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Arbeitskreis Luft- und Raumfahrt

Invitation to an RAeS lecture in cooperation with the DGLR and VDI

Aircraft Fire and Evacuation Simulation

Prof. Edwin Galea,

Director, Fire Safety Engineering Group, University of Greenwich

Lecture followed by discussion

Entry free ! No registration required !

Download: http://hamburg.dglr.de

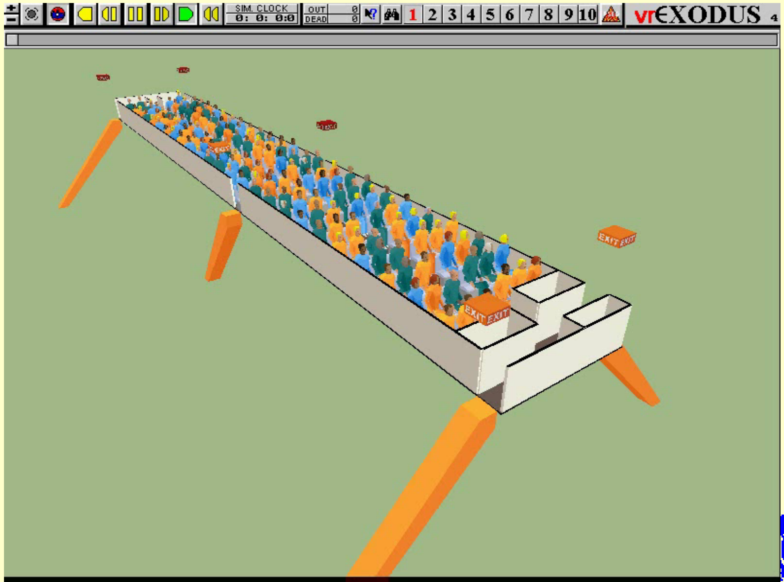
Date: **Thursday, 16th October 2014, 18:00**
Location: **HAW Hamburg**
Berliner Tor 5, (Neubau), Hörsaal 01.12

Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

Praxis Seminar Luftfahrt

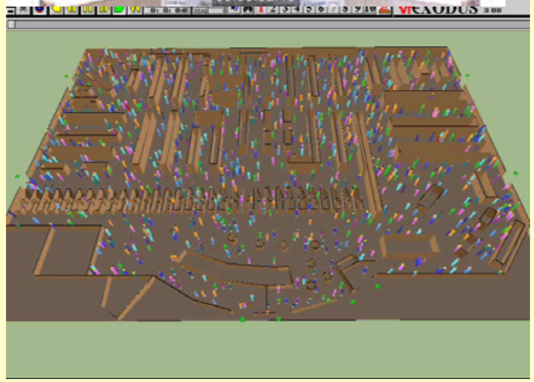
Exploring the Appropriateness of the Aviation Industry Evacuation Certification Requirements Using Fire and Evacuation Simulation

Prof Ed Galea
Fire Safety Engineering Group (FSEG)
University of Greenwich



FSEG: Modelling Safety and Security

- FSEG was Founded in 1986 by Prof Galea in response to the Manchester Airport B737 fire.
- Today it consists of 30 researchers including:
  - fire engineers, CFD specialists, psychologists, mathematicians and software engineers.
- Research interests include the mathematical modelling and experimental analysis of:
  - evacuation dynamics in complex spaces,
  - pedestrian dynamics in complex spaces,
  - combustion and fire/smoke spread,
  - fire suppression,
  - homeland security
- Application areas include:
  - aerospace, built environment, marine and rail.



Applications of FSEG Software


A380 – Super Jumbo


Millennium Dome


Airbus flying wing


Stadium Australia


Royal Ascot

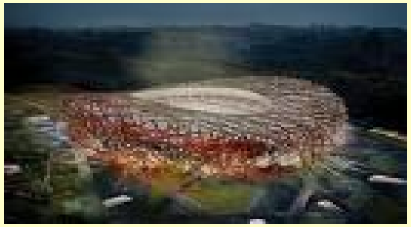

Canary Wharf


Historic Buildings


Rail Stations

Large PAX Ships


Naval Ships


Beijing Olympic Stadium


Statue of Liberty


WTC 9/11 analysis


Pentagon Shield


Forensic analysis
Rhode Island

INTRODUCTION

❑ Post-crash Fires

- One of the most serious threats to passengers in survivable aircraft accidents.
- Initial external fuel fire spreads into aircraft interior either via ruptures or burn-through.
- For conventional aircraft, time to Flashover is a critical factor for evacuation and survival.

Thailand Phuket, 16/09/07

Toronto, Canada 02/08/05

❑ Certification Trial

- **50%** of exits available, one from each exit pair.
- **90 seconds** maximum allowable time for evacuation

Japan Okinawa, 20/08/07

❑ Varied Openings in Accidents

- In real incidents, various number of exits are likely to be available for evacuation.
- Fire and evacuation modelling can be used to investigate the impact of accident events on survivability and can also be used for certification analysis.

FSEG Evacuation Data Collection

Aircraft evacuation exit behaviour – Type A

Aircraft pax stair behaviour

Aircraft evacuation - pax behaviour in smoke

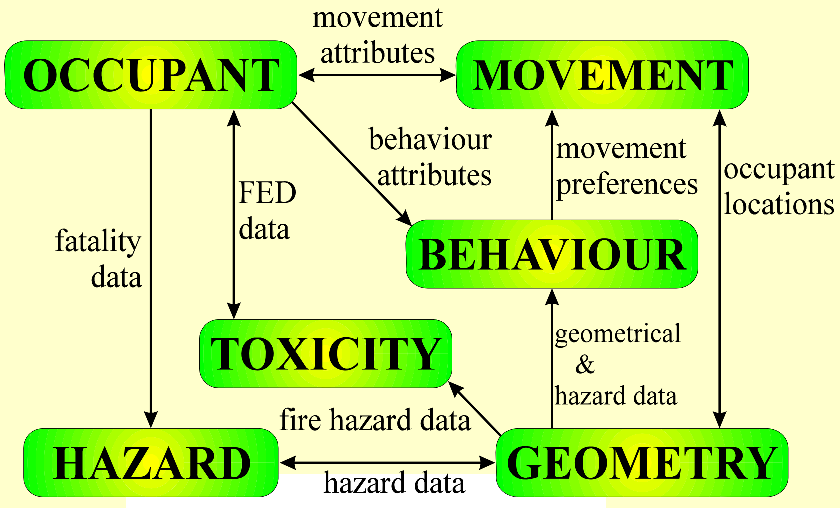
Upper deck Type A slide behaviour

Seat climbing pax behaviour

BWB pax exit selection

airEXODUS Software

- Developed by FSEG and under constant development since 1989
- **Agent based model with Rule Based Behaviour.**
  - •Behaviour is adaptive
  - •Some rules stochastic.



- **Behaviour model considers:**
  - •People-people
  - •People-fire
  - •People-Structure
- **airEXODUS unique features include:**
  - ability to simulate impact of heat, smoke and toxic gases on evacuation capability of individuals
  - ability to include interaction of crew with paxs
  - extensive validation history

airEXODUS — TOXICITY MODEL

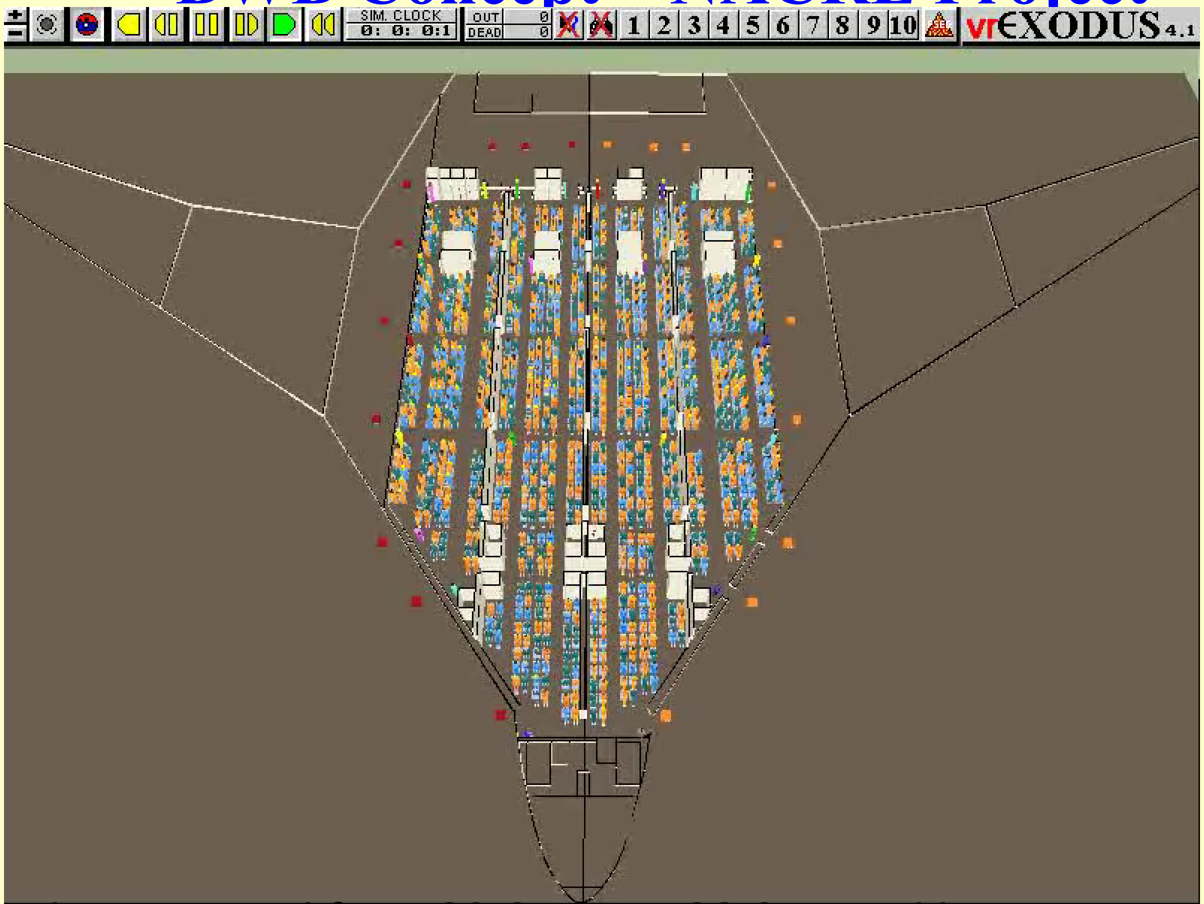
- **Toxic, Irritant and Physical Hazards include:** elevated temperature, thermal radiation, HCN, CO, CO_2, low O_2, HCL, HF, etc.
- Physiological impact of narcotic gases / temp / radiative heat determined using **FED Toxicity Models**. Impact of irritant gases determined through **FIC Model**.
- **FED Models -** effects of narcotic gases related to *dose* received rather than exposure *concentration*.
- **FIC Models** – effects of irritant gases related to conc
- **Incapacitation –** determined to occur when the ratio of dose received (heat or toxic gases) over time to dose required to cause incapacitation reaches unity
- As occupant moves through **Smoke**, travel speed is reduced according to experimental data of Jin, representing impact of reduced visibility.
- Occupants will crawl when smoke conc. or temp at head height exceed critical values.

