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interflam2013

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FIRE SCIENCE & ENGINEERING CONFERENCE

ROYAL HOLLOWAY COLLEGE
UNIVERSITY OF LONDON, UK
24-26th June 2013

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INTERFLAM 2013

Proceedings of the thirteenth international conference

interscience
communications

West Yard House, Guildford Grove
Greenwich, London, UK

www.intersciencecomms.co.uk

West Yard House, Guildford Grove, Greenwich, London SE10 8JT, England

ISBN 978-0-9556548-9-3 (set)

Conference Proceedings of the
Thirteenth International Interflam Conference

1623 pp
with 340 tables and 1121 illustrations

British Library Cataloguing-in-Publication Data.
A catalogue record for this book is available from the British Library

EXPLORING THE APPROPRIATENESS OF THE AVIATION INDUSTRY EVACUATION CERTIFICATION REQUIREMENTS USING FIRE AND EVACUATION SIMULATION

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ABSTRACT

The evacuation certification trial is an aviation benchmark which requires that all the passengers must safely evacuate from the aircraft within 90 seconds through 50% of the available exits. Typically a single exit from each pair of exits is selected resulting in all the available exits being located along one side of the aircraft along the length of the aircraft. In this study, the influences of exit availability in post-crash aircraft fires on passengers' survivability are investigated using a narrow body aircraft, which satisfies the certification requirement. Two exit configurations are investigated: one complying with the typical certification trial configuration and the other one being an exit configuration commonly occurring in real accidents. The work is carried out using the fire and evacuation engineering tools, SMARTFIRE and airEXODUS. Under a post-crash cabin fire situation, the certification trial exit configuration produces a longer time to flashover, a shorter evacuation time and as a result a significantly smaller number of fatalities and severe injuries than the other investigated exit configuration. As a safety indicator of aircraft evacuation performance, the exit configuration in the certification trial is demonstrated to be less challenging and less representative of actual accident situations and so is considered inappropriate as a measure and demonstration of safety.

INTRODUCTION

International evacuation certification regulations require aircraft manufacturers to demonstrate that the maximum number of passengers and crew that can be carried by an aircraft can be evacuated from the aircraft within 90 seconds through half the normally available exits. In the U.S. this is defined in FAR25.803[1] while other regions, such as Europe have similar (almost identical) requirements. This requirement is demonstrated through a full-scale certification trial using the actual aircraft and volunteer passengers. Modern passenger aircraft have exits which are configured in pairs, with an exit located on the left side of the fuselage and a corresponding exit located on the right, with the exits linked by an unobstructed aisle running across the width of the aircraft. These exit pairs are located along the length of the aircraft so that each section of the aircraft is serviced by at one exit pair. The exit configuration selected for the certification trial typically involves one exit from each pair of exits, resulting in all the exits along one side of the aircraft being available. It is understood that the evacuation certification trial is not intended to represent a real situation, but is intended to be a benchmark examination of both absolute (i.e. better than 90 seconds) and relative (i.e. one aircraft configuration against another) performance in evacuation. However, for the benchmark to be a meaningful indicator of safety, the associated scenario must be both as representative of reality and as challenging as practical.

Why is one exit from each pair and usually on one side of the aircraft selected in certification trials? It could be argued that in an emergency post-crash situation fire is likely to occur on one side of the aircraft (e.g. due to ruptured fuel lines/wing tank) and so it would be reasonable to assume that all the exits on that side of the aircraft would be unavailable. However, statistical investigations of survivable aircraft accidents suggest that most accidents involve a different exit combination to that used in the certification trial and furthermore, the certification exit combination rarely occurs[2]. A typical example is the Manchester Airport B737 post-crash fire accident in which the forward two exits and the right over-wing exits were utilised during the evacuation with 55 fatalities among 135 people on board. For narrow body aircraft such as the B737 and A320, this exit configuration frequently occurs in survivable accidents[2,4] and so is a more representative exit configuration than the certification configuration. While the exit configuration used in certification trials is not representative of real accidents, perhaps it poses a more challenging exit configuration and so is worthy of testing in the certification trial.

Through the use of computer simulation, it has been demonstrated for narrow body aircraft, that exit availability has a significant impact on evacuation time under certification trial conditions[4]. However, that analysis did not include the impact of fire. The aim of this study is to extend the analysis to systemically investigate the suitability of the certification trial as an indicator of safety in the more demanding post-crash evacuation scenario involving fire. This analysis makes use of the fire and evacuation simulation tools SMARTFIRE[5] and airEXODUS[6]. The geometry utilised for the analysis is identical to that of the earlier study[4] and involves a narrow body configuration consisting of three exit pairs and seating for 149 passengers and three cabin crew. The fire is represented by a post-crash external pool fire which gains access to the interior of the cabin via a fuselage rupture.

COUPLED FIRE AND EVACUATION SIMULATION 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[5,7-14] 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 spread model[9], 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[12].

