FIRE RISK MODELLING

George Mermiris[1], Angus Grandison[2], Nikos Themelis[3], Richard Pawling[4] and Philipp Lohrmann[5]

ABSTRACT

The fire safety regulations in SOLAS Ch.II-2 are founded on historical data and they are largely prescriptive in nature. As a result, the current regulatory framework does not facilitate efficiently the much needed innovation by the industry and unnecessary difficulties are imposed during the approval process. In direct response to this situation this paper reports on an analytical formulation for the quantification of fire risk onboard passenger ships, which is founded on the Risk-based design methodology. The outcome of the calculations are presented in the form of PLL and F-N curves in order to offer a direct means of comparison with the current industry safety levels. This development took place in the course of the FIREPROOF project, which is partially funded by the 7th Framework Programme of the European Commission.

KEY WORDS

Fire Safety; Risk-based Ship Design; Analytical Modelling; Passenger Ships

INTRODUCTION

Recent decades have witnessed a continuous increase in the size and complexity of passenger ships, stemming from the popularity of cruise liners for leisure and holiday purposes, and the transportation efficiency of Ro-Ro passenger ships. However, this trend has not been properly supported at regulatory level with a rationalised fire safety framework, which does not penalise arrangements falling outside the remit of past experience, and nurtures innovation. The *Probabilistic Framework for Onboard Fire Safety* project (FIREPROOF, www.fireproof-project.eu) has set out to change this situation by developing a Risk-based Design (RBD) assessment framework, (Vassalos, 2009), at the heart of which lies the holistic performance assessment of the ship with respect to both fire occurrence and the ensuing societal consequences.

Although such rationalised approach of treating safety contradicts with the philosophy advocated in SOLAS Ch.II-2, where the objectives to contain, control and suppress are achieved by a finite set of accident scenarios (vulnerability analysis), yet it complies with the performance-based philosophy, which already receives wide acceptance by the industry. The developments in FIREPROOF build on this trend, which is supported by the demonstrable results of the RBD methodology, and run in parallel to other research projects concerned with the analysis of flooding and damaged stability, namely GOALDS (www.goalds.org), FLOODSTAND (http://floodstand.aalto.fi), and smaller ones within the remit of the European Maritime Safety Agency (www.emsa.europa.eu).

In light of these parallel developments, the objective of this this paper is to report on the risk model that lies in the centre of the FIREPROOF methodology and to highlight the contribution, from the fire point of view, to the wider RBD approach to ship safety.

[1] The Ship Stability Research Centre (SSRC), University of Strathclyde
[2] Fire Safety Engineering Group (FSEG), University of Greenwich
[3] National Technical University of Athens
[4] University College London
[5] BMT Group Ltd

THE FIREPROOF CONCEPT

In light of a constant demand for larger, more complex and safer passenger ships, the pace of their evolution and innovation is too fast for comfort with respect to the underlying regulatory fire framework of SOLAS Ch.II-2, which is largely based on past experience and the assessment of a handful of extreme accident scenarios. As a result, approval becomes difficult and allows little flexibility to explore the much needed innovative arrangements of modern passenger ships. Although the introduction of performance-based assessment (fire engineering methods) of alternative design arrangements with Regulation 17, (IMO, 2001), was a step in the right direction, yet the process remains open-ended and a comprehensive approval process is still missing.

On the other hand, analysis of historical data has demonstrated that fire and flooding (due to collision and grounding) constitute 90% of accidents where ship had to be abandoned. Although fire frequency is some 8 times higher than flooding, fortunately enough it is far less catastrophic, (Nilsen, 2007). Because of these reasons and despite being one of the main priorities in ship design, fire safety can be compromised when addressed purely as compliance to prescriptive rules.

Bearing in mind the above and given a substantial body of knowledge generated in previous EU-funded and commercially supported research projects, FIREPROOF was defined as a sequel to the SAFEDOR project (www.safedor.org) in the area of fire risk analysis for passenger ships. Its aim is to build on the systems and methods developed within its precursor and develop a regulatory framework capable of ensuring fire safety of novel and existing designs through the application of the RBD methodology. That is, the rational assessment of fire risk, which pertains to events with catastrophic outcomes. 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.

