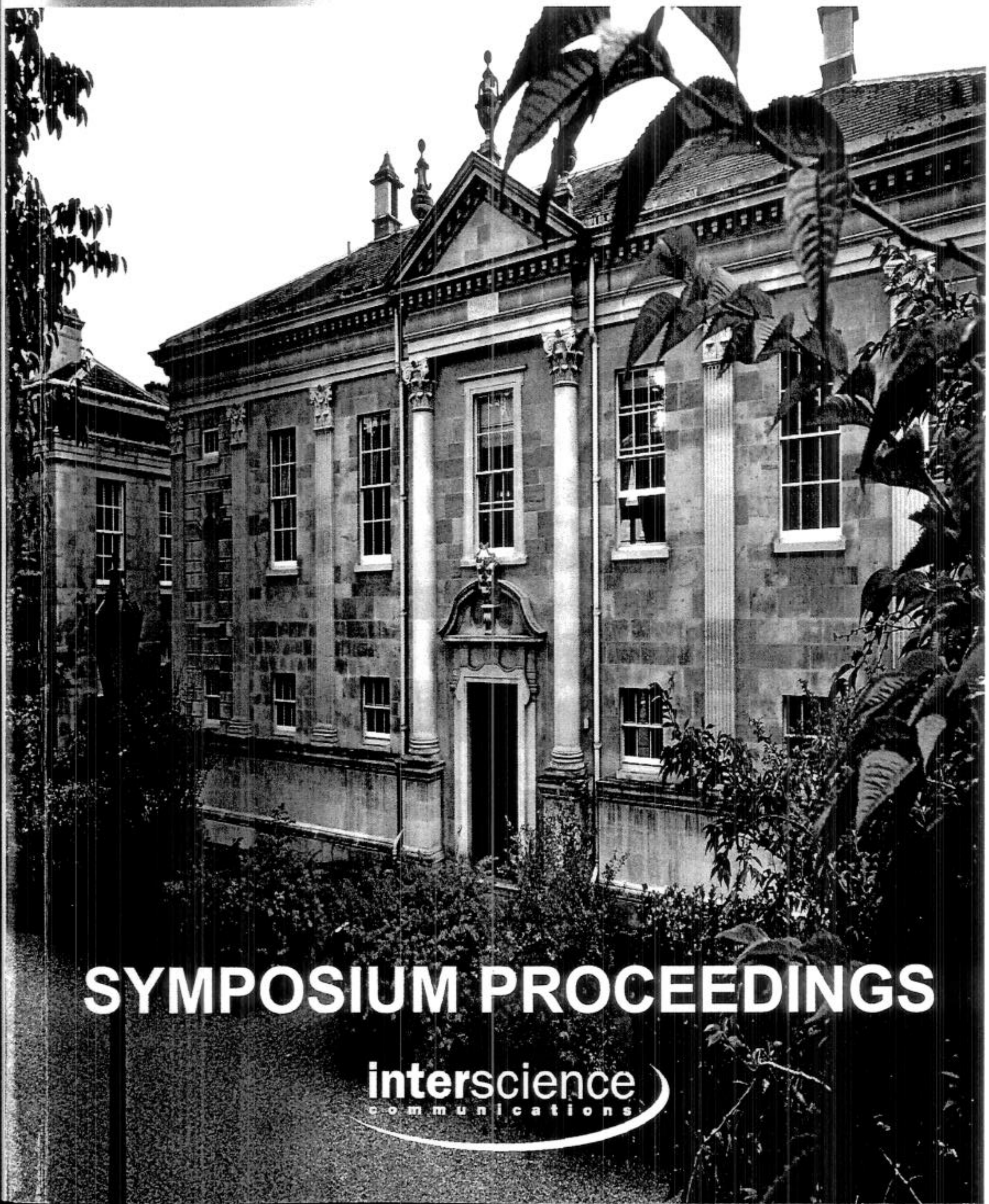
5th international Symposium

Human Behaviour in Fire 2012

Downing College, Cambridge, UK **19th - 21st September 2012**



SYMPOSIUM PROCEEDINGS

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INTRODUCTION

It gives me very great pleasure to welcome you all to this the 5th international symposium on Human Behaviour in Fire. Since the symposia's inception in 1998 we have directly influenced many changes and been prominent in the development of fire safety engineering. We see colleagues make career changes and sadly some are taken from us. All the more reason then to make the most of our time here together, to network and catch up with old friends and colleagues. Remember at this symposium there are no strangers here only friends waiting to be introduced.

