Probabilistic Framework for Onboard Fire Safety - FIREPROOF

Dracos Vassalos

The Ship Stability Research Centre (SSRC), University of Strathclyde

Kostas Spyrou, Nikolaos Themelis

National Technical University of Athens

Ed Galea, Angus J. Grandison

Fire Safety Engineering Group, University of Greenwich

Ana M. Henriques, Cláudia P. Dias

Instituto de Soldadura e Qualidade

Antoine Breuillard

Bureau Veritas, Research Department

George Mermiris

The Ship Stability Research Centre (SSRC), University of Strathclyde

ABSTRACT

There is little doubt in the maritime industry that the age of very large passenger ships has arrived with the recent delivery of the first cruise liner with capacity of over 8,000 passengers and crew. The fact of a single floating platform accommodating such a large number of people poses new challenges to designers, operators and regulators alike. Among these challenges, fire safety is one of the most pertinent ones, albeit less catastrophic than collision or grounding, according to accident statistics. Because of the innovative character of such large ships, from many aspects, and those that will soon follow, the fire regulations currently in force have been described as potentially inadequate as they impose constraints on novel designs, which although not inherently unsafe, may lead to difficulties when trying to satisfy existing rules. In response to this problem, the consortium of FIREPROOF (www.fireproof-project.eu) will elaborate on the development of a universally applicable regulatory framework for maritime fire safety, which, in principle, will be similar to the probabilistic framework for damage stability and it will address the fire risk onboard passenger ships. This paper reports on the philosophy, the main objectives and the structure of FIREPROOF.

INTRODUCTION

Historical evidence suggests that fire hazard comes next to the hazard of flooding in quantifying the life-cycle risk of ships, particularly so for passenger ships (Figure 1). Despite being one of the main priorities in ship design, fire safety can be compromised when addressed purely as compliance to prescriptive rules. The majority of the current prescriptive rules are based on past experience and accident occurrences, and has proven to serve reasonably well for conventional arrangements. However, the demand for larger, more complex and safer ships, and the pace of their evolution and innovation reduces substantially the effectiveness of this approach.

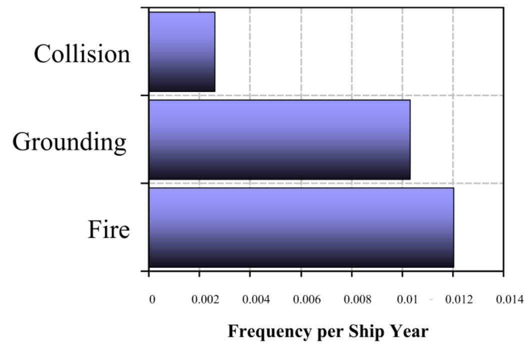

Figure 1: Frequency of collision, grounding and fire accidents of passenger ships, (Nilsen, 2007)

Although performance-based assessment (fire engineering methods) of alternative design arrangements has been introduced with SOLAS II-2, Reg. 17, and the associated guidelines implicit in MSC/Circ.1002, the process remains open-ended without a clearly defined basis of approval.

In light of the above and given the substantial body of knowledge that has been obtained through previous EU funded and commercially supported research, FIREPROOF is designed to be a sequel to SAFEDOR (www.safedor.org) in the context of fire accidents and incidents onboard passenger ships. Its aim is to build on the systems and methods developed within its precursor to develop a regulatory framework capable of ensuring fire safety of novel and existing designs through the application of risk-based design methodology.

FIREPROOF is co-funded by the 7th Framework Programme of the European Commission and its consortium is comprised by thirteen partners, including industry and academia, from eight countries. The project commenced in 2009 and will last three years. This paper elaborates on the general methodology of FIREPROOF and the description of its objectives.

THE CONCEPT OF THE PROBABILISTIC FIRE FRAMEWORK

The governing idea of FIREPROOF is the rational assessment of fire risk, and in particular the assessment of the level of safety against fire hazards onboard passenger ships. In this context, risk is used as the measure of safety that needs to be minimised or reduced as far as reasonably practicable.