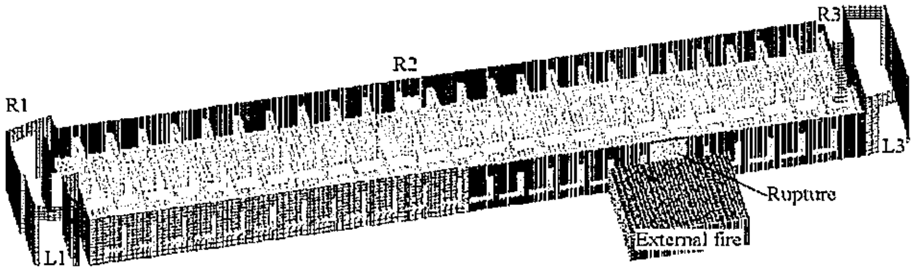
The airEXODUS software is one of the EXODUS suite of evacuation simulation software [4, 6-8,11,15-17]. airEXODUS is designed for applications in the aviation industry including, aircraft design, compliance with 90-second certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation. The EXODUS software takes into consideration people-people, people-fire and people-structure interactions. 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[18]. When a passenger moves through a smoke filled environment their travel speed is reduced according to the experimental data of Jin[19]. 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 (dual aisle aircraft configurations) and crew redirection etc.

The hazard data produced in prescribed hazard zones by SMARTFIRE is imported into the EXODUS model. It is important that the zones employed within the EXODUS geometry are consistent with those employed in the SMARTFIRE simulations to ensure that the environmental conditions are represented accurately; i.e., that the fire is represented appropriately within the simulated evacuation. Within the EXODUS model, when occupants are considered to be standing they are exposed to the hazards at head height (irrespective of their actual height); when the occupants elect to crawl, they are exposed to the hazards at knee height. Therefore, both layers produced by SMARTFIRE for each zone can influence the evacuating population according to their behavioural response. The coupled fire and evacuation simulation technique using SMARTFIRE and EXODUS has been used in a number of applications including incident reconstruction, investigation, and engineering design[7,8,11,15].

AIRCRAFT CABIN AND SCENARIO DEFINITION

The aircraft geometry used in this analysis is that of a narrow body aircraft with three exit pairs, seating 149 passengers in 25 seat rows (Figure 1). The cabin is 3.5 m wide (at the floor), 22.5 m long and has a ceiling height of 2.13 m. Three exits on the right side of the aircraft consist of two Type C exits (R1 and R3) and the over-wing Type III exit (R2). The L1 and L3 exits are Type B. Type B and C exits are floor level exits that allow a single passenger to pass through at a time and have a slide attached to the exit. The Type-III exit is a hatch exit that requires the passenger to climb into it and out onto the wing of the aircraft. Type-III exits require the passenger to operate the exit. The aircraft configuration used in this analysis is typical of the B737 and A320 aircraft types. Furthermore, the aircraft configuration is an actual aircraft which successfully passed the evacuation certification trial[6].

Figure 1. Aircraft cabin geometry presented in SMARTFIRE.



Two exit scenarios are investigated (Table 1). Scenario S1 complies with the certification exit requirement, i.e. three exits R1, R2, and R3 on the same side of the cabin are available for evacuation. The exit configuration used in Scenario 2 is one that frequently occurs in real accidents and is identical to the exit configuration that occurred in the Manchester Airport cabin fire[3], i.e. with two front exits (R1 and L1) and the right over-wing exit (R2) open. Corresponding to the two exit scenarios, four evacuation scenarios are investigated, with and without the impact of fire hazards.

Table 1: Scenario description

Exit scenario	**Evacuation scenario**	**Exits**	**Fire**	**Note**
S1	**S1a**	R1, R2, R3	No	Certification trial exit configuration
	S1b	R1, R2, R3	Yes	
S2	**S2a**	R1, L1, R2	No	Exit configuration commonly occuring in real accidents
	S2b	R1, L1, R2	Yes	

THE CFD SIMULATIONS AND RESULTS

Fire Simulation Set Up

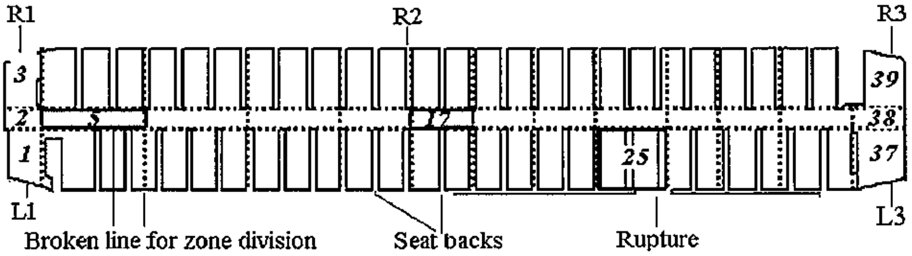
The fuselage rupture is located between the over-wing exit (L2) and aft exit (L3) and its size is 0.89 m wide and 1.65 m high (roughly equivalent to the minimum area of a Type B exit i.e. 0.81 m wide and 1.83 m high). The external pool fire is assumed to be rectangular in shape with dimensions of 2.5 m in width and 3.0 m in length, with a fire load of 7.8 MW. This fire size was selected such that the flame temperature in the external pool fire is close to 1480 K as observed in real pool fire tests using kerosene[10,11]. A mesh sensitivity study suggests that a mesh consisting of 149,496 cells is appropriate for the simulation of the post crash aircraft fire with the considered cabin configuration. The time step size varies between 0.5 seconds and 1 second.

