Sustainable Maritime Transportation and Exploitation of Sea Resources – Rizzuto & Guedes Soares (eds)
© 2012 Taylor & Francis Group, London, ISBN 978-0-415-62081-9

Managing uncertainty in performance-based fire safety assessments of ships

Nikos Themelis, Stavros Niotis & Kostas J. Spyrou
School of Naval Architecture and Marine Engineering, National Technical University of Athens, Athens, Greece

ABSTRACT: We address the problem of "uncertainty" that pervades all facets of performance-based studies of ship fire safety. Very often only a limited number of fire scenarios are examined and it is practically unknown whether the result could sufficiently characterize the entire design. Motivated by this, we have carried out several fire simulations referring to a fictitious cruise ship where key factors such as the location of a fire onboard, fire products' yields and safety criteria norms, are treated as uncertain. For each examined scenario we calculated, near to evacuation exits, the time required to reach conditions affecting the efficiency of evacuation, such as visibility loss and toxic incapacitation. The performance of a small group of cabins appears to be quite representative of the aggregate performance of all cabins of the deck, particularly with respect to the visibility criterion. Sensitivity analyses performed reveal notable variations in failure probabilities.

1 INTRODUCTION

Market's demand for innovative solutions in the design of large cruise ships has led to the introduction of alternative assessment procedures for evaluating fire vulnerability on board that deviate from the current prescriptive SOLAS-based practice. Regulation 17 of SOLAS Chapter II-2 in combination with MSC 1002 constitute the platform for performing fire safety engineering analysis in order to ascertain that the alternative designs and arrangement provide, at a minimum, an equal level of fire safety with the one deriving from application of the prescriptive framework. In reality, the introduction of Regulation 17 has opened the door to performance-based fire safety assessments. Their implementation is supported by a number of technical guidelines published by authoritative organisations like the International Organisation for Standardization; the Society of Fire Protection Engineers and the National Fire Protection Association (see for example ISO/TC92 1999; SPFE 2002; NPFA 101 2000). More narrowly to the maritime sector, classification societies have also produced their own guidelines for the implementation of MSC 1002 (e.g. ABS 2004). Even though this step forward in designer's freedom has already impacted upon design evolution in various respects (e.g. from layout and materials to the installed fire safety systems onboard), one should not disregard a few areas of concern, related with the implementation of the associated assessment procedures.

The usual practice in performance-based studies is to evaluate and compare the performance of trial designs and arrangements with respect to certain fire safety objectives, by subjecting them to a limited set of "representative" fire scenarios. Due to the intrinsically vast number of the parameters that affect the process of fire development and the often significant uncertainty about their most appropriate values, the level of confidence to the outcome may not be reasonably specified. In other words, one is not certain that the assumed set of fire scenarios comprises a sufficient basis for decision-making. Furthermore, variations in the input of the scenarios within the uncertainty limits might alter the conclusion about the acceptability of a design. As a matter of fact, it is not clear how to systematically treat the various uncertain parameters that are present in a "performance based" fire safety assessment. Fire scenarios are commonly selected empirically, by "expert judgment". On the other hand, promising works have appeared towards a more holistic treatment of fire safety within a probabilistic framework (Hakkarainen et al., 2009; Vassalos et al., 2010).

We have proposed recently a methodology for the probabilistic generation and analysis of design fires (Themelis & Spyrou 2010). A design fire comprises a core element of a fire scenario as it describes the fire development in the defined space and it is usually expressed by the rate of released heat in time ("HRR curve"). A mathematical model for the generation of a HRR curve has been developed taking into account: the amount and type of available combustible materials (described as "fire load"); various sizes of ignition items ("fuel packages") and their potential in terms of intensity of fire growth, ventilation restrictions, flashover occurrence etc. Even at such an early stage like the definition of design fires however, uncertainties in several parameters values can be identified. These are commonly classified as "epistemic uncertainties", referring to lack of knowledge or data about the values of the various quantities involved. For example, the fire growth characteristics, expressed by the HRR curve, of a specific chair placed in a certain position within an enclosure are not known theoretically in an exact sense and thus, burning tests should be relied upon. Nevertheless, due to the complex underling chemistry that governs the burning of an item as well as the dependence of growth upon many parameters (including the ignition source), repeatability of the result of tests that were carried out with the same specification should not be taken for granted. The use of experimental data is nostrum rather than true remedy for proper parameter selection during fire safety analyses. In the scientific uncertainties one should include also choices accruing from several, implicitly or explicitly made, assumptions in the mathematical model(s). One example is the model of flashover prediction that is often based on semi—empirical formulas. Detailed fire CFD codes are devoid of such uncertainties neither.