Conventionally, the risk (R) associated to an unwanted event is defined as the product of its probability of occurrence (P) and its ensuing consequences (C):

$$R = P \times C \tag{1}$$

In this way, the notion of risk clearly differentiates from the notion of reliability, as it refers to events with catastrophic outcomes that occur only once. In the context of FIREPROOF, the outcome of a fire accident is related to the number of fatalities (societal consequences) of the exposed passengers and crew onboard a ship. Along these lines, the conventional definition of risk can be formulated as follows, (Vassalos, 2009):

$$R_F = \sum_{i=1}^{n} \Delta R_i = \sum_{i=1}^{n} f_i \times \sum_{j=1}^{m} P(E)_{i,j} \times N_{i,j} \tag{2}$$

Where:

- R_F: total fire risk;
- i: counter for the number of spaces onboard;
- ΔR_i: risk for space *i*;
- f_i: frequency of ignition in space *i*;
- j: counter for the number of escalation outcomes;
- $P(E)_{i,j}$: probability of escalation from space *i* with outcome *j*;
- $N_{i,j}$: number of fatalities in space *i* with outcome *j*.

The indices *i* and *j* represent the fire scenarios and their variations respectively, as it is discussed in (Guarin et al., 2007). The elements of Eq. (2) will be analysed in more detail in the following two sections, namely, the *Scenario Generation* and the *Consequence Assessment*. The section on *Implementation and Benchmarking* will elaborate on the integration of the necessary tools for fire risk analysis. Finally, the section on *Probabilistic Fire Safety Certification* will discuss the way in which FIREPROOF findings will be turned into regulatory criteria for submission to IMO for discussion and further consideration.

SCENARIO GENERATION

A methodology for the generation of fire scenarios and the estimation of their probability of occurrence is one of the key elements of the project. A fire scenario describes the development of fire in a space onboard by taking into consideration the effectiveness of passive and active fire safety means, namely fire detection, containment and suppression. The fire development in an enclosure depends on various parameters, like the fire type and size, geometrical and ventilation characteristics as well on effectiveness and reliability of the fire fighting systems and crew (or passenger) intervention. In order to consider probabilistically the effect of various parameters in the generation of the scenarios, various mathematical tools can be incorporated, like models for generating fire characteristics, event and fault trees and even Bayesian networks. All these tools utilise data from an incidents database that was developed at the beginning of the project.

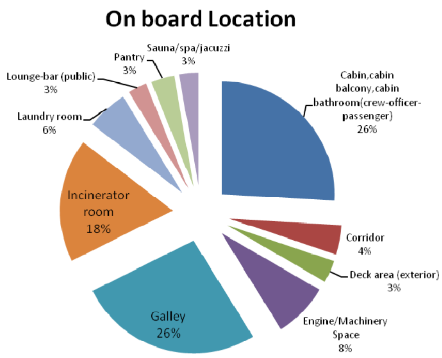

Figure 2: Probability of ignition for different onboard locations, (Ventikos et al, 2010)

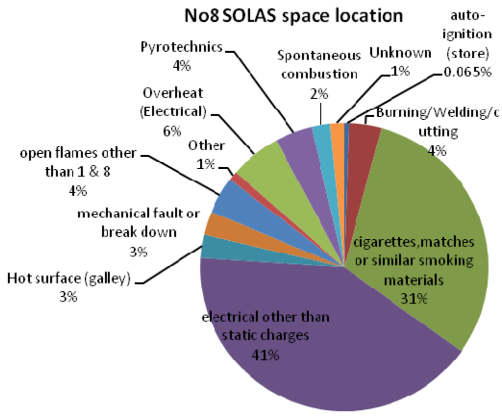

Figure 3: Probability of ignition sources for the No.8 SOLAS space, (Ventikos et al, 2010)

In this database, the dominant parameters, such as space type of fire origin (both detailed and grouped according to SOLAS II-2, Reg. 9), the type of ignition source, the state of boundaries, the severity, etc., have been identified followed by the calculation of the related probabilities, as it is presented for example in Figure 2 for the ignition probability for different spaces onboard, and Figure 3 for the probability of different sources of ignition for a specific SOLAS space.

