THE SAFEGUARD FIRE SCENARIO EVACUATION BENCHMARK AND RECOMMENDATIONS TO IMO TO UPDATE MSC CIRC 1238

E R Galea, A Grandison, D Blackshields, G Sharp, L Filippidis, S Deere Fire Safety Engineering Group, University of Greenwich, London, UK, **I Nicholls, Y Hifi** Safety at Sea Ltd, Glasgow, UK

SUMMARY

This paper describes research that was carried-out under the EU FP7 project SAFEGUARD to develop a fire benchmark evacuation scenario for large passenger ships that could be incorporated within a modified form of the IMO evacuation analysis guidelines. The analysis has involved detailed Computational Fluid Dynamics (CFD) fire modelling analysis of fire scenarios, analysis of experimental data relating to fires in passenger ships and extensive evacuation simulation using two established ship based evacuation modelling tools. The aim of the fire benchmark scenario was to include the impact of the fire on the evacuating passengers without introducing the need to undertake a full fire simulation. The primary impact of the generation and spread of fire hazards considered in the benchmark analysis is the reduction in travel speeds of passengers due to smoke obscuration and a change in the evacuation procedures associated with the fire zone containing the fire. As a result of this work it is proposed that a new degraded scenario be introduced into IMO MSC Circ 1238 that requires the passengers in the identified MVZ to evacuate from the zone horizontally into the neighbouring MVZs. The proposed fire benchmark scenario is demonstrated using a large cruise ship geometry.

NOMENCLATURE

AS	Assembly Station
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CWT	Cumulative Wait Time
EU	European Union
FDSM	Fire Degraded Speed Model
FED	Fractional Effective Dose
FP	Framework Programme
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HRR	Heat Release Rate
IMO	International Maritime Organization
MSC	Maritime Safety Committee
MVZ	Main Vertical Zone

1. INTRODUCTION

In the current IMO guidelines for ship evacuation analysis, IMO MSC Circ 1238 [1], fire is not considered to explicitly impact passenger performance. While evacuation scenarios 3 and 4 in MSC Circ 1238 are intended to represent a damage situation – including a potential fire situation – these scenarios do not represent the impact of the fire on the evacuating population. In these scenarios, the "fire" is only considered to force the passengers in the affected vertical fire zone to move into the neighbouring fire zones. However, it is possible that the passengers within the affected zone will be impacted by spreading fire hazards and as a result their movement rates are likely to be affected. A safety factor of 1.25 was introduced to the predicted total assembly time to account for this and other omissions and simplifying assumptions.

One of the aims of the EU FP7 project SAFEGUARD is to include a representation of the impact of the fire on the passengers in the affected zone. Fire effluent consists of smoke, irritant and toxic gases and heat. The impact of fire effluent on an exposed evacuating population is complex and varied. Smoke tends to obscure vision and as a result slows movement speeds of exposed individuals. Toxic gases such as Carbon Monoxide (CO) and Hydrogen Cyanide (HCN) can cause intoxication, resulting in staggered movement, slowed down movement and eventually incapacitation and death. Irritant gases such as Hydrogen Chloride (HCl) can affect the eyes making it difficult to see and the respiratory track and lungs making it difficult to breathe, both of which can impede the exposed passengers' evacuation progress, resulting in incapacitation and in extreme cases, death. Heat, both convective and radiative can cause pain to exposed skin, resulting in burns and may damage the respiratory track and lungs making it difficult to breathe. Excessive exposure to heat can result in a reduction in travel speeds, and can cause incapacitation and death [2].

The most straightforward and accurate way to include the impact of fire on passengers would be to undertake a fire simulation (using advanced computational fluid dynamics (CFD) fire simulation tools) for a prescribed fire scenario and couple the results to an evacuation simulation. However, this approach has the disadvantage of being prohibitively expensive in terms of time, resources and computational power. Furthermore, not all ship evacuation simulation software tools have the ability to incorporate the impact of fire hazards on individuals. An alternative approach is to define a generic data-set specifying both the temporal and spatial spread of fire hazards (smoke, temperatures, toxic gases) for a generic pre-determined fire. Hazard conditions on each deck would then be determined as a function of distance from the seat of the fire on the deck of fire origin. This approach was considered impractical as it is not possible to deduce scaling rules that could be reliably applied to any arbitrary geometry, and so it is not possible to define a generic fire hazard data-set that could be applied to any arbitrary ship geometry.

The approach which was finally adopted simply takes into consideration the reduction in passenger travel speeds that would result from exposure to fire hazards. Using this approach a representative set of reduced passenger travel speeds must be determined. As such, the resulting evacuation analysis will not require the fire hazard data to be input into the evacuation simulation. The specification of a travel speed reduction is also consistent with the specification of the current MSC Circ 1238.

This approach is the simplest solution and eliminates the need to calculate the effects of heat and toxic gases and trying to determine the spread of the fire atmosphere via CFD fire simulation or applying scaling methods to an arbitrary geometry. In addition, the proposed approach could also be used within the simplified evacuation analysis. It is however noted that the approach would not produce a prediction of expected fatalities or injury levels, nor would it provide an assessment of the fire safety provision afforded by the design. Finally, the only additional requirement imposed on the evacuation model by the suggested analysis process is that it has an ability to prescribe a passenger travel speed reduction factor within specified regions of the vessel. This approach is referred to as the Fire Degraded Speed Model (FDSM).

2. FIRE SIMULATION

To inform the development of the FDSM it was necessary to generate a plausible atmosphere within the context of the geometry of a cruise ship using appropriate heat, smoke, and toxic species release rates. This was necessary to determine the impact of the fire effluent on passenger travel speeds. Unfortunately, little detailed experimental fire data exists describing fires within a passenger ship geometry. As a result it was necessary to use CFD fire simulation to simulate possible fire scenarios. However, before this could be done with confidence, the CFD fire simulation tool would need to be validated using a ship fire scenario. The CFD fire simulation software SMARTFIRE [3-10] was used in the analysis and it was validated using ship fire data generated by the Swedish National Laboratory, SP Fire Technology. The laboratory performed a number of large-scale ship fire experiments involving a passenger cabin [11] and in one of these cases the fire Heat Release Rate (HRR) was recorded. Brief details of this validation exercise are described below. A more detailed account of the validation exercise can be found in [12].

2.1 VALIDATION EXERCISE

Before the SMARTFIRE software was used in the ship fire analysis it underwent validation using the SP fire data. The SP test geometry, consisting of two cabins (Cabin A and B) and a corridor (see Figure 1) was recreated using SMARTFIRE (see Figure 2). The temperature and gas measurements used for comparison with model predictions were collected from the locations shown in Figure 1. A non-uniform computational mesh consisting of 118,144 cells was used to define the geometry and the software was used to simulate the fire for over 40 minutes (2400s).

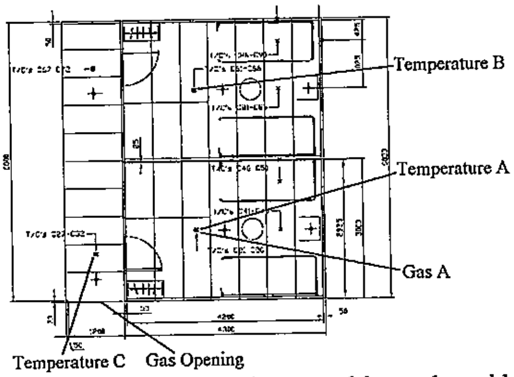

Figure 1 - Plan view of the test cabins and corridor (Figure reproduced from [11])

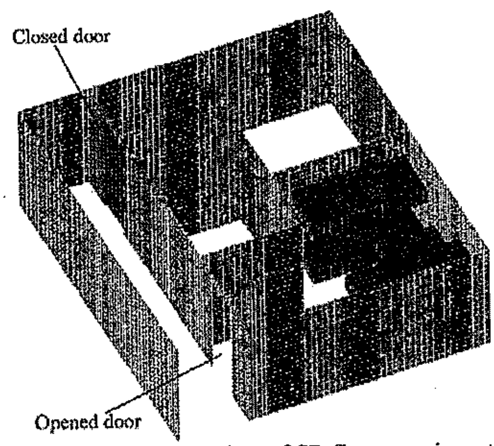

Figure 2 – Representation of SP fire experiment in SMARTFIRE.

The HRR derived from case 4b of the SP trials represented a mock up passenger cabin loaded with a set of typical furnishings and luggage for a passenger ship. In case 4b there were two safety failure modes incorporated into the experiment, the cabin door was left open and the water mist system in the cabin was inoperable. A small selection of results are presented here, more detailed results are available in [12]. Note that due to a malfunction during the experiment there are no results from the cabin of fire origin and corridor after 600s.