airEXODUS Applications

airEXODUS

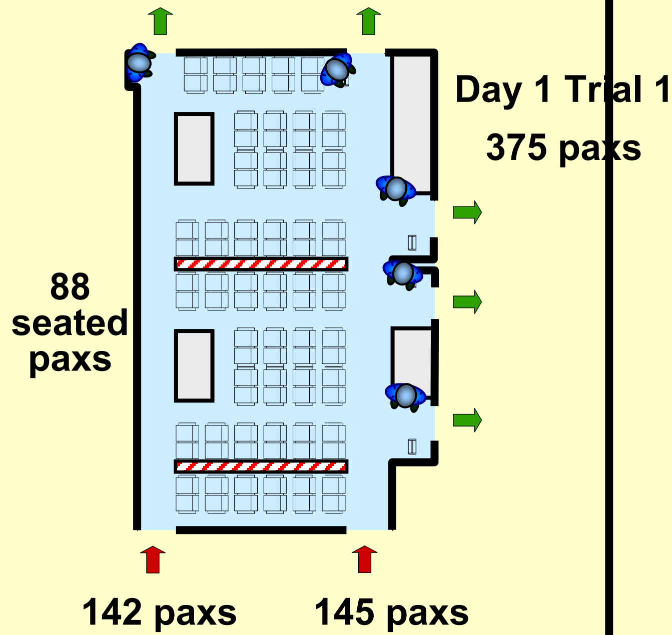
- **airEXODUS Applications**
  - aircraft design, including innovative concepts such as BWB
  - demonstrating compliance with 90-second certification requirements,
  - crew training,
  - development of crew procedures,
  - resolution of operational issues and
  - accident investigation.
  - Aviation applications include:
    - Airbus e.g. A380, A340-600, BWB
    - Bombardier e.g. Dash 8-400, RJ, concept aircraft
    - Mitsubishi e.g. MRJ
    - BA e.g. Novel cabin layout for B777
    - Jet Aviation e.g. VIP configurations
    - Zodiac e.g. novel business class cabin

BWB Concept – NACRE Project



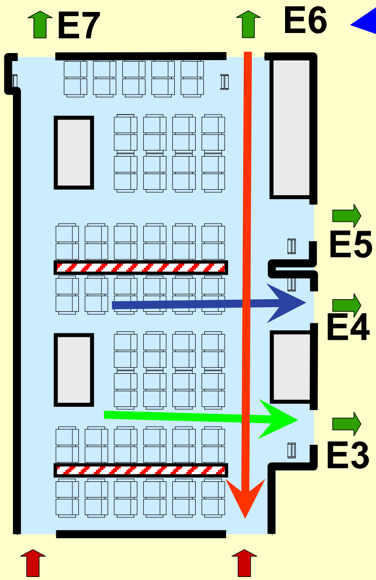
- Egress times ranged from 80.6 sec to 92.8 sec with an average of 85.9 sec.
- On ground times likely to be approx 3 sec longer.
- On average passengers spend 40% of their Personal Evacuation Time caught in congestion – while large, this compares to 56% for a conventional wide body aircraft

Experiment - Set Up



Validation of Egress Simulations

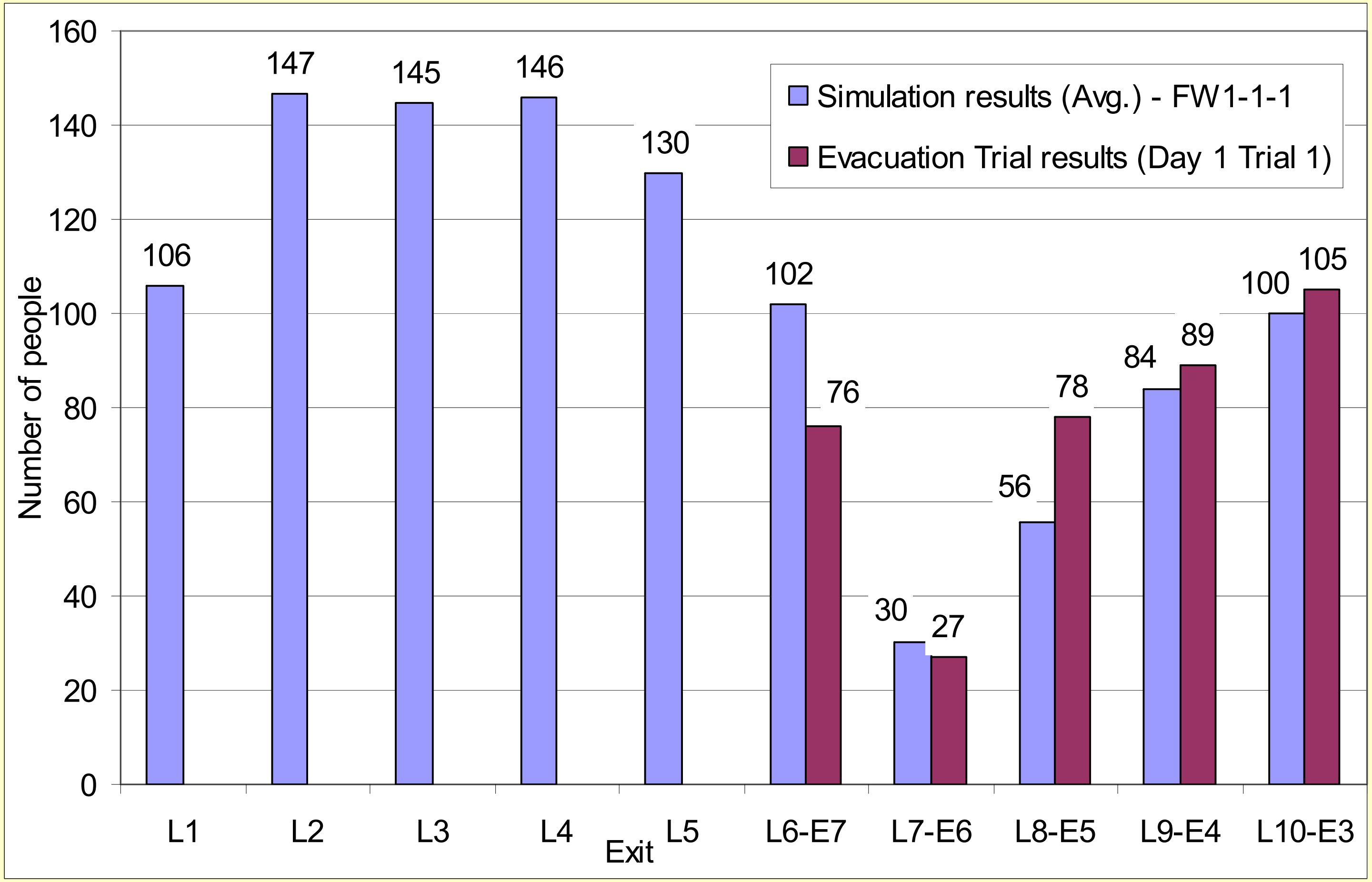
Cam7 O stream above Exit E6 (L7)



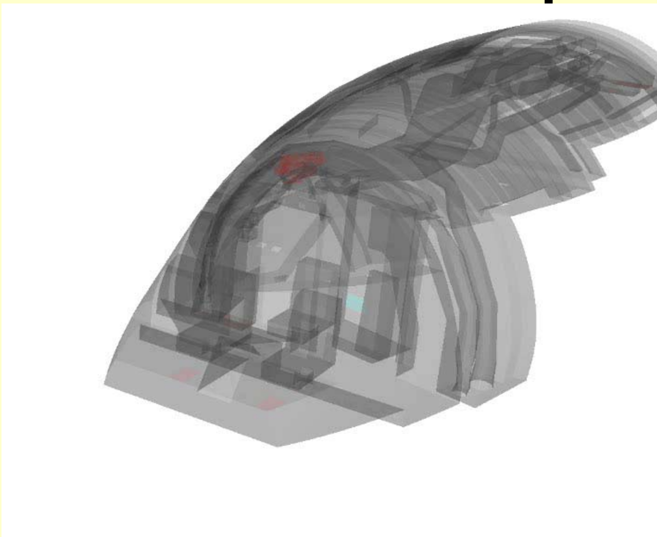
Head Cam Exit E3 (L10)

Blind Validation Results

- airEXODUS predicted exit usage reflected in the experimental results.



