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PREDICTING THE LIKELY IMPACT OF AIRCRAFT POST-CRASH FIRE ON AIRCRAFT EVACUATION USING FIRE AND EVACUATION SIMULATION

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ABSTRACT

The SMARTFIRE Computational Fluid Dynamics (CFD) fire field model has successfully reproduced the observed characteristics including measured temperatures, species concentrations and time to flashover for a post-crash fire experiment conducted by the FAA within their C-133 cabin test facility. In this test only one exit was open in order to provide ventilation for the developing cabin fire. In real post-crash fires, many exits are likely to be open as passengers attempt to evacuate. In this paper, the likely impacts on evacuation of a post-crash fire in which various exiting combinations are available are investigated. The fire scenario, investigated using the SMARTFIRE software, is based on the C-133 experiment but with a fully furnished cabin and with four different exit availability options. The fire data is imported into the airEXODUS evacuation simulation software and the resulting evacuations examined. The combined fire and evacuation analysis reveals that even though the aircraft configuration is predicted to comfortably satisfy the evacuation certification requirement, when fire is included, a number of casualty's result, even from the certification compliant exit configuration.

1. INTRODUCTION

The aircraft evacuation certification protocol [1] is designed around the threat of a post crash fire and the resulting onset of non-survivable conditions which may develop within the passenger cabin. The certification trial assumes that 50% of the exits will be available with one exit from each pair of exits being used. The trial imposes the performance requirement that the last person must safely evacuate from the aircraft within 90 seconds. These two core certification assumptions are examined in a series of papers presented by the authors at this conference using computer simulation of both fire and evacuation [2-3].

The requirement that a single exit from each exit pair is used in the certification evacuation trial has been examined by Galea et al [2, 4] and found to be both unrepresentative of actual accident conditions [4] and unchallenging [2]. Other more commonly occurring combinations of 50% of the available exits have been shown through evacuation simulation to produce longer egress times.

The rationale for the prescribed evacuation performance requirement is that after 90 seconds, non-survivable conditions are likely to develop within the cabin. Flashover is a critical point in post crash cabin fire where the fire rapidly grows to engulf the entire cabin [5, 6]. The time to flashover is generally considered to mark the end of the survivability period for those passengers still within the cabin. By comparing predictions made by the SMARTFIRE [7-9] fire simulation software to experimental data from a full scale fire test [5, 10], Wang et al [3] demonstrated that the software was capable of providing a reasonable approximation to flashover time. In addition the model produced reasonable agreement with experimental observations for the ignition of seats and bins close to the initial entry point of the external fuel, the confined burning locations during the initial stage of the fire development, the spread of flame along the solid surfaces, and smoke filling the cabin. The predicted temperatures and concentrations of O_2 and CO were also in reasonable agreement with the measured data. Using SMARTFIRE Wang et al [3] went on to examine the impact on time to flashover of cabin ventilation provided by available exits. Their results suggest that the more cabin exits that are open the greater the delay in flashover time. This is significant since the full-scale fire tests undertaken by the US Federal Aviation Administration (FAA) generally have limited ventilation provided by only a single exit [5, 10]. Furthermore, in real evacuation situations, a number of exits are likely to be open as passengers attempt to evacuate as quickly as possible. With so many exits open, the ventilation of the aircraft cabin is likely to have a significant impact on the developing internal fire and the passengers' evacuation.

In this paper we examine the impact of varying exit availability on survivability given a post-crash external fuel fire. The developing fire conditions within the cabin are predicted using SMARTFIRE and the evacuation, including the impact of the developing fire atmosphere on the passengers, is determined using airEXODUS [11-16]. The geometry of the FAA C-133 test facility [3, 5, 10] is utilised in these numerical demonstrations.

2. EVACUATION and FIRE SIMULATION SOFTWARE

The airEXODUS evacuation model is used to perform the evacuation simulations presented in this paper. EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of people from a variety of complex enclosures. airEXODUS [11-16] 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 airEXODUS model and its validation has been described previously and so only the components relevant to this study will be briefly described here.

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 software describing these sub-models is rule-based, the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. These sub-models operate on a region of space defined by the **GEOMETRY** of the enclosure. The **GEOMETRY** of the enclosure can be defined manually or read from a Computer Aided Design using the DXF format. The **MOVEMENT** sub-model controls the physical movement of individual passengers from their current position to the most suitable neighbouring location, or supervises the waiting period if one does not exist. The movement may involve such behaviour as overtaking, side stepping, or other evasive actions. 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. Cabin crewmembers can also be represented and require an additional set of attributes such as, range of effectiveness of vocal commands, assertiveness when physically handling passengers and their visual access within certain regions of the cabin.

The **HAZARD** sub-model controls the atmospheric and physical environment. It distributes pre-determined fire hazards such as heat, radiation, smoke and toxic fire gases throughout the atmosphere and controls the opening and closing times of exits. The HAZARD sub-model can read data generated by the SMARTFIRE CFD fire model and the CFAST zone model [17]. To transfer CFD fire hazard data the user must define a consistent set of zones within both the SMARTFIRE and EXODUS geometry. These zones are intended to represent regions in which the fire hazard data is expected to be near uniform i.e. exhibiting small spatial variation. The hazard data within SMARTFIRE is averaged over these zones to produce two values, a hazard value at an arbitrary nominal head height and a value a nominal knee height. It is these zone averages which are then mapped to the appropriate zone within the EXODUS model. When passengers are considered to be standing erect, they are exposed to the hazards at head height (irrespective of their actual height) and when the passengers elect to crawl, they are exposed to the hazards at the knee height.