In order to be in line with concurrent developments in damage stability, FIREPROOF will condense its findings in a probabilistic framework in direct analogy to the one in SOLAS, Ch. II-1, which is currently under revision in the GOALDS project, (Figure 1).

Flooding

$$A = \sum_{j=1}^{J} \sum_{i=1}^{I} w_j \cdot p_i s_{ji}$$

j: loading condition under consideration;
J: number of loading conditions;
i: compartment or group of compartments under consideration;
I: set of all feasible flooding scenarios comprising single compartments or groups of adjacent compartments;
w_j: probability mass function of the loading conditions;
p_i: probability mass function of the extent of flooding;
s_{ij}: probability of surviving the flooding of the group of compartment(s) "i", given loading conditions j occurred.

Fire

$$A_{\text{fire protection}} = \sum_{i}^{N} w_i \times p_i \times s_i$$

p_i: Probability of fire ignition in a single space i

s_i: Probability of fire protection

N: Number of spaces

w_i: weighting factors to address space criticality in relation to e.g.: fire effluents, occupancy, space topology (closeness to MVZ bhd, staircases, fire mains, etc.)

Figure 1: Probabilistic frameworks for flooding (existing) and fire (to be developed and proposed)

It is the intention of the FIREPROOF consortium to submit the project findings to IMO (FP sub-committee) for discussion and further consideration.

RISK FORMULATION

In the RBD methodology, risk is defined as *the chance of a loss* and it is obtained by the product of probability of occurrence of an unwanted event and its ensuing consequences. For all practical purposes, risk is expressed as the frequency of occurrence of exactly N number of fatalities per ship-year (s-y), (Jasionowski and Vassalos, 2006):

$$fr_N(N) = \sum_{i=1}^{n_{hz}} fr_{hz}(hz_i) \cdot pr_N(N \mid hz_i) \quad [1]$$

Where

hz_i: a loss scenario (a series of events with catastrophic outcome)

n_{hz}: number of loss scenarios considered
fr_N: frequency of exactly N fatalities per s-y
fr_{hz}: frequency of occurrence of loss scenario hz_i per s-y
pr_N: the probability of occurrence of exactly N fatalities conditional on the occurrence of hz_i

In the context of the current development care should be taken with respect to the following points, which signify the specific nature of the fire as a physical phenomenon, the compliance with concepts and definition in SOLAS Ch.II-2, and the introduction new elements in the safety assessment process.

- The element of probability is mutually associated to the fire ignition and the escalation of fire outside the space of origin. The notion of space here refers to the 14 types of fire spaces prescribed in SOLAS. The fire *ignition* is treated as an event that takes place at any time and in any space onboard, ignoring the causes of fire in the first place (i.e. root cause analysis is excluded from this development). For this reason it is presented in the form of frequency of occurrence per s-y and SOLAS space.

- The *escalation* of fire outside the space of origin is associated to the failure to contain, control and suppress the fire by the installed means (mechanical or manual) onboard and through human (passenger or crew) intervention. Fire escalation signifies the exposure of all passengers and crew located in the same fire zone to the fire effluents (poisonous gases, oxygen depletion, heat, and visibility reduction) and the impairment of the evacuation process to adjacent fire zones, which could result in injuries and fatalities.

- The *consequences* in the context of the current development correspond to loss of life, i.e. fatalities, which occur due to exposure to fire effluents and delays in the evacuation process. The latter element signifies the importance of the spatial arrangement of the accommodation area of passenger ships, the easiness to reach a place of safe refuge in such events, and the manner in which the location of fire blocks the main escape routes.

- The fire risk is expressed as the frequency of a number of (statistical) fatalities that could occur due to the fire occurrence in a space per s-y. However, a *holistic* risk assessment process (according to the basic premise of the RBD methodology) implies that the total fire risk should correspond to the *summation* of all risk due to fire occurrences on all spaces onboard.