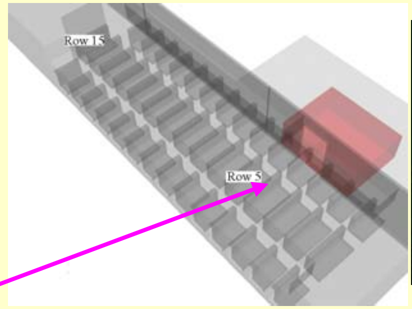
SMARTFIRE Software

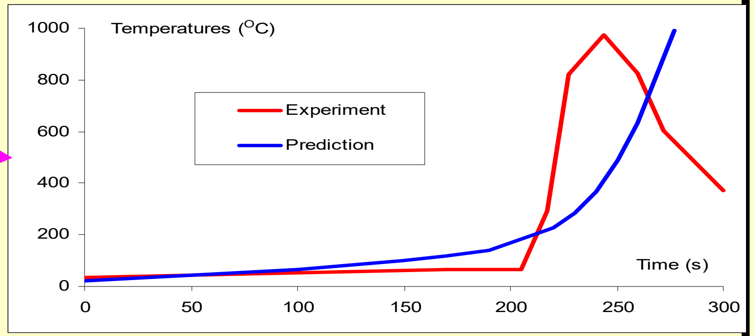


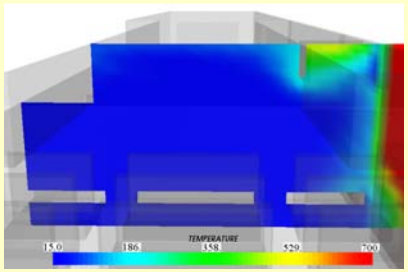
- Developed by FSEG and under constant development since late 1980s
- Software is CFD based.
- Main features include:
  - Two equation K – EPS turbulence model
  - 24 ray discrete transfer radiation model.
  - Eddy Dissipation combustion model.
  - Advanced flame spread model for aircraft fire simulation.
  - Advanced toxicity model for predicting generation of toxic species in fire.
  - Unstructured mesh capability for dealing with complex curved geometries
  - Parallel implementation capable of utilising standard PC computers connected via Ethernet.
  - Developing a GPU version with speedups of 30X achieved.

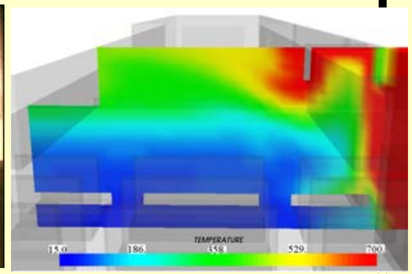
SMARTFIRE Aircraft Fire Validation

- Model Application — simulation of C133 FAA test
  - > Time to flashover
    - – Often taken as the time when upper layer temp exceeds 600^{O}C
    - – In this study: time when the seat (**Row 5**) top **temperature** rapidly escalates
    - – Experiment: **210** seconds
    - – Prediction: **225** seconds
  - > Flame front





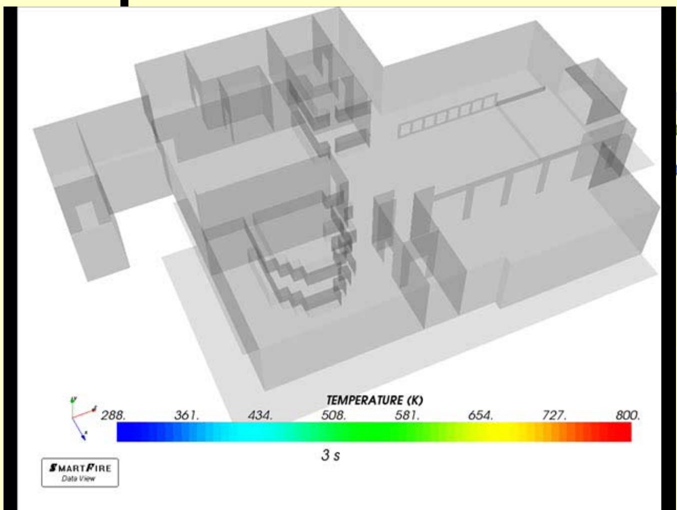


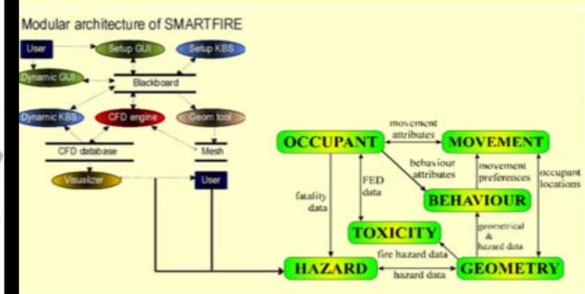


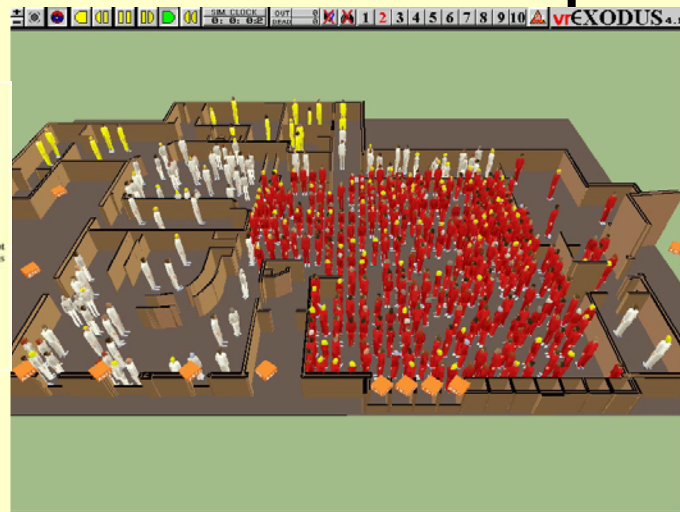
At 20 seconds At 180 seconds

buildingEXODUS and SMARTFIRE Simulation of Station Nightclub Fire

- Link fire simulation directly with evacuation analysis
- Directly expose agents to developing hazard environment
- Predict fatalities and injury levels.







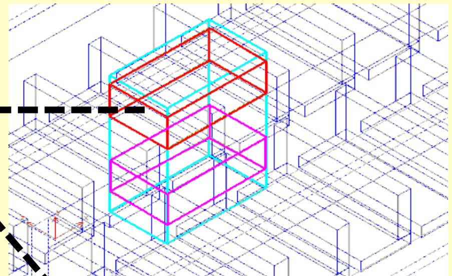
- Last survivor evacuates after approx 127 seconds.
- Simulation predicts :
    - 84 fatalities compared with 100 in actual incident.
    - 25 serious injuries, of which 6 are life threatening.

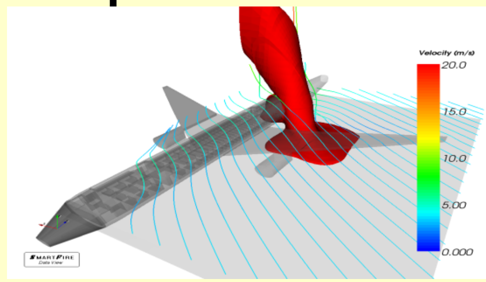
Coupled Fire/Evacuation Simulation Methodology

