- The implemented evacuation model appears to be very robust to most of the input parameters despite the implicit uncertainty. The obtained COV for a set of initial conditions and evacuation dynamics is of the order of 1%-4%.

CONCLUDING REMARKS

Undoubtedly, advanced evacuation simulation tools – used within an appropriate evaluation framework (of the type suggested in the IMO guidelines), will allow for a rigorous quantification and valid evaluation of the evacuation performance of a ship, being it for design or operational purposes. In this respect, it has to be emphasised that in the actual IMO guidelines, the evaluation of evacuability is currently made on the basis of 60 minutes as the life safety criterion (40 minutes for assembly time). It is felt that the adoption of a prescriptive (fixed) criterion is rather inconsistent with the performance-based approach adopted in the evacuation analysis. Instead, such a criterion should derive from life safety and/or performance criteria from a number of ship-related critical scenarios associated with fire and/or large scale flooding of the vessel's hull, or both; these constitute the two principal hazards for which a ship may need to be evacuated. On the basis of this study, the first systematic evaluation of the IMO guidelines onboard a real ship of the type these guidelines are meant to apply, it can be stated that there is still some ground to cover, aiming towards close form expressions of evacuability as functions of the aforementioned variables if application to other ship environments demonstrated tendency to shape functions that can be standardised. Moreover, there is still considerable effort required to address sensitivity of design and operation-related variables to populate data bases or in time create knowledge bases to facilitate design for ease of evacuation or to address the risk of passenger evacuation in an all embracing risk-based approach. These are some of the issues of ongoing research at SSRC, results of which will be reported in the near future.

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SIMULATING SHIP EVACUATION UNDER FIRE CONDITIONS

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ABSTRACT

When designing a new passenger ship or modifying an existing design, how do we ensure that the proposed design and emergency procedures are safe for an evacuation resulting from fire or other incident? In the wake of major maritime disasters such as the Scandinavian Star, Herald of Free Enterprise, Estonia and in light of the growth in the numbers of high density ferries and large cruise ships, issues concerning the evacuation of passengers and crew are receiving renewed interest. Fire and evacuation models with features such as the ability to realistically simulate the spread of heat and smoke and the human response to fire as well as the capability to model human performance in heeled orientations linked to a virtual reality environment that produces realistic visualisations of the modelled scenarios are now available and can be used to aid the engineer in assessing ship design and procedures. This paper describes the maritimeEXODUS ship evacuation and the SMARTFIRE fire simulation model and provides an example application demonstrating the use of the models in performing fire and evacuation analysis for a large passenger ship partially based, but exceeding the requirements of MSC circular 1033.

INTRODUCTION

Demonstrating compliance with evacuation requirements through full-scale evacuation exercises poses considerable ethical (threat of injury to volunteers limiting the realism of the event), practical (only a single trial is usually conducted) and financial (trials are expensive) problems that bring into question the value of their overall contribution to safety. Consequently this form of proof of concept is impractical as a routine aid to assessing ship safety. More sophisticated evacuation analysis through computer simulation is both desirable and achievable. In recognition of this IMO established a Correspondence Group (CG) of the Fire Prevention Sub-Committee FP46 to develop a set of standards for the use of sophisticated evacuation modelling techniques. In Feb 2002 the CG put its proposed methodology to FP46. The approach was accepted by FP46 and in the 75th Session of MSC (May 2002) was formally adopted as the Interim Guidelines for evacuation analysis of new and existing passenger ships including ro-ro[1]. These define two benchmark scenarios (along with two variants) that must be simulated as part of the certification process. These are defined as the "night" and "day" scenarios. While arbitrarily defined, they establish a baseline performance for the vessel and crew allowing comparison with both the set target time and alternative designs. The scenarios only address the mustering or assembly phase of the evacuation and involve conditions of dead calm (i.e. zero list, heel and roll) and do not explicitly take into consideration the impact of fire. To allow for these omissions a safety factor is added to the predicted muster time.