Another category of uncertainties, the so called "aleatory uncertainties", are also (tacitly or loudly) present (Notorianni 2002). They arise from the truly random character of several parameters affecting fire growth (for example, an open or closed door, the exact position of some ignition item etc). The treatment of aleatory uncertainties in a probabilistic framework seems almost natural. In fact, all types of uncertainties can be treated in such manner if suitable distributions could be reasonably assumed. However, it is easier to obtain distributions for parameters with respect to aleatory uncertainties (where measurement and statistics can be used) than for the epistemic.

It becomes apparent that our aim in this paper is to address the management of uncertainties associated with ship fire safety assessments. The field is of course vast; but here we are interested specifically on the relation between the location of a fire onboard and the fire products' yields. A cruise ship will be used (in particular a cabin deck area), while numerical simulations based on a well-known CFD code ("FDS") will be employed for predicting the time histories of fire products (McGrattan et al., 2010).

Better understanding about the relationships of uncertain parameters can be very beneficial. This relates also with the fact that, in practice only a limited number of fire scenarios can be studied with detailed CFD models because the associated simulations are CPU time consuming. Therefore, it should be ensured that, the few fire locations selected for performing detailed simulation constitute a good basis for calculating the inherent risk associated with "all possible" locations.

In the first part of the study the location of the fire ignition cabin will be considered as random. This is an aleatory uncertainty, reflecting that ignition might take place in every cabin of the considered deck. In the second part we focus on the variation of fire product yields (specifically smoke and CO yield) whose values could be considered as "epistemically uncertain". These parameters affect directly the risk imposed to passengers during an evacuation process, so differences in this input of fire scenarios could change design characterization from safe to unsafe.

Simulation results are analyzed taking into account passenger hazards faced during an evacuation process. In more detail, we study performance against specific safety targets, expressed in terms of the time to achieve life threatening conditions during evacuation (e.g. reduced visibility, high temperature and high concentration of toxic gases).

In summary, the current work is a first attempt towards elucidating the effect of the uncertain parameters that permeate in a performance-based fire safety assessment; hoping to contribute towards the establishment of a more robust and rational fire safety assessment methodology that would lessen the need for expert judgment.

2 MODEL SET UP

2.1 *Considered space characteristics*

Cabins' layout corresponds to a fictitious but plausible design, based on a cruise ship. The length of the fire vertical zone has been extended to 47 m.

The deck is 2.5 m high and 20 m wide. It is equipped with three longitudinal and one transverse 1.5 m wide corridors, which connect the 40 cabins with a pair of staircases (aft and forward). The staircases are demonstrated as open hatches—3.4 m length by 1.4 m wide—through where air and/or smoke can freely communicate with the external environment. Port and starboard corridors are outfitted with 16 cabins each, evenly distributed, while the middle corridor hosts the other eight.

The deck area of each cabin is 13.4 m^2 with corresponding height 2.5 m, except from the extreme aft cabins, which are 15 m^2. Every cabin door is

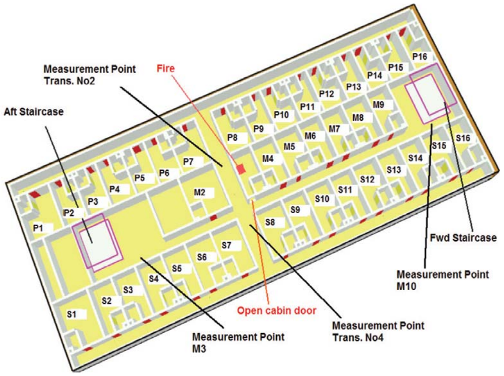

Figure 1. Deck overview showing the cabins and the location of measurement devices.