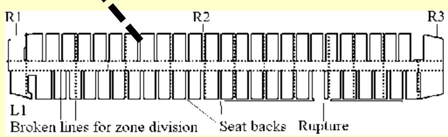
CFD
Fire Simulation

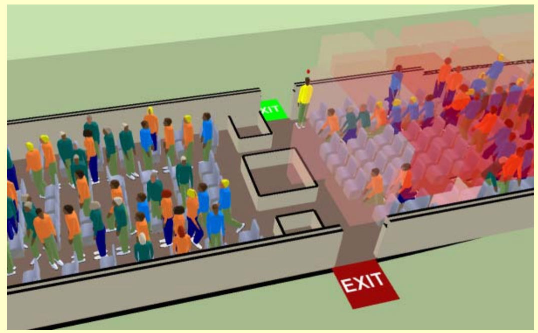
Fire Hazards at Specified Zones

Evacuation simulation



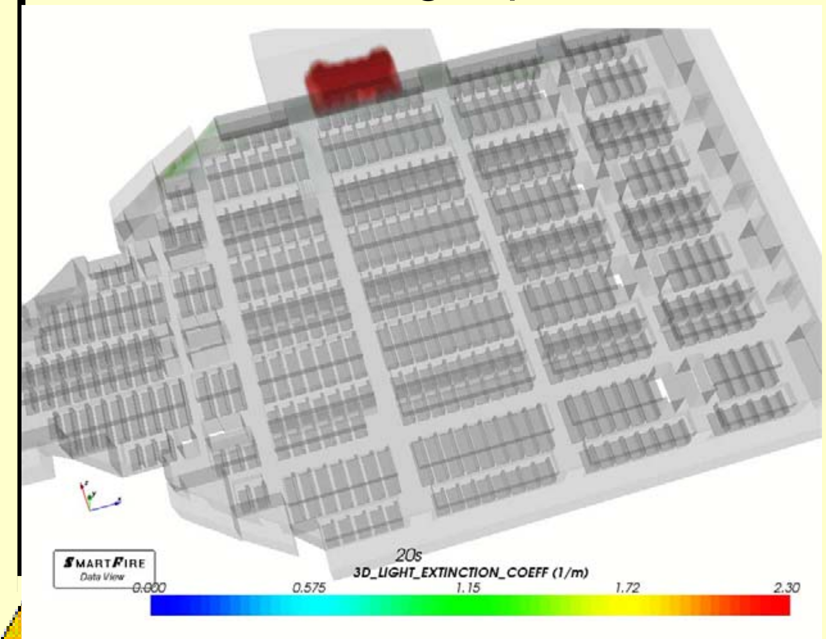






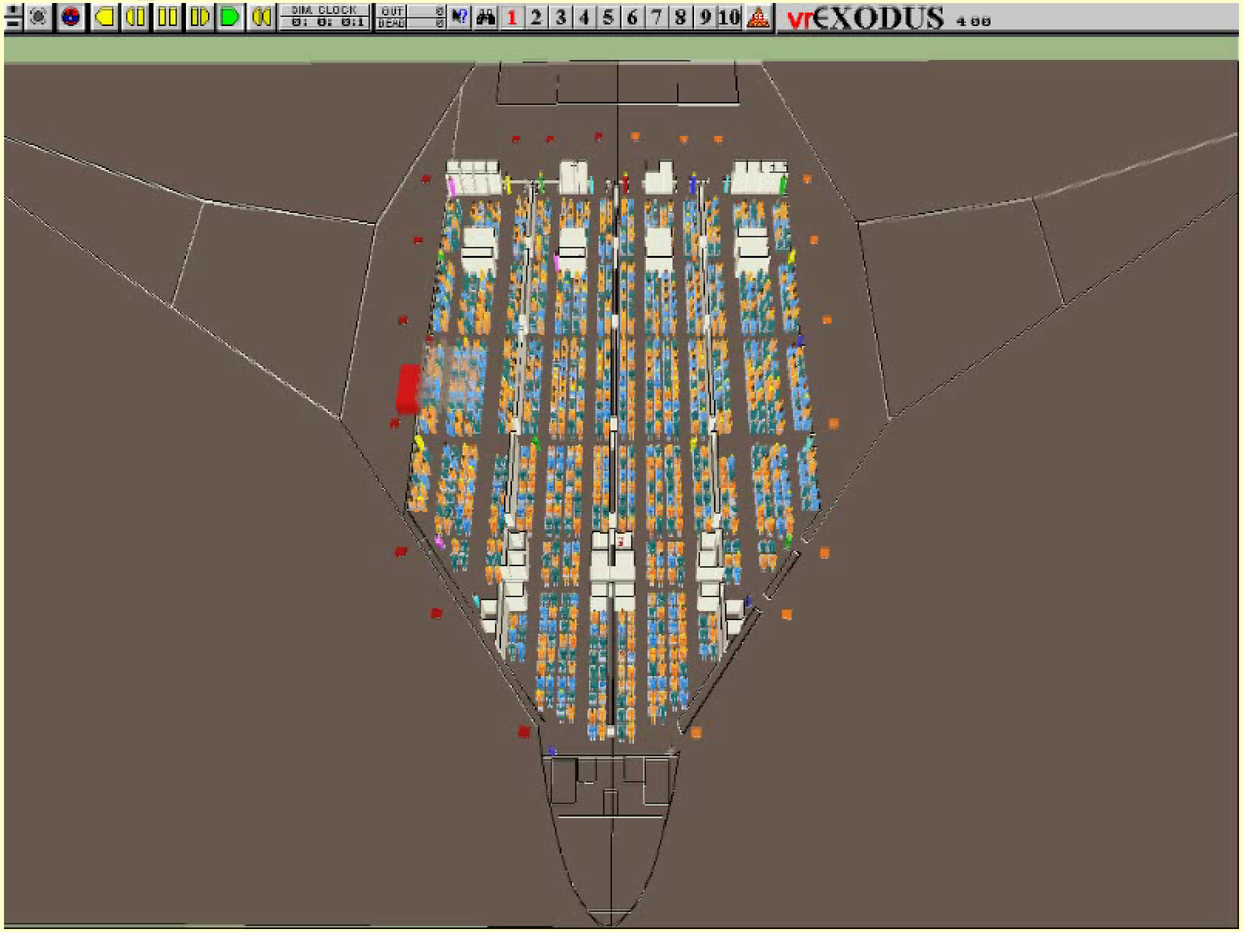
Fire Simulation Results Scenario 3

- Light Extinction Coefficient (2.30/m is equivalent of visibility of 1 m)
  - Over first 100 sec, poor visibility restricted to cabin section containing rupture
- Temp at 1.7 m above floor (skin burns occur at temp above 120^{O}C, incapacitation follows after 1 minute exposure to 190^{O}C).
  - Over first 100 sec, dangerous temp restricted to cabin section containing rupture



RED: 185^{O}C; YELLOW: 143^{O}C; GREEN: 100^{O}C; LIGHT BLUE: 58^{O}C

Coupled Fire and Evacuation Simulation



• Average egress time for S3 89.3 sec, a slight increase over S0 of 85.9 sec.

• 12 fatalities and 25 paxs injured due to heat exposure, 3 of these have life threatening injuries (FIH>0.6)

EVACUATION CERTIFICATION

- **International Evacuation Certification Trial requires:**
  - ***50% of exits available, one from each exit pair.***
    - It is assumed that post-crash external fire occurs on one side of the aircraft and so it is further assumed that all the exits on that side of the aircraft are unavailable.
  - ***90 seconds maximum allowable time for evacuation*.**
    - It is assumed that after 90 seconds, conditions inside the cabin are non-survival or that flashover has occurred.
  - ***Applied to all passenger aircraft*.**
    - Size or configuration of aircraft irrelevant, so same rules apply to A320 and A380.

FAA test 1989

Manchester, UK

22/08/85

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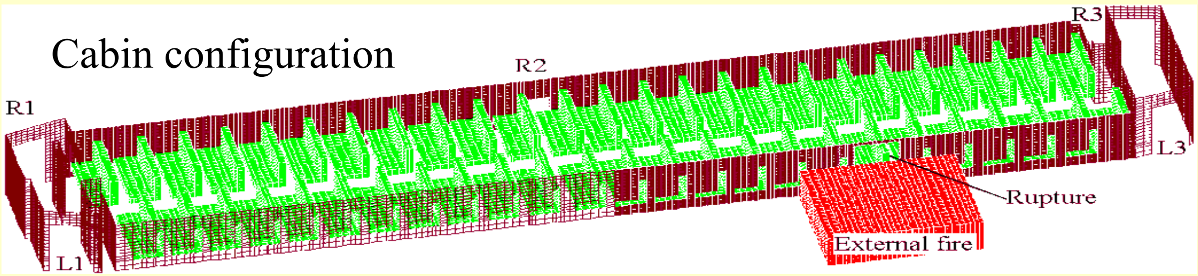
PROBLEMS WITH EVACUATION CERTIFICATION

❑ (Some) Shortcomings of Certification Trial

- Certification trial exit configuration is **not representative:**
  - *most survivable accidents involve a different exit combination from that used in the certification trial [Galea 2006]*
- Certification trial exit configuration is **not challenging:**
  - *with 50% exits available for evacuation, the standard certification trial exit configuration results in the shortest evacuation time [Galea 2007]*
- 90 second requirement is **arbitrary**
  - *Influence of fire on survivability is not considered*
- Certification trial is **not robust**:
  - Only a single evacuation trial is conducted which cannot provide a robust representation of the natural variation in the evacuation process.

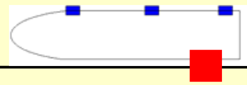
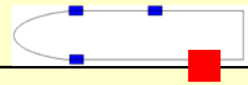
AIM OF THIS STUDY

- For an aircraft configuration that has satisfied the FAR25.803 certification requirements, investigate the deficiencies of the certification trial as a safety indicator in post-crash situations involving fire
- **Cabin Configuration**
  - Narrow body aircraft – similar to B373 or A320
  - Three exit pairs (T-C/B, T-III , T-C/B)
  - Seating for 149 passengers
- **Fuselage Rupture**
  - Assume a cabin rupture located between the L2 and L3 exits
  - Size of rupture is 0.89 m wide and 1.65 m high (the area of a T-B exit).

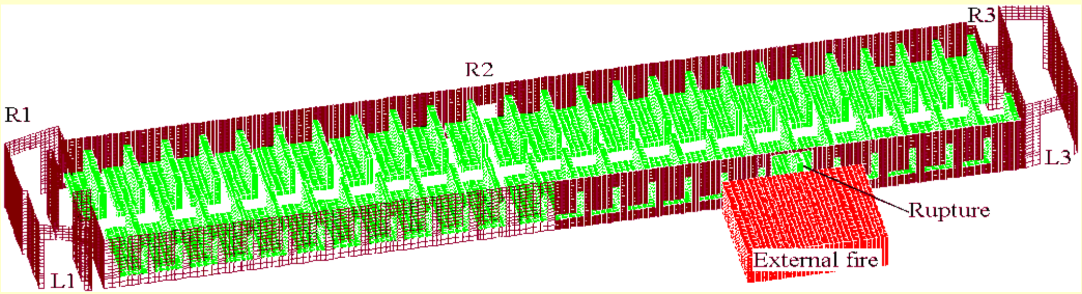


TWO EXIT SCENARIOS

Two Exit Scenarios are considered:

Scenario	**S1** 	**S2** 
Open exits	R1, R2 and R3	R1, R2 and L1

- S1: normal certification exit configuration
- S2: exit combinations commonly found in real accidents, e.g. Manchester Airport B737 fire, 1985.