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) concept. The FED model implemented within EXODUS [12, 18] follows the formulation of Purser [19, 20]. FED models assume that the effects of certain fire hazards are related to the *dose* received rather than the exposure *concentration*. The model calculates, for these fire hazards, the ratio of the dose received over time to the effective dose that causes incapacitation or death, and sums these ratios during the exposure. When the total reaches unity, the toxic effect is predicted to occur. Within airEXODUS, as the FED approaches unity the occupant's mobility, agility, and travel rates can be reduced making it more difficult for the affected occupant to escape. The airEXODUS toxicity model considers the toxic and physical hazards associated with elevated temperature, thermal radiation, HCN, CO, CO_2 and low O_2 and estimates the time to incapacitation. The impact of the irritant fire gases (such HCL, HBr, HF, SO_2, NO_2, Acrolein and Formaldehyde) are determined using a Fractional Irritant Concentration (*FIC*) model [20, 18] which is dependent on the instantaneous concentration of irritant gas that the individual is exposed to. An *FIC* value is determined by taking the instantaneous concentration the individual is exposed to and dividing by the concentration required to cause a given effect (i.e. incapacitation or death). An *FIC* value is calculated for each of the irritant gases that the individual is currently exposed to. If any of these individual *FIC* values is greater or equal to 1.0 or if the combined impact of all of these *FIC* ratios is similarly greater or equal to 1.0 then the individual is assumed to succumb to the impact of the particular irritant component or the combined effect of the irritant gases. Finally, when a passenger moves through a smoke filled environment their travel speed is reduced according to the experimental data of Jin [21, 22]. All these effects are communicated to the **BEHAVIOUR** sub-model which, in turn, feeds through to the movement of the individual.

The **BEHAVIOUR SUB-MODEL** determines an individual's response to the current prevailing situation on the basis of his or her personal attributes, and passes its decision on to the movement sub-model. The behaviour sub-model functions on two levels, global and local. The local behaviour determines an individual's response to the local situation e.g. jump over seats, wait in queue, etc while the global behaviour represents the overall strategy employed by the individual. This may include such behaviour as, exit via the nearest serviceable exit, exit via most familiar exit or exit via their allocated exit. The local behaviour of the passenger may also be affected through the intervention of cabin crew. As certain behaviour rules e.g. conflict resolution and model parameters e.g. passenger exit hesitation times, are probabilistic in nature, the model will not produce identical results if a simulation is repeated. In studying a particular evacuation scenario, it is necessary to repeat the simulation a number of times in order to produce a distribution of results.

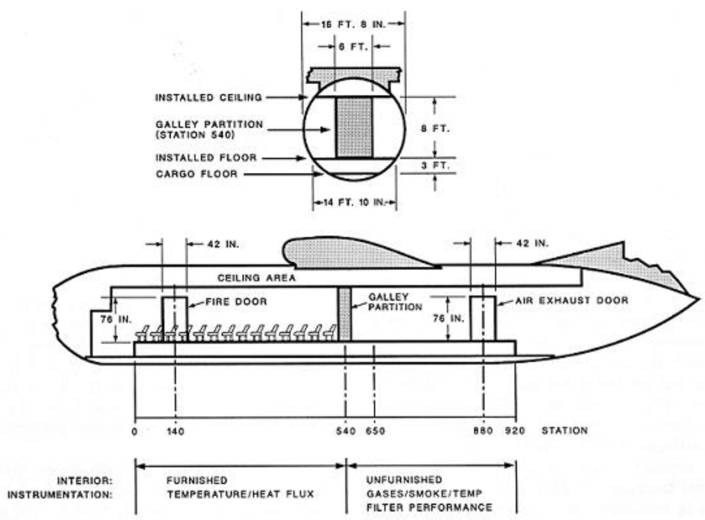
In this paper several terms are used to describe the results produced by airEXODUS. These include:
TET: Total Evacuation Time, essentially the time for the last person to evacuate;
PET: Personal Evacuation Time, evacuation time associated with an individual;
CWT: Cumulative Wait Time, the amount of time spent by an individual in congestion during the evacuation;
Jumps: number of seats an individual jumps over during the evacuation;
Response Time: the time a passenger takes to respond to the call to evacuate, release their seat restraint and stand;
FIH: FED model measuring the individual's cumulative exposure to radiative and convective heat;
***FIH_c*:** FED model measuring an individual's cumulative exposure to convective heat;
***FIH_r*:** FED model measuring an individual's cumulative exposure to radiative heat;
FIN: FED model measuring an individuals cumulative exposure to narcotic gases.