0.6 m wide and 2.0 m high. The cabin door remains open only when the subject cabin is the place of primary ignition. Figure 1 illustrates deck's general arrangement. For illustration, fire is shown ignited in the middle corridor cabin M3 (they are counted from aft to forward). All interior and exterior boundaries are assumed as B-15 class layered walls consisted of PVC paint, galvanized steel and Rockwool insulation. The exact distribution and properties of the materials used appear in Table No. 1.

2.2 *Fire specifics and simulation parameter settings*

The basic input data required are the HRR curve and the yields of fire effluents (soot and CO). The cabin door has been assumed open all the time and the fire load has been based on experimental data concerning full scale fire tests in a passenger cabin (Arvidson et al., 2009). Other parameters like the incipient time duration, the size and growth characteristics of the "fuel package", have been treated probabilistically. The general framework has been described in Themelis & Spyrou (2010). From the generated set of 200 fires, we select the HRR curve that corresponds to the same approximately maximum HRR and the time to achieve it with the respective experimentally measured HRR (see Figure 2).

Furthermore, the yields for soot and CO have been assumed corresponding to polyurethane and they were taken equal to 0.013 (g/g) and 0.035 (g/g). Specie's yield expresses the specie's mass that emanates from the fire, in terms of fuel mass loss (Karlsson & Quintiere 2000).

The longitudinal corridors are equipped with 10 measurement devices each, equally spaced every 5 m. The transverse corridor has been provided with five measurement points, also spaced every 5 m. The 35 devices in total are placed at 1.5 m height. They record temperature, CO, CO2, O2 volume fraction and smoke obscuration at every time step.

Table 1. Boundary materials (type: "sandwich").

Material	Thickness mm	Density kg/m³	Thermal Conductiv. W/mK	Specific heat kJ/kgK	Ignition temperature °C
PVC	2 × 0.5	1,380	0.192	1.290	750
Galvanized Steel	2 × 0.6	7,850	51.900	0.483	–
Rockwool	50.0	229	0.041	0.750	750

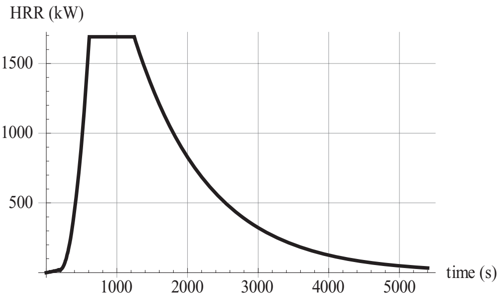

Figure 2. Selected curve of heat release rate.

In total, 320,000 cells have been generated with each cell size (in m) equal to 0.25 × 0.25 × 0.15. Average computational time for 90 minutes of simulation in a standalone PC (3.4 GHz) was 38 hr.

2.3 *Safety objectives*

Trial designs need to be assessed against effective performance criteria (also named here as "safety objectives"). However, even the setting of such criteria entails uncertainty because procedures of criteria development have subjective elements. Different criteria could produce different notions of acceptable design. Since we do not intend to perform evacuation analysis, quantitative criteria can be deduced from the limiting values of fire effluents at specific locations, implying the encounter of threatening conditions to human life during evacuation. The choice of measurement locations brings in another subjective influence that could be handled through a sensitivity analysis.

The following criteria and associated norms have thus been set:

1. Inability to view a light-reflecting-sign at 4 m distance due to smoke obscuration.
2. Temperature should not exceed 60°C.
3. Toxic gases' effect (basically CO) should not reach the incapacitation level.

We examine whether they are satisfied at locations near to evacuation exits and in the transverse middle corridor (see points M3, M10 and Trans. No. 2 in Figure 1). For the third criterion in particular we note that, in an evacuation process the toxic gas dose that a passenger could receive depends on the path that he follows. Here however we are not targeting the received dose by an individual who participates in the evacuation. Instead, we determine the time required to reach the incapacitation level, for a person that stands at one of the three specified locations.