Cabin configuration

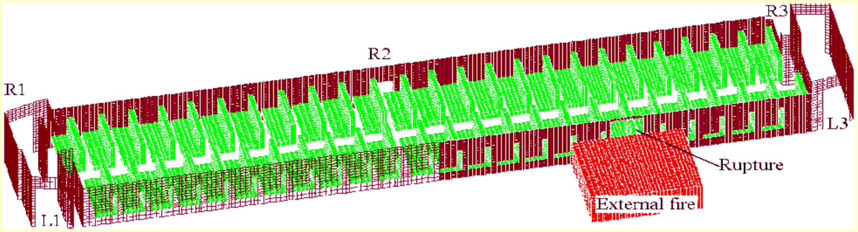
FIRE SIMULATION SET UP

Geometry Set Up

- External fire volume is 2.5m by 3.0m; HRR 7.8 MW, so that flame temp are close to experimental values of 1,480 K
- Mesh: 149,496 computational cells
- Red: external fire volume; Green: seats; Brown: walls; overhead bins removed for good visualization

Fire Models

- **Flame spread model** for ignition of solid surfaces;
- **Eddy Dissipation Combustion model** for release of heat due to combustion of gas fuel generated by pyrolysis of solid materials;
- **48-ray Radiation model** for exchange of heat due to radiation;
- **Toxicity model** for the generation and transportation of toxic fire gases;



SMARTFIRE set up

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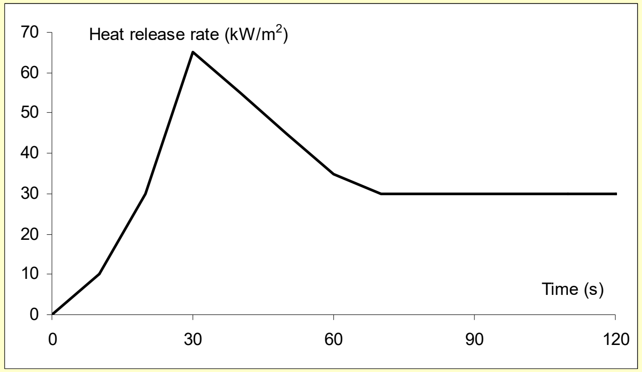
SIMULATION SET UP

Material Properties

- Same as those in the previous work of C133 cabin fire simulations [Wang et al, 2013]
- **Molecular structure:** Epoxy $CH_{1.3}O_{0.2}$ for all materials; Eexternal Kerosene fire is represented as Epoxy
- **Heat release rate**

  A hypothetical heat release rate curve, derived from small-scale experimental tests; satisfies the criterion of 65 kW/m^2 /65 kW-min/m^2



- Other model parameters such as density, conductivity, specific heat, ignition temperatures, yields of toxic gases, etc. derived from various publications.

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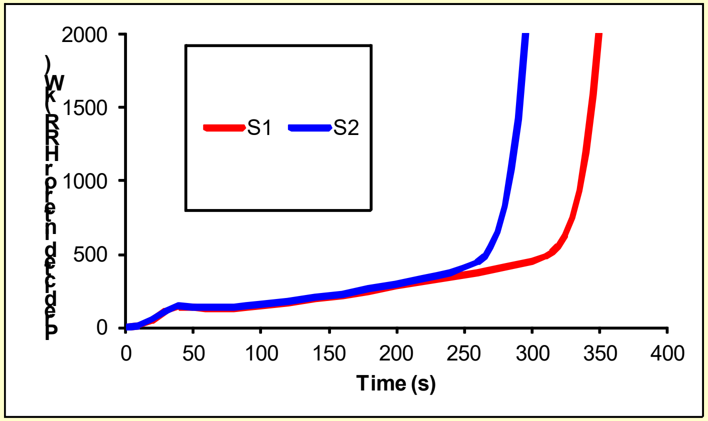
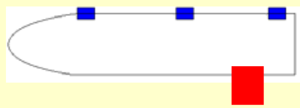
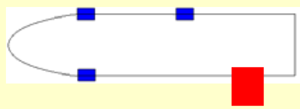
IMPACT OF OPEN EXITS ON FLASHOVER

HRRs and Times to Flashover

- Similar HRRs up to 250 seconds for the two scenarios;
- Onset of flashover: defined as the time at which the predicted interior HRRs rise sharply
- Time to flashover >> 90 seconds – certification requirement



Predicted HRRs from combustion of cabin interior material

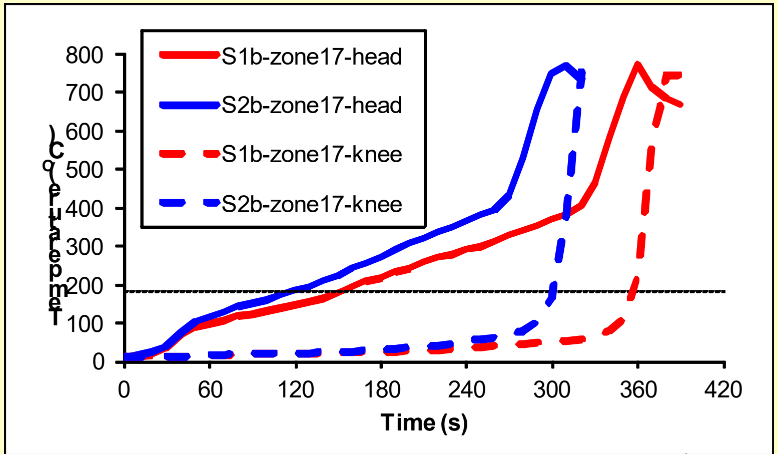
Scenarios		Time to flashover (s)
S1		325
S2		275

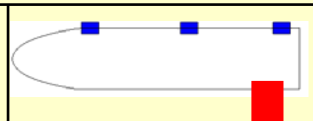
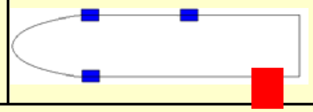
S2 is more challenging than S1 (flashover occurs 18% sooner in S2) and both at least 3x longer than 90 s

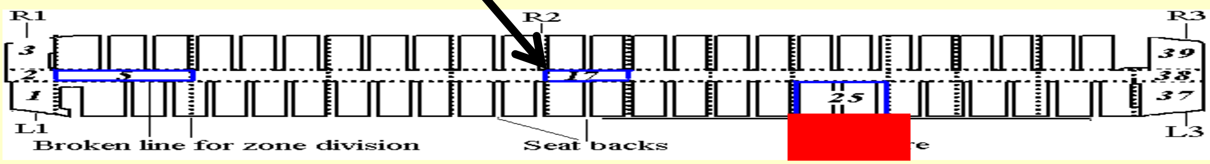
IMPACT OF OPEN EXITS ON HAZARDS

Temperature (as Example)

- Zone 17 in the aisle close to the over-wing exit
- With an air temp of 185^{O}C, there is a 1 min survivability time
- Lower layer temp reach 185 ^{O}C: soon after onset of flashover in each scenario



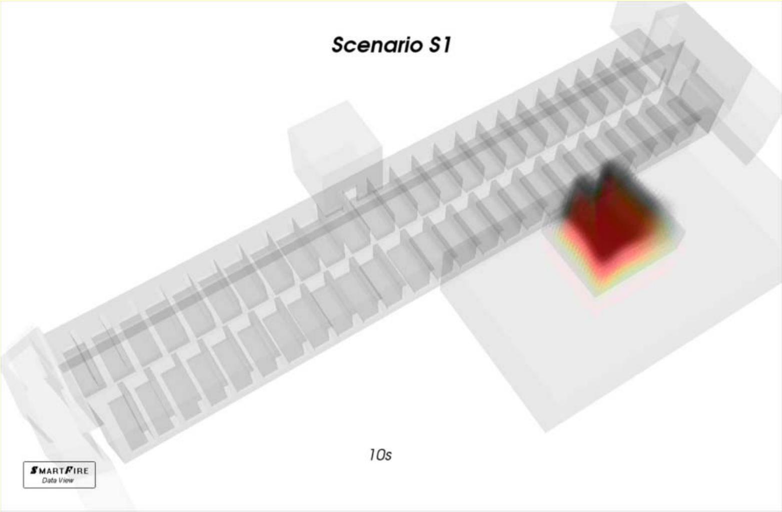
Scenarios		Time for upper temp to reach 185^{O}C (s)
S1		155
S2		120

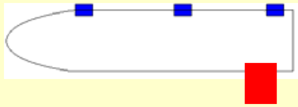


S2 is more challenging than S1

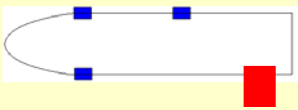
IMPACT OF OPEN EXITS ON HAZARDS

Temperature (as Example)

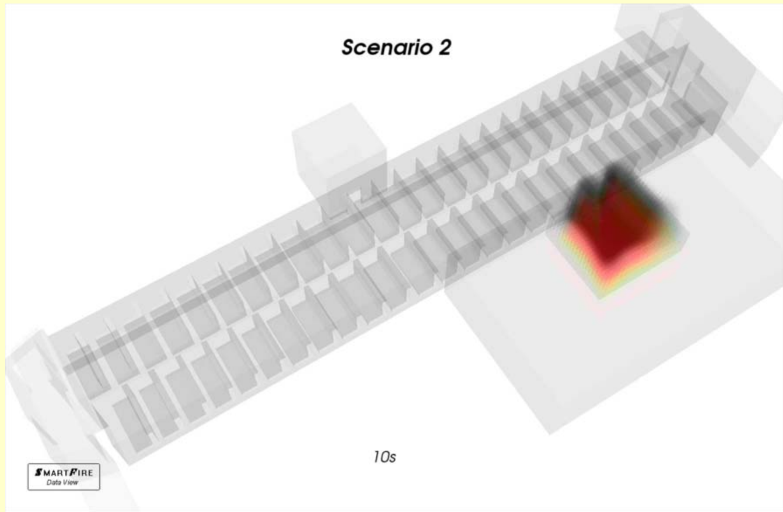


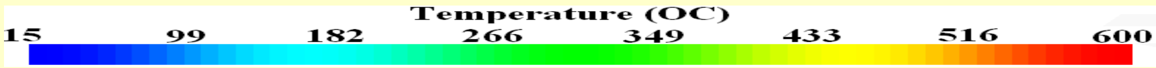


S1



S2



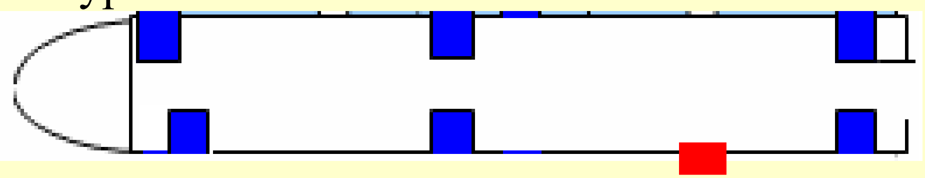


S2 is more challenging than S1

EVACUATION SIMULATIONS

Evacuation Set Up

- Type B/C exits in the front/rear and Type III over the wing
- **149 passengers** with response times no more than **8 seconds**;
- Passengers move to **their nearest viable exits**
- Results for each scenario represents average of **1000 repeat simulations**
  - 10 different certification compliant populations
  - Simulation repeated 100 times for each population
  - Passenger seating allocation is **randomised** in each simulation
- Egress times refer to **on-ground** times