Finally, within airEXODUS two models are provided for the determination of FIH_r, the so-called Pain Threshold model and the Incapacitation model. The Pain Threshold model has as its end-point the onset of pain due to radiative heat. If this model is used within the evacuation simulation, individuals who receive a cumulative dose of thermal radiation sufficient to cause pain are deemed to be unable to continue. The Incapacitation model has as its end-point incapacitation due to excessive exposure to radiative heat. If this model is used in the evacuation simulation, when individuals receive a cumulative dose of thermal radiation sufficient to cause incapacitation, they are deemed to be unable to continue. Clearly if the Incapacitation model is used, individuals will be able to tolerate higher doses of thermal radiation prior to reaching the end-point. However, using the Incapacitation model, individuals with a FIH_r of 1.0 are considered fatalities having received a sufficient dose to cause incapacitation. In the simulations presented here the Incapacitation model is used.

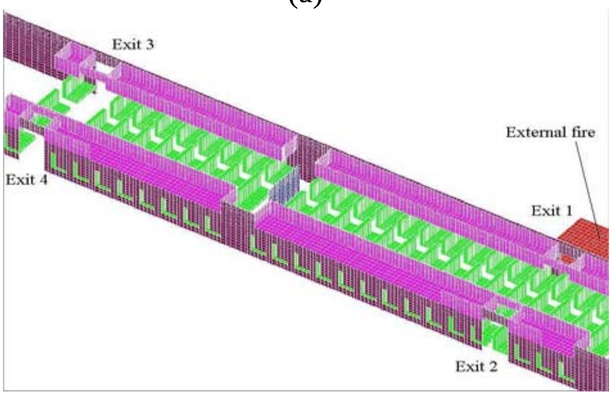
The fire simulation software used to generate the fire atmosphere is the SMARTFIRE software [7-9]. A full description of the software may be found in these proceedings [9] and so this will not be repeated here. In brief, the fire simulation software incorporated a range of sophisticated sub-models including a flame spread model, the EDM combustion model, a multi-ray radiation model and a toxicity generation model based on the local equivalence ratio concept.

3. THE AIRCRAFT GEOMETRY

The aircraft geometry used in these simulations is based on the FAA C-133 test article [5, 10]. A schematic of the facility is shown in Figure 1a. The facility is 4.52 m wide (at the floor) and has a ceiling height of 2.44 m. The section of the cabin containing the raised floor has a length of 23.37 m. The interior is partitioned into two cabins, a forward cabin and an aft cabin. The cabins are separated by a solid partition (see Figure 1). The forward part of the cabin (containing the raised floor) is 13.7m (45 feet) long while the rear part of the cabin containing the raised floor is 9.67 m long. Within these simulations, the entire internal length of the cabin is 29.9 m.



(a)



(b)

Figure 1: C-133 geometry (a) full-scale test facility (reproduced from [3]); (b) configuration used in fire simulation

In the full-scale experiments conducted by the FAA, only the forward part of the cabin was fully furnished (see Figure 1a). In these computer simulations the entire cabin is furnished. The cabin is configured with a double-triple-double seating configuration with 15 seat rows in the forward section (the same as in the experiment [10]) and 9 seat rows in the aft section creating a seating capacity of 168 (see Figure 1b). Just as in the fire experiment [10], the seats in line with Exit 1 and 2 are positioned in the fire model to represent the type of condition that may occur if the exit represented an actual cabin rupture, the seats providing fuel for the initiation of the internal fire. However, in the evacuation simulation the seven seats in this row are removed, reducing the seating to 161. The seats are protected with fire blocking layers. The carpet was 90/10 wool/nylon. The side walls and storage bins were assemblies constructed of epoxy-Fiberglas honeycomb panels. The ceiling was composed of flat sheets of epoxy-Fiberglas and epoxy-Kevlar honeycomb panels.

The cabin has four Type A exits, two in the front of the cabin (Exits 1 and 2) and two in the aft of the cabin (Exits 3 and 4). The external fuel fire is located outside the open Exit 1 (see Figure 1b).

4. THE FIRE SCENARIOS FIRE MODEL CONFIGURATION

The initial fire is defined as a kerosene pool fire located outside Exit 1. The pool was rectangular in shape with dimensions 2.44m wide and 3.05m long and generated a total heat release rate of 10 MW. In total four scenarios are considered. These vary only in the nature of the ventilation conditions applied to the cabin. The list of ventilation conditions are presented in Table 1.

Table 1: Scenario description

Scenario	Open Exits
1	1 and 3
2	1, 3 and 4
3	1, 2 and 4
4	1, 2, 3 and 4

The fire model was configured as indicated in [3]. In addition, as data was produced for the evacuation simulation a set of 26 hazard zones were defined in both the fire and evacuation model. Within each zone, hazard values in the layer from 1.5m to 2.0m were averaged and taken to represent the upper layer (i.e. head height) condition while hazard values from 0.3m to 0.8m were averaged for the lower layer values (i.e. knee height).