In the building industry, performance based fire safety engineering requires the determination of essentially two factors: the time available to the occupants for safe egress, sometimes referred to as the Available Safe Egress Time (ASET) and the time required by occupants to evacuate from the structure, often referred to as the Required Safe Egress Time (RSET). For the building to be considered acceptable, the RSET (plus some safety factor) should be less than the ASET[2]. For a particular fire/evacuation scenario, these calculations are typically performed in isolation, with the ASET being determined through fire simulation - either zone or field[3] - and the RSET being determined through an evacuation calculation or simulation. For the scenarios under consideration, fire simulation is typically used to determine at what time non-survivable conditions develop within the enclosure, for example, when the smoke level reaches a particular critical height deemed detrimental to evacuation or when radiative fluxes reach a critical value leading to the onset of flashover. The evacuation calculation is then used to determine if the people can evacuate before these critical conditions develop. However, today's Computational Fire Engineering (CFE) tools such as fire field models and complex evacuation models are capable of much more, such as the prediction of toxic gas and smoke generation and distribution, oxygen depletion, etc, and the reduction in travel speed due to smoke obscuration, incapacitation due to the inhalation of toxic products, impact of irritant gases on individual evacuation etc respectively. They can even be linked so that the output of one feeds into the other. Using such CFE tools it is possible to combine the calculation of the ASET and RSET and determine if the outcome of a given scenario is acceptable by using more sophisticated measures such as, for example, zero fatalities result from the simulated scenario, or occupant exposure to fire effluent are limited to acceptable threshold values. Using such an approach a more meaningful comparison could be made between alternative structural configurations, active/passive systems, evacuation procedures or even between the nature of the building materials. In the work presented in this paper we demonstrate the current capabilities of this approach using state-of-the-art CFE tools maritimeEXODUS[4-7] and SMARTFIRE[8,9]. In addition to meeting the IMO requirements, maritimeEXODUS has the ability to simulate the impact of heel and list on the passengers, the impact that fire effluent will have on the passengers and the ability to simulate the abandonment phase. The models ability to link fire with evacuation will be demonstrated in this paper.

THE maritimeEXODUS SOFTWARE

EXODUS is a suite of software tools designed by the Fire Safety Engineering Group of the University of Greenwich to simulate the evacuation of large numbers of people from a variety of complex enclosures. Research and development on EXODUS began in 1989. Today, the family of models consists of buildingEXODUS[10], airEXODUS[11], with the most recent addition being maritimeEXODUS[4-7]. maritimeEXODUS builds on the well-established "EXODUS" suite of evacuation simulation software. Going beyond the traditional examination of layout and safety features, the software allows designers, certification authorities and operators to incorporate human performance and environmental factors into the evacuation analysis.

The EXODUS software takes into consideration people-people, people-fire and people-structure interactions. It comprises five core interacting sub-models: the Passenger, Movement, Behaviour, Toxicity and Hazard sub-models. The software describing these sub-models is rule-based, the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. Many of the rules are stochastic in nature and thus if a simulation is repeated without any change in its parameters a slightly different set of results will be generated. These submodels operate on a region of space defined by the GEOMETRY of the enclosure. The key components of these submodels will be briefly described. The spatial and temporal dimensions within EXODUS are spanned by a two-dimensional spatial grid and a simulation clock. The spatial grid maps out the geometry of the structure, locating exits, internal compartments, obstacles, etc. and can involve multiple decks, which are connected by staircases. The structure layout can be specified automatically using a DXF file produced by a CAD package or manually using the interactive tools provided. In addition to the representation of the structure itself, the abandonment system can also be explicitly represented within the model, enabling individual components of the abandonment system to be modelled individually.