Some characteristics of a fire scenario related with the fire type, size and development in a space are represented by the Heat Release Rate (HRR) curve. An HRR curve describes the main fire stages, namely the *incipient*, the *growth*, the *fully developed* and the *decay* stage. A physically rational model that generates probabilistically HRR curves based on key parameters like fire load, incipient time, growth potential and others has been developed (Themelis et al, 2010) and (Themelis and Spyrou 2010). Due to the uncertainty of the values of these parameters, such as the amount and type of the combustible materials present in a space, the model addresses them as random variables. For example, distributions of the fire load density can be generated as depicted in Figure 4. As a result, a number of HRR curves have been produced probabilistically (Figure 5), which are utilised as input in terms of fire characteristics in the scenario generation methodology, as well as in the numerical tools for fire modelling.

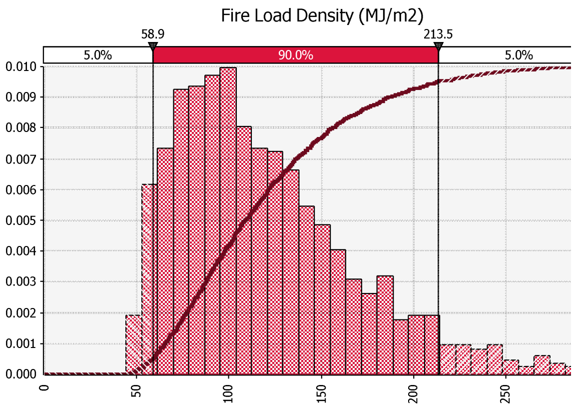

Figure 4: Fire load density for a passenger cabin

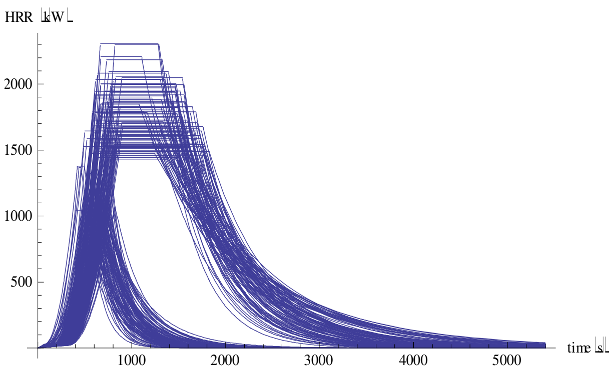

Figure 5: Probabilistically generated HRR curves

In addition, the reliability and effectiveness of the fire safety systems is incorporated in the methodology using generic fault trees (Figure 6). For the component failure rates, manufacturers' data and data available from similar equipment is used.

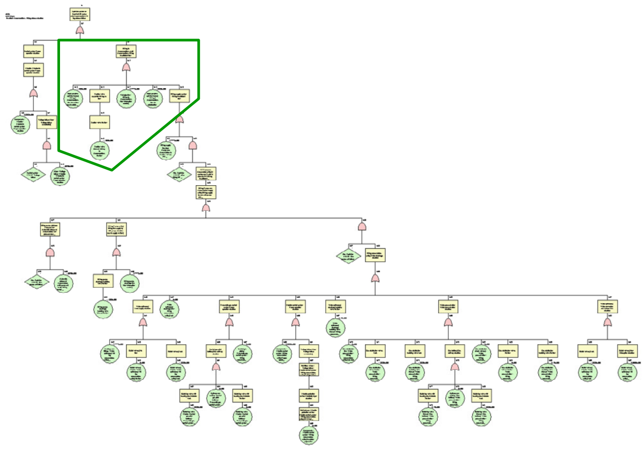

Figure 6: Specific fault tree on an automatic water mist system using Bureau Veritas VeriSTAR Machinery software

Human intervention, e.g. presence of crew and fire fighting teams onboard, is also incorporated as Figure 7 shows.

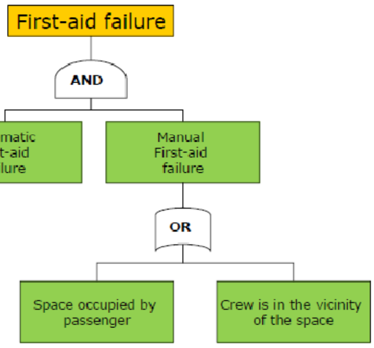

Figure 7: Fault tree for failure of suppression at first level, (Guarin et al., 2007)

Scenarios can be generated using event trees (Figure 8) or Bayesian Networks (Figure 9) as mentioned before, where the critical set of events will be identified on the condition that fire containment and suppression have failed and escalation to adjacent spaces has occurred according to SOLAS Ch. II-2. The probability of occurrence of each scenario can be calculated by the above mentioned models, while the critical ones will be analysed further in consequence assessment with detailed numerical fire modelling and egress tools.