Collation of the above elements in a single expression results in the following equation:

$$fr_N(N) = \sum_{i=1}^{n_{space}} fr_{ign}(space_i) \cdot pr_{esc}(space_i) \cdot pr_N(N \mid space_i) \qquad [2]$$

Where
$fr_N(N)$: number of exactly N fatalities per s-y
$fr_{ign}(space_i)$: frequency of ignition in $space_i$ per s-y
$pr_{esc}(space_i)$: probability of fire escalation outside the space of origin
$pr_N(N|space_i)$: probability of experiencing exactly N fatalities due to fire in $space_i$

The nature of Equation 2 readily allows the expression of fire risk in two conventional (and accepted by IMO) ways:

- *Potential Loss of Life (PLL)*

$$PLL = E(N) = \sum_{j=1}^{N_{\max}} j \cdot fr_N(N) \qquad [3]$$

- *F-N curve*

$$F_N(N) = \sum_{j=1}^{N_{\max}} fr_N(N) \qquad [4]$$

Where N_{max} is the number of passengers and crew onboard the ship. The following sections elaborate on the details of the three factors of Equation 2, all of which are developments that have taken place in FIREPROOF.

FREQUENCY OF IGNITION

The formulation of the frequency of ignition is based on statistical analyses of fire incident data in buildings, (BSI, 2003), and it is adopted as follows:

$$fr_{ign}(space_i) = \gamma(space_i) \cdot A(space_i) \qquad [5]$$

Where

- $\gamma(space_i)$ is the historical frequency of ignition, in units of (s-y × m^2)$^{-1}$, for the SOLAS category *i* that the space under consideration is classified under (Table 1), and
- $A(space_i)$ is the floor area of the space under consideration.

In the context of FIREPROOF, where the development of a probabilistic framework is pursued, the historical frequency of ignition per SOLAS space category will be derived according to existing designs. For this purpose, three sample passenger ships (named Ship 1, Ship 2 and Ship 3) have been used from past research projects. The actual floor area for each space (A_i) is *design input* to the calculations.

Table 1: 14 spaces defined in SOLAS Ch. II-2, Regulation 9, (IMO, 2004)

SOLAS Code	Space definition
1	Control station
2	Stairway
3	Corridors
4	Evacuation stations and external escape routes
5	Open deck spaces
6	Accommodation spaces for minor fire risk
7	Accommodation spaces for moderate fire risk
8	Accommodation spaces for greater fire risk
9	Sanitary and similar spaces
10	Tanks, voids and auxiliary machinery spaces having little or no fire risk
11	Auxiliary machinery spaces, cargo spaces, cargo and other oil tanks and other similar spaces of moderate fire risk
12	Machinery spaces and main galleys
13	Store-rooms, workshops, pantries, etc.
14	Other spaces in which flammable liquids are stowed

The model presented in Equation 5 requires some further justification with respect to the variables included concerning:

(i) The representation of the combustible materials in a space, and
(ii) The independency of the historical frequency and the floor area of the space, which will make the chosen formulation meaningful.

The first point has been considered in past fire incident data and studies, (Tillander, 2004), and it is indicated that there is a degree of correlation between the floor area of a space and its combustible contents (various pieces of furniture, floor material, wall and ceiling coverings, fittings, etc.). In this respect, the floor area of a space can be used in the formulation as a representative measure of the fuel contained in this space.

On the other hand, this is not the case for the ignition frequency per unit area and the floor area of a space. The derivation of historical frequency of ignition is based on the FIREPROOF incident database, which contains 1521 records and corresponds to 463.13 s-y. The average fire ignition is 3.28/s-y. The graph presented in Figure 2 demonstrates that the floor areas per SOLAS space category for the three sample ships has very poor correlation (as it is demonstrated by the scatter of the data points and the values of the correlation coefficient R for the exemplified linear model fit in each case) with the frequencies extracted from the database. It is therefore reasonable to assume that the two variables included in Equation 5 are independent and the model is mathematically valid. This result is also confirmed with fire accidents statistics in buildings, (Hasofer et al., 2007).