The fire model and material properties used in this study are the same as those in previous aircraft fire simulations for the C133 fire test[10] and in the reconstruction of the Manchester airport B737 fire[11]. The flame spread model[9] is used to simulate the spread of the fire along interior solid surfaces; the Eddy dissipation combustion model[20] is used to release the heat from the combustion of the gaseous fuel generated by the pyrolysis of solid materials; a 24-ray radiation model is used to represent the exchange of heat via radiation; the smoke and toxicity model[13,14] are used to calculate the gas concentrations inside the cabin. The main interior combustible materials are assumed to have the molecular structure of Epoxy, i.e., $CH_{1.3}O_{0.2}$ and its properties are summarised in Table 2. The heat release rate curve and the parameters for toxicity calculation for this material can be found in previous publications[10,11]. The ambient temperature is set to be 13^{O}C. In addition, a set of 39 hazard zones are defined in the fire model for outputting fire hazards (Figure 2) to the evacuation simulations.

Table 2. Material properties used in the simulation[10]

Density (kg/m^3)	116	**Conductivity (W/mK)**	0.05
Heat of combustion (kJ/kg)	12800	**Specific Heat (J/kgK)**	2090
Flame spread (m/s)	0.003 upward; 0.0015 downward	**Thickness (m)**	0.06
HRR ((kW/m^2)/ (kW-min/m^2))	65/65	**Ignition temperature (^{O}C)**	505
Ignition under critical flame temperature (^{O}C)/ with time (s)	800 / 10	**Ignition under critical heat flux (kW/m2s)/ with time (s)**	35 / 10

Figure 2. Hazard zone definition with broken lines representing hazard zones.



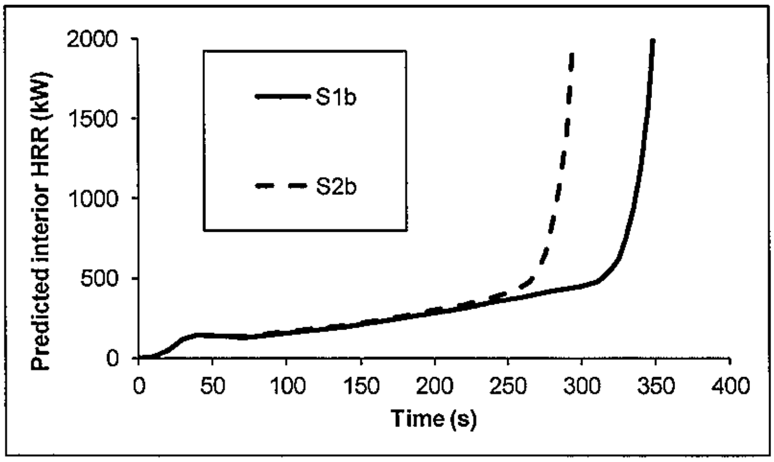
Analysis of Fire Results

Time to flashover

The time to flashover is generally considered to mark the end of the survivability period for those passengers still remaining in the cabin. The definition of flashover for enclosure fires is generally accepted as occurring when the upper layer gas temperature exceeds 600^{O}C. The simulation of the C133 post-crash cabin fire test has demonstrated that the rapid rising of heat release rates resulting from the combustion of the interior cabin materials is a good indication of the occurrence of flashover[10]. Therefore, the onset of flashover is defined here as the moment at which the predicted HRRs rise abruptly.

The predicted interior HRRs for the two exit configurations and hence ventilation scenarios are depicted in Figure 3. Prior to 250 s, the predicted HRRs for the two scenarios are almost identical. After this time, the HRR rises rapid indicating a time to flashover of 325 s for Scenario 1b and 275 s in Scenario S2b. Thus the more realistic exit configuration (Scenario S2) results in flashover occurring 50 s or almost 1 minute (15%) sooner than the case of the certification exit configuration (Scenario S1). Thus based on the time to flashover, the realistic exit configuration is more challenging than the certification exit configuration for this particular fire scenario. Furthermore, based simply on the time to flashover, the time available for evacuation is significantly longer than 90 s for both the exit scenarios – between 3.1x and 3.6x longer than 90 s. However to better understand issues associated with tenability it is necessary to further analyse conditions within the cabin.

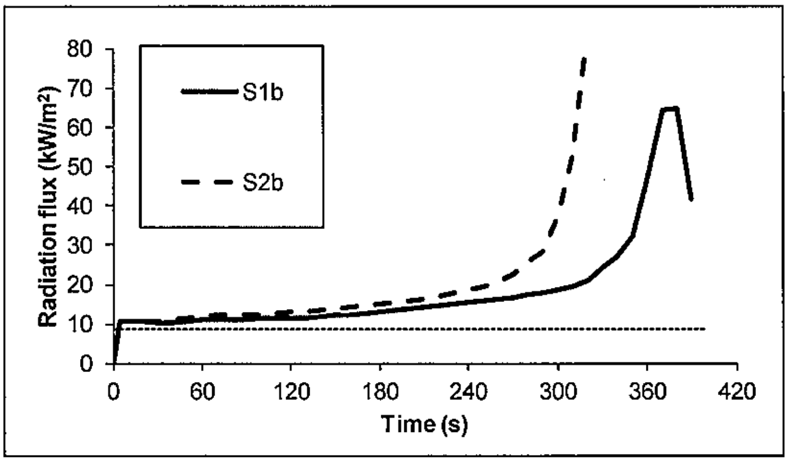
Figure 3. Predicted heat release rates from the combustion of cabin interior materials.