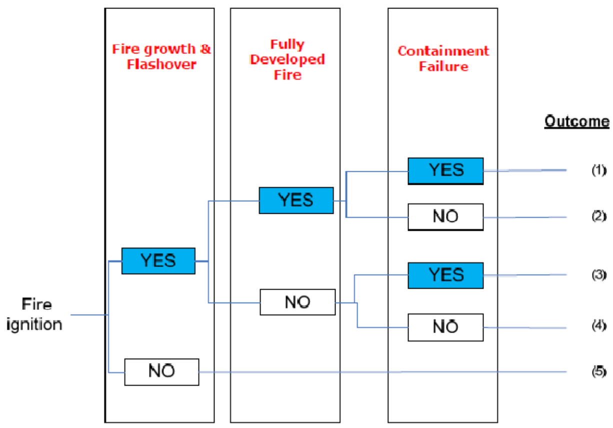

Figure 8: Example of event tree scenario generation

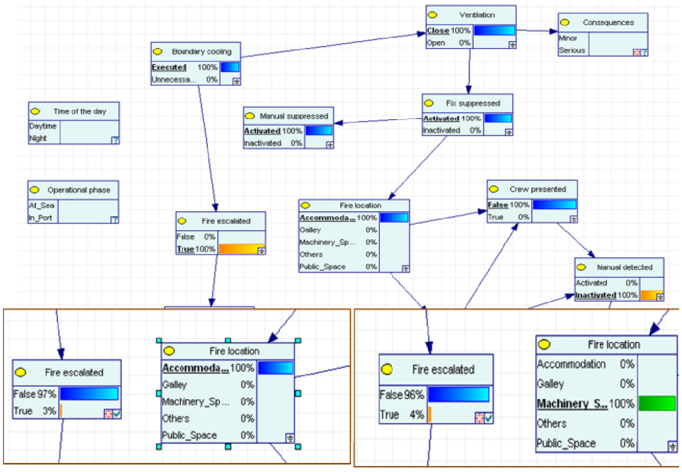

Figure 9: Example of a Bayesian Network

CONSEQUENCE ASSESSMENT

Through the scenario generation model the scenarios of highest risk will be examined in greater detail using predictive simulation tools in order to gain deeper insight into their potential consequences.

The outcomes of fire scenarios and their variations will be assessed with (i) the formulation and development of an integrated fire model (based on a hybrid between Computational Fluid Dynamics (CFD) and zone models that combines the advantages of both models by reducing the computation time compared to a full CFD model and increased applicability and fidelity compared to a zone model for a wide range of fires), and (ii) the appropriate use of a societal consequence model (based on the coupling of initial occupancy of various spaces, evacuation behaviour and fire growth simulations).

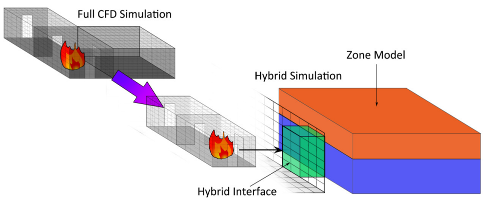

Figure 10: Conceptual view of Hybrid fire model

The integrated fire model, based on the SMARTFIRE model, will use CFD modelling for complex geometries and areas beyond the reliable application of empirical zone models and the zone models will be applied in areas where the empiricism can be consistently applied, (Burton et al., 2007). By combining these two methods it is possible to achieve high fidelity results for the predicted environment whilst reducing the overall runtime compared to a pure CFD simulation. The CFD and zone models are interfaced to ensure that the solution created by the two methods is consistent (as illustrated in Figure 10-Figure 12 below) at the adjoining volumes. Figure 10 shows the conceptual overview of the hybrid model.