The Programme Committee have selected a cross section of papers to stimulate the mind and hopefully the organisers will include some moments in the social programme to stimulate the senses! Some 43 technical papers and 14 poster papers are included along with Panel Discussions and Workshops on:-

- Life Safety Options for People with Disabilities - How far have we come? - Implications of Our Aging Society on Design and Management of Buildings
- Fundamentals of Egress Calculations for Life Safety Assessment
- Workshop on the Ethics of Behavioural Studies

As we approach the 5th symposium there many big issues to be addressed. For example, where exactly are we, in human behaviour terms, with respect to fire safety engineering and performance based design? Given our well established foundations what should be our focussing on for the next decade? These issues will be addressed at the symposium and your active partition in discussions surrounding them is eagerly anticipated.

I hope you will enjoy the next 3-4 days and like me, make the most of your time here in the fine surroundings of Downing College, Cambridge.

Prof. T Jim Shields

Symposium Chair

FIRE AND EVACUATION SIMULATION OF THE FATAL 1985 MANCHESTER AIRPORT B737 FIRE

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ABSTRACT

In this paper, fire and evacuation computer simulations are conducted to determine the impact of exit opening times on the evacuation and survivability during the Manchester Airport B737 fire of 1985. The fire and evacuation simulation tools, SMARTFIRE and airEXODUS are used in the analysis. The work is in two parts, the first part attempts to reconstruct the actual fire incident and ensuing evacuation using the known facts derived from the official investigation report. The second part investigates the impact of exit opening times on the aircraft fire development and subsequent evacuation. The results suggest that the number of fatalities could have been reduced by 92% had the delays in opening two of the three exits been avoided. Furthermore, it is suggested that opening of the unused aft right exit during the accident did not contribute to the high loss of life in this accident. Indeed, it is suggested that the opening of this exit improved survivability within the cabin and reduced the death toll by some 17%.

INTRODUCTION

On the 22[nd] of August 1985, a B737-236 suffered an uncontained engine failure and fire during its take-off roll at Manchester Airport, England[1]. During the accident, the external fuel fire entered the cabin after burn-through of the fuselage. During the fire incident, two of the four cabin crew and 53 of the 131 passengers died and a further 15 passengers were severely injured by the effects of the fire and toxic gases. In total the aircraft had three pairs of exits. From front to rear they were Type-I (a floor level exit sufficiently wide to allow one person to pass through at a time) crew operated exits, Type-III (small hatch type exit in which the passenger must climb up into the exit and down to the wing) passenger operated over wing exits and Type-I crew operated exits. Of these only the forward left (L1), forward right (R1) and right over-wing (ROW) exits were utilised during the evacuation.

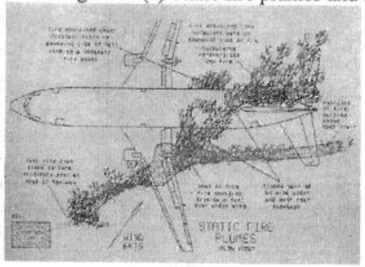
During the evacuation the passengers and cabin crew experienced difficulty in opening most of the exits. Indeed the ROW exit was opened by passengers approximately 45 s after the aircraft had stopped. Due to a malfunctioning R1 exit, the L1 exit was opened by the crew after approximately 25 s and the R1 exit was eventually opened after 70 s. In contrast, the average exit opening times from certification trial records are 8.2 s for the Type-I exit and 12 s for the Type-III exit[2]. Although the aft right exit (R2) was opened before the aircraft completely stopped, it was not used by passengers due to the heavy smoke accumulated in that area. From the accident report, it is suggested that the delay in opening the exit doors was one of the key factors contributing to the high loss of life in this accident[1]. While not identified as a factor in the accident report, the opening of the R2 exit may have contributed to the high loss of life by providing a possible means of entry of fire and smoke.

As a result, we raise the following questions concerning the exit opening times; could the loss of life have been significantly reduced if the R1 exit did not malfunction, did the delay in opening ROW exit impact survivability and finally, did the opening of the unused R2 exit contribute to the high loss of life? To address these questions we make use of coupled CFD fire and evacuation simulations. The authors have used this approach to study the Station Nightclub fire[3] and post crash aircraft fires[4,5]. Here we apply these techniques to numerically investigate the impact of exit opening times on the evacuation and survivability associated with the Manchester B737 aircraft accident.

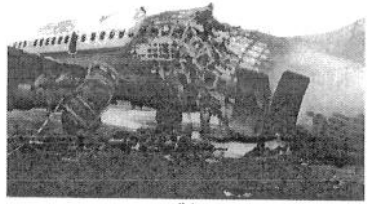
THE OFFICIAL INVESTIGATION

The B737-236 involved in the Manchester disaster is shown in Fig. 1. In the accident, the prevailing wind caused the fire plume from the left engine to be directed onto the aircraft fuselage, resulting in a severe cabin fire after the burn-through of the vent grills, cabin walls and window seals (Fig. 1). The timings of the main events in the accident sequence are measured from when the aircraft came to a complete stop i.e. $t = 0$ s. As seen in Fig. 1, the final burn-through damage to the cabin wall is estimated to be approximately 2 m wide. The time for the rear fuselage and tail to collapse was not established, but is some time after the last passenger had evacuated.