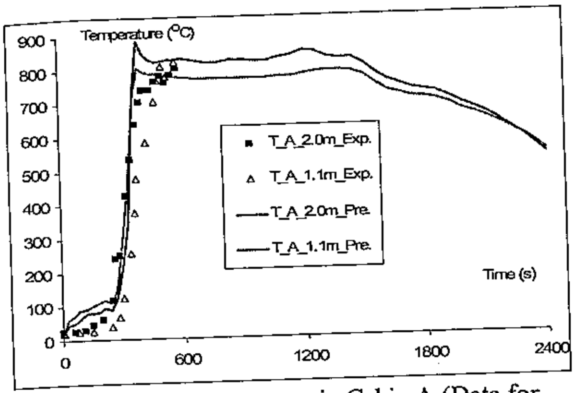

Figure 3 - Temperatures in Cabin A (Data for experimental values extracted from [11])

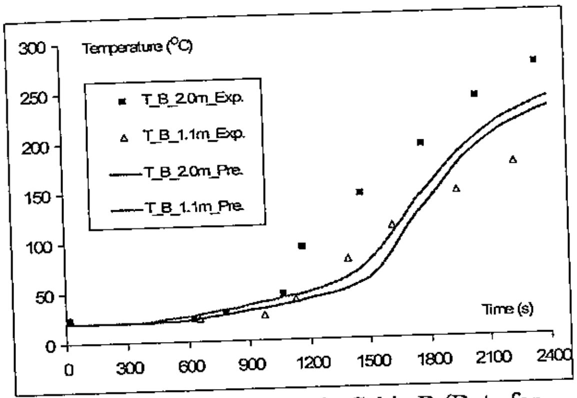

Figure 4 - Temperatures in Cabin B (Data for experimental values extracted from [11])

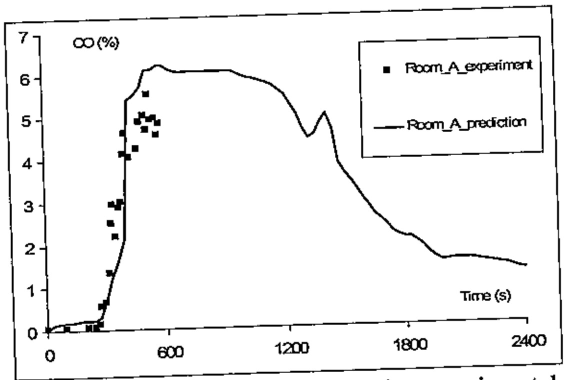

Figure 5 - CO in Room A (Data for experimental values extracted from [11])

Similarly good agreement was also found with gaseous species concentrations (see Figure 5 and Figure 6). This validation exercise demonstrates that SMARTFIRE is capable of modelling the SP ship cabin experiment and the SP case can be used as a basis for the scenarios to be simulated within arbitrarily complex cruise ship geometry.

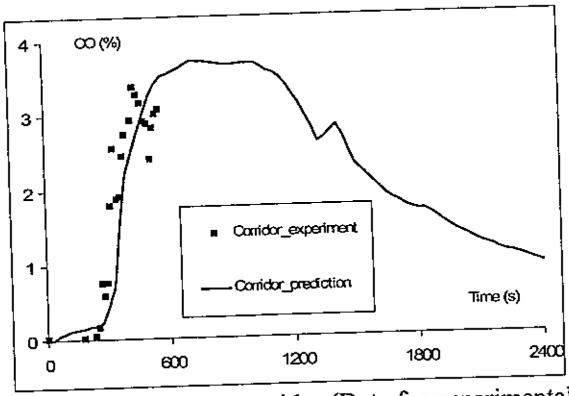

Figure 6 - CO in the corridor (Data for experimental values extracted from [11])

2.2 SHIP TEST GEOMETRY

A hypothetical vertical fire zone geometry based on a typical cruise ship configuration was developed. This geometry was used to investigate the impact of a developing fire on passengers within the vertical fire zone. The geometry consists of two 40m corridors connected by a cross passage (see Figure 7) replicated over five decks. The geometry incorporates five accommodation decks connected by an open stairwell (see Figure 7). With the exception of the cabin of fire origin, the geometry does not explicitly represent the other cabins on the five decks nor the lifts connecting the decks as these components do not take part in the fire simulation. It is assumed that, with the exception of the cabin of fire origin, all the other cabin doors are closed and the lifts are not functioning. The ends of the corridor are also assumed to be closed. The stairwell is assumed to be open to allow the potential spread of heat, smoke and toxic species to other decks in the Vertical Zone. It is further assumed that the fire does not cause secondary ignition to other potential fuel sources in the geometry.

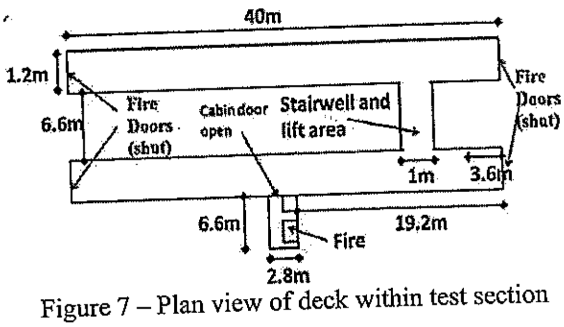

Figure 7 – Plan view of deck within test section

The fire HRR used in the fire simulations in the cruise ship vertical fire zone was based on the fire in the SP test [10]. However, the HRR was modified to take into account under-ventilation effects which occurred in the hypothetical cruise ship vertical fire zone. In the SP fire test, the geometry had a short corridor that was open to the "outside", allowing it to be well ventilated.

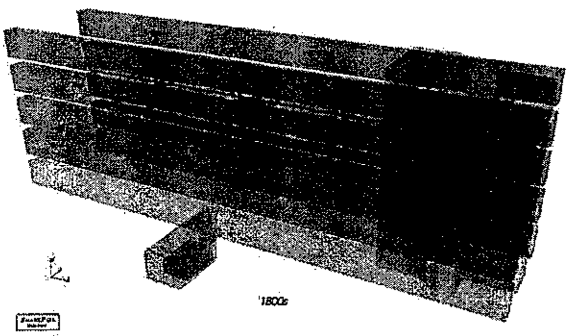

Figure 8 – 3D view showing 5 deck geometry

Only results relevant to the development of the FDSM model will be presented here, further details are available as part of the SAFEGUARD project [12]. The FDSM model is only concerned with the reduction of mobility of passengers exposed to the fire hazards and is not intended to predict incapacitation, injury or death of exposed passengers. Thus, the most important result from this perspective is the level of smoke obscuration caused by the fire.

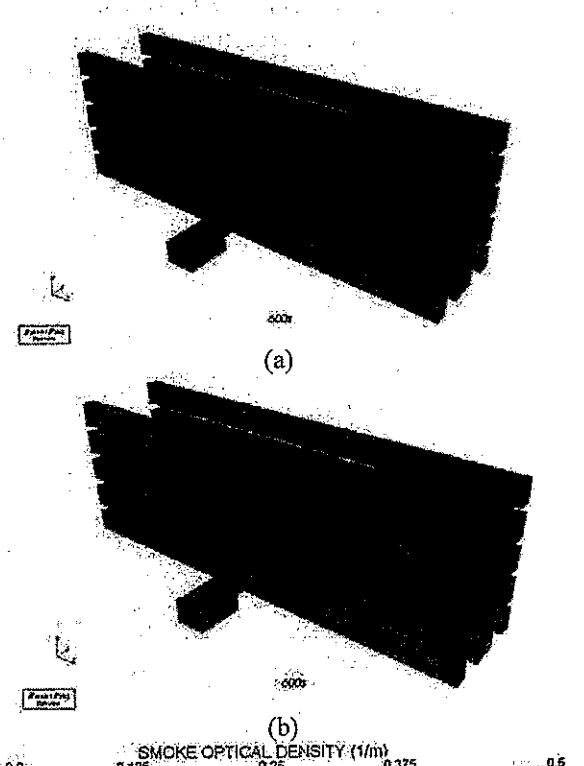

Figure 9 - Smoke distribution through the test section after 600 seconds (a) unsuppressed fire; (b) water mist system active in the corridors

Two fire scenarios were considered, one without a water mist fire suppression system active and one with a water mist fire suppression system active, but only in the corridors. The suppression system almost fully restricted the spread of heat, smoke, and toxic species to the deck of fire origin. The system also reduced the heat in this area to essentially ambient levels. Within the corridor of fire origin the CO level and smoke concentration levels were far higher than predicted for the case without the fire suppression system.

In Figure 9 the contour maps for smoke optical density are plotted with the red contour indicating a value of 0.5/m or greater. A smoke optical density of 0.5/m indicates a very low level of visibility that would significantly impair mobility [13]. From Figure 9(a) it can be seen that in the unsuppressed fire the smoke optical density is above 0.5/m on the four lower decks and is above 0.5/m on the top deck above head height. From Figure 9(b) it can be seen that the deck of fire origin has high levels of smoke but the suppression system has essentially been successful in preventing the spread to the other decks.

3. THE FDSM MODELS

Based on the fire simulation results produced in the hypothetical cruise ship main vertical fire zone, two possible simple models for mobility degradation are suggested. In the first model, the fire products have spread to all the decks in the Main Vertical Zone (MVZ) due to the fire being unsuppressed and due to the doors to the main stairs being left open. In the second model, the fire products are restricted to the deck of fire origin due to the fire suppression system in the corridors being active.

The results from the SMARTFIRE CFD fire simulation for each fire case were used as part of a coupled fire-evacuation simulation using the maritimeEXODUS evacuation software [8-10, 14-16]. The test geometry was modified to include additional vertical zones to either side of the fire zone. The spread of fire hazards is restricted to the central MVZ. The three MVZs are identical and based on the MVZ used in the fire simulations. Each corridor was initially populated with 52 agents, 104 per deck, 520 per MVZ producing a total of 1560 agents for the simulated ship geometry.

A night scenario was considered in which the agents were given response times in the range of 400 s to 700 s. In both fire cases (fire hazards spread to all decks and fire hazards restricted to a single deck) the agents have their walking speed reduced in the affected MVZ and are assumed to horizontally evacuate the affected zone to the nearest neighbouring zones as it is assumed that the stairwells within the MVZ affected by the fire are untenable. Once the passengers/crew members have left the affected MVZ it is assumed that they travel with their normal walking speed. It is assumed that muster decks are still available in these zones and that passengers can enter these muster decks horizontally from neighbouring zones. No speed reduction is applied to muster decks. These areas can be used to horizontally travel through an affected MVZ if a passenger's assigned muster station is blocked by an affected MVZ.