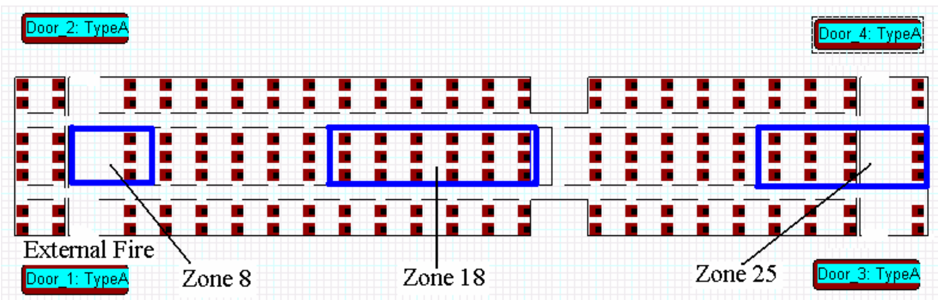


Figure 2: Evacuation set up

The averages of predicted temperatures, species concentrations (CO, CO_2, O_2), 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 the evacuation simulation. Three of the 26 zones are depicted in Figure 2. These are: Zone 8 which covers the central seat near the rupture; Zone 18 which covers the central seats of 6 rows just before the partition and Zone 25 which covers the central seats in the last 4 rows in the rear of the cabin.

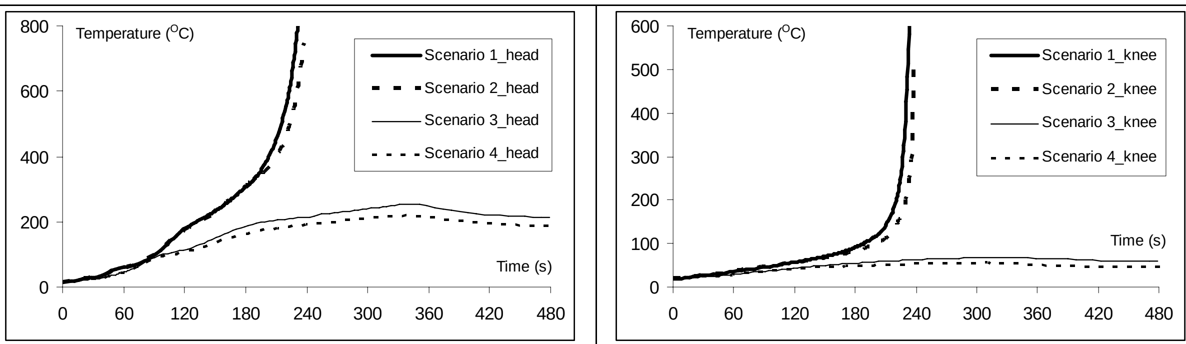
5. FIRE PREDICTIONS

Two of the four scenarios produce flashover conditions within the first 480 seconds (see Table 2). Flashovers occur in Scenario 1 within 187 seconds and Scenario 2 within 193 seconds [3]. In these cases we find only one or two rear exits are open. An important observation is that flashover does not occur within the first 480 seconds when the exit opposite the fire (Exit 2) is open.

Table 2: Predicted flashover times for the various exit scenarios [3]

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Open Exits	Exits 1 and 3	Exits 1, 3, 4	Exits 1, 2, 4	Exits 1-4
Time to Flashover (s)	187	193	--	--

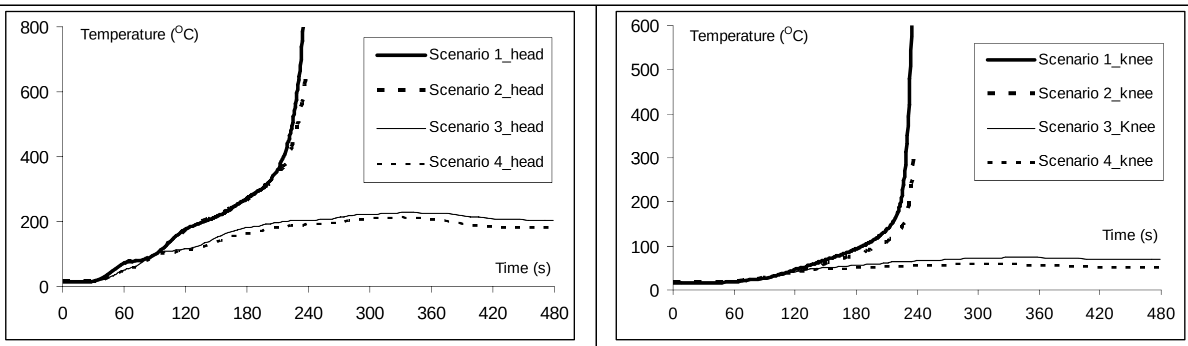
The predicted temperatures in the three identified zones (Zone 8, 18 and 25) are presented in Figures 3-5. In Zone 8, the predicted head height temperatures for Scenario 1 and 2 follow the same curve for the first 90 seconds and reach approximately 100^{O}C at 90 seconds (see Figure 3a).