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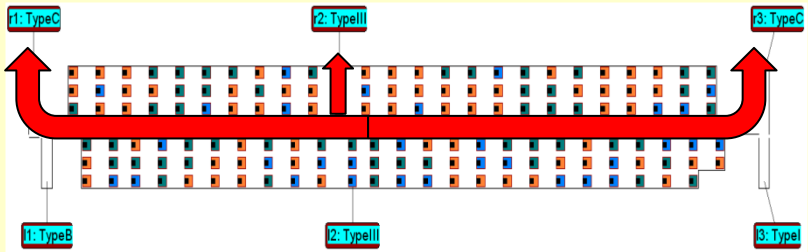
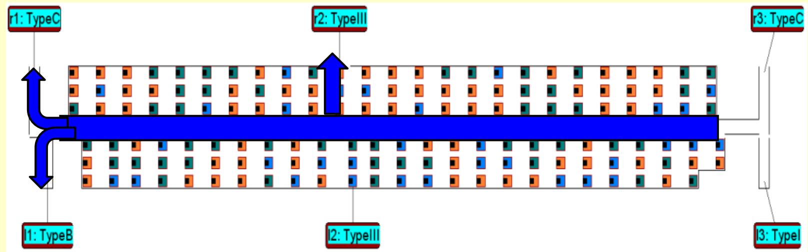
IMPACT OF OPEN EXITS ON EVACUATION

• Evacuation without fire

certification exit configuration **S1** realistic exit configuration **S2**



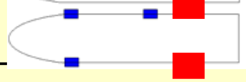


- Exit locations impact average travel distance: **S1: 6.1m ; S2: 10.2m**
- Exit locations impact achieved flow rates, **58.8 ppm** for exit R1 in **S1** and **38.4 ppm** for exit R1 in **S2**
  - the aisle is unable to supply sufficient passengers to keep both exits (R1, L1) working at full capacity in S2
  - Lower flow rate implies longer wait time in the ailse
- For **Scenario S1,** cabin can be emptied within **71.2s** without fire; satisfying '90s requirement'; however, exit configuration **Scenario S2** requires evacuation time of **98.1s**, longer than '90s requirement';

S2 is more challenging than S1

IMPACT OF OPEN EXITS ON EVACUATION

Evacuation with fire

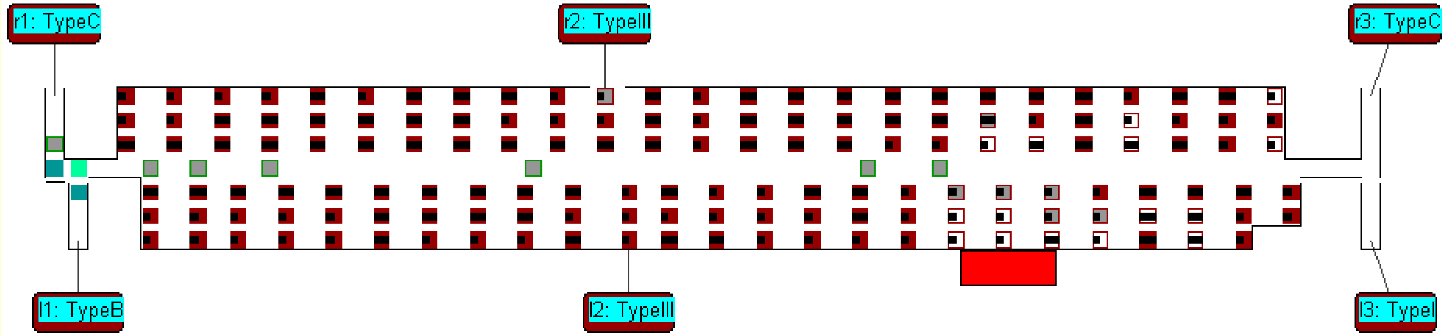
Scenarios		Flow rate at R1 (person per minute)	Travel Distance (m)	Evacuation time (s)
S1		29.9	8.2	149.2
S2		13.5	12.3	260.8

- As noted in the evacuations without fire, S2 has lower exit flow rate and longer average travel distance than those in S1;
- Evacuation times in the presence of fire have greatly increased compared to the non-fire cases:
  - **149.2 s** for S1,
    - S1 with fire is 2X as long as case without fire (71.2 s)
  - **260.8** for S2
    - **S2 with fire is 3X as long as case without fire (98.1);**

S2 is more challenging than S1

IMPACT OF OPEN EXITS ON EVACUATION

Scenario	Number of fatalities	Time for first fatality (s)	Time for last fatality (s)	Average Distance (m)
S1	1.2	31.8	35.9	3.4
S2	14.6	28.2	248.6	12.3

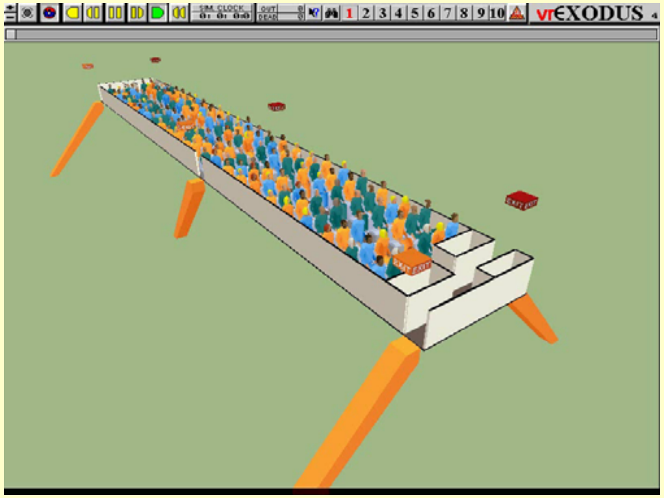


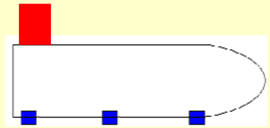
Starting location (open symbols) and death locations (grey symbols) for a single S2 simulation

- **1.2 fatalities in S1**
  - Located in seats adjacent to the rupture, died of heat from external fire, with a short survival time/travel distance;
- **14.6 fatalities in S2**
  - Located in the rear of the cabin, died on the seats near the rupture, aisle, and places near the exits; with longer survival times/travel distances