Cabin Fire hazards

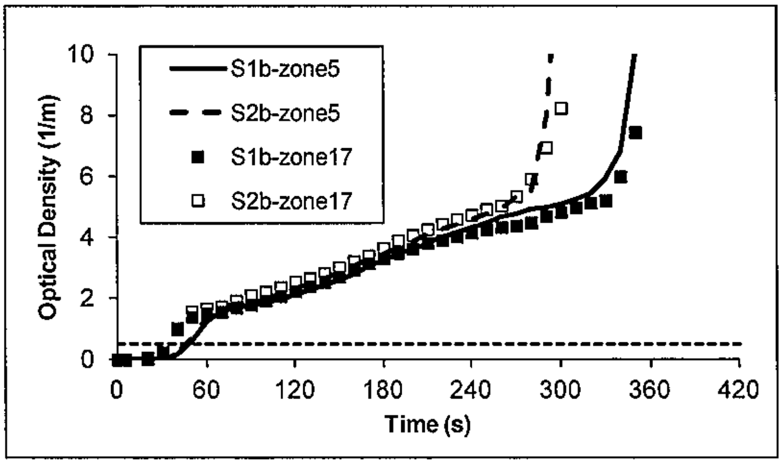
To investigate the tenability of the cabin atmosphere, cabin fire hazards within three fire hazard zones, Zone 25, Zone 17 and Zone 5, are investigated (see Figure 2 for zone locations). Zone 25 is located immediately adjacent to the cabin rupture, zone 17 is in the aisle towards the centre if the aircraft (in the vicinity of the over-wing exits) and zone 5 is in the aisle towards the forward end of the cabin. Within zone 25 strong radiation fluxes are transferred from both the combustion of the external pool fire and the burning seats and overhead bins in the early fire development stage. As seen in Figure 4, the predicted radiation fluxes at knee height in this zone are as high as 13 kW/m^2 just a few seconds after the start of the external fire for the two investigated exit scenarios. This level of radiation flux is much higher than the critical value of 8.6 kW/m^2, which is expected to cause mortality within one minute for 1% population[18].

Figure 4. Predicted radiation fluxes at knee heights in Zones 25.



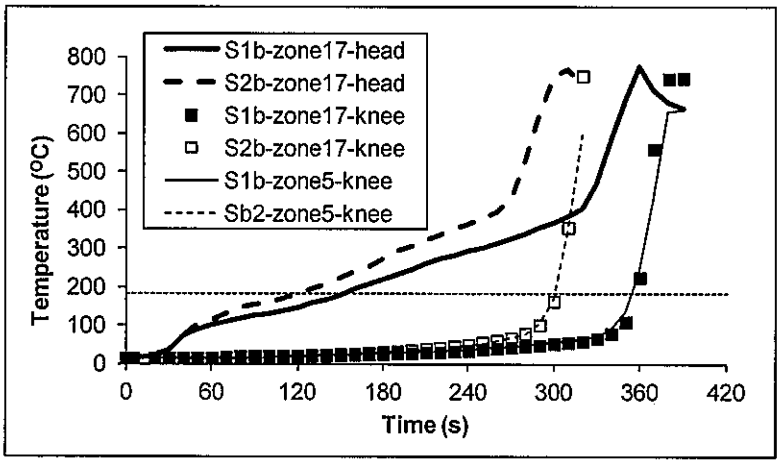
For the passengers at locations somewhat removed from the rupture, the first fire threat is due to the heavy smoke in the upper layer of the cabin. As seen in Figure 5, the predicted smoke optical density at head height in Zone 17 rapidly increases to a critical value of 0.5/m at approximately 35 s for the two scenarios. With this value of optical density, the visibility distance is approximately 2m. The time for smoke optical density in Zone 5 to reach 0.5/m is just 15 s later than those in Zone 17 in the two scenarios. The two exit opening configurations thus have little impact on the smoke obscuration throughout the cabin.

Figure 5. Predicted smoke optical density at head height of zone 5 and zone 17.



The predicted temperatures in Zone 5 and Zone 17 are depicted in Figure 6. The predicted head height temperatures in Zone 17 start to increase from as early as 30 seconds into the fire. The temperature increases to a critical value of 185^{o}C at 155 s in Scenario S1b and 120 s in Scenario S2b. At this temperature exposed occupants will be incapacitated after 1.0 minute[18]. Therefore, if the passengers in this zone have not started to crawl when the smoke becomes heavy, they would be exposed to the fatally high temperatures. In contrast to the rapidly increasing head height temperature, the knee height temperatures change relatively slowly prior to flashover. As seen in Figure 6, the times for the temperatures to reach the value of 185^{o}C are 355 s in Scenario S1b and 305 s in Scenario S2b respectively. Similar temperature profiles can also be seen in Zone 5 (Figure 6). As expected, the temperature throughout the cabin rapidly increases after flashover.

Figure 6. Predicted temperatures in Zone 5 and 17.



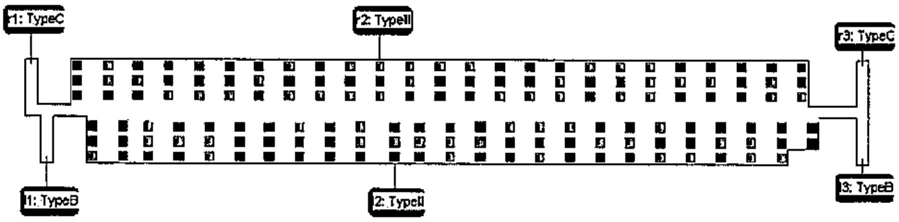
The rapid increase in temperatures in Scenario 2b further demonstrates that this exit configuration (realistic exit configuration) is more challenging than that of Scenario S1 (certification exit configuration).