A main outcome of this analysis was that most of the passengers on the affected decks would rapidly reduce their travel speeds to their minimum travel speed allowed by maritimeEXODUS due to smoke obscuration (> $0.5m^{-1}$), regardless of which fire case was considered. As a result of this analysis, two Fire Degraded Speed Models (FDSM) are suggested:

- Fire Degraded Speed Model 1 (FDSM 1): Representative Fire Scenario: Severe fire scenario with no fire suppression active. Fire hazards spread rapidly to all decks in the affected MVZ.
  - Resulting Passenger Travel Speed: All the passengers/crew within the MVZ that contains the fire utilise a smoke affected walking speed until they have horizontally evacuated into the nearest neighbouring vertical zone(s). Once they are in the neighbouring zone(s) they are assumed to use their normal walking speed.
  - Nature of Evacuation Simulation Required: Only one evacuation simulation is required as all the passengers/crew within the effected MVZ are forced to travel at the minimum walking speed during the horizontal evacuation phase.

- Fire Degraded Speed Model 2 (FDSM 2):
  - Representative Fire Scenario: Several types of fire scenarios may be considered: (1) severe fire scenario with fire suppression active in the corridors but not the room of fire origin e.g. rapid fire growth, water mist in corridors, resulting in fire effluent spread only to the deck of fire origin. (2) less severe fire scenario, as FDSM 1 but with a 360s delay offset i.e. slow fire growth, resulting in fire effluent spread only to the deck of fire origin and no passengers predicted to be incapacitated;
  - Resulting Passenger Travel Speed: Only the passengers/crew on the deck of fire origin within the MVZ that contains the fire utilise a smoke affected walking speed until they have horizontally evacuated into the nearest neighbouring vertical zone(s). All passengers/crew on other decks within the MVZ that contains the fire utilise their normal walking speed and also evacuate horizontally to their nearest neighbouring vertical zone(s).
  - Nature of Evacuation Simulation Required: A number of evacuation simulations are required, one for each accommodation deck. This is required as the fire may be located on any of the accommodation decks within the MVZ and so a simulation is required for each deck.

For comparison purposes a third FDSM is considered. In this case the passengers/crew within the affected deck do not reduce their travel speeds, but the evacuation procedure is applied to the affected zone. This case is only considered in order to determine whether the change in evacuation procedures associated with the fire or the reduction in travel speed due to the fire has the greater impact. This case is known as FDSM0.

- Fire Degraded Speed Model 0 (FDSM0):
  - Representative Fire Scenario: While the passengers are not exposed to fire hazards, the same evacuation scenario that is used in FDSM1 and FDSM2 is employed without a reduction in passenger travel speed.
  - Resulting Passenger Travel Speed: Passengers/crew within the affected MVZ travel with their normal walking speeds and evacuate horizontally to the nearest neighbouring vertical zone(s).
  - Nature of Evacuation Simulation Required: Only one evacuation simulation is required as all the passengers/crew within the effected MVZ travel with their normal walk speed during the horizontal evacuation phase.

These FDSM scenarios represent a step towards the SOLAS 2010 concept of 'Safe return to port" [17]. This concept involves evacuating the passengers from the entire fire zone, and moving them to safe areas on board the vessel. The incident (fire or flood) is contained in that fire zone while the vessel safely returns to port or the vessel waits assistance. The difference in the proposed fire scenarios is the availability of the assembly stations within the affected fire zone.

An important component of the FDSM1/FDSM2 model is the reduced travel speed that is imposed on the agent when exposed to severe smoke obscuration. There is little data describing walking speeds of people in severe fire situations. Reduced walking speeds that have been reported in the literature are between 0.2 m/s and 0.4 m/s depending upon the person's age and gender [18], while Jin [13] observed that the walking speed dropped to approximately 0.4 m/s as the smoke extinction coefficient reached 0.5/m. However, more severe smoke obscuration conditions can develop within a fire. It is thus possible that a slower movement speed must be applied to real fire scenarios than that reported by Jin. Furthermore, Bukowski [19] observed that a blindfolded person walked at a speed of 0.3 m/s. It is thus suggested that a minimum speed of 0.3 m/s is used as the default reduced travel speed in the FDSM.

The FDSM model only imposes reductions in travel speed resulting from smoke obscuration generated by the fire. It is noted that fire hazards may also result in injury, incapacitation and even death to those exposed. Incapacitation and death are determined using a

Fractional Effective Dose (FED) model [2]. While FED models are included in the maritimeEXODUS model they cannot be included in the FDSM approach as the FED models require the actual hazard atmosphere produced by the fire. This would require the fire to be simulated and included in the evacuation analysis.

It is worth noting that when FED models where included in the maritimeEXODUS analysis of the hypothetical cruise ship section using the CFD generated fire data, it was found that a significant number of the exposed agents were incapacitated. In particular, it was noted that when full heat and toxicity effects were included for the first model (fire hazards spread to all decks) that 89 agents were incapacitated [12]. In the second fire model (fire restricted to a single deck) 51 agents were incapacitated [12]. Only by increasing the incipient growth phase of the fire by 360 seconds were no agents incapacitated and only mobility effects were noted. By necessity, the potential for incapacitation/death resulting from exposure to fire hazards is excluded from the proposed FDSM approach as the detailed fire hazard data is not included. However, one way of estimating the potential number of fatalities associated with the FDSM analysis is to consider the deck clearance times for the decks exposed to the fire hazards. For this type of analysis to be meaningful it is necessary to also stipulate maximum acceptable deck clearance times, and this can only be done with knowledge of the spread of the fire hazards.

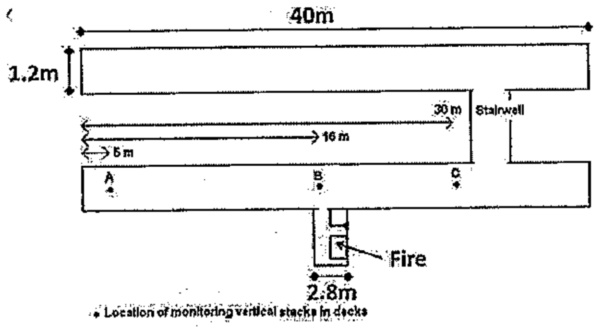

Figure 10 – Locations of FED monitoring points in accommodation section in corridor of fire origin.

In Table 1 incapacitation times for three locations in the corridor of the hypothetical cruise ship section (see Figure 10) are tabulated. These are based on the maritimeEXODUS evaluation of the FED at the three locations at head height. For this particular fire, survival time is driven by exposure to the narcotic gases, HCN and CO. Based on these hazards, an agent located in the corridor will have between 312 s to 337 s to survive. Clearly for this particular fire it is necessary to have cleared the fire deck within this period of time (as measured from the start of the fire, not the start of the evacuation) to avoid fatalities. However, it is not possible to generalise this to other ship geometries and other fire scenarios. The difficulty with this approach is identifying the maximum allowable deck clearance time unless a full CFD fire simulation is undertaken.

Table 1 – Time to incapacitation according to location for a static agent in the located in the corridor with cabin of fire origin

Position	Time to incapacitation due to HCN and CO	Time to incapacitation due to Heat
A	337s	366s
B	312s	319s
C	334s	360s

3.1 INITIAL ANALYSIS OF THE FDSM MODEL

The simplified FDSM models were initially tested using two geometries:

- The hypothetical cruise ship section described above.
- A hypothetical RO-PAX Ferry geometry.

The FDSM models were applied to these two geometries to determine the impact that they may have on the total time to assemble. The hypothetical cruise ship section was used to explore the impact of the FDSM models on a night case scenario, while the RO-PAX geometry was used to explore the impact of the FDSM models in both day and night case scenarios [12]. Analysis of these results suggested that the greatest impact of the FDSM model was in the night scenario for the RO-PAX vessel. This resulted in the greatest difference in assembly times between the FDSM models and the normal IMO night case scenario. It was also noted that there was little difference between the FDSM1 and FDSM2 models, suggesting that both models lead to similar conclusions. This is important as it would be preferable to adopt the FDSM1 model as this requires considerably fewer scenarios to be run than the FDSM2 model. Furthermore, there was little difference between the FDSM0 and FDSM1/2 models. This suggests that the reduction in travel speeds has little impact on the overall assembly time with the change in the assembly procedures generating the increase in the overall assembly times.

From the results generated for the hypothetical ferry additional refinements were added to the FDSM approach.

- The safety active crew, e.g. performing searches, would respond with the lowest value for the possible response times. This was immediate response for day time case and 400s for the night time case. In both cases these crew response times provide an opportunity for the crew to be involved in counter-flow situations without unduly delaying their response. Other crew members are assumed to use the same response time distribution as passengers.

- Crew assigned to searching cabins do not use the stairs in the MVZ containing the fire. Crew enter the identified MVZ horizontally and proceed to the most distant end of the zone.

3.2 FDSM Applied to a Full Scale Cruise Ship

The final demonstration case involved application of the FDSM models to a full scale cruise ship geometry. The model was simulated by the Fire Safety Engineering Group (FSEG), University of Greenwich using their maritimeEXODUS software [8-10, 14-16] and Safety At Sea Ltd (S@S) using their EVi software [20, 21]. FSEG examined the day case scenarios while S@S focused on the night case scenarios. More details concerning this analysis can be found in [22].

3.2.1 Ship Geometry

The vessel has 13 decks and seven main vertical zones. Passenger cabins are located on decks 2 to 10. The muster stations are located on deck 6 and 5 as shown in Figure 11 and Figure 12. The main vertical zones numbered from the forward to the aft end as depicted in Figure 13. Fire Zone 7 (FZ7) was identified as the slowest zone in the IMO night case and Fire Zone 6 (FZ6) was identified as the slowest zone in the IMO day case.