S2 is more challenging than S1

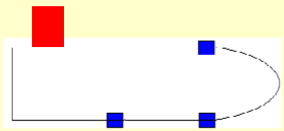
IMPACT OF OPEN EXITS ON EVACUATION

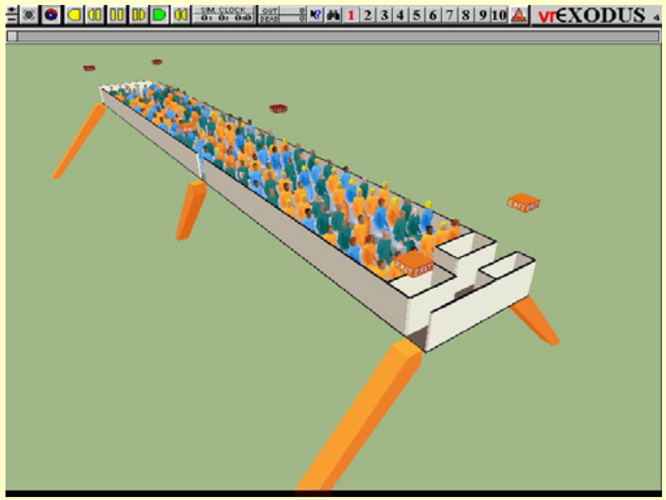




S1

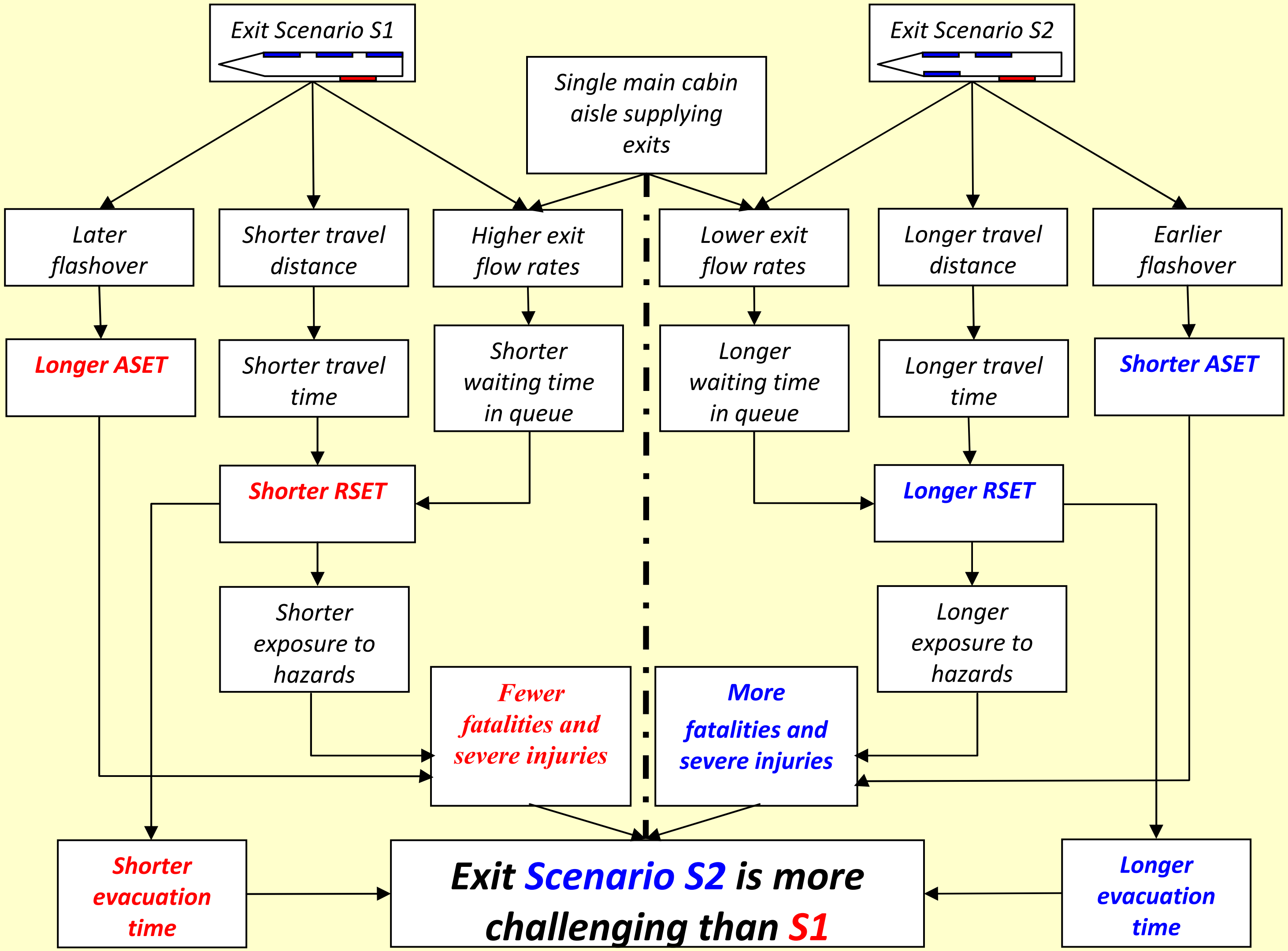
S2





S2 is more challenging than S1

EVACUATION EFFICIENCY COMPARISON



Wide-Body Analysis

- **Geometry**
  - Aircraft is based on a A350 geometry as used in the AircraftFire FP7 project.
  - Four pairs of Type A exits
  - Composite fuselage and composite interior panels – materials not necessarily those used in the A350.

- **Population**
  - 297 passengers and crew are generated from the default certification parameter set.

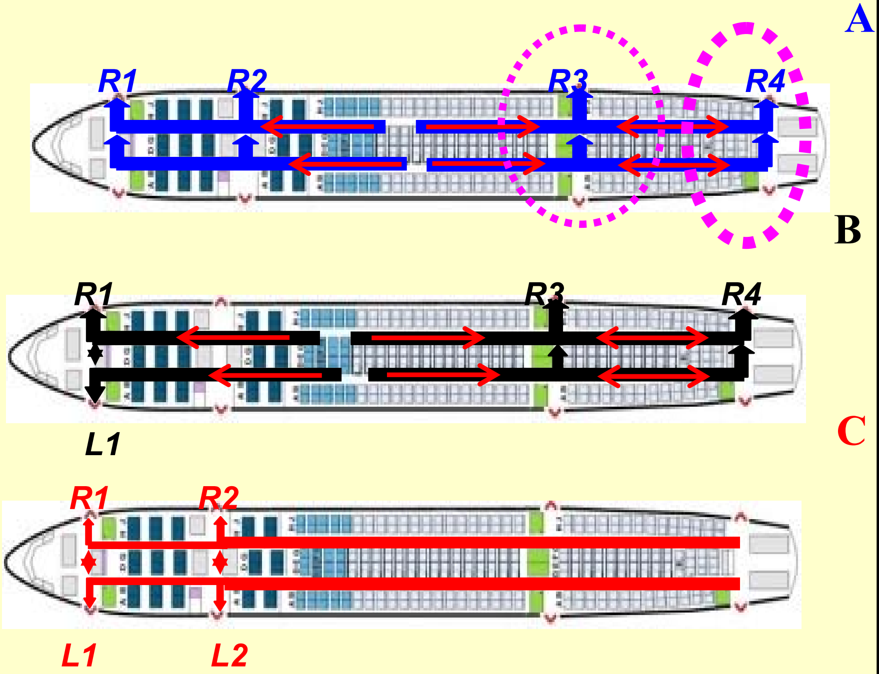
78 hazard zones

Evacuation without Fires

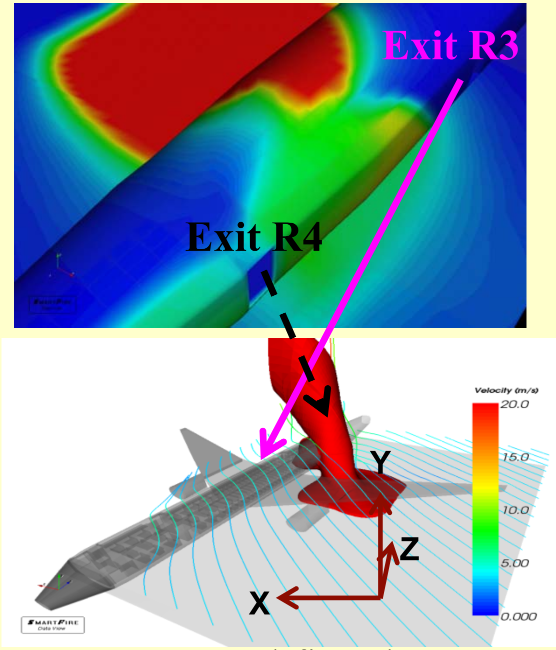
Exits	A Cert	B Acc 1	C Acc 2
Evacuation time (s)	72.1	74.3	140.4

- The configuration **satisfies the 90 s certification trial requirement** in Scenario **A** (R1,R2,R3,R4) with an evacuation time 72.1 s

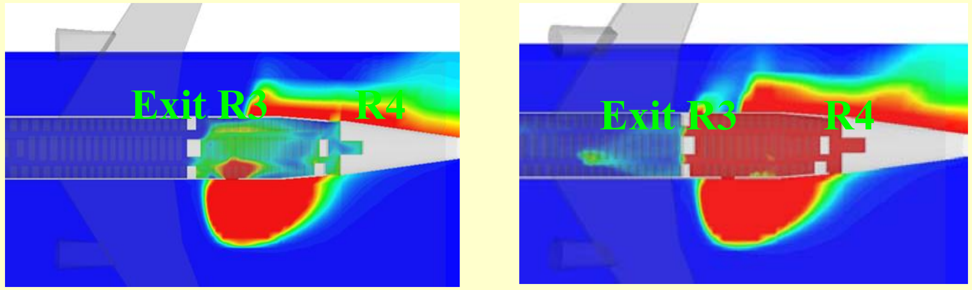
- Scenario **C** (L1, R1, L2, R2) produces an evacuation time of 140.4 s, much longer than 90s ; the exit locations affect the travel distance and flow rate, subsequently the evacuation time



Cabin Rupture with External Pool Fire and Wind

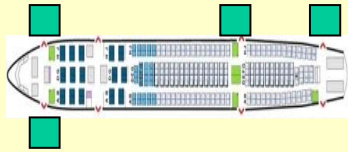


External fire plume



30 seconds 90 seconds

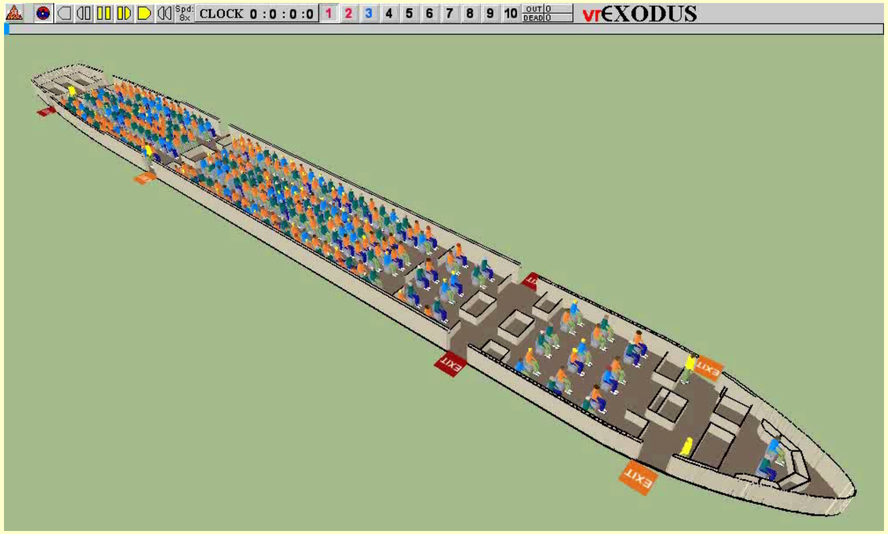
Temperature (red: 120^{O}C) at 1.5 m above cabin floor



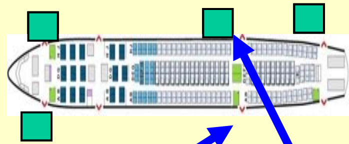
The results are based on **Scenario B** (L1, R1, R3, R4)

- ➢Local flashover occurs at 55 s, much sooner than the required evacuation time;
- ➢Not all the open exits are viable for evacuation
  - Exit R4 is never used as it is engulfed by the external fire;
  - Exit R3 becomes unviable after the cabin interior fire has developed;
- ➢55 fatalities occur from 111.8s to 270.1s into the evacuation.