(a) (b)

Figure 3: Predicted temperatures at (a) head height and (b) knee height in Zone 8

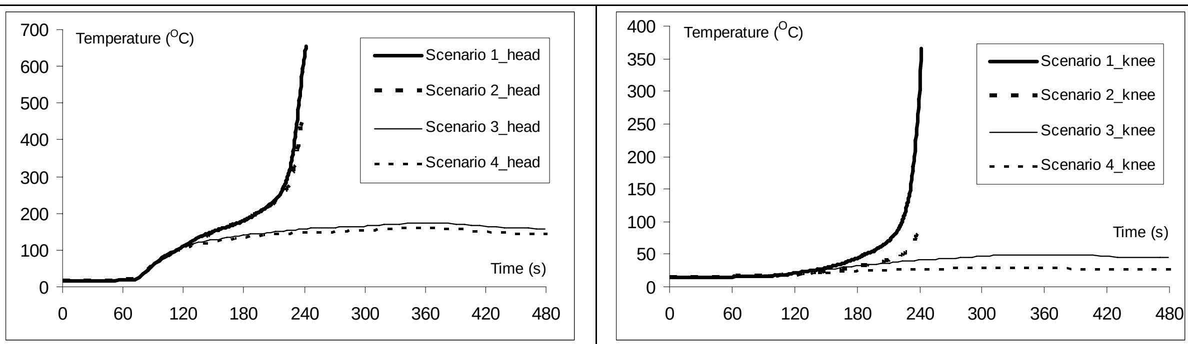
After 90 seconds, the predicted head height temperatures increase rapidly in both Scenario 1 and 2. Soon after the predicted onset of flashover in both scenarios the predicted head height temperatures in Zone 8 reach 600^{O}C. The predicted head height temperatures in Scenario 3 and 4 gradually increase after 90 seconds. After 180 seconds the head height temperatures in Scenarios 3 and 4 reach a quasi-steady state with temperatures around 200^{O}C. In the lower layer (see Figure 3b), the predicted temperatures in Scenario 1 and 2 gradually increase to 100^{O}C prior to flashover and then quickly rise to 600^{O}C after flashover. The lower layer temperature in Scenario 3 and 4 increase slowly and are around 60^{O}C after 180 seconds.



(a) (b)

Figure 4: Predicted temperatures at (a) head height and (b) knee height in Zone 18

The predicted temperatures in Zone 18 (see Figure 4) and 25 (see Figure 5) display a similar evolution to those in Zone 8. However, the temperature rise in these regions are slightly delayed compared to those in Zone 8. For the first 70 seconds the predicted head height temperatures in Zone 25 for all scenarios are close to the ambient values. The lower layer temperatures in Zone 25 for Scenarios 1 and 2 are less than $50^{O}C$ prior to the predicted onset of flashover.



(a) (b)

Figure 5: Predicted temperatures at (a) head height and (b) knee height in Zone 25

6. EVACUATION SIMULATION RESULTS

6.1 Survivability

Prior to running full evacuation simulations the impact of the atmospheric conditions on survivability was evaluated (see Table 3). This was achieved using the airEXODUS software by taking a single person and forcing them to stay in the designated zone for the entire duration of the fire simulation. The changes in their FED values were noted for both the standing and crawling position. In this way it was possible to estimate survival times for various locations within the cabin for the four different ventilation scenarios. It should be noted that the fire atmospheres for Scenarios 1 and 2 were only determined up to 250 and 240 seconds respectively. If survival times for these scenarios are greater than these times, it is assumed that the atmospheric conditions have reached a steady-state and continue past the stated fire simulation times.

Table 3: Predicted survival times (seconds) for standing and crawling individuals within Zones 8, 18 and 25 for each fire scenario

Position		Survival Time (seconds)			
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Standing	Zone 8	88	88	84	84
	Zone 18	147	148	188	202
	Zone 25	200	201	257	275
Crawling	Zone 8	91	91	89	90
	Zone 18	220	226	>480*	>480
	Zone 25	242	277	>480+	>480

Note: *: Individual has *FIH* = 0.8 at 480 seconds so is likely to be severely burnt.
+: Individual has *FIH* = 0.2 at 480 seconds and so may suffer burn injuries.

Exposure to narcotic fire gases, primarily CO, produces an *FIN* value of approximately 0.11 in the most severe exposure. Thus the generation and dispersion of narcotic fire gases is not a key component deciding survivability in these cases. However, it should be noted that in these simulations the fire atmosphere does not contain HCl as this was not included in the fire simulation. The presence of HCl, generated from burning plastic materials, may have a significant impact on survivability due to the extreme irritant nature of the gas even in relatively low concentrations of 200 ppm. In all cases, excessive heat is the primary factor contributing to incapacitation. Furthermore, exposure to thermal radiation is the primary factor limiting survivability in Zone 8 while convective heat is the primary factor limiting survivability in Zone 25. In Zone 18 thermal radiation can contribute up to 25% of the thermal dose causing incapacitation.

Zone 8 is the least survivable zone with survivability times less than 91 seconds across all four scenarios whether the individual is standing or crawling (see Table 3). Furthermore, for Zone 8, situations in which Exit 2 is open (Scenarios 3 and 4) prove to be the least survivable, despite there being no flashover in these cases. This is because a considerable volume of the hot fire gases are drawn to this exit making the conditions in the forward part of the cabin less survivable. Radiation is the primary factor reducing survivability in Zone 8. However, opening Exit 2 increases survivability in the other cabin regions. Thus opening the exit immediately opposite the fire decreases survivability for those closest to the fire, but increases survivability for everyone else. As expected, across all scenarios, survivability increases the further removed the zone is from the fire source and survivability for crawlers is greater than that for standing individuals within each zone.