3.2.2 Day Case

The day population consisted of 2502 passengers and 668 crew members and followed the demographic required by IMO MSC Circ 1238. Following the IMO MSC Circ 1238 protocols the slowest zone to assemble as identified for the standard IMO day scenario; this was identified as FZ6. The FDSM models were then applied to this zone. Using IMO MSC Circ 1238 protocols for running simulations the cases were run 50 times each. The FDSM0 model was performed using both 50 simulations and 250 simulations. In the following discussion the FDSM0 case is the basis for comparison and so it was decided to generate more than the standard 50 repeat simulations. In total 250 simulations were run for the FDSM0 case.

3.2.2.1 Overall Assembly Time

The assembly times calculated for the IMO Day case and the FDSM models are presented in Table 2. FDSM2 was only applied to cases where passengers would be affected by the speed reduction. These decks were 2, 4, 11, 12, and 13 (denoted by FDSM2-2, FDSM2-4 etc). If there were no passengers on a deck that the FDSM2 model was applied to, the resulting simulation would be equivalent to that produced by the FDSM0 model.

Table 2 - Overall Assembly Times for Cruise Ship (day case)

Case	Min (s)	Average (s)	Max (s)	95th %ile (s)	%diff FDSM0 (average)	%diff FDSM0 (95th %ile)
IMO Day	773	841	914	909	-22	-25
FDSM 0	842	1080	1305	1219	0	0
FDSM 1	915	1089	1280	1265	0.8	3.7
FDSM 2-2	883	1081	1255	1215	0.0	-0.3
FDSM 2-4	879	1076	1238	1210	-0.4	-0.8
FDSM 2-11	930	1079	1250	1191	-0.1	-2.3
FDSM 2-12	853	1074	1226	1207	-0.6	-1
FDSM 2-13	897	1071	1206	1199	-0.9	-1.7

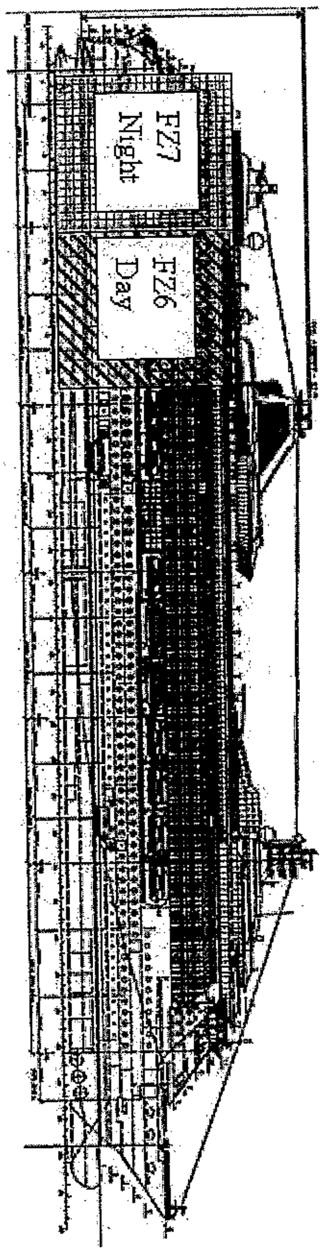

Figure 13 Cruise Ship Geometry with slowest fire zones for IMO night and day cases highlighted

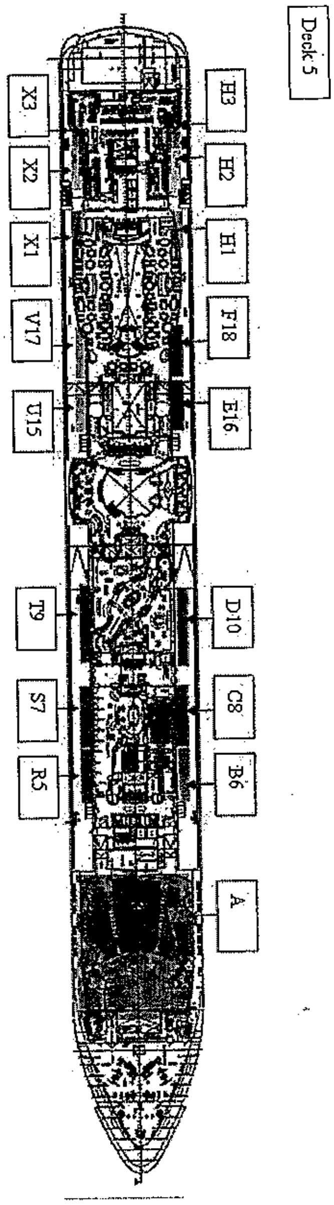

Figure 12 – Muster Station Arrangement Deck 5 of Hypothetical Cruise Ship

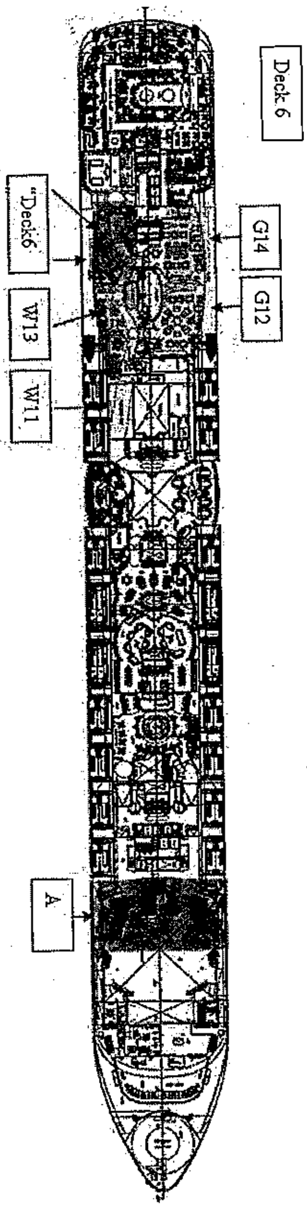

Figure 11 - Muster Station Arrangement Deck 6 of Hypothetical Cruise Ship

Examination of the predicted assembly times reveals that the standard IMO day case was 22% quicker than the FDSM0 model on average and 25% quicker for 95th percentile case. It can be clearly seen that the change of procedure has significantly increased the overall assembly time for this particular scenario. The addition of speed reduction appears to have very limited effect. For the FDSM1 case the increase in average assembly time is only 0.8% (9s) and for 95th percentile case is 3.7% (46s) over that of the FDSM0. From this analysis we conclude that the procedural change associated with the FDSM models has a much more significant impact on the total assembly times than the decrease in travel speeds for the day case. Furthermore, if we compare the FDSM1 case with the FDSM2 cases we note that the maximum difference in the average assembly times is only 2% while the average difference in the 95th percentile cases is only 6%. Thus there is little difference in the total assembly time produced by the FDSM1 and FDSM2 models.

3.2.2.2 Deck Clearance Times

Analysis of the overall assembly times suggest that the speed reduction associated with the FDSM models has only a modest effect on the overall assembly times. Here we examine the impact of the speed reduction on the deck clearance times. Due to the random variation within the simulations it is difficult to isolate the impact that the change in model specification has on the simulation outcome compared to the random variation inherent in the simulation i.e. population demographics, agent assigned response times, agent starting locations and agent decision making associated with congestion conditions. In an attempt to minimise the impact of the natural randomness within the simulation, only one simulation of both the FDSM0 and FDSM1 models are compared however, all the population initial conditions (population demographics, agent assigned response times and agent starting locations) are identical in both cases. The only randomness which is not controlled is that associated with the agent decision making.

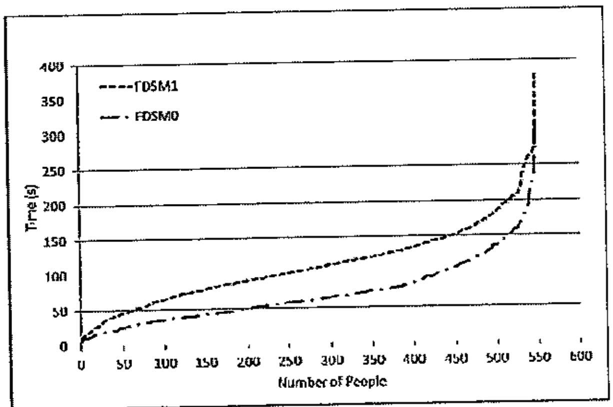

Figure 14 – Overall Fire Zone (FZ6) Exit time

Presented in Figure 14 is the overall zone clearance time for FZ6 produced by the FDSM0 and FDSM1 models. Clearly the time required to clear the fire zone is significantly greater with the reduction in agent travel speeds.

Presented in Table 3 are the deck clearance times for the FDSM0, FDSM1 and FDSM2 models (the longest clearance time for each deck is highlighted). It can be clearly seen that the FDSM1 model takes significantly longer for the decks to clear compared to the FDSM0 model. Furthermore, the FDSM2 cases are essentially the same as the FDSM0 case when clearing the non-speed reduced deck and has essentially the same clearance time as the FDSM1 case on the deck where the speed reduction is applied. The time for the last occupant to leave the FZ6 zone is 322s for FDSM0 and 378s for FDSM1, a difference of 56s. The maximum difference in deck clearance times is for deck 13; for the FDSM0 case this was 166s and for FDSM1 the time was 262s, a difference of 104s or an increase of 67% compared to the FDSM0 case. Thus, while the increase in total assembly time associated with the speed reduction is small, the increase in deck and fire zone clearance times can be significant. In the presence of a hazardous fire atmosphere, these increases in deck and zone clearance time could result in a number of fatalities being produced.