The HAZARD SUBMODEL controls the atmospheric and physical environment. It distributes pre-determined fire hazards such as heat, radiation, smoke concentration and toxic fire gas concentration throughout the atmosphere and controls the availability of exits (i.e. opening and closing times of exits). While the thermal and toxic environment is determined by the Hazard submodel, EXODUS does not predict these hazards but distributes them through time and space. EXODUS will accept hazard data either from experimental measurements or numerical data from other models including a direct software link to the CFAST fire zone model. In this paper a link to the SMARTFIRE fire field model will also be demonstrated. The TOXICITY SUBMODEL determines the effects on an individual exposed to toxic products distributed by the hazard submodel. These effects are communicated to the behaviour submodel, which in turn, feeds through to the movement of the individual. To determine the effect of the fire hazards on occupants, EXODUS uses a Fractional Effective Dose (FED) toxicity model[12]. This model considers the toxic and physical hazards associated with elevated temperature, thermal radiation, HCN, CO, CO_2 and low O_2 and estimates the time to incapacitation. In addition to this behaviour, the passengers are able to respond to the environmental conditions by adjusting their behaviour.

The BEHAVIOUR SUBMODEL is the most complex module, and incorporates adaptive capabilities that include, structural knowledge, reaction to communication, affiliative behaviour, occupant motivation and reaction to fire hazards. The Behaviour Sub-model determines the passenger's response to the current situation, and passes its decision on to the Movement Sub-model. Social relationships, group behaviour and hierarchical structures are modelled through the use of a "gene" concept[13], where group members are identified through the sharing of social "genes". With regard to the environmental conditions, passengers will stagger through smoke filled environments. Furthermore, as the smoke concentration increases and visibility decreases, the travel speed of the occupants is reduced according to experimental data[14]. Passengers and crew can also be assigned a list of tasks to perform. This feature can be used when simulating emergency or non-emergency conditions. Another important aspect of human behaviour is the manner in which passengers react to the ship orientation. Their movement rates in corridors on stairs and through doorways at various angles of heel is represented within model and based on data generated from large-scale trials using the BMT Fleet Technology SHip Evacuation Behaviour Assessment (SHEBA) facility[6] and small-scale data using the TNO Ship Motion Simulator (SMS). The SHEBA facility has recently been modified to include watertight doors, vertical ladders, hatches and 60 degree stairs. These facilities are being used to simulate key components of naval vessels not typically found on board civilian ships. This data forms the basis of new structural and behavioural components for maritimeEXODUS to better simulate conditions found on naval vessels.

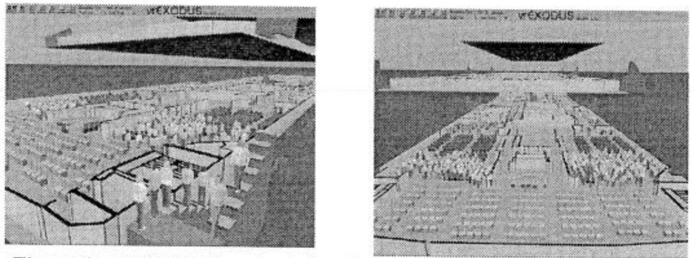


Figure 1: vrEXODUS output showing the top three decks of a 10 deck passenger ferry during passenger mustering.

maritimeEXODUS produces a range of output, both graphical and textual. Interactive two-dimensional animated graphics are generated as the software is running that allows the user to observe the evacuation as it takes place. The graphics can be displayed in individual mode or population density mode. In the later, rather then graphically show individuals, a colour contour fill is used to represent the number of people per square meter. This mode of view provides an immediate indication of points of congestion. In addition, a post-processor virtual-reality graphics environment known as vrEXODUS has been developed, providing an animated three-dimensional representation of the evacuation (see Figure 1).