We also note that there is little difference in survival times between Scenario 1 and 2, however there are interesting differences between Scenarios 1 and 2 and Scenarios 3 and 4 (see Table 3). Given the severity of the conditions in Scenarios 1 and 2, it is somewhat surprising that survivability times in zone 25 is as high as 200 seconds for standing individuals. It is important to note that survival times for standing individuals in Zone 8 and 18 in Scenarios 1 and 2 are significantly shorter than the predicted flashover times. Furthermore, even though flashover is not predicted to occur in Scenarios 3 and 4, the survival times for standing individuals in Zones 18 and 25 in these scenarios are not significantly greater than those in Scenarios 1 and 2, being some 33% longer (average difference of approximately 48 and 66 seconds respectively). The most significant result is the large difference crawling can make to survival times. While the standing survival times for Zones 18 and 25 in Scenarios 3 and 4 are only 33% longer than those in Scenarios 1 and 2, the crawling survival times for Scenarios 3 and 4 are more than 100% longer than those for Scenarios 1 and 2. However, while conditions low down in the cabin are more survivable, crawling will also increase personal evacuation times prolonging exposure to the fire conditions within the cabin. To determine if crawling can actually improve survival rates it is necessary to undertake a full evacuation simulation.

In addition, excluding Zone 8, survival times in all scenarios – even those in which flashover occurs – are significantly greater than 90 seconds. The shortest survival time (excluding Zone 8), is 147 seconds or some 63% longer than 90 seconds.

6.2 Evacuation

Here we examine the evacuation of all 161 passengers from the C-133 cabin in each of the four ventilation scenarios defined in Table 1. A default “certification” population is used to populate the aircraft and in each case airEXODUS is configured to allow passengers to evacuate as efficiently as possible. In these scenarios passengers are drawn to their nearest exits. However, in Scenarios 3 and 4, Exit 2 is made less attractive as it is in the “hot” zone. Thus passengers will try and avoid this exit unless they are initially located very close to the exit. In these scenarios passengers are assumed to react very quickly, responding in 0 to 8 seconds from the start of the simulation. Furthermore, all of the exits are assumed to be open at the start of the simulation and passenger exit hesitation times appropriate for Type A exits with assertive crew are imposed. The egress times presented in this paper represent on-ground times. Each scenario was repeated 100 times. At the start of each simulation the population was randomised so that passengers occupy a different seat at the start of each simulation. The results presented here represent the average values derived from these 100 repeat simulations.

Table 4: Average TET, number of fatalities and exit usage derived from 100 repeat simulations

Scenario	***TET* (s)**	**Flashover time (s)**	**Fatalities**	**Door 2**	**Door 3**	**Door 4**
1	231	187	7.2	--	153.8	--
2	151	193	1.1	--	79.9	80.0
3	179	>480	0.0	23.0	--	138.0
4	61.1	>480	0.0	21.4	68.1	71.5
Certification case	54.5	--	--	86.0	--	75.0

We note from Table 4 that using two Type A exits the aircraft can be evacuated in 54.5 seconds under certification conditions. Furthermore, the certification evacuation time is the fastest evacuation time achieved, even though Scenario 4 has more exits available. Only in Scenario 4, in which all the exits are open, can the aircraft be emptied within the certification requirement of 90 seconds.

The long egress times are the result of a number of factors. Clearly, the number of available exits will impact the egress time. However passenger behaviour also contributes to the long egress times. Due to the heavy smoke and resulting poor visibility in the cabin, passengers move much slower than under normal visibility conditions. Within airEXODUS the reduction in travel speed is determined through the use of the Jin relationships [21, 22].

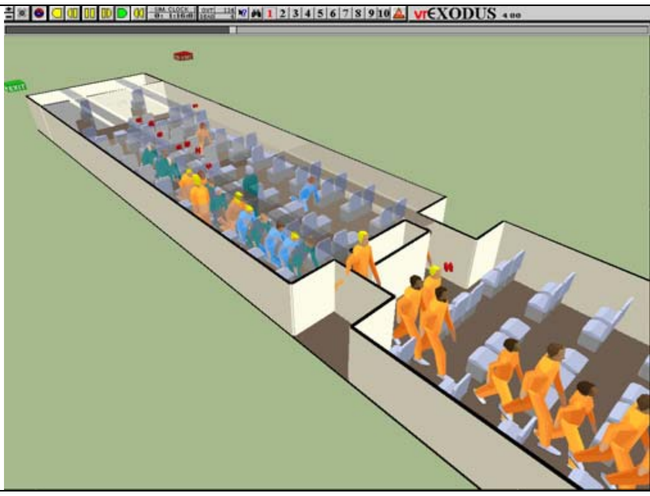


Figure 6: Passengers crawling under smoke layer (forward part of cabin) in Scenario 1

In addition, as the temperature or smoke concentration in the upper layer reaches prescribed critical values, passengers will fall to the floor and begin to crawl. Presented in Figure 6 is a frame from the vrEXODUS animation of the Scenario 1 evacuation prediction, 76 seconds into the simulation. At this stage of the evacuation some four people have perished and a number of others are suffering from excessive heat exposure (individuals with an "H" above their heads in Figure 6). All the passengers remaining in the forward cabin can be seen to be crawling under the smoke layer. In contrast, those passengers in the aft of the cabin are relatively smoke free and are seen to be walking upright.