Table 3 - Deck Clearance Times for FDSM0, FDSM1 and FDSM2 models

	Deck Clearance Time (s)			
Deck	FDSM0	FDSM1	FDSM2 Deck 2	FDSM2 Deck 4
2	131.1	162.3	162.3	131.1
4	229.1	277.4	228.8	277.4
11	321.9	377.5	322.0	322.0
12	175.0	182.1	175.0	175.0
13	166.4	261.7	166.4	166.2
Max	321.9	377.5	322.0	322.0

Deck	FDSM2 Deck 11	FDSM2 Deck 12	FDSM2 Deck 13
2	131.1	131.1	131.1
4	228.8	228.5	228.8
11	377.8	321.9	322.0
12	175.0	182.1	175.0
13	166.2	166.4	261.7
Max	377.8	321.9	322.0

3.2.2.3 Assembly Stations

While the speed reduction introduced into the FDSM1 and FDSM2 models has a significant impact on the deck clearance times, it has little impact on the overall assembly time. Here we examine whether the speed reduction has an impact on the assembly times associated with the various assembly stations. The assembly times for each assembly station produced by the standard IMO Day Case, FDSM1 and FDSM0 models are presented in Table 4. This data clearly shows that there is little difference between the FDSM0 and FDSM1 assembly times for each assembly station. This suggests that the reduction in travel speed does not have a significant impact on the assembly time for the individual assembly stations.

However, there is a significant difference in the predicted assembly times produced in the IMO Day Case and the FDSM model. In most cases the FDSM assembly times are significantly greater than those for the IMO Day Case. This difference is due to the procedural change. However, in a few cases, the assembly time for the IMO Day Case is greater than that for the FDSM case i.e. assembly stations X2, X3, G14, H2 and H3. In these cases the increase in assembly times could be due to random variations or to changes in the congestion associated with crew in contra-flow.

Table 4 - Average assembly station assembly times (day case)

AS	IMO Day (S)	FDSM1 (S)	FDSM0 (S)
A	764	982	989
B6	539	674	652
C8	562	685	686
D10	559	714	706
Deck_6	765	759	764
E16	538	603	607
F18	499	581	579
G12	467	521	508
G14	590	555	552
H1	739	754	743
H2	584	580	559
H3	558	520	519
H4	764	759	764
R5	618	848	839
S7	620	868	851
T9	580	722	717
U15	513	579	576
V17	474	545	540
W11	505	588	576
W13	427	480	448
X1	697	711	730
X2	632	617	600
X3	568	511	522

3.2.2.4 Analysis of last agent to assemble

It has been shown that the reduction in agent travel speed within the fire zone makes little difference to the overall assembly time. In order to gain greater insight into why the speed reduction makes little difference the performance statistics for the last agent to assemble in each of the 50 simulations for the FDSM1, FDSM0 and standard IMO day cases are examined. Furthermore, it is clear that the change of procedure makes a large difference to the overall assembly time but it is not clear why. By exploring performance statistics such as response time, travel speed, distance travelled, congestion, etc for the last agent to assemble we can understand why these results are produced.

(a) Agent Response Time

One possible explanation for the increase in the assembly time of the FDSM cases compared to the standard IMO day case is that the last agent to assemble has a significantly longer response time in the FDSM cases than the agents in the IMO case. Presented in Table 5 are the average response times for the last agent to assemble derived from the 50 simulations for the standard IMO Day Case and the FDSM1 and FDSM0 cases. Also shown is the average response time for the entire population of the vessel as sampled from the standard IMO population demographic. As can be seen, the average response time for the last agent to assemble in the FDSM cases is not significantly different to the population average. The last agents to assemble for the IMO day case have a longer average response time than the average response time for the entire population and indicates that for the IMO day case the response time is a factor in determining the overall assembly time. Presented in Figure 15 is the distribution of the response time for the final agent to assemble. This shows that in the majority of cases, the response time for the final agent to assemble is reasonably small.

Table 5 – Mean Response Time for last agent to assemble

Case	Population	IMO Day	FDSM1	FDSM0
Time (s)	46	82	45	52

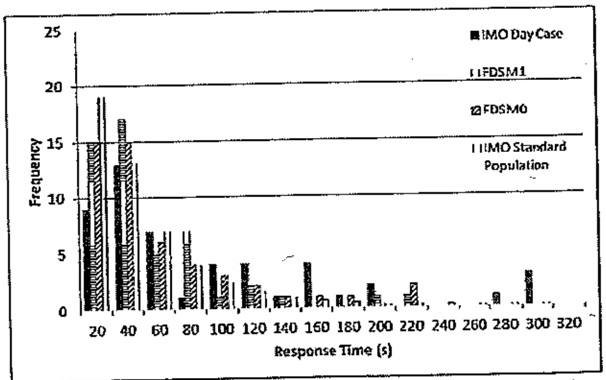

Figure 15 – Response times of last agent to assemble

A parameter produced by maritimeEXODUS for eacl agent is the Cumulative Waiting Time (CWT). This is measure of the total amount of time spent in congestio by the agent. Presented in Figure 16 is the distribution o the CWT as a function of the response time for the las agent to assemble for the IMO day case and the tw

FDSM cases. As can be seen, there is a general trend for shorter response times to have longer CWT – indicating that agents waste more time in congestion. This possibly explains why response time is not a major factor in the time to assemble as a longer response time generally results in less time spent in congestion, e.g. they join the congestion later and therefore spend less time in congestion.

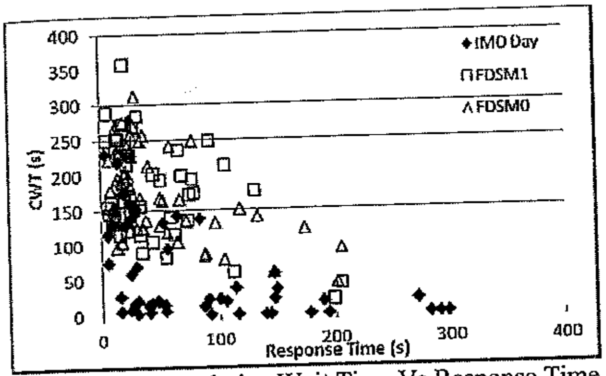

Figure 16 – Cumulative Wait Time Vs Response Time for last agent to assemble

Similarly, the effect of the speed reduction in the FDSM model essentially slows down an agent and potentially reduces the time spent in congestion as they will be queuing at the stairs for a shorter duration. The agents from the affected zone will arrive later compared to the FDSM cases but this is at least partly compensated by the reduction in the amount of time they will spend in congestion once they arrive.

(b) Travel Speed

Another possible explanation for the increase in the assembly time of the FDSM cases compared to the standard IMO day case is that the last agent to assemble has a significantly slower walking speed in the FDSM cases than the agents in the IMO case. Presented in Table 6 are the average travel speeds for the last agent to assemble derived from the 50 simulations for the standard IMO Day Case and the FDSM1 and FDSM0 cases. Also shown is the average travel speed for the entire population.

As can be seen, the average travel speed for the last agent to assemble in the FDSM cases is not significantly smaller compared to the IMO day case, indeed, the average travel speed for the FDSM cases is greater than that for the IMO day case. It is noted that the travel speed of the last agent to assemble in both the IMO day case and the FDSM cases are significantly slower than the population average, which indicates that the last person to assemble in all the cases is an agent with reduced mobility. Furthermore, as the travel speed of the last agent to assemble is generally low, the impact of reducing the travel speed to 0.3 m/s within the fire zone will have less of an impact on the total assembly time.

Table 6 – Mean Travel Speed for last agent to assemble

Case	Population	IMO Day	FDSM1	FDSM0
Walking Speed (m/s)	0.82	0.39	0.41	0.41

Presented in Figure 17 is the distribution of the travel speed for the final agent to assemble. This shows that in the majority of cases, the travel speed for the final agent to assemble is reasonably small and the maximum travel speed of the final agents to assemble for any of the scenarios is 0.6 m/s, again significantly lower than the average speed for the global population (0.82 m/s).

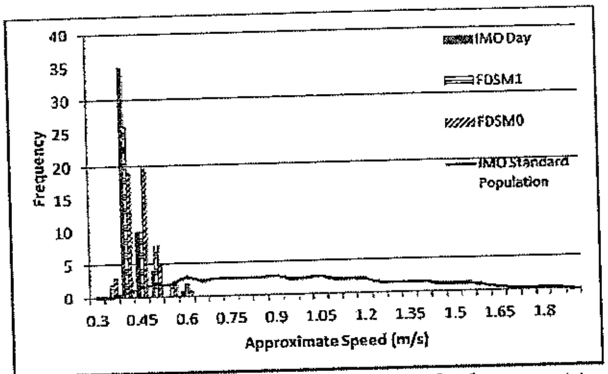

Figure 17 – Travel Speed Distribution for last agent to assemble

(c) Distance travelled

Another possible explanation for the increase in the assembly time of the FDSM cases compared to the standard IMO day case is that the last agent to assemble must travel a significantly longer distance to assemble in the FDSM cases due to the change in procedure than the agents in the IMO case. Presented in Table 7 are the average travel distances for the last agent to assemble derived from the 50 simulations for the standard IMO Day Case and the FDSM1 and FDSM0 cases.

It can be seen that the distance travelled by the last agent to assemble is significantly increased for the FDSM cases compared to the IMO day case due to the change in the procedure. This increase in travel distance has a significant impact on the assembly time. The increase in assembly time purely from the extra travel distance can be estimated to be 182s (3 minutes), assuming a travel speed of 0.44 m/s for the last agent to assemble.

Table 7 – Mean Travel Distance for last agent to assemble

Case	IMO Day	FDSM1	FDSM0
Distance (m)	272	352	358

Presented in Figure 18 is the distribution of the travel distance for the final agent to assemble. This clearly shows that the distance travelled by the final agent to assemble for the FDSM cases in the majority of cases is significantly greater than the distance travelled in the standard IMO day case.