SMARTFIRE

The SMARTFIRE V3.0 software is used to perform the fire simulations in this study. SMARTFIRE is an open architecture CFD environment written in C++ that is comprised of four major components: CFD numerical engine, Graphical User Interfaces, Automated meshing tool and the Intelligent Control System. The SMARTFIRE system has been described in previous publications[8,9], and so only a brief outline is presented here. The CFD engine in SMARTFIRE has many additional physics features that are required for fire field modelling[3,8,9]. These include a six-flux radiation model, a multiple ray radiation model, provision for heat transfer through walls, a volumetric heat release model or gaseous combustion model (using the eddy dissipation model) to represent fires, smoke modelling and turbulence (using a two equation K-Epsilon closure with buoyancy modifications). Within SMARTFIRE the user can define a range of scalar variables. These can be used to represent the transport of products such as toxic gases and smoke. SMARTFIRE uses three-dimensional unstructured meshes, enabling complex irregular geometries to be meshed. The code uses the SIMPLE algorithm and can solve turbulent or laminar flow problems under transient or steady state conditions. As part of the SMARTFIRE development, the software has undergone considerable validation (e.g.[9,15]).

The fire environment to which the passengers are exposed in maritimeEXODUS can be determined by means of the CFAST zone model. As part of on-going research, a software link to CFD based fire models is also being developed. In this paper we explore the linkage of maritimeEXODUS to the CFD fire model SMARTFIRE. The link is achieved through the use of a SMARTFIRE routine that converts the fire data generated by SMARTFIRE into a format that can be read by maritimeEXODUS. To harmonise the three-dimensional control-volume discretisation used in SMARTFIRE with the meshing and zoning system used within maritimeEXODUS, a volume averaging technique is used. This effectively groups together potentially large numbers of CFD cells, averaging the data within them, in order to be easily utilised within maritimeEXODUS. The averaging is also extended over time, so as to provide the evacuation simulation with the data that is required at times appropriate to the evacuation simulation. This technique was developed as part of a European Union funded project called Fire Exit which is part of the Growth Programme. The information provided will relate to the temperature, the gas concentrations, thermal radiation from any hot layer and smoke concentration.

DEMONSTRATION INVOLVING A LARGE PASSENGER SHIP

To demonstrate the operation of maritimeEXODUS, the software is applied to a hypothetical ship layout using the IMO night scenario specification as a guide to the analysis. The analysis is repeated using a fire case.

SHIP LAYOUT

A large passenger ship consisting of 10 decks is defined within maritimeEXODUS using CAD drawings (see Figure 2). The ship has a compliment of 650 passengers. The ship is divided into three vertical fire zones accommodating 348 passengers in the first fire zone, 52 passengers in the second fire zone and 249 passengers in the third fire zone. Depicted in Figure 1 are two views of top three decks generated using vrEXODUS.

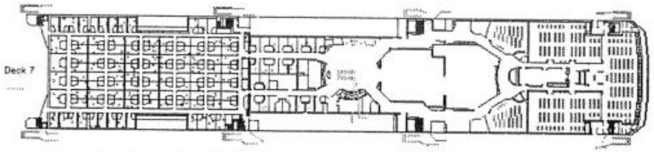


Figure 2: Deck 7 of the 10 deck hypothetical ship layout used in maritimeEXODUS analysis

The lowest passenger deck is Deck 6 while Deck 10 is the highest. The assembly areas are located on Deck 8 and there are two for fire zone 1, two for fire zone 2 and four for fire zone 3 (see Figure 1). There are two passenger decks below the muster deck accommodating 400 passengers and two passenger decks above, accommodating 250 passengers. Each deck of the first fire zone is serviced by four staircases located within the far corner of the fire zone connecting each deck. The second fire zone only possesses a single staircase centrally located within the fire zone. Fire zone 3 has a similar layout to fire zone 1. All the stairs are similar in construction and are narrow, capable of allowing only a single lane of passengers to use the stairs. The only exception is the dual lane staircase in fire zone 2. Passenger cabins are located on both decks 6 and 7 in fire zone 1 and 2 and both decks 9 and 10 in fire zone 3. A large theatre is located on deck 7 in fire zone 3, dinning areas and bars are located throughout deck 8 and within fire zone 2 on deck 9.