The visibility criterion will be satisfied as soon as the parameter FEC_{smoke} ("fractional effective concentration"), which is calculated according to Equation 1 below, becomes equal to unit. FEC_{smoke} depends on the optical density parameter OD that is calculated in turn by Equation 2 (Mulholand 2002):

$$FEC_{smoke} = \frac{OD}{0.25} \tag{1}$$

$$OD = \frac{C}{2.3 \cdot S} \tag{2}$$

C is a non-dimensional constant characteristic of the type of object viewed through the smoke cloud. For the specific calculations we selected $C = 3$, corresponding to a light-reflecting sign. S is the visibility distance (in m).

The toxic effect of the asphyxiating gases (in fact the increase of CO and CO_2 concentrations and the decrease of O_2) will be considered through the parameter FED_{IN}, which is the "fractional effective dose" for incapacitation (Purser 2002):

$$FED_{IN} = FED_{CO} \cdot V_{CO_2} + FED_{O_2} \tag{3}$$

where:

$$FED_{CO} = \sum_{t_1}^{t_2} \frac{K \cdot [CO]^{1.036}}{D \cdot 60} \cdot \Delta t \tag{4}$$

$$V_{CO_2} = \frac{exp(0.1903 \cdot [CO_2] + 2.0004)}{7.1} \tag{5}$$

$$FED_{O_2} = \sum_{t_1}^{t_2} \frac{1}{60 \cdot exp[8.13 - 0.54(21\% - [O_2])]} \cdot \Delta t \tag{6}$$

$[CO]$, $[CO_2]$ and $[O_2]$ are the average volumetric concentrations (in ppm for CO,% volume for CO_2 and O_2) during a time increment Δt (in s). K and D are parameters related with human activity (for "light work" they take the values 8.2925×10^{-4} and 30 respectively according to Purser). High percentage of CO_2, which in small concentrations (less than 5%) can be considered as non toxic, results in acceleration of breathing (hyperventilation), while the reduction of O_2 causes oxygen hypoxia.

3 RESULTS AND CHARACTERISTIC LOCATIONS

3.1 *Time histories of fire effluents*

Figure 3 shows a screenshot of smoke spreading (produced by the Smokeview program of NIST (Forney 2008) for a fire in a cabin that is located at the middle corridor. Furthermore, Figures 4–5 show the time histories of temperature and CO concentration at specific points on the deck for a variety of fire case scenarios. We can observe the significant variation during a 5 min time period (from 10 to 15 min).

3.2 *Statistical analysis based on all cabins*

Next we calculate the required time for satisfying the criteria at the selected spot locations, for each examined scenario. At first stage the location of the cabin of fire ignition has been considered as uncertain. This means practically that all cabins had to be examined. In Figure 6 is plotted the estimated

Figure 3. Overview of the deck at time 430 s. Fire case scenario—ignition at cabin M5.

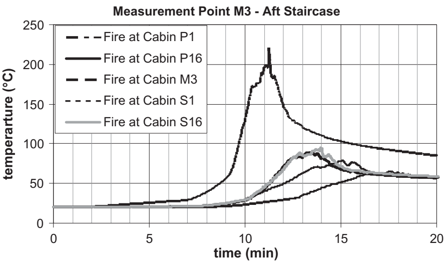

Figure 4. Time series of temperature at aft staircase for 5 different fire scenarios.

critical time required for reaching the visibility threshold due to smoke obscuration, at the three spot locations and for a fire at any of the cabins in the middle row. Furthermore, in Figure 7 is seen the critical time for reaching the incapacitation level due to toxic gases, for the starboard cabins. Lastly, in Figure 8 is shown the critical time with reference to the temperature criterion, considering the port set of cabins.

We have performed statistical analysis of the calculated critical times based on all cabins of the deck. Some key results are summarised in Tables 2, 3 and 4. They will be utilized subsequently in order to determine the probability some criterion to be violated during evacuation, at the three considered locations (see Figures 9–11). Some variability of the critical time is noticeable, depending on the location of fire origin.