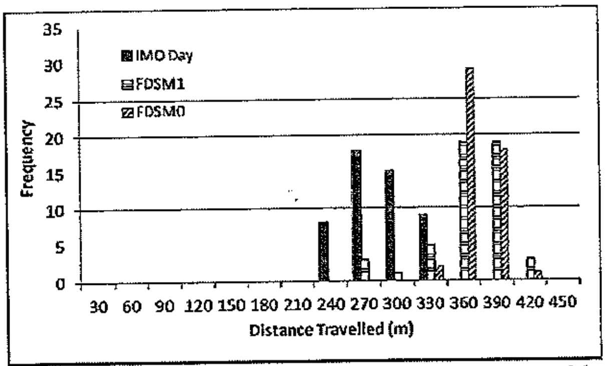

Figure 18 – Distance travelled by last agent to assemble.

(d) Congestion

Another possible explanation for the increase in the assembly time of the FDSM cases compared to the standard IMO day case is that the last agent to assemble experiences significantly greater congestion in the FDSM cases than the agents in the IMO case. Presented in Table 8 are the average CWT incurred by the last agent to assemble derived from the 50 simulations for the standard IMO Day Case and the FDSM1 and FDSM0 cases. As can be seen, the average CWT experienced by the last agent to assemble is significantly greater in the FDSM cases compared to the standard IMO day case.

Table 8 – Average Congestion experienced by the last agent to assemble

Case	IMO Day	FDSM1	FDSM0
Time (s)	63	182	172

Presented in Figure 19 is the distribution of the CWT for the final agent to assemble.

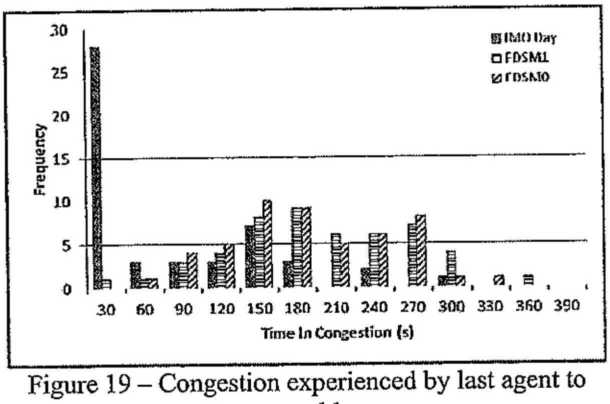

Figure 19 – Congestion experienced by last agent to assemble.

This clearly shows that the FDSM cases have significantly greater frequency of experiencing higher congestion durations for the final agent to assemble compared to the standard IMO day case.

These results provide an explanation as to why the reduced travel speed imposed on agents in the fire zone has little impact on the overall assembly time while the change in assembly procedure for the FDSM cases results in a large increase in assembly time compared to the standard IMO day case. In summary, the final agents to assemble in all cases are agents which already have a significantly reduced travel speed compared to the average population travel speed. Thus decreasing the travel speed a little more for the agents in the affected zone will have little impact on the overall assembly time. Furthermore the speed reduction in the FDSM model essentially slows down an agent and potentially reduces the time spent in congestion as they will be queuing at the stairs for a shorter duration. The agents, with speed reduction (FDSM1), from the affected zone will arrive later compared to the FDSM0 case but this is at least partly compensated by the reduction in the amount of time they will spend in congestion once they arrive. The increase in assembly time resulting from the change in procedure is due to an increase in the total travel distance incurred by the last agent to assemble and an increase in the amount of time wasted in congestion that they will experience on their way to the assembly station.

3.2.3 Night Case

The night population consisted of 3001 passengers and 801 crew members. The night case simulations were performed by S@S using the EVi [20, 21] maritime evacuation software. Following the IMO MSC Circ 1238 protocols, the slowest zone to evacuate was identified for the standard night scenario as FZ7. As FZ7 is the final zone located at the stern of the ship, all occupants in FZ7 must horizontally evacuate to FZ6. The FDSM models were then applied to this zone. Using the IMO MSC Circ 1238 protocols for running simulations the cases were simulated 50 times each. The assembly times calculated for these cases are detailed in Table 9 below. FDSM2 was only applied to cases where passengers would be affected by the speed reduction; these were decks 3, 7, 8, 9 and 10.

Table 9 - Overall Assembly Times for Cruise Ship (night case)

Case	Min (s)	Mean (s)	Max (s)	95th %ile (s)	%diff FDSM0 average	%diff FDSM0 95th %ile
IMO Night case	1247	1361	1971	1542	-30	-23
FDSM0	1869	1946	2042	2012	0	0
FDSM1	1854	1955	2189	2050	0.4	1.9
FDSM2-3	1841	1964	2098	2045	0.9	1.6
FDSM2-7	1871	1972	2377	2098	1.3	4.3
FDSM2-8	1868	1956	2114	2064	0.5	2.6
FDSM2-9	1812	1983	2284	2063	1.9	2.6
FDSM2-10	1875	1999	2267	2086	2.7	3.7

Examination of the predicted assembly times reveals that the average assembly time for the IMO night case is 30% (586 s) faster and the 95th percentile assembly time is 23% (470 s) faster than the FDSM0 case. It should be noted that for the night case there is a minimum of 400 s (response time off-set) before any of the passengers or crew begin to assemble. This means that the IMO night case is faster, in terms of actual moving time, compared to FDSM0 by 38% for the average and 30% for the 95th percentile assembly times. It can be clearly seen that the change of procedure has significantly increased the overall assembly time for the night scenario. However, the addition of speed reduction appears to have little effect. The speed reduction effect ranges from a 0.4% (9 s) increase for the average FDSM1 case over the FDSM0 case with a maximum increase of 4.3% (86 s) increase for the 95th percentile FDSM2-7 case.

Considering the assembly station data in Table 10 for the average time to assemble at each station for each scenario it can be seen that:

- For some of the assembly stations there is a vast increase in assembly time caused by the procedural change of the FDSM scenario that contributes to an increased overall assembly time. This can be clearly seen for "Deck 6", E16, F18, G12, G14, U15, V17, W11, W13 and X3.
- There are a notable number of assembly stations where there is a decrease in assembly time when the procedural changes of the FDSM scenario are applied. These are A, B6, C8, D10, R5, S7, T9, X1 and X2. These reductions in assembly time do not affect the overall assembly time.

The majority of assembly stations that are faster for the FDSM cases compared to the standard IMO night case are not directly affected by the closure of FZ7 and tend to be towards the bow of the ship (with the exception of X1 and X2). However, there are procedural changes to the crew at assembly stations who search the ship that still effect the assembly process. In the original IMO night case crew assigned to searching duties had the same response as passengers. In the FDSM cases this was modified so that searching crew would respond with the lowest night response time (i.e. 400s). This reduces the amount of counter-flow produced and therefore makes the assembly of these stations faster. The FDSM1 cases can have up to a 100s reduction for individual assembly stations compared to the standard IMO night case. X1 and X2 are also two faster assembly stations for the standard IMO night case but are located near FZ7. These are crew assembly stations and due to passengers being slowed down in the affected zone because of procedural changes the congestion experienced by the crew members is reduced allowing them to assemble more quickly.

The increase in assembly time for the assembly stations Deck 6, E16, F18, G12, G14, U15, V17, W11, W13 and X3 and also the increase in overall assembly time is due to the increase in congestion caused by the increased counter-flow of crew and passengers on stairwells assembling at different stations in the FDSM model compared to the standard IMO night case.

Table 10 - Average Assembly Station Assembly times for night case

AS	IMO Night (s)	FDSM0 (s)	FDSM1 (s)
A	1110	1030	1015
B6	1028	955	950
C8	1088	983	995
D10	1069	1068	1076
Deck 6	1214	1760	1755
E16	1317	1922	1921
F18	1236	1706	1704
G12	1072	1884	1881
G14	993	1824	1833
H1	1226	1265	1268
H2	1249	1271	1273
H3	1203	1235	1237
R5	1013	950	949
S7	1016	971	970
T9	1082	1053	1067
U15	1300	1930	1943
V17	1197	1849	1848
W11	1031	1676	1674
W13	1062	1864	1875
X1	1250	1212	1219
X2	1256	1236	1239
X3	1273	1553	1483

The areas of congestion on deck 5 are indicated in Figure 20. In a normal night case FZ 7 is available and agents going to deck 5 (Assembly Stations E16, F18, U15 and V17) remain in their fire zone until they reach deck 5. They then exit to the open deck and use the outside walkways to reach their muster stations. In FDSM scenarios these same agents evacuate horizontally and are not able to use the stairs in FZ 7. To reach deck 5 they use the stairs in FZ 6. In the meantime, crew assigned to the crew assembly station on deck 6 use these same stairs in FZ 6 to get to deck 6 when they reach deck 5. In a normal night case the crew are the only ones using the stairs between deck 5 and 6 in FZ 6, but in the fire scenario, they have to go against the flow of passengers trying to reach deck 5. This causes considerable congestion in and around the stairs on both deck 5 and 6. In addition, in a fire scenario, doors leading outside from FZ 6 are used by a larger number of people as the occupants of FZ 7 are also using the exits. This also causes congestion at these doors.