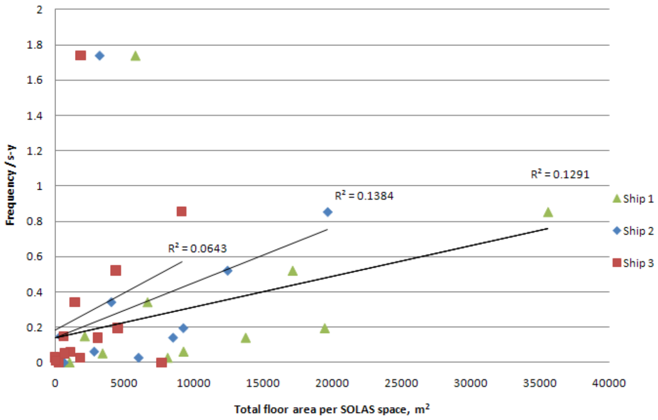

Figure 2: Statistical analysis on the correlation between ignition frequency and total floor area

The last ingredient of the historical frequency is the typical area per SOLAS space. This parameter reflects the exposure of the space to ignition and it will be included in the model as follows:

$$\gamma(space_i) = \frac{historical\ \ frequency\ of\ \ ignition}{s-y} \times \frac{1}{n(space_i) \times A_{typical}(space_i)} \qquad [6]$$

Where
- $n(space_i)$ is the number of spaces of the SOLAS category i,
- $A_{typical}(space_i)$ is the typical space area in m^2.

The typical floor area per space (a design input) is introduced in the formulation of the ignition model according to the statistical properties of the space floor areas collected from the sample ships and it will be represented by the Rayleigh distribution. An example is presented in Figure 3 for SOLAS category 6.

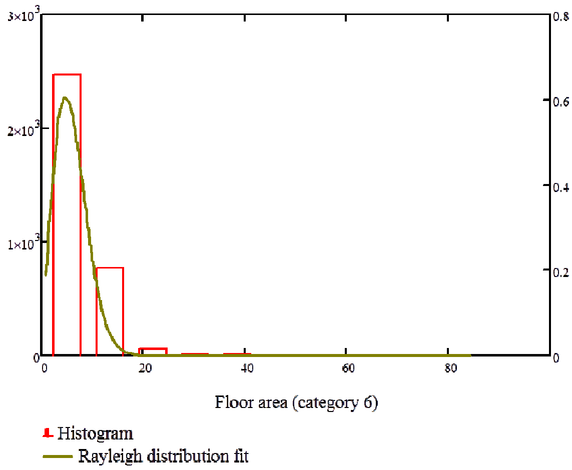

Figure 3: Histogram and Rayleigh distribution fit

The development of the ignition model is presented in detail in (Themelis et al, 2010).

PROBABILITY OF ESCALATION

Introduction

The Heat Release Rate (HRR) curve is one of the most important elements in fire safety engineering analysis. It is used for defining "design fires" that include the main stages of a fire in an enclosure. These are, the *incipient*, the *growth*, the *fully* *developed* and *decay* stage (Figure 4). Its shape controls important fire characteristics and its ensuing consequences.

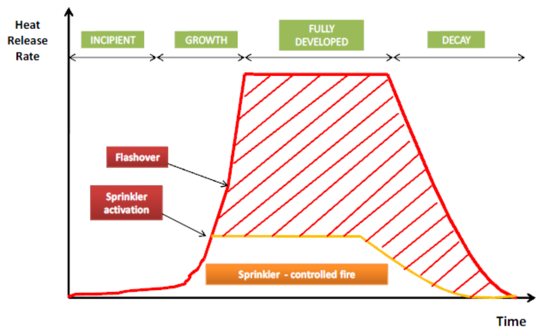

Figure 4: Development of fire in an enclosure in terms of HRR (extracted from ISO 1999)

As it is discussed earlier in this paper, the prescriptive nature of fire safety regulations in the maritime industry tends to change with the introduction of the Regulation 17 for alternative design and arrangements, the guidelines for the implementation of which originate to organisations like ISO (1999) and SFPE (2002). Along these lines, a set of *design fires* are specified and their consequences are compared to those corresponding to the prescriptive design solutions through utilisation of fire modelling tools.