Figure 1. (a) Static fire plumes and (b) damaged B737-236 fuselage in the accident[1].



(a)



(b)

Based on the official investigation report a number of key facts and information concerning the incident have been established[1]. This information is used to set up the fire and evacuation models and provide a basis for the comparison between the model predictions and what actually happened. The key known outcomes extracted from the investigation report are summarised as follows:

O1: Cabin wall burn-through commenced within one minute;
O2: The location of the thermally damaged seats (see Fig. 2);
O3: Initial fire penetration via the floor level air-conditioning grills occurred within 20 s;
O4: Smoke began to enter the galley area after the R1 exit was opened at 70 s;
O5: 23 of the 51 passengers exiting via the R1 and L1 exits were not exposed to thick smoke;
O6: There were a total of 55 fatalities;
O7: The exits used by the survivors (see Fig. 3);
O8: The seating locations of the fatalities (see Fig. 3);
O9: 46% of the survivors that exiting via the ROW climbed over seats;
O10: 86% of fatalities died from inhalation of toxic gases while 6% died from thermal assault;
O11: 15 survivors were severely injured by heat/toxic smoke gases;

Figure 2. Seat damage (top: below squab level; bottom: squab level and above)[1].

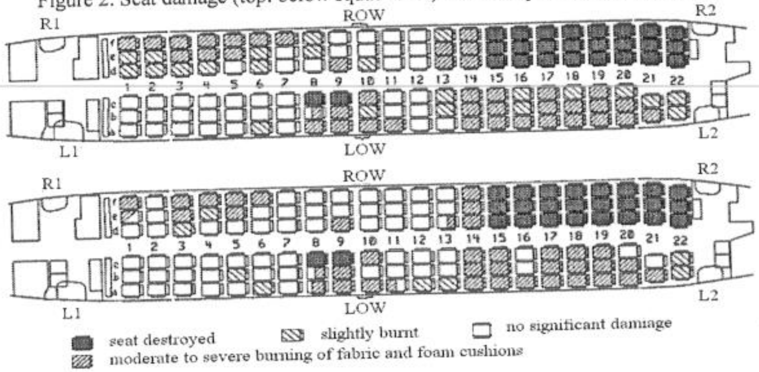
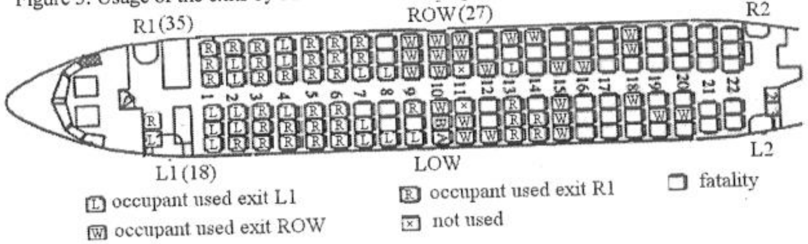


Figure 3. Usage of the exits by survivors and locating seats of the fatalities in the accident[1].



Some of the factors, identified in the official investigation, which contributed to the outcomes are:

F1: An external wind of 7 kts with an angle of 250^{O} to the fuselage;
F2: The size and location of the cabin burn-through (see Fig. 1);
F3: Exit opening times for the R1 (70s), L1 (25s) and ROW (45s) exits;
F4: Seating locations of the passengers (see Fig. 3);
F5: The exit used by each survivor (Fig. 3).

It is also noted that the R2 exit was opened at -6 s i.e. just before the aircraft came to a complete stop.

COMPUTATIONAL FIRE AND EVACUATION ENGINEERING TOOLS

A research version of the SMARTFIRE V4.1 software is used to perform the fire simulations in this study. The SMARTFIRE software has been described in previous publications[3,4,6-9] and so is not described in detail in this paper. The CFD engine in SMARTFIRE has many physics features that are required for fire field modelling, such as the multiple ray radiation model, the volumetric heat release model, the gaseous combustion model, smoke model, toxicity model, flame spread model and k-epsilon turbulence model. The flame propagation model[7], which is used to simulate the ignition of interior solid materials in the current analysis, plays an important role in successfully simulating the

spread of fire inside the cabin. This model has been recently refined to minimise the mesh dependence of numerical predictions of flame spread over solid burnable surfaces[9].