The hybrid model requires a two way coupling between the SMARTFIRE CFD model and the zone model. Figure 11 illustrates how values from the CFD model are communicated to the zone model. Figure 12 illustrates how the values from the zone model are communicated back to the SMARTFIRE CFD model. Figure 13 illustrates a SMARTFIRE CFD cut plane of smoke concentration of an example ship deck.

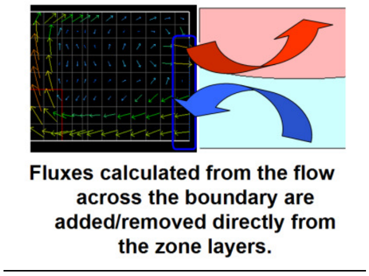

Figure 11: Communicating values from CFD to zone model

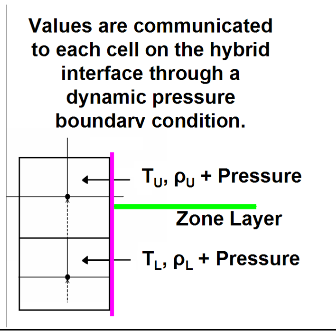

Figure 12: Communicating values from zone model to the CFD code

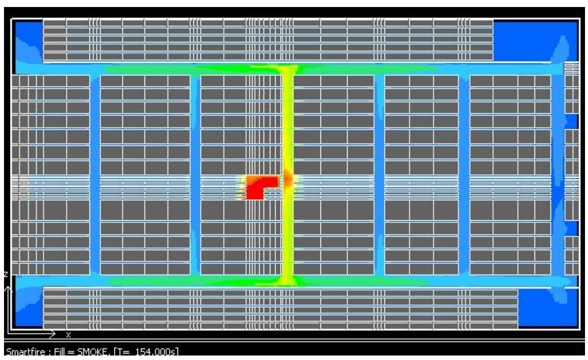

Figure 13: Instantaneous visualization slice of smoke concentration on an example ship geometry.

Using the data produced by the hybrid fire model (Figure 13) a societal consequence model will simulate passenger evacuation under the influence of hazardous environmental conditions. The maritimeEXODUS model, (Galea et al, 2004), will be used within the FIREPROOF framework as the societal consequence model, and it will focus on the evacuation behaviour and dynamics of the passenger movement. The model itself can utilize physiological toxicity models such as the Fractional Effective Dose (FED), which predicts injury, incapacitation and fatality based on exposure to toxic fire products such as carbon monoxide and hydrogen cyanide. The FED model also takes into account effects of fire products like the smoke

no more a standard temperature curve but can now be estimated and assessed based on large number of realistic scenarios (Gottuk and Lattimer, 2005). However, from a probabilistic point of view, the number of variables, parameters and possible risk control option is substantial, as well as the degree of human interaction with the fire development and outbreak. Analysing past accidents provides good general statistics for the average fleet but the probabilities and expected consequences related to fire on a specific ship with specific crew and systems are harder to quantify. This is even truer in case of novel designs as it was stated above.

Having general fire safety objectives and functional requirements, the IMO Maritime Safety Committee (MSC) and the Fire Protection (FP) sub-committee in particular defines prescriptive regulations applied on local aspects of possible defects, failures, lack of protection, isolation and evacuation problems onboard ships. When designing a ship the minimum requirement is to apply the regulation to the extent possible and resolve to alternative design techniques on specific cases that deviate from the regulation (Breuillard and Corrignan, 2009). This will cover all the local fire safety issues and ensure control over the related fire hazards. However, future ships will probably be designed beyond what is known today in terms of size, type of spaces, capacity, propulsion type and combinations of all of these novelties. This is the reason why FIREPROOF raises rightfully the issue of the overall fire risk level of a ship, Eq. (2).

One challenging aspect of the certification of such method is to define the limiting values and ranges for the risk metrics that will be used as criteria. In FIREPROOF, such ranges will be determined by implementation of the proposed methodology and benchmarking studies. It is desirable that the same criteria would be universally applicable to all ship types and sizes at various occupancy levels, but in reality the wide range of population distribution and fuel load categories might force the definition of separate criteria for different ship types.