Rupture Scenarios with Wind



- Exit Scenario L1, R1, R3, R4

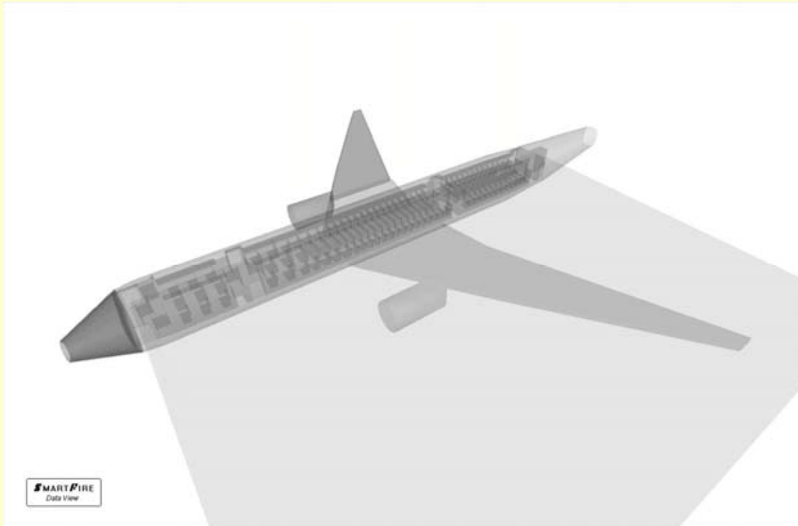


R4 not used due to spread of fire

Fuselage rupture due to crash

R3 not viable after 90 s

- 297 passengers and crew
- Local flashover occurs at 55 s, much sooner than the required evacuation time;
- 55 fatalities occur
- Evacuation time 270.1s



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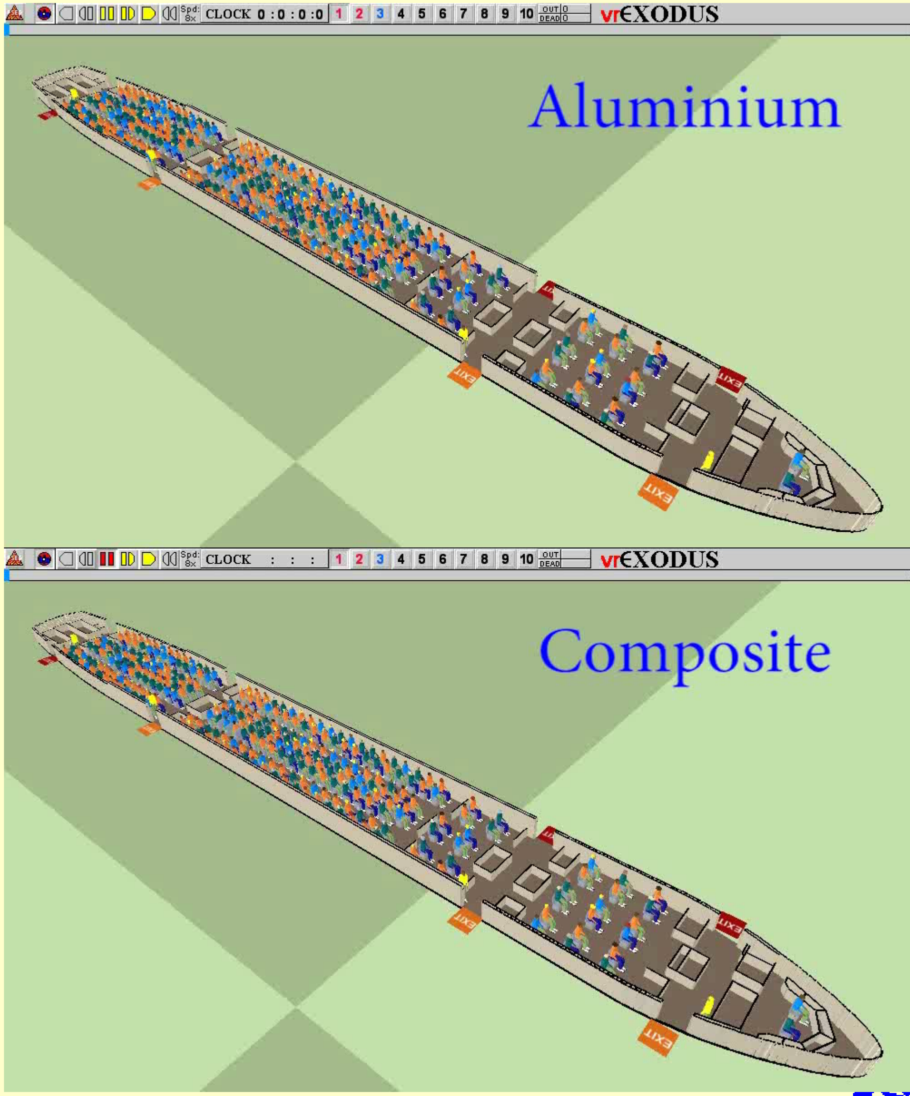
Burn-through Scenarios with Wind

- **Evacuation with post-crash fire and wind**
- **Exits R1, R2, R3 and R4**
- **External fire makes R4 non-viable almost immediately.**
- **Aluminium fuselage**: burn-through occurs with flashover at 119 s and exit R3 becomes unviable; evacuation completed at 226s with 3.2 fatalities;
- **Composite fuselage**: evacuation completed after 85s without any injuries.



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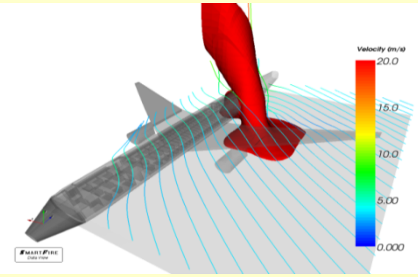
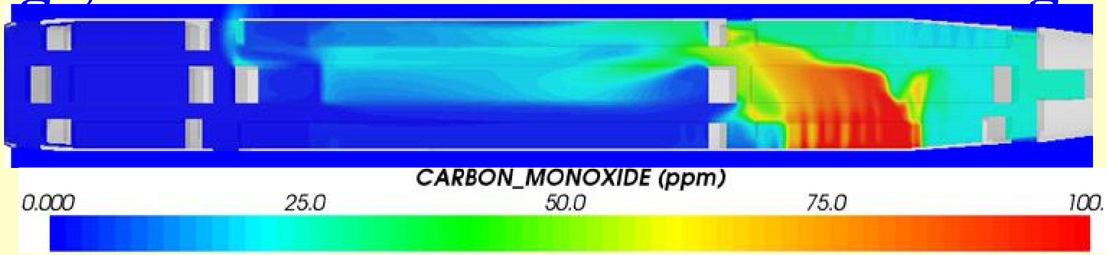
Composite Fuselage, Fire and Wind – NO Burn-Through

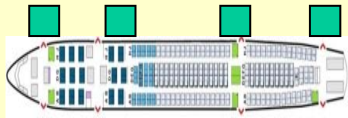


Exit R4 is engulfed



Low CO concentrations at 1.7m above cabin floor at 600 s

- Based on AircraftFire data, the composite fuselage does not burn through however, consider the impact of fire hazards on paxs during evacuation.
- **Fire hazards – heat and toxic gases (excluding SO_2) - from the investigated composite fuselage have negligible impact on evacuation**
  - No passengers are injured by heat or toxic gases from the combustion of the composite fuselage;
  - The unavailability of Exit R4 (even it is opened in exit scenario **A (R1, R2, R3, R4)** affects the evacuation time



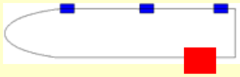
- **Irritants from composite materials**

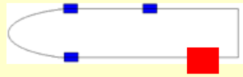
  If SO_2 was produced in the same quantities as CO (as observed in FAA tests (Marker 2011)), it could have a significant impact on passengers during evacuation (approx 18 paxs are at high risk of incapacitation)

❖ **Recommendation:** composite materials with a low yield of highly irritant compounds such as SO_2 should be used in aircraft construction

CONCLUSIONS

- **Evacuation performance has been compared between two different exit scenarios for an aircraft satisfying 90 second certification test;**

S1: 

S2: 

- A narrow body aircraft configuration similar to a B737 or A320 .
- Study involved a given fire size and assumed post-crash fuselage rupture.

- **The certification trial exit configuration S1 is less challenging than the exit scenario S2 which is more likely to occur in real post-crash accidents by producing:**

- Longer time to flashover (325 s > 275 s);
- Shorter required evacuation time without fire (71.2 s < 98.1 s)
- Shorter evacuation time with fire (149.2 s < 260.8 s); and
- Fewer fatalities (1.2 < 14.6)

CONCLUSIONS

- The aviation industry certification trial requirement
  - *50% of exits available, one from each exit pair.*
  - *90 seconds maximum allowable time for evacuation*.

  is inappropriate as a safety indicator as it is not:
  - Representative of likely survivable accident exit configurations
  - A sufficiently challenging exit configuration.
- The alternative exit combination which utilises the same number and type of exits as the current standard, but located in a more realistic accident combination provides a more Representative and Challenging exit combination and so should be used for certification applications.
- It can be argued that modelling should also be used for certification analysis and used to investigate additional exit configurations and additional repeat cases.

CONCLUSIONS

- Coupled fire and evacuation simulations can provide more insight into the fire safety of aircraft cabins than what can be found in certification trials
- Also provides significant insight when used forensically for accident analysis.