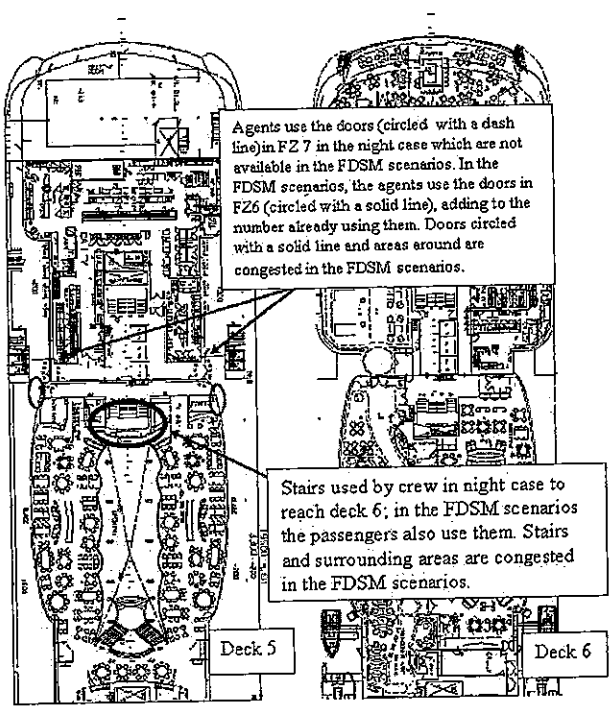

Figure 20 – Areas of congestion on deck 5 caused by procedural change of FDSM models

3.2.3.1 Comparison between Night and Day scenarios

Although the geometries are the same and population demographics are the same there are notable differences in how the FDSM model affects the day and night case. There are three main differences between the day and night scenarios, namely the response time distribution, the starting locations and the number of passengers. In the night case there are 499 more passengers than in the day case (as required by IMO MSC Circ 1238) which has the potential to produce greater levels of congestion in the night case. In addition, in the night case passengers are assigned to assembly stations that will be in the same vertical zone as their cabin. In the day case, the passengers could be in any public area but their assembly station is assigned based on their cabin. It is therefore likely that many passengers will traverse multiple zones to reach their allocated assembly station, which is unlikely to occur in the night case. For the night case the population is likely to spend a higher proportion of their travel time ascending/descending stairs, whereas the day case will see a higher proportion of their travel time spent horizontally traversing. The effect of the searching crew is likely to be greater in the night case as they cause counter-flow on the stairwells heading in an opposite direction to the passengers. Both day and night alternative cases show a significant increase due to the change of procedure. The effect of the speed reduction of the FDSM models has only a limited additional effect.

3.3 MODIFICATION TO THE ASSEMBLY PROCEDURE FOR THE FIRE CASE

The current formulation of the FDSM models partially closes the affected vertical zone. It assumes that all passengers must leave the affected zone and that passengers can only enter the affected zone on the decks with assembly stations. These assembly station decks also provide pathways for passengers to travel through the affected zone if the assembly station is on the other side of it. It is plausible that the entire zone could be considered lost and even the decks with assembly stations are unavailable. This would effectively cut the ship into two separate sections isolated from one another by the affected zone, unless the affected zone is at one of the ends of the vessel. It also requires that some passengers are reassigned to new assembly stations if their original assembly station is either in the affected zone or the route to their assembly station is now cut off because of the loss of the affected zone. Introducing this concept into the model requires alternative assembly stations to be identified for each assembly station within a different MVZ.

To demonstrate this variation of the proposed assembly procedures requires the following changes to the FDSM scenarios:

- All assembly stations in FZ 6 are removed.
- Agents in FZ 7 cannot pass through FZ6 and agents in FZ 1 to FZ 5 cannot pass into FZ 6.
- Agents within FZ 6 travel horizontally to their nearest neighbouring FZ. In this case, this meant that approximately 50% travel to FZ 7 and approximately 50% travel to FZ 5.
- Agents in FZ 6 who are forced to move to FZ 5 and who had an assigned assembly station in FZ 1 to FZ 5 move to their previously assigned assembly stations. If agents were assigned an assembly station in FZ 7 or FZ 6 they are reassigned to a secondary assembly station located on deck 6 in FZ 4.
- Agents in FZ 6 who are forced to move to FZ 7 and who had an assigned assembly station in FZ 7 move to their previously assigned assembly station. If agents were assigned an assembly station in FZ 1 or FZ 5 they are reassigned to a secondary assembly station located on deck 6 in FZ 7.
- Agents in FZ 7 who were assigned assembly stations in FZ 1 to FZ 6 are reassigned to a secondary assembly station located on deck 6 in FZ 7.
- Agents in FZ 1 to FZ 5 who were assigned an assembly station in FZ 6 or FZ 7 are reassigned to a secondary assembly station located on deck 6 in FZ 4

The modified FDSM scenarios are labelled FDSM0b and FDSM1b. The minimum, average, maximum and 95th percentile total assembly times for the modified FDSM scenarios along with the original FDSM scenarios and the standard day case are presented in Table 11. As can be seen, the results for the FDSMb cases are significantly smaller than those for the FDSM cases and the minimum and average results are even smaller than the standard IMO day case results. These results are counterintuitive as one would perhaps anticipate a longer assembly time when the entire assembly station (FDSMb cases) is removed and that the results would be significantly longer then those for the FDSM cases.

Table 11 – Comparison of IMO day case and FDSM1 and FDSM1b

	IMO Day Case	FDSM0	FDSM1	FDSM0b	FDSM1b
Min	773	926	915	743	726
Average	841	1100	1089	837	837
Max	914	1305	1279	995	1000
95%ile	909	1266	1265	937	965

However, these results can be explained through a detailed examination of the nature of the assembly process in the FDSMb scenarios. The last agent to assemble in the FDSM scenarios generally came from FZ 7 and assembled in Assembly Station A towards the front of the ship. In the FDSMb scenarios these agents are no longer able to travel to Assembly Station A and are reassigned to an alternative assembly station in FZ 7. Similarly, any agents that were located fore of the affected zone that originally would have assembled in FZ 6 or FZ 7 now assembles in FZ 4, reducing the time to assemble for these agents.

The day case, due to the nature of agent locations with their assembly stations dictated by their allocated cabin, is strongly affected by these changes as agents could be initially located very far away from their assigned assembly station. It is anticipated that the FDSMb scenario applied to the night case will not be affected in the same way as in the day case as agents are located in the same zone as their assembly station and so agents do not have to cross zones.

The night case variant of FDSM1b was performed by S@S. In the night case the affected fire zone is FZ 7 which is at the stern of the ship. It was found that the FDSM1b produced essentially the same total assembly time as FDSM1 as there was little difference between the FDSM1 and FDSM1b in terms of alternate assemble stations. The case only changed the location of crew assembly stations in FZ 7 as there were no passenger assembly areas in FZ 7. These stations are depicted in Figure 21 along with the alternative stations now placed in a restaurant area. The original crew assembly stations did not affect the final overall time to assemble and similarly the new assembly stations did not affect the final overall time to assemble.

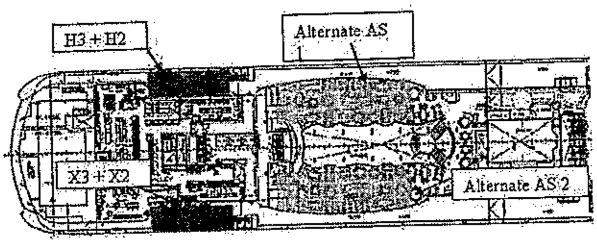

Figure 21 – Location of original assembly stations (H2, H3, X2, X3) and alternate assembly stations.

There are two difficulties associated with the FDSMb scenario concept. The first is that every assembly station must have an alternative assembly station within a different fire zone. This may be difficult to achieve in reality and may not be practical. The second difficulty is that the passengers must know where their secondary assembly station is located. This creates two types of problems, one for the computer simulation and one for the real world situation. In the real world situation passengers will not necessarily know that their assembly station is no longer available or no longer accessible and so are likely to move towards their primary assembly station. Only when they arrive at the closed off section will they realise that they cannot access their primary assembly station. At this point the passengers will be assigned secondary assembly stations or will be directed to their pre-assigned secondary assembly stations. This process is bound to lead to confusion and hesitation and create contra-flow situations, all of which will further delay the assembly process. Within the current computer simulation, the agents moved directly to their secondary assembly station as if they were informed from the start that they had to use their secondary assembly station. While some models, such as maritimeEXODUS and EVi, have the capability to represent passenger redirection by crew, it is not a capability that many egress models have and so it was not utilised in these simulations. Thus implementing the FDSMb scenarios may be difficult for the vast number of maritime egress models.

4. PROPOSED MODIFICATIONS TO THE IMO EVACUATION ANALYSIS GUIDELINES

An attempt has been made to develop a benchmark fire scenario that could be included in a modified form of the IMO evacuation analysis guidelines. The aim of the benchmark scenario was to include the impact of a severe fire on the evacuating passengers without introducing the need to undertake a full fire simulation. The primary impact of the generation and spread of fire hazards considered in the benchmark analysis is the reduction in travel speeds of passengers due to smoke obscuration and a change in the evacuation procedures associated with the fire zone containing the severe fire. The reduction in agent travel speeds was not found to have a significant impact on the time to assemble, even when the travel speeds of the affected agents was reduced to 0.3 m/s. Thus it is suggested that there is no need to include a speed reduction in the proposed fire benchmark scenario. However, the modified evacuation procedures were found to have a significant impact on the time to assemble. Furthermore, two fire scenarios were considered, one in which all the decks within the affected MVZ are considered to be impaired by fire hazards and a scenario in which only a single deck within the affected MVZ is impaired. In the former, there is only a single case that must be examined, while in the latter each deck within the affected MVZ must be examined in turn, resulting in a case for each deck in the affected MVZ. Analysis suggests that both scenarios produce essentially identical results and as the former requires less effort it is selected as the fire scenario. The fire scenario is intended to represent a severe fire requiring the evacuation of the affected MVZ with all vertical access considered to be non-tenable.