In this approach, the definition of a proper design fire scenario plays a central role in the safety assessment process. A scenario is not only based on the parameters related to the ignition and growth stages, but also on the performance of the fire safety systems and the intervention of the crew, which can affect the development course and outcomes of a fire incident. The necessity to quantify fire risks comes in direct contradiction to the inherent uncertainty and variability of all entailed parameters in the definition of a fire scenario, a fact that calls for a probabilistic approach for fire modelling onboard ships.

In the work presented here, the objective is to develop a comprehensive probabilistic model for managing uncertainty in the dominant fire development parameters. The shape of the HRR curve will be determined by a generic formulation that takes into account various stages of fire development, the intensity and duration of the fire growth stage, the restrictions of growth due to ventilation, the maximum value of HRR achieved, the possible occurrence of flashover and the duration of the fully developed and decay stages. The values of these parameters depend mainly on the fuel availability, the geometry of the space and the size of the openings. There are several sources of uncertainty, e.g. for the amount, the location, the type and the fire growth characteristics of the combustible materials in the space under consideration. As such, the dominant parameters are treated as random variables. However, the specification of suitable probability distributions is one of the laborious tasks of the current methodology as relevant data from the maritime industry is not always available. A detailed analysis of the model for probabilistic generation of HRR curves is presented in Themelis and Spyrou (2010).

Basic Formulation – Uncontrolled Fires

Considering the physics of a fire development, the shape of an HHR curve could be determined by the following key parameters:

- The actual time until established burning occurs;
- The maximum HRR achieved;
- The time to reach the maximum HRR;
- The restriction of the HRR growth due to ventilation conditions,
- The occurrence of a steady phase and its duration; and
- The time of starting the decay phase.

The generic formula that defines the HRR curve is:

$$\dot{Q}(t)=\begin{cases}\dot{Q}_{inc}\cdot t/t_{inc}\,,\ 0\le t\le t_{inc}\\ \alpha\cdot\left(t-t_{inc}\right)^2+\dot{Q}_{\text{inc}}\,,\ t_{inc}\le t\le t_g\\ \dot{Q}_{\max}\,,\ t_g\le t\le t_d\\ \dot{Q}_{\max}e^{-\frac{t-t_d}{\tau}}\,,\ t>t_d\end{cases} \qquad [7]$$

Where

$\dot{Q}(t)$:	Heat release rate in kW,
α:	Fire growth coefficient in kW/s^2,
t_{inc}:	Time until established burning occurs in s, and
τ:	Decay coefficient.

The intention is to relate parameters describing fire characteristics (e.g. fire growth, fuel and fire load) with the parameters that control the shape of the HRR curve in a probabilistic manner. This is achieved by defining appropriate distributions for the following parameters:

- The duration period t_{inc} of the incipient stage and the HRR $\dot{Q}_{inc}$ that defines established burning;
- The fire load density distribution Q'', MJ/m^2, for the enclosure;
- The fire growth coefficient α, which determines the intensity of the growth;
- Maximum HRR density $\dot{Q}''_{\max}$, kW/m^2, obtained by the amount and type of fuel;
- The area of the fuel package A_f, m^2;
- The required HRR for flashover $\dot{Q}_F$, kW, which depends on the geometry of the enclosure, the thermal properties of the boundaries and the size of the ventilation openings;
- The maximum HRR $\dot{Q}_V$, kW, which can be achieved in ventilation controlled burning and it is determined by the existing ventilation conditions;
- The time t_d, where decay starts and it is calculated assuming that some percentage of the fire load has been consumed; and
- The decay parameter τ, which is estimated by integrating the HRR curve and setting it equal to the total fire load Q.

It should be noted that the growth stage is described as a *t*-squared fire, the fully developed (or steady) stage at a constant HRR value, and the decay follows an exponential law. Moreover, the incipient stage, where the fire is not immediately growing with a power law, has been included in the models considering that (i) smoke generation may lead to the fire detection well before any more rapid fire growth, and (ii) toxic gas production is much more prominent and threatening to life. Figure 5 presents a set of generated HRR curves and their comparison with experimental data for a cabin fire.