The airEXODUS evacuation model is used to perform the evacuation simulations presented in this paper. airEXODUS[(3-5,10-13)] 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. It comprises five core interacting sub-models: the PASSENGER, MOVEMENT, BEHAVIOUR, TOXICITY and HAZARD sub-models. The PASSENGER sub-model describes an individual as a collection of defining attributes and variables such as name, gender, age, maximum unhindered fast walking speed, maximum unhindered walking speed, response time, agility, etc. The HAZARD sub-model controls the atmospheric and physical environment by importing the fire data, like those generated by the SMARTFIRE CFD fire model. The TOXICITY sub-model determines the physiological effects on an individual exposed to the toxic and thermal environment distributed by the HAZARD sub-model. This is determined using the Fractional Effective Dose (FED) and Fractional Irritant Concentration (FIC) concept[14]. When a passenger moves through a smoke filled environment their travel speed is reduced according to the experimental data of Jin[15]. All these effects are communicated to the BEHAVIOUR sub-model which, in turn, feeds through to the movement of the individual. The behaviours in airEXODUS include crawling, jumping over seats, maintaining target exits, wayfinding, aisle swapping and crew redirection etc.

RECONSTRUCTION OF THE FIRE AND EVACUATION

Methodology

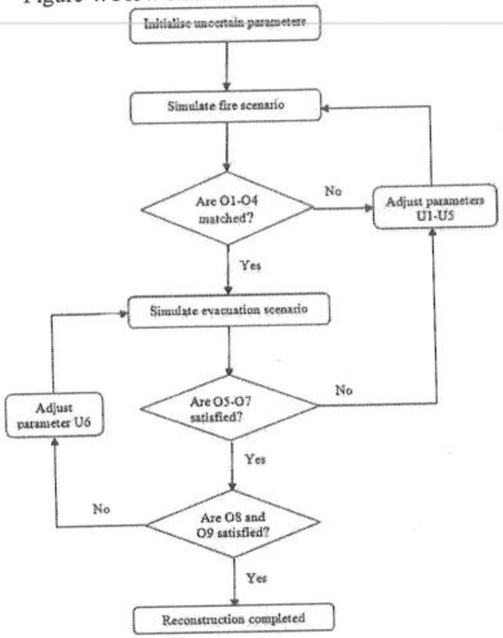
The reconstruction of the accident involves a two-step process, first the fire is simulated and then the coupled fire and evacuation is simulated. The results from the fire simulation are part of the input to the evacuation simulation to predict the impact of the fire on the evacuating passengers. The passengers are exposed to the fire hazards determined from the fire simulations which include; temperature, radiative flux, concentrations of toxic gases, low oxygen and smoke obscuration. In these simulations, the identified contributing factors F1-F5 taken from the accident investigation report are used as input parameters. However, there are still many uncertain details which have an impact on the fire development and the evacuation dynamics. The key parameters that are required as part of the simulation setup but which cannot be determined from the investigation report include:

U1: The volume and heat release rate (HRR) of the external fire;
U2: The rate of smoke entry via the air-conditioning grills;
U3: The impact on the external wind of the obstruction circle formed by the fire engines;
U4: An accurate estimation of the start time and duration of the cabin wall burn-through;
U5: The burn-through time for the cabin ceiling;
U6: Human factors such as passenger response times.

Although the smoke entry via the air-conditioning grills (U2) is not considered to make a major contribution to the death toll, it possibly impacts the evacuation behaviour of the passengers, i.e. whether they are considered to be walking or crawling. The parameters U2-U5 relate to the damage of the cabin, the injuries to passengers and the number of fatalities. U6 will impact the overall evacuation time and the possibly the number of injuries and the number of fatalities.

To reconstruct the incident estimations for the unknown quantities (U1 to U6) have to be determined. A method presented in the flow chart in Fig. 4 is used to derive appropriate values for these parameters. This is achieved by modifying these parameters and comparing the outcomes of the fire and evacuation analysis with the key known outcomes O1-O9. Outcomes O10 and O11 are not used as the FED model makes use of the incapacitation threshold values rather than fatality levels.

Figure 4. Flow chart for accident reconstruction.



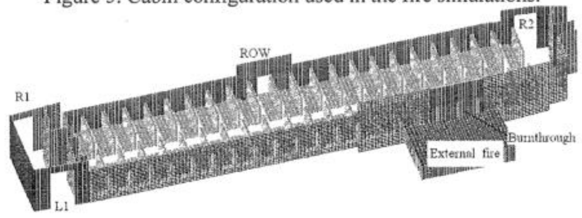
Fire simulation set up

The B737-236 aircraft geometry is represented using 144,305 computational cells in the SMARTFIRE simulations (Fig. 5). The time step size is 1 second. The burn-through opening of the cabin wall close to seat rows 17-19 is set to be 2 m long and 0.9 m high, which is modelled by the removal of the cabin wall patch by patch from the level of the cabin floor. A ceiling burn-through between seat rows 18 and 19 from the left side of the cabin to the aisle is also represented in the model. Along the two cabin sides, two 0.08 m wide floor sheets are modelled as porous faces with a porosity value of 0.01, which represents the air conditioning grills. The external fire is simplified as a volumetric fuel source measuring 3.4 m long, 1 m wide and 0.5 m high. The exit opening times for the R1, L1, ROW and R2 exits are those that occurred in the accident. As exit R1 was not completely open until 70 s, only one third of this door is opened between 10 and 70 s during the simulation. The material properties of the cabin interior materials are identical to those used in the simulation of the C133 fire test[8].