Table 5: Average evacuation statistics for the survivors (averaged over 100 simulations)

Scenario	***TET* (s)**	***CWT* (s)**	***PET* (s)**	**Crawl Time (s)**	**Seat Jumps**
1	231	28.6	65.1	19.8	1.1
2	151	14.2	35.5	2.1	0.6
3	179	21.4	47.7	7.1	0.8
4	61.1	10.6	27.9	0.0	0.4

While crawling slows the egress progress of the passengers, they are able to survive for longer in the less hazardous atmosphere found in the lower layer (see Section 6.1). Presented in Table 5 are the average passenger crawl durations through the cabin for the various scenarios. From Table 5 we note that scenarios with the longest evacuation times also have the longest average *PETs* and crawl times. In Scenario 1, the average crawl time for a survivor is 19.8 seconds, which is 30% of the average *PET* while in Scenario 4 passengers manage to evacuate without crawling.

However, crawling does not guarantee survival. Presented in Table 6 are the average travel statistics for the fatalities. We note that those who perished in the evacuation also attempted to escape by crawling. In Scenario 1 the survivors spent on average approximately 44% of their PET caught in congestion and 30% crawling (see Table 5) while fatalities spent 42% of their PET in congestion and 68% crawling (see Table 6). In Scenario 2 the survivors spent on average approximately 40% of their PET caught in congestion and 5.9% crawling (see Table 5) while fatalities spent 50% of their PET in congestion and 21% crawling (see Table 6).

Table 6: Average evacuation statistics for the fatalities (averaged over 100 simulations)

Scenario	**First Fatality (s)**	**Last Fatality (s)**	***CWT* (s)**	***PET* (s)**	**Crawl Time (s)**	**Seat Jumps**
1	34.9	197.1	40.0	96.3	65.6	0.3
2	33.0	36.0	17.5	34.5	7.5	0.1

Thus, if an individual spends a large proportion of their personal evacuation time caught in congestion and crawling, this may prove fatal. In both Scenarios 1 and 2 it is passengers who were located furthest from viable exits (and hence suffering the greatest impact of congestion and crawling) that succumbed to the fire conditions. While crawling through the cabin does not guarantee survival, it can improve chances of survivability. This is demonstrated by enforcing a no-crawl condition in Scenario 3 (the regulatory compliant exit configuration). With this condition enforced, an average of 8 fatalities is produced in Scenario 3 compared with 0 fatalities if crawling is allowed. It should be noted that without crawling, the total evacuation time (for the survivors) decreases from 179 seconds to 137 seconds.

Within the simulations, passengers also jump seats in an attempt to circumvent bottlenecks in the aisles. In Figure 6 a number of seats in the forward cabin (with smoke) appear to have no backs. Seats which are depicted in this way indicate that at least one passenger has successfully jumped over the seat. Presented in Table 5 are the average number of seats jumped in each scenario. The average varies from 0.4 to 1.1 seats and occurs in all the scenarios. Detailed investigation of a single simulation from each scenario indicates that passengers may jump as many as 9 seats. While a number of passengers attempt to jump seats these numbers are not significant.

From Table 4 we note that the scenario with the most open exits (Scenario 4) produces the shortest evacuation time (61.1 seconds) and results in no fatalities. In contrast, the scenario with the least number of open exits (Scenario 1) produces the longest egress times (231 seconds) and results in the highest average number of fatalities (7.2). From Table 6 we also note that the first fatalities in both Scenario 1 and 2 occur very early in the evacuation sequence, on average some 35 seconds after the evacuation starts. This is well before the predicted flashover in both cases. Furthermore, in this scenario the last passenger evacuates over 40 seconds after flashover. It is thus likely that the last people to evacuate from this scenario will be severally injured.

To investigate the likely number of injuries resulting in each scenario a single simulation from each scenario is investigated in detail (see Table 7). In each case the particular simulation is selected such that the *TET* is close to the mean time identified in Table 4. It should be noted that passengers with *FIH* values in excess of 0.5 are likely to be suffering from severe burn injuries. From Table 7 we note that the two most severe fire scenarios, Scenarios 1 and 2 result in the largest number of passengers suffering severe burn injuries with seven and three respectively. Scenarios 3 and 4 produce one and two passengers suffering severe burn injuries respectively. From Table 7, we also note that the maximum FED values resulting from the narcotic gases (i.e. *FIN*) are very small suggesting that narcotic gases had little impact on the overall survivability in these scenarios.