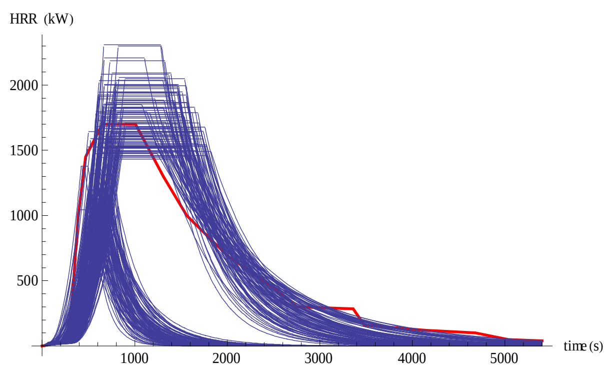

Figure 5: Generated HRR curves and comparison to experiments by Arvidson et al., (2008)

Fire Safety Systems

Although the basic formulation refers to uncontrolled fires, in reality the presence of the fire safety systems has a significant effect on the fire development and the shape of the generated HRR curves (Figure 6). The systems which are taken into consideration in the current context are the following:

Smoke detectors: The detection of a fire will activate the fire alarm and call for the on-duty fire fighting duty crew, i.e. it will define the starting point of the call. The detector type (ionisation or optical (photoelectric) and its obscuration rating are considered. The objective is to estimate the response of a smoke detector knowing the available fuels in the space (or the ignited fuels). The type and the characteristics of the detector are expressed by the percentage of smoke obscuration per metre. The principles of the calculations were developed by Heskestad and Delechatsios (1977), where the smoke detector is assumed to be a low-temperature fast response heat detector.

Fixed–temperature heat detectors: Each sprinkler can act as a heat detector, thus, its modelling is primarily focused on the response time index (RTI) and the activation (or else operating) temperature, (Schifiliti et al, 2002).

Automatic sprinkler: Its activation will produce a suppression effect that can be modelled by introducing a suitable decrease of the HRR curve. The characteristics of the sprinkler, such as the RTI, the activation temperature and the water mass flux are taken into account. Both for the detector and the sprinkler the activation time and their position relatively to the fuel package are included in the models, (Fleming, 2002). Finally, the reliability of the sprinkler systems is also taken into consideration as reported in Lohrmann et al., (2011). A demonstration of the incorporation of fire safety systems on HRR curves is presented in Themelis and Spyrou (2012).

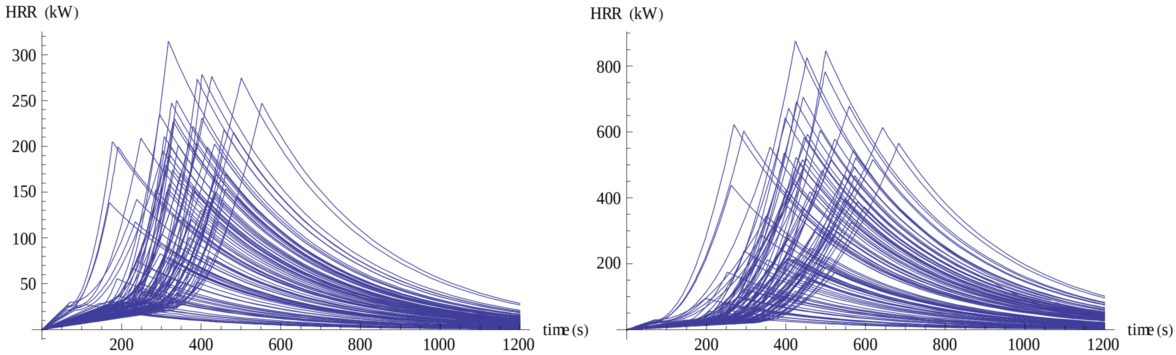

Figure 6: HRR curves for fast (left) and slow (right) heat detectors and sprinkler respectively. The relative position of the fuel package to the sprinkler has been randomly considered

Manual Intervention and Fire Extinguishment

Information about the probabilities of failure or success in manual fire extinguishment for a given size of fire (in terms of flame area) and skill levels (one person with an extinguisher, Fire Brigade and Fire Department) are given by McDaniel (2003). Obviously this data refers to building fire extinguishment and association of such probabilities to shipboard fires is not straightforward. Here it will be assumed that the efficiency of an average crew person with an extinguisher and the efficiency of the intervening crew as a team to match the respective efficiencies of land based fire-fighting personnel, although the dedicated training of the crew members (and their familiarity with the ship layout) suggests that they should be more efficient.