EVACUATION SCENARIO

IMO stipulates that two main benchmark evacuation scenarios be examined, the so-called "day" and "night" cases. There is also a variation of each of these scenarios that must also be considered making a total of four different benchmark scenarios that must be investigated. Here we only consider the main night scenario and one other variation that is not currently required by IMO. In the cases considered here, all the passengers are initially located in their cabins and have response times varying from 7 – 13 minutes as required by the IMO specification. This time is intended to represent the time required to arouse a sleeping passenger and get them dressed and ready to move to the assembly station. The passenger attributes are defined according to the IMO specification[1]. In Scenario 1 the vessel is level with 0^0 of heel. This case is then repeated but a fire is included in the scenario (Scenario 2).

THE RESULTS

All of the simulations presented here were run on a 1.9 GHz Pentium 4 PC with 2 Gb of RAM. When run in maritimeEXODUS interactive graphics mode each simulation requires approximately 1 minute 35 seconds to complete. The simulations presented here were run in batch mode which significantly reduces the time required to complete the simulations.

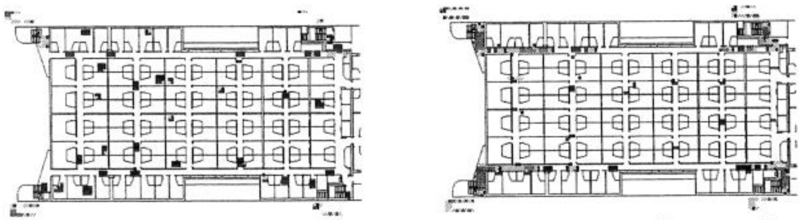
IMO Compliant Night Scenario (Scenario 1)

To be fully compliant with IMO regulations[1], it is necessary to perform a total of 50 repeat simulations for each of the four IMO benchmark scenarios. The representative assembly time for the vessel for each scenario would be determined from the distributions by selecting the time that is larger than 95% of the generated values. Finally, the representative assembly time for the vessel is taken as the largest of the four values. Once this time has been determined a safety margin of 10 minutes is added to the calculated time[1]. This is intended to account for all of the assumptions involved in the modelling approach. For the cases presented here, we present the minimum, average and maximum values from which we determine the 95 percentile value representing the assembly time for the vessel. As can be seen the average total time to muster is approximately 15 minutes 32 seconds with a maximum muster time of 15 minutes 58 seconds (see Table 1). Fire zone 1 is the last to muster in all of the cases considered. Note that of the three fire zones, fire zone 1 has the largest number of passengers and all the passengers are below the muster deck, requiring them to travel upstairs, - thereby incurring the slowest travel speeds.

Table 1: Range of assembly times generated by maritimeEXODUS for each muster zone

	Fire Zone 1	Fire Zone 2	Fire Zone 3
Min	14' 59"	13' 34"	13' 42"
Avg	15' 32"	14' 00"	14' 32"
Max	15' 58"	14' 43"	15' 24"