EVACUATION ANALYSIS

Evacuation Simulations

The aircraft geometry used in the fire simulations is also represented within airEXODUS for the evacuation simulations (see Figure 7). In the evacuation simulations, the default generalised passenger exit hesitation time distribution (assuming assertive crew) appropriate for the various exit types are used[21].

Figure 7. Schematic layout of the test aircraft showing seating configuration and exit location.



The default exit ready times (time to open exit and make exit ready for evacuation) for each exit type was also used, i.e. 8.2 s for the R1 and R3 exits, 12.0 s for the passenger operated R2 and L2 exits and 9.4 s for the L1 and L3 exits[21]. The airEXODUS parameter "Off-Time distribution" (i.e. the time required to descend the slide or wing) was also assumed to follow the default distribution appropriate for the various exit types[21]. All other passenger attributes (e.g. response times, walking rates, etc) are set from the default certification parameter set[6]. Passenger behaviours which are activated for the fire cases include crawling, jumping over seats, way-finding, etc.

For the evacuations involving fires, Scenario S1b and Scenario S2b, airEXODUS imports the fire hazards in 39 predefined zones derived from the SMARTFIRE fire simulations for these scenarios. Each scenario is run 1000 times using 10 different populations which fitted the scenario description (i.e. each population was run 100 times).

Evacuation Simulation Results

Evacuation time

The average exit flow rates, evacuation times (on-ground time) and travel distances derived from the 1000 simulation repetitions with and without the influence of fire hazards are summarised in Table 3. The egress times in the simulations without fire are analysed first. With the evacuation certification trial exit configuration, Scenario S1a produces on-ground times of between 67.0 s and 76.8 s with a mean of 71.2 s. The time achieved by this aircraft in the actual certification trial falls between the predicted minimum and mean times[6,22]. This result, in addition to those presented in[6] suggests that the airEXODUS model is capable of predicting the likely outcome of certification trials. Clearly, this aircraft configuration satisfies the evacuation certification requirements. In contrast, scenario S2a produces on-ground times of between 86.7 s and 112.3 s with a mean of 98.1 s. Using the likely accident exit configuration, the predicted mean egress time of 98.1 s (Scenario 2a) suggests that the aircraft would not satisfy the 90 s requirement.

At first sight these results may appear surprising but can be explained by the evacuation dynamics[4]. As seen in Table 3, when there is a single exit operating out of an exit pair (Scenario S1a), the flow rates achieved by the exit is greater than that when both exits in a pair are operating (Scenario S2a).

Table 3: Average on-ground time, exit flow rate and travel distance derived from 1000 repeated simulations

Scenario	**Flow rate (person per minute)**				**Travel Distance (m)**	**Evacuation time (s)**
	R1	**L1**	**R2**	**R3**		
S1a	58.8	--	39.2	58.9	6.5	71.2
S1b	29.9	--	22.1	24.9	8.2	149.2
S2a	38.4	35.1	35.2	--	10.2	98.1
S2b	13.5	9.1	12.3	--	12.3	260.8

When only a single exit from a pair is functioning, the limiting factor on exit performance is the capacity of the exit, the aisle being able to feed sufficient passengers to keep the exit functioning at its full capacity. However, when two exits in a pair are functioning the single aisle cannot supply sufficient passengers to keep both exits working at full capacity and hence a drop in exit flow rate is achieved. Furthermore, the average travel distance in Scenario S2a is 10.2 m compared with only 6.5

m for Scenario S1a. In addition to the slower exit flow rates in Scenario S2a, the passengers have to travel further on average in Scenario S2a compared to Scenario S1a. We note that the average travel distance in the fire cases is greater than the cases without fire. This is due to some of the agents attempting to find alternative exit routes during the fire scenario, in particular to circumvent congestion.

When the impact of fire is included, the on-ground time for Scenario S1b (certification configuration) is 149.2 s, an increase of 110%. However, this time is significantly less than the predicted time to flashover of 325 s. The on-ground time for Scenario S2b (realistic exit configuration) is 260.8 s, an increase of 166%. Thus the presence of fire more significantly impacts the realistic exit configuration. Furthermore, the predicted egress time in the presence of fire is comparable to the predicted time to flashover of 275 s for this scenario. It is thus very likely that some passengers may not be able to evacuate before flashover in Scenario 2b.

Number of Fatalities and Injuries

As seen in Table 4, Scenario S1b produces an average of 1.2 fatalities while S2b produces an average of 14.6 fatalities. It has already been shown that Scenario S2b (realistic exit configuration) produces a shorter time to flashover than Scenario S1b (certification configuration) and produces a greater on-ground evacuation time without fire which also fails to satisfy the 90 seconds requirement. Therefore, it is not too surprising that a greater number of fatalities are produced in this scenario compared to the certification case. Long waiting times (as measured by the Cumulative Wait Time – CWT) in the exit queues are the key factor resulting in the greater fatalities. As seen in Table 4, the average waiting time for the 14.6 fatalities in Scenario S2b is 58.1 s, approximately three times that of the fatalities in Scenario 1b.