To reduce the number of unknown parameters (U1 to U6), the fire volume and the impact of the fire engines on the external wind speed are fixed while all others vary with the simulations and their optimal values are determined as part of the evaluation process described in the flow chart in Fig. 4. In addition, the entry rate of smoke via the air conditioning grills is made to correlate with the HRRs of the external fire.

In order to represent the predicted fire hazards on the evacuation, a set of 30 hazard zones are defined in both the fire and evacuation model. Within each zone, hazard values predicted in the fire simulation in a layer from 1.5 m to 2.0 m are averaged and taken to represent the hazards at head height while hazard values from 0.3 m to 0.8 m are averaged and taken to represent the hazards at knee height (for crawling agents). The averages of predicted temperatures, species concentrations, radiation fluxes and optical density at the head and knee heights in each zone are output into a data file. This data file is then imported by airEXODUS to produce the atmospheric conditions for evacuation simulations.

Figure 5. Cabin configuration used in the fire simulations.



Evacuation simulation set up

The aircraft geometry and the passenger exit opening times used in this analysis are the same as those for the fire simulation. Passengers identified as accident survivors have their personal attributes set from the default certification parameter set (not provided in the accident report). Passengers identified as accident fatalities are set with their actual ages and genders. Among the 131 passengers, one child and two infants, who evacuated in adults' arms, are not specially taken into account in the reconstruction. Considering the severity of the incident, passengers are allowed to undertake extreme behaviours within the model such as climbing over passenger seats and crawling. All other passenger attributes such as walking speeds assume the default airEXODUS values.

In order to generate a similar seating distribution of fatalities and exit usage the following model setup is highlighted:

- Relatively short response times and low patience are set for the passengers who survived and were located in the aft of the cabin. This enables these passengers to start to move early and climb over seats to get to the exits if the aisle is blocked by other passengers.
- The accident survivors will attempt to maintain their assigned target exits, which match those that were used in the actual accident.
- The accident fatalities select their nearest available, i.e., the overriding ambition of these passengers is to exit via their nearest exit, rather than to travel further[13,16].

While the fire simulation duration is limited to 250 s, the evacuation simulations run until no survivors remain inside the cabin. The evacuation results presented in this paper represent the average values derived from 200 evacuation simulation repetitions.

RESULTS FROM THE ACCIDENT RECONSTRUCTION

The reconstruction of the fire development and evacuation process for the Manchester aircraft fire accident is considered to be completed when appropriate values for the unknown parameters (U1-U6) are identified. The parameter set which produces the closest agreement with the known outcomes has the following values. The external HRRs (U1) are shown in Fig. 6, which have a maximum HRR of 4.3 MW from 70 s to 140 s.

Figure 6. External pool fire HRR in the reconstruction.

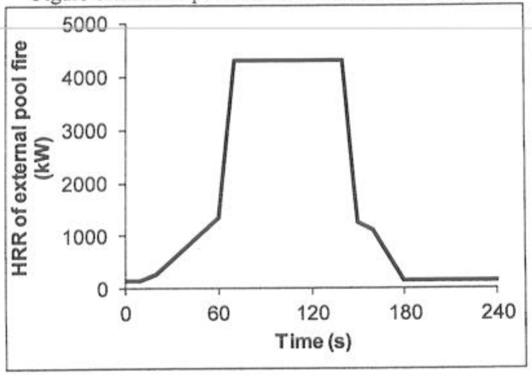


Table 1. Comparison the outcomes between the accident and reconstruction

Outcome	Accident	Reconstruction
O1	The start of the wall burn-through occurs within one minute	The first patch is removed at 70 s; a smoothed curve predicts a start time of 40 s
O2	The damage to the seats on the right half of the cabin and on the aft cabin was more severe than that on the left half and the forward half of the cabin (Fig. 2).	Distribution of the burnt seats (Fig. 7) is in reasonably good agreement with the finding in the aftermath of the accident. However, the seats in the vicinity of the burn-through are more severely damaged in the reconstruction than in the actual accident. The differences are expected to be due to the nature of the burn-through. Furthermore, the significant damage to the seats in the vicinity of the burn-through occurs after the last passenger is predicted to have evacuated.
O3	Fire penetration via floor air-conditioning grills occurred within 20 s.	Occurs at around 10 s in the model.
O4	Smoke began entering the galley area some time after 70 s.	Smoke appears in the forward part of the cabin at 80 s.
O5	23 of the 51 passengers who exited via the front exits escaped before thick smoke had reached them.	On average, 29 passengers who exit from the front exits have FED values less than 0.01, representing light exposure to fire products.
O6	There were 55 fatalities	There are an average of 55.3 fatalities
O7	Number of survivors who exit via R1, ROW and L1 are 35, 27 and 18.	Average number of survivors who exit via R1, ROW and L1 are 30.7, 30.4 and 15.6 respectively.
O8	Most of the fatalities were initially seating in the aft of the cabin (Fig. 3)	The seating locations of the fatalities (Fig. 8) are comparable with the actual distributions.
O9	46% of the 27 survivors that exit via ROW exit had to climb over seats.	57% of the predicted survivors that exit via ROW climb over seats.
O10	Of the 54 fatalities on board, 48 (89%) died from toxic fire gases while 6% died solely from thermal assault.	85% of the predicted fatalities (incapacitations) are due to heat and 15% from inhalation of toxic smoke. Predicted results are incapacitations while actual results are the medically derived cause of death.
O11	15 survivors were severely injured due to heat or toxic/irritant smoke.	15 passengers have FIH, or FIN or FIC value greater than 0.2, implying severe injuries.