The process for determining the probability of failure of the fire staff initiates by the definition of a probability density function referring to the time required for arriving at the fire site, and takes into account delays related to human reaction and decision-making, assembly and traveling towards the site, (Guarin et al 2007). The type of this distribution should be deduced from relevant statistical data, but at this stage of development the gamma distribution is assumed for the reaction time (from the fire alarm until reaching the fire location), along with a minimum value for the reaction time. This should be increased by the time for the activation of the fire alarm, which is assumed to coincide with the smoke detection time.

Therefore, given the time of arrival of the fire unit (person or fire duty staff) to the fire location, the fire size at this time instant could be known by the HRR curve (“uncontrolled” or “suppressed” fire). Then the fire size area could be specified considering also the geometrical characteristics of the space and ratios of height to flame area of pool fires. Thus, the probability of failure of the fire fighting unit could be calculated. Table 2 and Table 3 summarises results for the fire extinguishment failure presented in Themelis and Spyrou (2012).

Table 2: Parameters for the definition of the gamma distribution

	1 % percentile	50% percentile	95% percentile
Average trained person	1.0 min	2.5 min	6.0 min
Fire duty staff	3.0 min	6.5 min	12.0 min

Table 3: Summary statistics for fire fighting unit's probability of failure

	Fire duty staff	Average trained person
Mean	5.32%	2.93%
St.deviation	13.61%	14.36%
95%	31.54%	9.03%

Probability of Insulation Failure and Fire Escalation

A straightforward way to examine insulation failure at the boundaries of the considered space is to compare the temperatures that develop during the fire event with those of the standard fire time curve (BS, 1999). According to SOLAS (Chapter II-2, Reg.3) the effectiveness of the insulation boundary should be tested (for example for a passenger cabin B-15 class boundaries should be assumed). If in a specific time interval the temperature becomes greater than that of the standard fire time curve it should be deduced that there is insulation failure. Thus, the rise of the temperature in the considered space should be calculated. This could be obtained by CFD simulations.

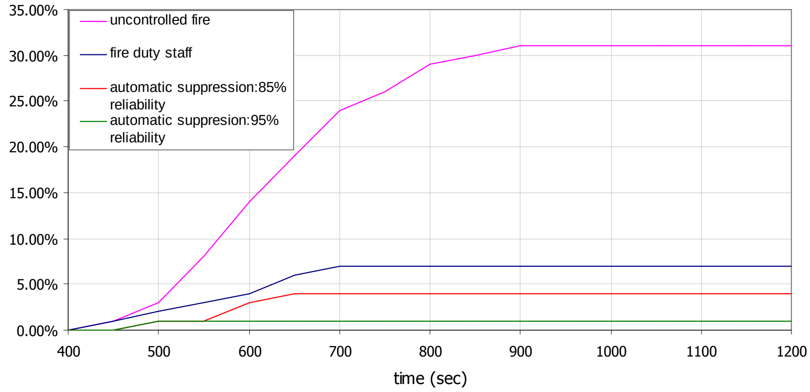

Figure 7: Probability of insulation failure for sprinkler with slow response time and different on-demand reliability levels and manual suppression by crew considering a photoelectric smoke detector. Uncontrolled fires are also included.