The criteria should be specified at sufficient level of detail for incorporation in a regulatory text. A strict requirement for entering the regulatory adoption phase is that the entire process of the FIREPROOF framework should be unambiguous and clearly specified. Every detail starting from the requisite product model to the calculation procedure and the criteria has to be completely and clearly documented so that the produced documentation can be used to thoroughly re-implement the entire procedure by a third party without assistance from the FIREPROOF consortium.

This overall fire risk analysis of future ships could be investigated and certified in the first place within the framework of an additional class notation. Therefore this checking could only provide enhanced safety, which would be good by itself, and it would allow time to designers and regulatory bodies to have hindsight on the validation, robustness and support of the proposed methodology. Consequently, after this period, if the method demonstrates actually enhanced safety for a reasonable amount of design work and practicable solutions, then this additional certification work could be presented to MSC with a view to achieve a consensus at some point on including such criteria in a future version of SOLAS.

For that, the dissemination objective of FIREPROOF is to publish and present the developed fire safety framework to relevant forums, conferences and journals. Regulatory criteria can neither be directly promulgated nor enforced by the FIREPROOF consortium. Instead, recommendations would have to be made to IMO and national regulatory authorities stating the specifications and efficacy of modernised and performance-oriented fire safety regulations for merchant ships.

ACKNOWLEDGEMENTS

The financial support from the European Commission and the industry are greatly appreciated and acknowledged by the authors and the FIREPROOF (contract number 218761) consortium in general.

DISCLAIMER

The opinions expressed in this paper are those of the authors and under no circumstances should they be interpreted as the policy of their employer organisations.

REFERENCES

Breuillard, A. and Corrignan P. (2009), “Alternative Design Methodology for the Fire Safety of Composite Superstructures”, SNAME annual meeting 2009, Providence RI, USA

Burton, D. J., Grandison, A. J., Patel, M. K., Galea, E. R. and Ewer, J. A. (2007), “Introducing a Hybrid Field/Zone Modelling Approach for Fire Simulation.”, Proceedings of the 11th International Fire Science & Engineering Conference, Interflam 2007, 3-5th September 2007, Royal Holloway College, University of London, UK, Volume 2, pp. 1491-1497

Galea E.R., Grandison A. J., Filippidis L., Gwynne S., Ewer J. and Lawrence P., (2004), “Safer by Design: Simulating Fire and Escape at sea”, Proc 1st Int. Conference Escape, Evacuation and Recovery, Survival from Ships and Offshore Structures, Lloyds List Events, London 10-11 March 2004, Session 3, pp 1-22

Gottuk, D. and Lattimer, B., (2005), “Two-model Monte Carlo simulation of fire scenarios”, Proceedings of the Eighth International Symposium on Fire Safety Science, Beijing, China, 18–23 September 2005

Grandison, A. and Galea E., (2010), “Randomized Scenario Generation Specification”, FIREPROOF, draft report for task 1.4

Guarin, L., Logan, J., Majumder, J., Puisa, R., Jasionowski, A. and Vassalos, D. (2007), “Design for Fire Safety”, Proceedings of the 3rd Annual Conference on Design for Safety Conference, Berkeley, USA

Majumder, J., Puisa, R., Azzi, C., Guarin, L. and Psarros, G., (2007), “Quantitative Risk Analysis (QRA)”, SAFEDOR Project, Deliverable 2.5.2

Nilsen, O. V. (2007), “Risk Analysis for Cruise Ships”, SAFEDOR Deliverable 4.1.2

Themelis, N., Mermiris, G. and Wenkui, C. (2010), “Fire Ignition Model Specification”, FIREPROOF Project, Deliverable 1.2

Themelis, N. and Spyrou, K. (2010), “An efficient methodology for defining probabilistic design fires”, 4th International Maritime Conference on Design for Safety, 18-20 October, Trieste, Italy

Vassalos, D. (2009), Risk-based Ship Design (Chapter 2). In “Risk-Based Ship Design – Methods, tools and applications”, ed. Papanikolaou, A., Springer, 2009

Ventikos, N., Petsiou, M., Papamichalis, G. and Anaxagorou, P., (2010), “Comprehensive fire accidents database”, FIREPROOF Project, Deliverable 1.1