The 95% value for the mustering time for these simulations is 15 minutes 57 seconds. Thus, the predicted time to muster for this vessel under the IMO night conditions is 15 minutes 57 seconds. If the IMO specified safety margin of 10 minutes[1] is added to this time we note that the vessel will require 25 minutes 57 seconds to muster and so satisfies the IMO standard. According to the IMO regulations, regions in which the local population density exceeds 4 persons/m^2 for a duration exceeding 10% of the overall assembly time are identified as congestion regions. As the assembly time for this vessel is 957 seconds, congestion should not exceed 4 persons/m^2 for periods of 96 seconds. One of the outputs generated by maritimeEXODUS for each passenger is a measure of the amount of time the passenger wastes in congestion. This is known as the Cumulative Wait Time (CWT). This can be averaged for each passenger in the simulation and a representative average CWT generated for each person and for each simulation. The average CWT for these 50 simulations was 6 seconds. As the average muster time was 15 minutes and 32 seconds, it is clear that significant congestion does not develop within these simulations. Here again we note that the protracted passenger response times result in low levels of congestion throughout the vessel for the duration of the mustering process. A more detailed analysis of the congestion can be derived using the maritimeEXODUS population density mode visualisation. Using this feature it is possible to generate a coloured contour map of the population density throughout the vessel as the evacuation takes place, an example of this is presented in **Figure 3**. Regions in which the population density exceeds 4 persons/m^2 are coloured black. In viewing the population density contours (see Figure 3 (a)) we note that the most heavily congested areas occur at the base of the staircases on deck 7 leading to the muster deck. Congestion in this area achieved values of between 2.2 and 3.5 persons/m^2 of a period of 19 seconds. For the remainder of the simulation, congestion in this area never exceeded 2.2 persons/m^2. As is to be expected, the staircases also proved to be areas of heavy congestion. On the landings, the longest periods of congestion lasted for approximately 28 seconds where concentrations of people reached levels of between 2.2 persons/m^2 to 3.5 persons/m^2. For a brief period of time lasting approximately 2 to 4 sec, congestion on the staircase landing reached 4 persons/m^2. At all other times the congestion levels throughout the vessel were less than 2.2 persons/m^2.



(a) IMO night scenario (b) Instant response time scenario

Figure 3 Population density contours for the (a) IMO specified night response time distribution and (b) instant response time distribution.

The vessel is therefore deemed to comply with the requirements of the IMO night-time assembly scenario. If we repeat this scenario using an instant response time distribution (i.e. all of the evacuees respond immediately and simultaneously) rather than the IMO specified response time distribution, we find a very different situation (see Figure 3 (b)). In this situation we note that there are significant congestion regions developing in the vicinity of all the stairs, we also note that the average CWT reaches 42 seconds. Thus if in the night scenario, passengers react immediately to the call to evacuate, significant congestion can be expected to develop.

Scenario involving fire (Scenario 2)

In this scenario, the assumptions relating to the configuration of the vessel, the population and the procedures are identical to those previously described. The only new factor in this simulation is the presence of an evolving fire, located in a cabin on the lowest passenger deck, deck 6. The data for this incident was produced using the SMARTFIRE CFD model. For the purposes of this example the only the fire hazards associated with elevated temperature, thermal radiation and smoke concentration are considered. While maritimeEXODUS is capable of including the impact of the toxic fire gases they are ignored in this demonstration example. The SMARTFIRE fire simulation produced 22 minutes and 32 seconds worth of fire data. The fire is assumed to have started in a cabin on deck 6 within fire zone 1 and the fire effluent is allowed to spread throughout the fire zone through decks 6, 7 and 8. No attempts at controlling the fire are considered in this simulation however, the fire effluent is prevented from spreading to other fire zones. As in the previous examples, the muster stations are located on deck eight. As fire effluent spreads to the muster deck in fire zone 1, passengers in this zone are allowed to move to the neighbouring fire zone when they reach the muster deck. Given that this scenario is beyond the IMO requirements some minor modifications have been made in the nature of the results presented. The times presented relate to the time for the entire population to muster. This was felt more appropriate when dealing with the fire scenario. Only a single scenario is presented involving zero heel or list angle. The evacuation simulations were repeated 10 times with the location of the individuals swapped at the end of each simulation.

(a) The Fire Data Produced by SMARTFIRE

SMARTFIRE was used to determine the evolution of the fire incident within the vessel. The geometry used for the CFD simulation consisted of one vertical fire zone (fire zone 1) and three decks forming a volume 50.4 m long by 28.0 m wide by 8.8m tall. It was assumed that the door to the fire compartment was open and that the doors to all other compartments were closed. While SMARTFIRE can include the impact of forced ventilation these simulations did not include the action of mechanical ventilation. Thus, for the purposes of this demonstration simulation, it was assumed that the passenger cabins were not affected by the fire effluent and that the effluent could spread freely throughout the fire zone. Therefore heat and smoke generated by the fire escaped from the compartment of fire origin and travelled along corridors, up stairwells and through open public spaces.