Figure 9 contains sufficient information for building an index of evacuation efficiency. One observes that, if the evacuation time lasted for more than 12 minutes, there would be failure due to smoke obscuration. In the worst-case, a fire in cabin M3 seems to incur the lowest average critical time at the evacuation exits (the corresponding time is about 8.12 min). Designing by such an objective would lead to a $P = 0.975$ probability of successful evacuation, for all possible fire locations.

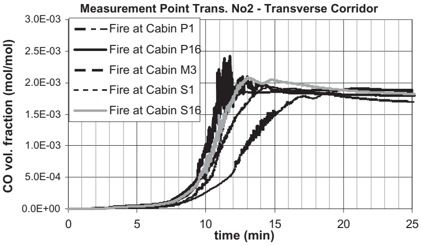

Figure 5. Time series of CO volume fraction at transverse corridor, for different fire scenarios.

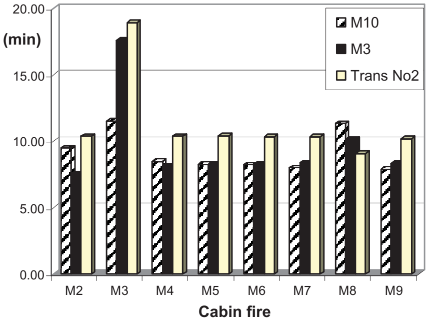

Figure 6. Critical time for smoke (middle set of cabins).

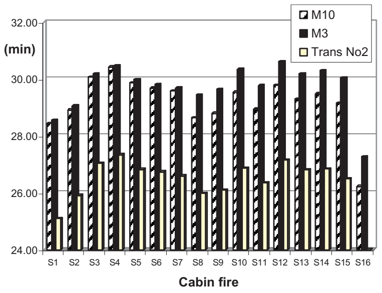

Figure 7. Critical time for toxic gases (starb'd set of cabins).

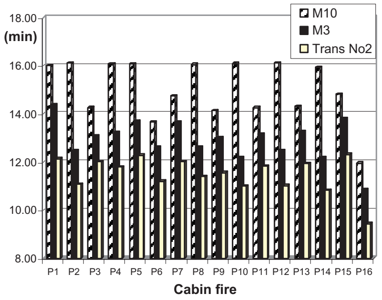

Figure 8. Critical time for temperature rise (port set of cabins).

Table 2. Statistics of time until visibility loss due to smoke.

Measurement point	M10	M3	Trans N2
Mean (min)	11.006	9.846	9.661
Variance (min)	1.383	2.140	2.554
Minimum (min)	7.887	7.560	7.726
Maximum (min)	12.034	17.598	18.908

Table 3. Statistics of time until incapacitation from toxic gases.

Measurement point	M10	M3	Trans N2
Mean (min)	27.810	28.583	26.281
Variance (min)	6.512	4.104	1.070
Minimum (min)	20.851	23.282	23.708
Maximum (min)	30.430	30.605	28.862

Table 4. Statistics of time until critical temperature.

Measurement point	M10 temp	M3 temp	Trans N2
Mean (min)	13.827	12.677	12.094
Variance (min)	6.672	3.507	1.426
Minimum (min)	8.248	8.236	9.232
Maximum (min)	16.679	16.133	14.173

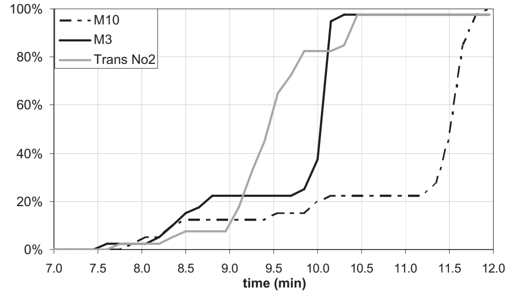

Figure 9. Probability of failure of the safety objective corresponding to visibility incapacity.

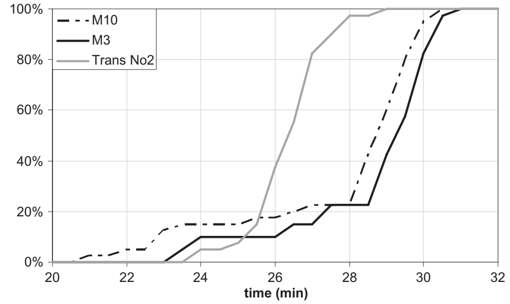

Figure 10. Probability of failure of the safety objective corresponding to toxic gases effect.