Table 7: Number of surviving passengers with high *FIH* values and the maximum values for *FIN* amongst survivors in a single simulation for each of the four fire scenarios.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
1>FIH>0.9	1	0	0	0
0.9>FIH>0.8	1	1	0	0
0.8>FIH>0.7	2	0	0	1
0.7>FIH>0.5	3	2	1	1
Maximum FIN	0.04	0.02	0.02	0.01

Using the results from Tables 4, 6 and 7 we conclude that:

- Scenario 1 results in an average of 7 fatalities, the first occurring after 35 seconds and at least 7 serious injuries;
- Scenario 2 results in an average of 1 fatality, occurring after 33 seconds and at least 3 serious injuries;
- Scenario 3 results in an average of 0 fatalities and at least 1 serious injury;
- Scenario 4 results in an average of 0 fatalities and at least 2 serious injuries.

Thus the consequences arising from these scenarios varies widely, ranging from at least 1 person seriously injured (Scenario 3 i.e. right two exits open) to 7 fatalities and at least 7 serious injuries (Scenario 1 i.e. aft left exit open). It is important to note that all four scenarios experienced the same external fire but differing cabin ventilation conditions. Furthermore, only two scenarios produced flashover conditions and these were the two scenarios suffering fatalities.

Of the scenarios investigated, two cases meet the evacuation certification requirement of 50% exit availability i.e. Scenario 2 and 3 but only Scenario 3 meets the exit distribution requirement. In Scenario 3 the available exit distribution (i.e. Exit 2 and 4) complied with the certification protocol requirements of having one exit from each pair available, while Scenario 2 had both exits from a single pair available (i.e. Exit 3 and 4) and so did not comply with the exit distribution requirement. While both scenarios meet the 50% availability requirement they produce very different egress times and injury levels. Scenario 3 produced an egress time of 179 seconds compared with 150 seconds for Scenario 2, thus the fully compliant case (i.e. Scenario 3) produced the longer egress times, well in excess of the prescribed 90 second performance requirement. In addition, both cases resulted in casualties, the fully compliant Scenario 3 producing 1 serious injury while Scenario 2 produced 1 fatality and 3 serious injuries. Thus a scenario involving the regulatory compliant 50% exit availability but with a different distribution proved to be the more challenging case resulting in a higher number of casualties. Furthermore, it should be noted that the very same aircraft configuration passed the certification requirement producing an egress time of 55 seconds.

This case demonstrates the inappropriateness of setting arbitrary performance requirements such as 90 seconds to assess the suitability of an aircraft design for passenger safety. Factors such as fire size and location, rupture size and location, aircraft size, exit state and type of cabin materials will all exert a significant impact on the development of non-survivable conditions and hence should be taken into consideration in setting the evacuation performance requirement. This analysis also reinforces the arguments of Galea et al [2] concerning the inappropriateness of selecting only a single exit distribution for certification analysis as two cases with the same number of exits can result not only in very different egress times but also different casualty levels. Furthermore, this work supports the suggestion made by Galea [23] that aircraft evacuation certification should adopt the approach of setting aircraft and scenario specific evacuation performance requirements for both the available (determined from the imposed fire scenario) and required (determined from the imposed evacuation scenario) egress times.

7. CONCLUSION

In this paper, a validated CFD fire simulation model was used to generate the thermal and toxic environment within an aircraft cabin resulting from a post-crash external fuel fire. The fire scenario consisted of a post-crash external kerosene pool fire which gained access to the aircraft cabin via an open forward exit. The fire model simulated the spread of the fire over combustible surfaces within the cabin and the resultant generation of heat, smoke and toxic gases. The ensuing evacuation was simulated using an evacuation model which took into account the physiological impact of the fire atmosphere on the evacuating population.

This work suggests that the generation and dispersion of narcotic fire gases is not a key component determining survivability in these cases. In all cases examined, excessive heat is the primary factor contributing to incapacitation. However, it should be noted that HCl was not included in these simulations. The presence of HCl, generated from burning plastic materials, may have a significant impact on survivability due to the extreme irritant nature of the gas even in relatively low concentrations. While fatalities were observed only in the cases in which flashover occurred, some fatalities occurred well before the onset of flashover. Thus time to flashover is not the only factor determining survivability in aircraft cabin fires. In addition, a number of serious burn injuries were predicted to occur even in cases which did not flashover. Furthermore, it was noted that while crawling beneath hot toxic fire gases may prolong egress times, it can significantly improve chances of surviving. However, crawling does not guarantee survival.

More generally, this work demonstrates a numerical simulation environment that can measure the impact of post-crash fire and cabin ventilation on evacuation and survivability. This work further demonstrates that changing the cabin ventilation through exit availability can have a significant impact on delaying the onset of flashover and the likelihood of achieving a successful evacuation.

Finally, the study demonstrates the importance of linked fire and evacuation simulation in determining likely survivability conditions in post-crash aircraft fire situations. While further testing and development is required, it is suggested that analysis of this type is a powerful tool in assessing realistic evacuation scenarios for aircraft evacuation certification. Indeed it provides more insight into the suitability of aircraft configuration than a single full-scale evacuation demonstration based on an arbitrary exit configuration with an arbitrary performance measure of 90 seconds.

It should be noted that this study is based on the fire conditions used in FAA full-scale fire experiments, in particular; cabin dimensions, nature of cabin materials, fire size and the lack of fuselage burn-through. Further work is required to investigate the impact of external wind conditions, different cabin configurations and materials, burn-through, fire size and location, location and size of ruptures, the impact of HCl, etc.

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