A detailed combustion model was not included in these calculations, instead the fire was modelled as a volumetric heat and smoke source. The fire source was given the rough dimensions of a single bed (2.1m long by 0.8 m wide by 0.5 m high) and placed at the back of the cabin. The heat release rate used in the simulations are equivalent to that of a mattress with a peak Heat Release Rate (HRR) of around 1 MW. The smoke concentration predicted by SMARTFIRE on deck 6, 150 seconds into the simulation is depicted in Figure 4(a) while its representation in maritimeEXODUS and vrEXODUS is shown in Figure 4(b) and Figure 4(c) respectively.

For the purposes of the data transfer link between SMARTFIRE and maritimeEXODUS, 79 non-uniform output zones were applied across the domain. These zones were used to calculate and export averaged values over two set heights, a 'low' height of between 0.3m and 0.8m, and a 'high' height of between 1.5m and 2.0m.

(b) Evacuation Results produced by maritimeEXODUS

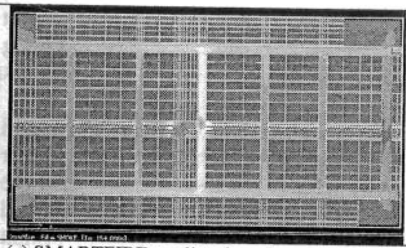
While a vast amount of detailed data can be generated for these simulations, only a summary of the results will be presented here. The average time to muster is approximately 31 minutes and 03 seconds, this compares to 15 minutes 32 seconds without the fire (see Table 1). As can be seen, the presence of the fire is predicted to double the required muster time. Fire zone 1 is the last to muster in all of the cases considered. This is to be expected as this is the fire zone that contains the fire. In addition, the passengers in fire zone 1 are forced to muster in fire zone 2. This was necessary as fire effluent reached the muster zone on deck 8.

Table 2: Clearing times for each deck at 0^0 of heel

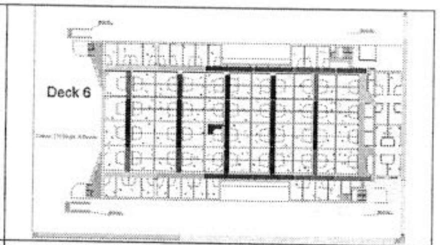
	Deck 6	Deck 7	Deck 9	Deck 10
Average non-fire case	14' 18"	14' 43"	14'19"	13' 58"
Average fire case	18' 18"	20' 06"	14'18"	13' 47"

The deck clearing times are shown in Table 2. These times represent the time required to completely clear the deck of all passengers, those starting on the deck in question and those passing through the deck on their way to the muster deck. The decks below the muster deck take longer to clear than the upper decks. The upper decks in the fire case take approximately the same amount of time to clear as they did in the non-fire case. This is due to the location of the fire. The fire is located on the lower decks and only affects the lower decks. The passengers passing through the smoke are slowed down to a crawl, delaying their passage through the deck and prolonging their exposure to the life threatening fire hazards. The 95% value for the mustering time for these simulations is 32 minutes 37 seconds. Thus, the predicted time to muster for this vessel under the IMO night conditions including a fire is 32 minutes 37 seconds. However, this time does not include the IMO specified safety factor of 10 minutes.