Table 4: Average statistics for fatalities derived from 1000 repeated simulations

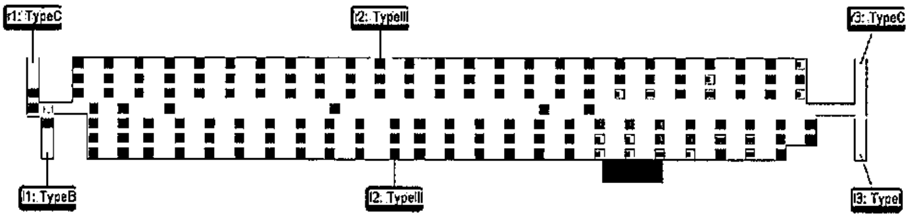
Scenario	**Openings**	**Number of fatalities**	**Time for first fatality (s)**	**Time for last fatality (s)**	**Distance (m)**	**CWT (s)**
S1b	R1, R2 and R3	1.2	31.8	35.9	3.4	18.6
S2b	R1, R2 and L1	14.6	28.2	248.6	12.3	58.1

In both scenarios, the first fatality appears at an average time of approximately 30 s. These early fatalities occur for passengers initially located close to the rupture. This can be seen by the average distance travelled by the fatalities in Scenario S1b which is only 3.4 m indicating that these fatalities occur close to their starting location. The fatalities are due to exposure to high temperature and high radiative flux. Due to the high levels of congestion in the vicinity of the rupture, passengers initially located in the vicinity of the rupture have to wait for a period of time before they can move away. As a result, it appears that these initial fatalities are unavoidable.

As seen in Figure 8, the fatalities in Scenario S2b are either originally located on seats in the vicinity of the rupture or in the rear of the aircraft. This is demonstrated by the average distance travelled by fatalities in this scenario, which is greater than that travelled by fatalities in Scenario S1b, and the same as that travelled by survivors in Scenario S2b (see table 5). The actual fatalities either occur in their starting seats, nearby to their starting seats, along the aisle and in the vicinity of the available exits (all three exits). These fatalities can be classified into two categories based on their death locations. Category 1 includes those with death locations in the rear half of the cabin and Category 2 with death locations in the forward half of the cabin.

For passengers in Category 1, the long wait time in the aisle queue (average of 58.1 s) results in their incapacitation in the rear half of the cabin near their initial seating locations before they have a chance to move to a relatively safer place. For those in Category 2, they have managed to move into a relatively safer part of the cabin, but have been severely injured due to their prolonged exposure to the rapidly developing hazardous conditions in the rear of the cabin. This combined with the longer egress times associated with this scenario resulting from the use of two exits in an exit pair mean that they continue to be exposed to hazardous conditions, albeit less hazardous than in the rear of the cabin. Therefore, although passengers in Category 2 can escape from the deadly region near the rupture, they cannot get out of the cabin before they are overcome.

Figure 8. Start locations (open squares) and death locations (grey squares) for fatalities in Scenario 2b.



The slower egress times for the survivors associated with Scenario S2b (realistic exit configuration), greater wait times (average of 33.7 s compared to 24.0 s), longer average travel distance (12.3 m compared to 8.2 m) and the faster development of the cabin fire result in an average of 25.2 passengers in this scenario being severely injured by heat with FIH values greater than 0.3 (see Table 5). In comparison, the number of severe injuries in Scenario S1b (certification exit configuration) is only 6.3.

The significantly greater number of fatalities and severe injuries in Scenario S2b (realistic exit configuration) clearly demonstrate that the certification trial exit configuration (Scenario S1b) is less challenging than the realistic exit configuration.

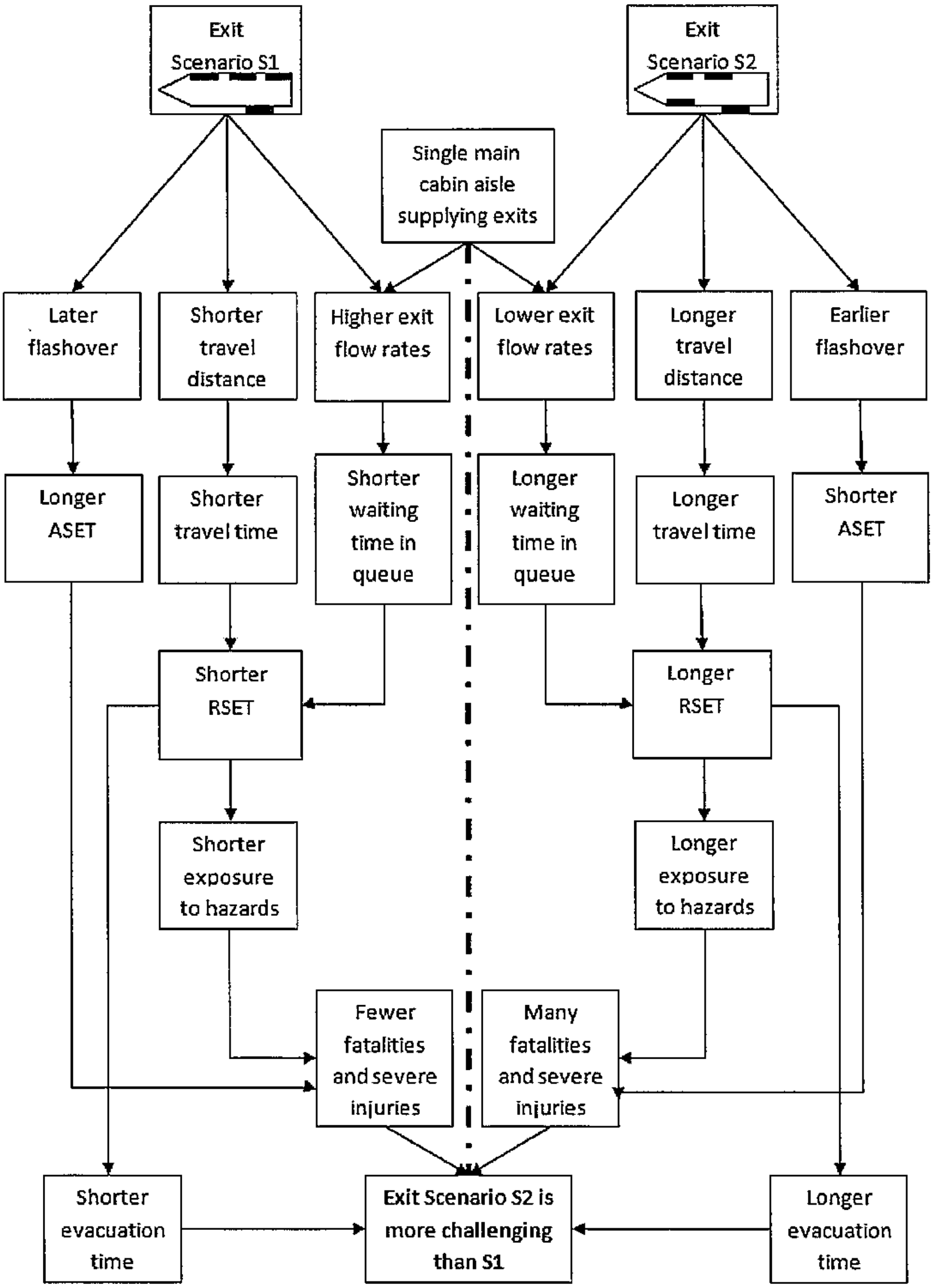
Table 5: Average statistics for survivors derived from 1000 repeat simulations

