical to the control case. In the control case, no fatalities are reported; however, one passenger has FIN > 0.9. In Scenario 1, one fatality is reported and two passengers have FIN > 0.9, whereas in Scenario 2, there are two fatalities and one passenger with FIN > 0.9. Furthermore, in Scenario 3, one fatality is reported but in this case no passengers are found to have FIN > 0.9. This suggests that Scenario 3 produces the best outcome for the majority of the passengers, while Scenario 1 arguably produces the worst outcome – a situation opposite to that found in the fire-free scenarios. It should be noted that in both Scenarios 2 and 3, PAX A is amongst the fatalities, whereas in Scenario 1, PAX A survives.

The difference in outcome between the fire and fire-free cases is due to the additional wait time experienced by the passengers in Scenario 1. With PAX A located furthest from the exit, the total wait time becomes 40.7 minutes, only marginally greater than the corresponding value in the control case. Unlike in the previous simulations, Scenario 1 now produces a longer total evacuation time than in Scenarios 2 and 3. This is because in Scenario 2, PAX A is incapacitated and exerts less influence on the evacuation than in the corresponding simulation without fire, and in Scenario 3 PAX A is last into the aisle thereby not interfering with the evacuation of any other passengers. Furthermore, placing PAX A in a window seat (Scenario 3) as opposed to an aisle seat (Scenario 2) reduces the severity of the outcome.

In summary, for the cases involving a fire, Scenario 1 (PAX A nearest to exit) results in the most severe impact to the majority of passengers, while Scenario 3 (PAX A furthest from exit) results in the least. However, it is important to view these results in light of the assumptions made. These simulations are intended to highlight the functionality of airEXODUS and to suggest ways in which it can be used to investigate safety issues.

Finally, the results from these simulations suggest that the choice of seating for mobility-impaired passengers has implications beyond those simply of comfort and convenience. Safety issues – for both the individual and the other passengers – need to be considered and where necessary, procedures developed to improve survivability for everyone concerned.

Work on the airEXODUS 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. These features are intended to both improve model accuracy and enable the model to be used in cabin crew training applications. Data analysis is also continuing with the further development of the AASK database and the analysis of aircraft manufacturers' 90 second certification data.

5. CONCLUSIONS

In this paper evacuation models have been suggested as a possible alternative to the current practice of performing a single evacuation demonstration with live people. The demonstrated success of the airEXODUS evacuation model in predicting the outcome of the Cranfield trials, previous 90-second certification trials, and most significantly, a recent evacuation trial *prior* to the actual event are compelling arguments for 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 airEXODUS evacuation model is continuing through the simulation of past 90 second certification trials.

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