The modified assembly procedure for the fire case is as follows:

- Identify the MVZ that has the longest assembly time as in the current requirements. This zone is considered to contain the fire.
- Any assembly stations within the affected MVZ are considered viable and agents may pass through the affected MVZ only on the decks containing the assembly stations.
- All stairs within the affected MVZ (i.e. primary and secondary) are considered non-viable.
- Agents within the affected MVZ exit the zone horizontally moving to their nearest neighbouring MVZ. If the affected MVZ is an end zone then all agents move horizontally to the nearest neighbouring MVZ.
- Crew involved in searching tasks are assumed to start their search based on the lowest response time associated with the scenario.
- Crew and passengers may only use stairs in the unaffected zones.
- The process is repeated for both the day and night cases.

The impact of the suggested fire benchmark scenarios was assessed for a large cruise ship configuration consisting of seven MVZs and 2502 passengers and 801 crew members in the day case and 3001 passengers and 801 crew members in the night case. The assembly time for the 95th percentile case in the fire benchmark day case was found to increase by 34% (310 s) compared to the standard day case. For the fire benchmark night case, the assembly time for the 95th percentile case is increased by 30% (470 s). For this vessel, the total assembly time for the fire benchmark day and night cases are 20.3 min and 33.5 min respectively, both well within the maximum allowed.

5. CONCLUSION

This paper has presented the results of research that was carried out to develop a fire benchmark evacuation scenario for large passenger ships that could be incorporated within a modified form of the IMO evacuation analysis guidelines. The analysis has involved detailed Computational Fluid Dynamics (CFD) fire modelling analysis of fire scenarios, analysis of experimental data relating to fires in passenger ships and extensive evacuation simulation using two established ship-based evacuation modelling tools.

The aim of the fire benchmark scenario was to include the impact of the fire on the evacuating passengers without introducing the need to undertake a full fire simulation. The primary impact of the generation and spread of fire hazards considered in the benchmark analysis is the reduction in travel speeds of passengers due to smoke obscuration and a change in the evacuation procedures associated with the fire zone containing the fire. The key points from this analysis are:

- Two fire scenarios were considered, one in which all the decks within the affected MVZ are considered to be affected by fire hazards and a scenario in which only a single deck within the affected MVZ is affected.
  - In the former there is only a single case that must be examined, while in the latter each deck within the affected MVZ must be examined in turn resulting in a case for each deck in the affected MVZ.
  - Analysis suggests that both scenarios produce identical results and as the former requires less effort it is selected as the fire scenario.
- In both the day and night case, the reduction in agent travel speeds associated with smoke obscuration was not found to have a significant impact on the time to assemble, even when the travel speeds of the affected agents was reduced to 0.3 m/s.
  - This is because the final agents to assemble in all cases are agents which already have a significantly reduced travel speed compared to the average population travel speed. Thus decreasing the travel speed a little more for the agents in the affected zone will have little impact on the overall assembly time.
- In both the fire day and night cases, the change in the assembly procedure was found to have a significant impact on the total assembly time.
  - For the fire day case, the increase in assembly time is due to an increase in the total travel distance incurred by last agent to assemble and an increase in the amount of time wasted in

congestion that they will experience on their way to the assembly station.
  - For the fire night case, the increase in assembly time is primarily due to the increase in congestion in FZ 6 caused by additional passenger load and counter-flow of crew moving to their assembly stations
- The impact of the suggested fire benchmark scenarios was assessed for a large cruise ship configuration.
  - The 95th percentile assembly times for the fire benchmark day/night cases were found to increase by 34%/30% compared to the standard day/night cases.
  - While this represents a significant increase in the total assembly time for both the day and night cases, both were comfortably within the maximum allowed times.

Thus the proposed fire benchmark scenario is considered appropriate. It is however noted that the suggested approach does not produce a prediction of possible fire related fatalities or injury levels, nor does it provide an assessment of the fire safety provision afforded by the design. To do this requires a detailed fire simulation for a prescribed fire scenario coupled with an evacuation simulation. While this approach is currently possible and normally used in the land-based building industry, it has the disadvantage of currently being expensive in terms of time, resources and computational power.

6. ACKNOWLEDGEMENT

Project SAFEGUARD (contract 218493) is funded under the European Union Framework 7 Transport initiative and Transport Canada Marine Safety and the Newfoundland and Labrador Research and Development Corporation. The authors acknowledge the co-operation of their project partners.

7. REFERENCES

[1] IMO, 'Guidelines for Evacuation Analyses for New and Existing Passenger Ships', *International Maritime Organisation MSC.1/Circ. 1238*, 2007.

[2] PURSER, D.A., 'Assessment of hazards to occupants from smoke, toxic gases, and heat', *The SFPE handbook of fire protection engineering, 4th Edition, Chapter 2-6, p. 2.96-9.193*, 2008.

[3] EWER, J., JIA, F., GRANDISON, A., GALEA, E.R., and PATEL, M.K., 'Technical reference manual, SMARTFIRE 4.1.', *Ewer et al.*, 2008.

[4] JIA, F., GALEA, E.R., and PATEL, M.K., 'The prediction of fire propagation in enclosure fires', *Fire Safety Science – Proc. of 5th Int. Symp., p. 345-354, Jia et al*, 2006a.

[5] 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 I: Prediction of the pre-fire air flow within the cockpit and surrounding areas', *The Aeronautical Journal of the Royal Aeronautical Society, 110, p. 41-52, Jia et al*, 2006b.

[6] WANG, Z., 'Predicting toxic gas concentrations resulting from enclosure fires using local equivalence ratio concept linked to fire field models', *PhD thesis submitted at University of Greenwich, Wang et al*, 2007a.

[7] 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, p. 27-51, Wang et al*, 2007b.

[8] GALEA E.R., WANG, Z., VEERASWAMY, A., JIA, F., LAWRENCE, P., and EWER, J., 'Coupled Fire/Evacuation Analysis of the Station Nightclub Fire', *Proceedings of 9th IAFSS Symposium Karlsruhe, Germany, ISNN 1817-4299, p. 465-476, Galea, et al*, 2008.

[9] 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, 114, p. 271-277, Galea et al*, 2010.

[10] GALEA, E.R., LAWRENCE, P., GWYNNE, S., SHARP, G., HURST, N., WANG, Z., EWER., J., 'Integrated fire and evacuation in maritime environments', *2nd Int Maritime Safety Conference on Design for Safety, Sakai Japan, Publisher Ship and Ocean Foundation, p.161-170*, 2004.

[11] ARVIDSON, M., AXELSSON, J., and HERTZBERG, T., 'Large-scale fire tests in a passenger cabin', *SP Report 2008:33, SP Technical Research Institute of Sweden*, 2008.

[12] GALEA, E.R., GRANDISON, A., DEERE, S., FILIPPIDIS, L., BROWN, R., 'WP D-D3 – Fire Scenario Report', *SAFEGUARD EU Project*, 2011.

[13] JIN, T., 'Visibility Through Fire Smoke', *Report of Fire Research Institute of Japan, 2 (33), p.12-18*, 1971.

[14] CALDEIRA-SARAIVA, F., GYNGELL, J., WHEELER, R., GALEA, E.R., CARRAN, A., SKJONG, R., VANEM, E., JOHANSSON, K.,

RUTHERFORD, B., and SIMOES, A.J., 'Simulation of ship evacuation and passenger circulation', *Proc 2nd Int Maritime Safety Conference on Design for Safety, Sakai Japan, Publisher Ship and Ocean Foundation, pp 197-205*, 27-30 Oct 2004.

[15] GALEA, E.R., DEERE, S., SHARP, G., FILIPPIDIS, L., LAWRENCE, P., and GWYNNE, S., 'Recommendations on the nature of the passenger response time distribution to be used in the MSC 1033 assembly time analysis based on data derived from sea trials', *International J of Maritime Eng, Vol 149, Part A1, 15-29*, (2007).

[16] DEERE, S., GALEA, E.R., LAWRENCE, P., FILIPPIDIS, L., and GWYNNE, S., 'The impact of the passenger response time distribution on ship evacuation performance', *International J of Maritime Eng, Vol 148, Part A1, 35-44*, (2006).

[17] IMO, 'SOLAS amendments 2010 and 2011', *Chapter II-2, Regulation 21, p20-22, London: International Maritime Organization*, (2011).

[18] JENSEN, G., 'Evacuating in Smoke', *IGS AS, Trondheim, Norway*, (1993).

[19] BUKOWSKI, R.W., 'Fire Hazard Assessment (Section 11/Chapter 7)', *NFPA Fire Protection Handbook, 18th ed., Linville, J., ed., NFPA Boston, MA*, (1996).

[20] VASSALOS, D., KIM, H., CHRISTIANSEN, G., MAJUMDER, J., 'A Mesoscopic Model for Passenger Evacuation in a Virtual Ship-Sea Environment and Performance-Based Evaluation', *Pedestrian and Evacuation Dynamics – April 4-6, 2001 – Duisburg. pp369-391. ISBN: 3-540-42690-6*, (2001).

[21] VASSALOS, D., GUARIN, L., VASSALOS, G.C., BOLE, M., KIM, H.S., and MAJUMDER, J., 'Advanced Evacuation Analysis – Testing the Ground on Ships', *International Conference in Pedestrian and Evacuation Dynamics (PED) – 2003 – Greenwich. pp147-158, ISBN: 1-904521-08-8*, (2003).

[22] GALEA, E.R., GRANDISON, A., DEERE, S., BLACKSHIELDS, D., SHARP, G., FILIPPIDIS, L., BROWN, R., 'WP E-E3 – Fire Benchmark Scenario Report', *SAFEGUARD EU Project*, 2012.

SAFEGUARD

Passenger Evacuation Seminar

30 November 2012
London, UK

PAPERS

SEVENTH FRAMEWORK PROGRAMME

THE ROYAL INSTITUTION OF NAVAL ARCHITECTS
10 UPPER BELGRAVE STREET, LONDON, SW1X 8BQ Telephone: +44 (0)20 7235 4622