Scenario	**Openings**	**Number of survivors**	**CWT (s)**	**Average Distance (m)**	**FIH>0.3**
S1b	R1, R2 and R3	147.8	24.0	8.2	6.3
S2b	R1, R2 and L1	134.4	33.7	12.3	25.2

APPROPRIATENESS OF CERTIFICATION TRIAL EXIT CONFIGURATION

The certification exit configuration (Scenario S1) produces shorter evacuation times and results in significantly less fatalities and severe injuries than the exit configuration commonly found in real accidents (Scenario S2). This is due to three main factors, the exit flow rate, the travel distances, and time to flashover, all of which are influenced by the evacuation exit configuration. The dependence of the severity of the scenario on exit configuration is illustrated in Figure 9.

Figure 9. Evacuation efficiency comparison between two exit configurations.



The exit configuration can significantly impact exit flow rates. Narrow body aircraft consist of only a single main cabin aisle feeding passengers to the available exits. In exit Scenario S1, the single cabin aisle is sufficient to allow all available exits to function at their full capability. However, in Scenario S2, two exits within an exit pair are being supplied by the single main cabin aisle. This aisle cannot supply sufficient passengers to both exits to maintain these exits at their maximum flow capabilities. The reduced exit flow rates achieved in this scenario (Scenario S2) result in longer wait times for passengers in exit queues than in the certification exit configuration (Scenario S1). As a result, the passengers in the aft of the cabin in Scenario S2 experience longer exposures to the hazardous fire conditions in the vicinity of the rupture during the early stages of fire development. This in turn results in the higher fatality and injury rate achieved in this scenario.

The exit configuration in which two exits are available in the front of the cabin and one exit in the middle of the cabin (Scenario S2) also results in greater average travel distances for passengers compared to the scenario in which a single exit in each exit pair is available (Scenario S1). The greater travel distances results in greater average evacuation times which result in longer exposure to fire hazards and hence a higher fatality and injury rate in Scenario S2 compared to that in Scenario S1. Finally, the available exit configuration also affects the interior fire development and the subsequent time to flashover. With two exits are available in the front of the cabin and one exit available near the middle of the aircraft (Scenario S2), the time to flashover is significantly shorter than that in Scenario S1. This means that the ASET in Scenario S2 is shorter than that in Scenario S1. Furthermore, the slower average exit flow rates and greater average travel distances in Scenario S2 means that the RSET in Scenario S2 is greater than that in Scenario S1. The coupled effect of a shorter ASET and longer RSET in Scenario S2 results in the greater number of fatalities and injuries in Scenario S2 compared to Scenario S1.

Therefore, the current certification trial requirement involving one exit from each exit pair is shown to be not only unrepresentative of actual accident conditions, but also not sufficiently challenging to be used as a meaningful benchmark indicator of safety performance.

CONCLUSIONS

The regulatory compliant exit configuration involving one exit from each exit pair has been shown to produce shorter evacuation times and longer times to flashover resulting in fewer casualties than an exit configuration which involves the same number of exits but distributed in a configuration more typical of accident scenarios. The certification exit configuration has therefore been shown to be both less representative and less challenging than real accident scenarios. An alternative exit configuration that uses the same number and type of exits as the current certification requirement, but distributed in a more likely accident configuration has been shown to be significantly more challenging than the current certification configuration. It is suggested that this configuration should be used for certification for narrow body aircraft as it is more representative of accident conditions and so better represents the type of performance that may be expected in accident conditions and thus is a better measure of the level of safety achieved. A similar analysis can be undertaken for wide body aircraft.