The burn-through times (U4) in the reconstruction, represented as the removal of the side wall, patch by patch, with a length of 2 m and a height of 0.1 m for each patch, are: first patch (0.1 m above the floor) is removed at 70 s, second patch (0.2 m above the floor) is removed at 90 s, the last patch (0.9 m above the floor) is removed at 150 s. The time to burn-through of the ceiling (U5) is approximately 150-170 s in the reconstruction. The response times (U6) and patience (U6) for those passengers that survive in the aft of the cabin are as small as 0 seconds and 1.0 respectively. The response times for some fatalities in the accident can be as long as 30 seconds in this reconstruction. The other surviving passengers have default response times (1-6 sec). The comparison between the known outcomes from the accident and those from the reconstruction simulation are presented in Table 1.

Figure 7. Predicted ignited seat locations at 180 s.

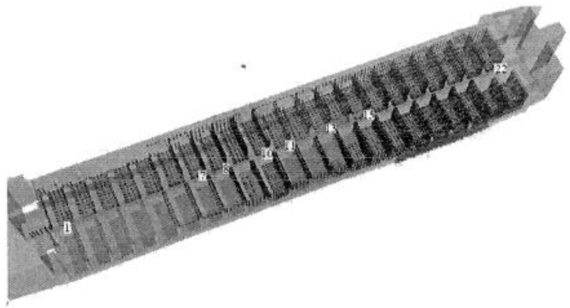
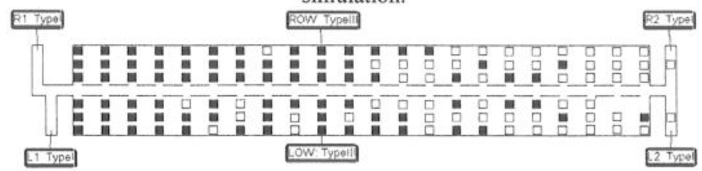


Figure 8. Predicted fatality starting locations (white squares) resulting from a single simulation.



IMPACT OF EXIT OPENING TIMES ON EVACUATION

The accident reconstruction identified the set of parameters (U1-U6) which provided the best agreement with the main accident outcomes. Using the values for these parameters, the impact of the exit opening times on the evacuation is now examined. Five scenarios are examined (see Table 2) in which only the exit opening times are varied. As the exit opening times will have an impact on the cabin ventilation and hence the spread of heat, smoke and toxic products throughout the cabin, it is necessary to simulate the fire for each of the exit opening scenarios. The fire atmosphere produced in each of these exit opening scenarios is then used in the evacuation simulation associated with each exit opening scenario. The scenario investigated in the accident reconstruction, here called Base Case, has the R1 exit opening 70 s after the aircraft has completely stopped due to an exit malfunction. This time is much longer than the normal exit opening time of 8.2 s derived from industry standard certification trials. Furthermore in the Base Case, the ROW exit was opened after 45 s due to difficulties encountered by the passenger seated by the over wing exit. This time is also much longer than the normal opening time of 12 s derived from industry standard certification trials. While