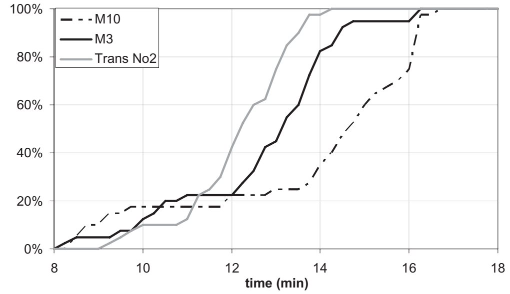

Figure 11. Probability of failure of the safety objective corresponding to temperature.

Nevertheless it is a matter of discussion what would constitute an acceptable probability level.

From the respective results for toxic gas concentration and temperature rise, we observe that toxicity incapacitation requires much more time; while temperature follows smoke with a time lag of 2–3 min. Furthermore, both failure probabilities show to obey a smoother distribution than the one for smoke in which rapid failure could be realized in less than 1 min. It is reminded that the result refers to a person standing at a fixed location and does not include any history of movement on the deck.

3.3 *Selection of representative set*

It becomes evident that it is unlikely to be able to capture the inherent risk from examination of a single cabin fire. Uncertainty of fire location is unavoidable and one wonders whether (and when) the selection of a single cabin could lead to a more or less conservative result. Not being capable to predict variations in risk by varying the fire location will lead to less confidence in the outcome of a performance-based study as different choices could change the acceptability of a trial design. However, carrying out tests for all possible scenarios in terms of location will be impractical due to the long simulation time required by CFD models.

A question naturally arising is thus, whether the required number of simulations could be significantly reduced, by identifying a representative group of cabins that provide similar average behavior, in terms of criteria satisfaction, as the entire set. This reduction process could be producing different representative sets, depending on the examined criterion. Consider for instance the visibility criterion that resulted earlier in smaller critical time than the similar time associated with the other two criteria. Say that we could afford to investigate up to 3 cabins. By empirical judgment and exploiting the privilege of having access to a large set of data referring to all cabins, we found the set comprised by cabins M2, S2 and P14 as the most representative. However we admit that we have not examined meticulously all possible combinations: due to limited time we were unable to perform exhaustively all calculations per criterion and set.

Failure probabilities were determined as functions of the average critical time, for the evacuation exits (M10 and M3). The obtained probabilities are compared against those corresponding to the whole set of cabins of the considered deck. A similar trend is noticed while there is a rather consistent quantitative difference in actual values.

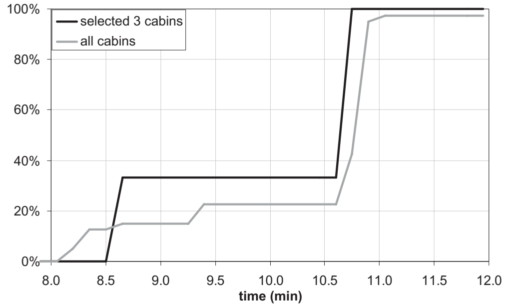

Figure 12. Probability of failure of the safety objective corresponding to visibility near evacuation exits: a) for the selected set of 3 cabins; and b) for all cabins.

4 UNCERTAINTY IN THE NORMS DEFINING VISIBILITY RANGE, SMOKE AND CO YIELD

We turn our focus now to some "epistemic" uncertainties that could affect evacuation efficiency. The uncertain parameters that will be examined are: the distance that defines visibility range in the presence of smoke; the soot and CO fire yields. The respective sensitivity analyses will be carried out for the set of three cabins that we found earlier as most representative.