REFERENCES

[1] Title 14, Code of Federal Regulations (14 CFR), Federal Aviation Regulations, Washington, USA, 1999.

[2] Galea, E.R., Finney, K., Dixon, A.J.P., Siddiqui, A., and Cooney, D.P., An analysis of exit availability, exit usage and passenger exit selection behaviour exhibited during actual aviation accidents, The Aeronautical Journal of the Royal Aeronautical Society, 2006, 110, (1106), pp 239-248.

[3] King, D. "Report on the accident to the Boeing 737-236 Series 1, G-BGJL at Manchester International Airport on 22 August 1985", Aircraft Accident Report 8/88. HMSO, London, 1988.

[4] Galea, E.R., Togher, M., Lawrence, P., "Investigating the Impact of Exit Availability on Egress Time using Computer based evacuation simulation." Proceedings of the International Aircraft Fire & Cabin Safety Conf, Oct 29 – Nov 1, 2007, Atlantic City USA. Web site: http://www.fire.tc.faa.gov/2007Conference/proceedings.asp

[5] Ewer, J., Grandison, A., Jia, F, Galea, E., Knight, B. and Patel, M. User guide and technical manual, SMARTFIRE V4.1, Fire Safety Engineering Group, University of Greenwich, UK, 2007.

[6] Galea E.R., Blake S. and Lawrence P.J., Report on Testing and Systematic Evaluation of the airEXODUS aircraft evacuation model. ISBN 0860399664, CAA PAPER 2004/2005. April 2005.

[7] Galea E. R., Wang Z., Veeraswamy A., Jia F., Lawrence P. J. and Ewer J. Coupled fire/evacuation analysis of station nightclub fire, Proc of 9th IAFSS Symp, Sep. 21-26, 2008, Karlsruhe, Germany, pp 465-476.

[8] Galea, E.R., Filippidis, L., Wang, Z., and Ewer, J. Fire and evacuation analysis in BWB aircraft configurations: computer simulations and large-scale evacuation experiment, The Aeronautical Journal of the Royal Aeronautical Society, 2010, 114, (1154), pp 271-277.

[9] Jia F., Patel M.K., Galea E.R., Grandison A. and Ewer J. CFD Fire Simulation of the Swissair Flight 111 In-flight Fire – Part II: Fire Spread within the Simulated Area, The Aeronautical Journal of the Royal Aeronautical Society, 2006, 110, pp 303-314.

[10] Wang Z., Galea E.R., Jia F. Computational fluid dynamics simulation of a post-crash aircraft fire test, Journal of Aircraft, Vol. 50, No. 1, 2013, pp 164-175.

[11] Wang, Z., Jia, F. and Galea, E.R., Fire and evacuation simulation of the fatal 1985 Manchester airport B737 fire, Proceedings of the 5th International Symposium on Human Behaviour in Fire, 2012, London, UK, pp. 159-170.

[12] Hu X., Wang Z., Jia F. and Galea, E.R. Numerical investigation of fires in small rail car compartments, Journal of Fire Protection Engineering, Vol. 22, No. 4, 2012, pp 245-270.

[13] Wang Z., Jia F. and Galea E.R., Predicting toxic gas concentrations resulting from enclosure fires using local equivalence ratio concept linked to fire field models, Fire and Materials 31(1), 27-51, 2007.

[14] Wang, Z., Jia, F., Galea, Patel M.K., Predicting toxic gas concentrations at location from the fire source, Fire and Materials, Vol. 35, No. 7, 2011, pp 505-526.

[15] Galea, E.R., Wang, Z., Togher, M., Jia, F., and Lawrence, P. Predicting the likely impact of aircraft post-crash fire on aircraft evacuation using fire and evacuation simulation, Proceedings of the International Aircraft Fire & Cabin Safety Conf, Oct 29 – Nov 1, 2007, Atlantic City USA.

[16] Blake, S. J., Galea, E. R., Gwynne, S., Lawrence, P. J., and Filippidis, L. Examining the effect of exit separation on aircraft evacuation performance during 90-Second certification trials using evacuation modelling techniques, The Aeronautical Journal of the Royal Aeronautical Society, 2002, 106, pp 1-16.

[17] Galea E.R., Blake S., Gwynne S. and Lawrence P. The use of evacuation modelling techniques in the design of very large transport aircraft and blended wing body aircraft, The Aeronautical Journal of the Royal Aeronautical Society, 2003, 107, pp 207-218.

[18] Purser, D.A., Toxicity Assessment Of Combustion Products, The SFPE, Handbook Of Fire Protection Engineering (3rd Edition), Ed: Dilenno, P.J., Drysdale, published by the National fire protection, Quincy, MA, 2002.

[19] Jin, T And Yamada, T. Irritating Effects From Fire Smoke On Visibility, Fire Science And Technology, 1985, 5, pp 79-90.

[20] Magnussen B.F. and Hjertager B.H., "On mathematical modelling of turbulent combustion with special embassies on soot formation and combustion," 16th Symp. (Int.) on Combustion, the Combustion Institute, 1977.

[21] Owen, M., Galea, E.R. and Dixon A.J.P. 90-second Certification Trial Data Archive Report, Prepared for the U.K. CAA for project 049/SRG/R&AD, March 1999.

[22] Claar, J.B., " Detailed Test Report – 737-300 Escape System Certification Demonstration – Full Scale Evacuation", Proprietary Final Report, T6-6691, 1984.