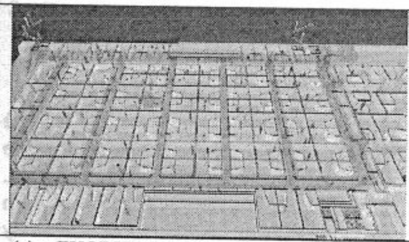
While it may still be appropriate to add a safety factor to account for issues excluded from these predictions (e.g. heel), it is not appropriate to add the entire safety factor to the predicted muster time as this simulation includes some of the features that the safety margin is intended to compensate for i.e. fire. While it may be argued that the vessel is capable of meeting the IMO target muster time of 40 minutes – even in situations involving fire – there are other factors that should be considered in judging the success or failure of this vessel under the scenario conditions.



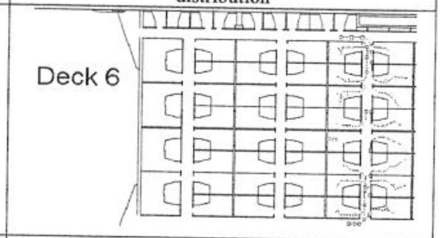
(a) SMARTFIRE predicted smoke concentration



(b) maritimeEXODUS depicted smoke distribution



(c) vrEXODUS depiction of smoke distribution



(d) Paths adopted by paxs who succumb to fire

Figure 4: Various views of the smoke distribution on deck 6 at 150 seconds as represented by (a) SMARTFIRE, (b)maritimeEXODUS and (c) vrEXODUS and (d) location of fatalities on deck 6.

Another significant difference between the fire and non-fire scenarios is that in the fire scenario there are a number of fatalities. Over the 10 repeat simulations, the number of fatalities varied from 26 to 27 passengers. The first fatality occurred at around 7 minutes and 6 seconds into the simulation while the last fatality occurred at around 19 minutes and 30 seconds into the simulation. All these fatalities occurred on deck 6 with the passengers involved being initially located close to the compartment of fire origin (see Figure 4(d)). Each of the fatalities travelled on average only 5 m before they succumbed to the intensity of the fire. The main reason for their demise was their proximity to the fire and their lengthy response time. The fatalities had an average response time of 10 minutes and 20 seconds, with the shortest response being 7 minutes and 10 seconds. The only way in which these individuals could have survived the incident would have been by responding much sooner to the alarm.

In addition to the fatalities it is also possible to determine the level of likely injury that the survivors have sustained. Although the majority of the surviving passengers had little or no interaction with the deteriorating conditions, several of them could be considered to be near death. Two passengers are expected to have severe exposure to thermal radiation having received a dose of thermal radiation greater than 70% of that which is required to cause incapacitation. All those exposed to severe doses of thermal radiation were initially located on the fire deck (i.e. deck 6). In total 25% of the passengers on deck 6 received doses of thermal radiation greater than 10% of that required to cause incapacitation. Had toxic fire gases been included in the simulation, the death toll and the injury level could be expected to be much worse. Conversely, it should be remembered that the scenario did not include any active fire fighting measures such as the use of sprinklers or forced ventilation.

This scenario has demonstrated the manner in which maritimeEXODUS and SMARTFIRE can be used to examine scenarios beyond the IMO regulations in order to investigate the success of the procedures on board, the impact of specified fire scenarios and suggesting potential solutions to these problems. The results presented are only a sub-set of that expected during a full analysis, but is indicative of the insight that could be gained.

CONCLUSIONS

Ship evacuation models will have a profound impact on safety at sea. They will be used by ship designers during the concept phase, classification societies for the certification of ship design and by ship operators for training both on shore and at sea. The software will have a similar impact on naval vessels, where issues such as lean manning, optimisation of crew movements during emergency and non-emergency situations as well as safety and evacuation are key to the design of efficient and well managed fighting machines. Furthermore, by combining detailed fire simulation with evacuation simulation, it is possible to obtain detailed insight into the performance of both man and machine under emergency conditions involving fire. This insight can be used in order to investigate the success of the procedures on board, the impact of specified fire scenarios and suggesting potential solutions to these problems. In this way the ship of the future will be safer by design.

ACKNOWLEDGEMENTS

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