Inability to see a light-reflecting sign in a distance of 4 m had been considered as a criterion in the previous calculations. We will now perform sensitivity analysis for a range (from to 2.5 m to 4 m visibility, with a step of 0.5 m). Such a range is used in practice in evacuation calculations. The obtained probability values are seen in Figure 13. Next we modify the soot yield by increasing stepwise the initially taken value (0.013 g/g) by 25%, 50% and 75%. The result is seen in Figure 14. Summary results, in terms of critical time, for various combinations of soot yield and visibility, for various percentiles of failure, are presented in Figure 15 and in Figure 16.

Lastly, we perform sensitivity analysis concerning the CO yield, which directly affects the critical time for toxic incapacitation. Figure 17 shows the probability of evacuation failure for a range of CO yields (up to 75% from the initially considered value). The critical time corresponding to various failure percentiles is presented in Figure 18.

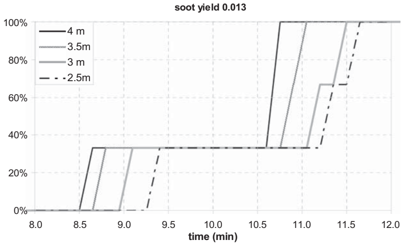

Figure 13. Probability of failure for different norms for smoke [soot yield is fixed at 0.013 (g/g)].

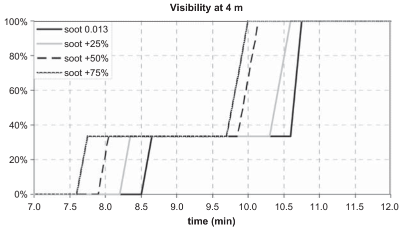

Figure 14. Probability of failure for different soot yields with 4 m visibility.

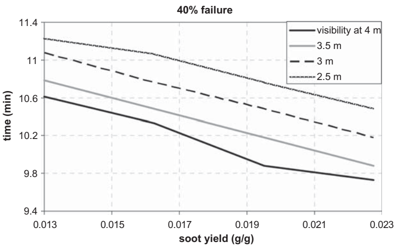

Figure 15. Critical time for soot yield with 40% probability of failure.

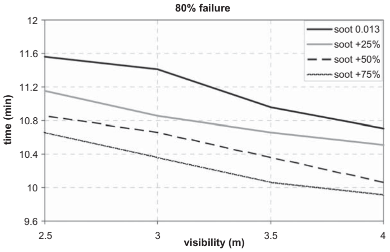

Figure 16. Critical time for visibility at 80% failure probability.

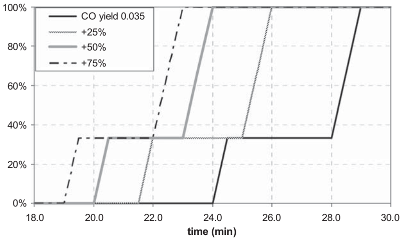

Figure 17. Probability of failure due to toxic incapacitation for different CO yields.

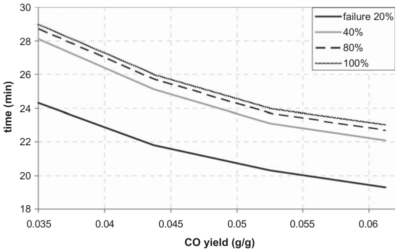

Figure 18. Critical time for toxic incapacitation, for different CO yields and failure percentiles.

From the above results we derive that, by reducing the distance of visibility loss by 0.5 m (12.5% of the initial value) and keeping constant the soot yield, we obtain approximately 3% increase of the critical time (this is natural since more time will be required for reaching a stricter condition).

On the other hand, by increasing 25% the soot yield the respective time will be decreased by 3.5%. Therefore it seems that the critical distance for visibility incapacity affects slightly more the available evacuation time than the soot yield. Also, we can conclude that variation of CO release during a fire, say 25% increase of the yield of CO, will bring about 9% reduction in the critical time for incapacitation. Thus the selection of materials in terms of CO emission should be particularly considered, keeping in mind also the fact that, in smouldering types of fire, the CO yield could be increased by 50–100 times.