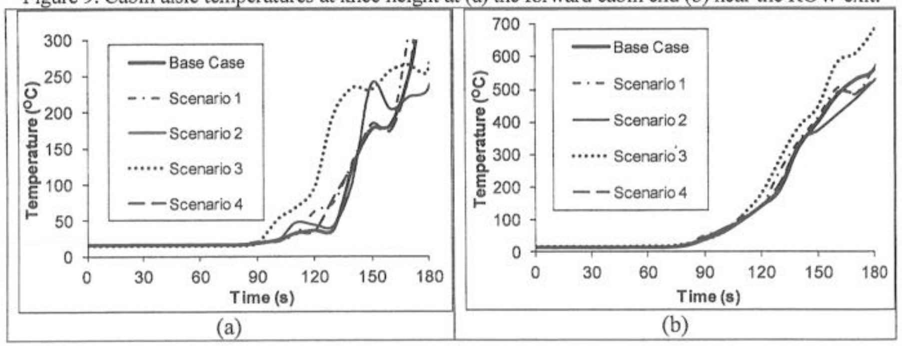
Scenario 1 has the same setup as the Base Case, the opening time for the R1 exit is reduced to 10 s enabling the impact of the delay in opening the R1 exit to be assessed. Scenario 2 has the same setup as the Base Case but with an opening time of 12 s for the ROW exit, enabling the impact of the delay in opening the ROW exit to be assessed. Scenario 3 is the same as the Base Case, but the R2 exit is not opened during the evacuation. This enables the impact of opening the R2 exit on the evacuation to be assessed. It is noted that while the R2 exit was not the main point for fire/smoke entry into the cabin, it was not used by passengers during the evacuation[1], probably because of the proximity of the external smoke/fire. Finally, Scenario 4 is the same as the Base Case, but the R1 and ROW exits are opened in the standard regulatory time. This scenario examines the impact on the evacuation of the delay in opening both the R1 and ROW exit.

Table 2. Definition of exit opening time scenarios

Scenario	Times to open exits (s)			
	L1	R1	ROW	R2
Base Case	25	70	45	0
1	25	10	45	0
2	25	70	12	0
3	25	70	45	--
4	25	10	12	0

The transient temperatures in the lower layer of the cabin in the forward and over wing cabin sections are shown in Fig. 9. As seen in Fig. 9, the earlier opening of the R1 exit (Scenario 1) or ROW exit (Scenario 2) or both R1 and ROW exits (Scenario 4) does not have a significant effect on the cabin temperatures in the lower layer of the cabin. Thus, the change in the fire atmosphere in these scenarios is not expected to have a significant impact on survivability. However, if the R2 exit is closed throughout the simulation, as in Scenario 3, this results in the rapid increase in temperature at the front of the cabin to occur at least 20 s sooner than in the Base Case. The temperatures at the front of the cabin are also considerably higher in the front of the cabin during the evacuation. The temperatures at the ROW exit in Scenario 3 are also marginally higher than in the Base Case. The lower temperatures in the front section of the cabin in the Base Case compared to Scenario 3 is due to the external wind blowing through the open L1 exit and passing out through the open R2 exit in the Base Case. The more severe conditions that result in Scenario 3 due to the closure of the R2 exit have a significant impact on evacuation as shown later in the paper. Furthermore, while the fire hazards in the Base case, Scenario 1, Scenario 2 and Scenario 4 are similar, the earlier opening of R1 and/or ROW does influence the outcome of the evacuation in these scenarios as shown later in the paper.

Figure 9. Cabin aisle temperatures at knee height at (a) the forward cabin end (b) near the ROW exit.



A summary of the evacuation simulation results are presented in Table 3 and Fig. 10. As can be seen from Table 3 and Fig. 10, while the total evacuation time (on ground time) does not vary significantly between the various scenarios, there is a significant variation in the number of predicted survivors.

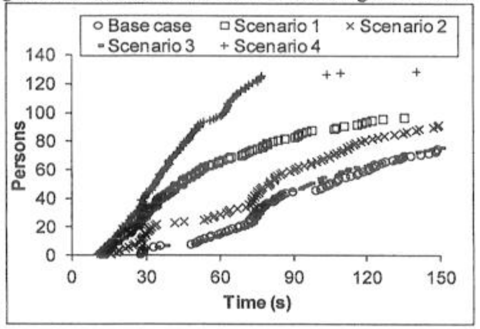
This suggests that in this accident, the exit opening times played a significant role in determining the survivability of this accident.

Without the malfunction of the R1 exit causing a delay of 60 s in the opening of this exit, the number of fatalities could be reduced from an average of 55.3 in the Base Case to 36.8 in Scenario 1, a reduction of 33%. It is noted that while the number of fatalities is significantly reduced, simply opening the R1 exit in the time achieved in the certification trials does not allow all the passengers to safely evacuate. It is noted from Fig. 10 that opening the R1 exit earlier allows the evacuation to start earlier, allowing a number of passengers to evacuate before the first passenger in the Base Case can exit. As a result, these passengers experience less severe conditions.