5 CONCLUDING REMARKS

In the first part of the current study we have focused on the randomness of the location of the space of fire origin that, in actual fact, could never be exactly anticipated. We have thus considered ignition incidents at any cabin of a deck expanding within a main vertical zone of a fictitious cruiser. We then calculated the probabilities corresponding to safety criteria failure. The key aspect of this part was an heuristic consideration whether a small group of cabins could produce similar tendency in failure probability. If that was true, one could capture inherent risk more efficiently and reliably. Of course the current study is a preliminary one as the issue is major and further research will be required for obtaining a concrete answer.

In the second part of the paper we studied the epistemic uncertainties associated with the proper setting of safety norms in the criteria. Summarizing the results presented in section 4, we can conclude that by reducing the visibility norm by 37.5%, the increase in the estimated critical time was approximately 0.8 min (about 8%). Besides, for the soot, a 50% increase of yield resulted in 1 min less available evacuation time (about 9.1% decrease for 20% success). Variations in the CO yield have also been considered: a fire that emits 50% more CO was found to give, approximately, a 21% decrease of the critical time (of course for the specific conditions assumed). Therefore, notable variations in the failure probabilities have been found and especially, CO yield variations proved to be the most significant.

Uncertainty in performance-based studies is a challenging area in fire safety assessments and it definitely deserves more attention. Modern numerical tools of fire modeling are very useful but they are not panacea since, if used in an unstructured and haphazard manner, they can produce different outcomes and thus lead to different design choices whose true effectiveness is very difficult to evaluate. More studies on these issues are necessary in order to formalize the selection of representative scenarios with respect to the various safety objectives that are relevant to the fire safety analysis of ships.

ACKNOWLEDGMENT

Part of the present study has been carried out within the framework of the EU project FIREPROOF: Probabilistic Framework for Onboard Fire Safety (Grant agreement number: 218761).

REFERENCES

ABS 2004. Guidance notes on alternative design and arrangements for fire safety, American Bureau of Shipping, Houston, USA.

Arvidson, M., Axelsson, J. & Hertzberg, T. 2008. Large-scale fire tests in a passenger cabin. *Fire Technology.* SP Report 2008:33.

Forney, G. 2008. NIST Special Publication 1017-1-User's Guide for Smokeview Version 5—A tool for Visualizing Fire Dynamics Simulation Data. Washington: U.S. Government Printing Office.

Hakkarainen, T., Hietaniemi, J., Hostikka, S., Teemu Karhula, S., Kling, T., Mangs, J., Mikkola, E. & Oksanen, T. 2009. Survivability for ships in case of fire, Final report of SURSHIP-FIRE project. *VTT Research notes* 2497. Finland.

International Maritime Organisation, MSC/Circ. 1002. Guidelines on alternative design and arrangements for fire safety, London, IMO, 2001.

International Organisation for Standardization (ISO), Fire safety Engineering—Part 2: Design Fire Scenarios and Design Fires, ISO/TR 13387-2, 1999.

Karlsson, B. & Quintiere, J.G. 2000. Enclosure fire dynamics. USA: CRC McGrattan, K., McDermott, R., Hostikka, S. & Floyd, J. 2010. NIST Special Publication 1019–5-Fire Dynamics Simulator (Version 5) User's Guide. Washington: U.S. Government Printing Office press, ISBN: 0-8493-1300-7.

Mulholland, G.W. 2002. *SFPE Handbook of Fire Protection Engineering, chapter Smoke Production and Properties, 3rd edition*. Quincy, Massachusetts: National Fire Protection Association.

Notorianni, K. 2002. *SFPE Handbook of Fire Protection Engineering, chapter Uncertainty, 3rd edition*. Quincy, Massachusetts: National Fire Protection Association.

Purser, D.A. 2002. *SFPE Handbook of Fire Protection Engineering chapter Toxicity Assessment of Combustion Products, 3rd edition*. Quincy, Massachusetts: National Fire Protection Association.

Themelis, N. & Spyrou, K. 2010. An efficient methodology for defining probabilistic design fires. *Proceedings, 4th International Maritime Conference on Design For Safety*, *October 2010*. Trieste.

Vassalos, D., Spyrou, K., Themelis N. & Mermiris, G. 2010. Risk- based design for fire safety—A generic framework. *Proceedings, 4th International Maritime Conference on Design for Safety, October 2010*, Trieste.