Table 3. Average evacuation statistics

Scenario	Number of Fatalities	Number of Survivors using R1 exit	Number of Survivors using L1 exit	Number of Survivors using ROW exit	On Ground Time (s)
Base Case	55.3	30.7	15.6	30.4	149.0
1	36.8 (-33%)	55.0	9.0	31.2	131.9
2	43.2 (-22%)	30.1	15.9	42.8	146.2
3	64.5 (+17%)	26.8	15.0	25.7	135.3
4	4.2 (-92.4%)	62.2	34.1	31.5	137.9

Figure 10. Exiting times of individual survivors from a single simulation of each scenario



At each point during the evacuation more passengers have exited in Scenario 1 compared to the Base Case (see Fig. 10) thus exposing the survivors to less severe fire conditions. However, it may be expected that opening the R1 exit 60 s earlier would have resulted in more than the 18.5 additional passengers being able to safely exit the aircraft. The small number of additional survivors is due to a combination of the agent behaviour and the aircraft cabin configuration. Firstly, passengers in aircraft accidents try to exit via their nearest viable exits[16]. This behaviour is also demonstrated by the usage of exits in the accident as seen in Fig. 3, with the majority of the survivors in the rear of the cabin exiting via the ROW exit. Thus, in the simulation, the agents in the aft of the cabin try to exit via their nearest exit, rather than travel to the forward exit. This results in agents queuing at the ROW exit. As the fire gained entry into the cabin mainly from the rear of the cabin, agents in the aft cabin are exposed for an unnecessarily longer period of time to the fire hazards compared to if they had decided to move forward to the R1/L1 exits. Secondly, as the aisle aperture between the forward cabin bulkheads is only 0.56 m wide, this restricts the evacuating passengers to single file flow. This narrow aisle aperture does not allow the forward L1 and R1 exits to be used to their full evacuation capacity[13]. Thus having two Type I exits available at the end of the narrow aisle does not provide twice the flow rate that could be achieved using a single Type I exit.

Without the 33 s delay in opening the ROW exit, the number of fatalities could be reduced from an average of 55.3 in the Base Case to 43.2 in Scenario 2, a reduction of 22%. It is noted that while the number of fatalities is significantly reduced, simply opening the ROW exit in the time achieved in the certification trials does not allow all the passengers to safely evacuate. The main issue here is that the flow rate that can be achieved through a Type III over wing exit is much lower than that of a Type I exit. Thus opening the exit 33 s earlier only provides marginal benefit compared to opening the Type I exit earlier. In this case, the 33 s earlier opening time results in 12.1 fewer casualties.

There was speculation that the opening of the R2 exit in the accident may have worsened the conditions in the cabin and thereby contributed to the number of fatalities. However, it was noted in the accident report that; "The aft right door aperture allowed the early entry of smoke and possibly some flame transients, but was not the principal point of entry of the fire into the cabin."[1]. In Scenario 3 the R2 exit was closed during the entire period and this results in an increase in the number of fatalities from 55.3 in the Base Case to 64.5, an increase of 17%. This is due to the higher temperatures in the front and over wing regions as shown in Fig. 9. Thus, the action of opening the R2 exit is likely to have saved lives in this accident.

Finally, in Scenario 4 both the R1 and the ROW exits are opened without difficulty within their certification times. In this scenario the number of fatalities is reduced from the Base Case 55.3 to 4.2, a reduction of 92.4%. Thus opening both exits without delay results in the minimum number of fatalities. Even in the fierce fire that resulted from this accident, as few as four people may have perished had the exits been opened early in the accident sequence.

CONCLUSIONS

SMARTFIRE and airEXODUS simulation tools have been used to numerically investigate the 1985 Manchester Airport B737 fire/evacuation. The purpose of this analysis was to understand the impact of exit opening times on evacuation and survivability during this accident. The first part of the analysis involved reconstructing the cabin fire as closely as possible, adjusting the key unknown parameters; external HRR, time to burn-through etc so that the predicted damage to seats, propagation of cabin smoke, the number and seating distribution of fatalities, the percentage of passengers climbing over seats etc were in reasonable agreement with the officially reported results. The second part of the analysis involved simulating four additional fire and evacuation scenarios, using the same fire parameters derived from the reconstruction, but with varying exit opening times. The key findings from this work are:

- In the Manchester accident, two exits were opened with 33 s and 60 s delays compared to their average opening times derived from certification trials. If one of these exits could have been opened within the certification time, the loss of life would have decreased by 22-33%. If both exits were opened within their certification time, the loss of life would have been reduced by 92%. The quick opening of exits is essential in aircraft evacuation involving fire.
- The opening of the R2 exit in the Manchester accident is not likely to have contributed to the high loss of lives in this accident. Indeed, the results from the simulations suggest that 17% more fatalities would be expected if the exit had not been opened.
- The behaviour of passengers to exit via their nearest exits, rather than travel further to more viable exits in fire evacuations limits global evacuation efficiency.
- The narrow aisle aperture between the twin forward bulkheads results in both forward Type I exits being unable to be used to their full evacuation capacity when both exits are available.

This analysis has shown that in aircraft fire situations, seconds can make the difference between life and death. It is thus essential that cabin crew undertake their evacuation duties as quickly as possible and passengers seated beside over wing Type III exits fully appreciate the importance of understanding how to open the exit in the event of an emergency. Airlines should also rigidly enforce the regulations associated with passengers seated by Type III exits.

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