However, an analytical formula referring to the upper layer temperature of the space of fire origin has been used here. According to Walton and Thomas (2002) and taking into account geometrical and thermal characteristics of the space (enclosure area A_T and effective heat transfer coefficient h_k of the boundaries), ventilation characteristics (height H_0 and area A_0 of the opening) and knowing the heat release rate $\dot{Q}$, the upper layer temperature in the fire space can be estimated by Equation 8:

$$T_g = T_{atm} + 6.85\left(\frac{\dot{Q}^2}{A_0\sqrt{H_0}h_k A_T}\right)^{1/3} \quad [8]$$

The crucial parameter in Equation 8 is the HRR value ($\dot{Q}$) which depends on the aforementioned parameters and discussion. Consideration of all this information will result in the probability of insulation failure and the fire escalation outside the space of origin (Figure 7).

CONSEQUENCE MODEL

The last element of Equation 2 is related to the consequences of fire. That is, the quantification of the probability of experiencing *exactly* N fatalities out of the total number of passengers onboard given fire occurrence in a space onboard, $pr_N(N|space_i)$. In accordance to parallel developments in the area of flooding, the *Poisson distribution* will be used, (Jasionowski, 2006). The Poisson distribution is a discrete distribution of a given number of events occurring in a fixed interval of time with known average rate and independently from the occurrence of the last event.

$$pr_N(N \mid space_i) = e^{-\lambda}\frac{\lambda^N}{N!} \qquad [9]$$

Where

- N: number of fatalities (N is a positive integer number)
- λ: average (expected) number of fatalities (λ is a positive real number)

The Poisson distribution is also called the *law of small numbers* because it is the probability distribution of an event that occurs rarely but with many opportunities to happen between occurrences. Applications of the distribution can be found in every field related to counting, with the classic example of nuclear decay of atoms (if a particle decays it does not decay again)[6]. This example has remarkable resemblance to catastrophic fire events (in accordance with the RBD premises) and their unfortunate outcomes.

Therefore, utilisation of Equation 9 requires the quantification of the average number of fatalities λ for each SOLAS space onboard. In the course of the FIREPROOF project this is achieved by a combination of CFD and evacuation simulations. This is a necessary approach as the historical data and analytical tools of the first two terms of Equation 2 are not readily available in this case. This is also a cumbersome approach considering the substantial number of simulations and the extended processing time that is needed for deriving the necessary fatality rates.

Bearing this in mind, the general arrangement of a generic passenger ship (used in past research projects) is populated with sufficient detail for the needs of fire and evacuation analysis, (Figure 8). That is, the quantification of the fire effluents and their dispersion time in the arrangement under consideration and superposition of the results in the evacuation process of all passengers and crew to the adjacent zone. In the course of this process the following points are of primary concern:

- The passenger ship and the two adjacent fire zones contain all SOLAS spaces (Table 1) and present with (i) sufficient variability between all kinds and sizes of spaces, and (ii) complexity (in order not to oversimplify the problem) that facilitate generalisation of the outcomes of the simulations. That is, the fatality rates that will take place for various SOLAS spaces can be used for other ships as well.

- The two generic fire zones allow the identification of a set of *risk metrics*, i.e. conditions during which the expected number of fatalities will increase even when fire occurs in the same type of SOLAS space. Examples of the risk metrics are the following:

    - The variation in the *distribution of passengers and crew* during night and day time will result in different evacuation times irrespective of the fire origin.
    - The *location of the fire origin* close to an escape route will deem it inaccessible and either limit the escape options or force the exposed passengers and crew to seek alternative routes to evacuate. In the latter case the exposure to toxic gases will be longer and the injuries and fatalities will increase.
    - The consistency of the fire effluents in terms of toxic gas production (CO, HCN, etc.), oxygen depletion, and soot in the atmosphere, which result in visibility reduction and extended evacuation times (due to speed reduction and loss of direction).

---

[6] http://en.wikipedia.org/wiki/Poisson_distribution

As a result the risk metrics will correspond to multiplication factors of the respective fatality rates, and will translate to the weighting factors presented in Figure 1.

- Finally, in order to manage the very large number of combinations of fire and evacuation situations and the equally large number of egress outcomes, a set of scenarios has been defined for a selected set of spaces that would result in the highest exposure of the onboard population. That is, cabins, public spaces like restaurants and theatres, engine room, car deck and balcony, as it is reported by Mermiris et al, (2011).

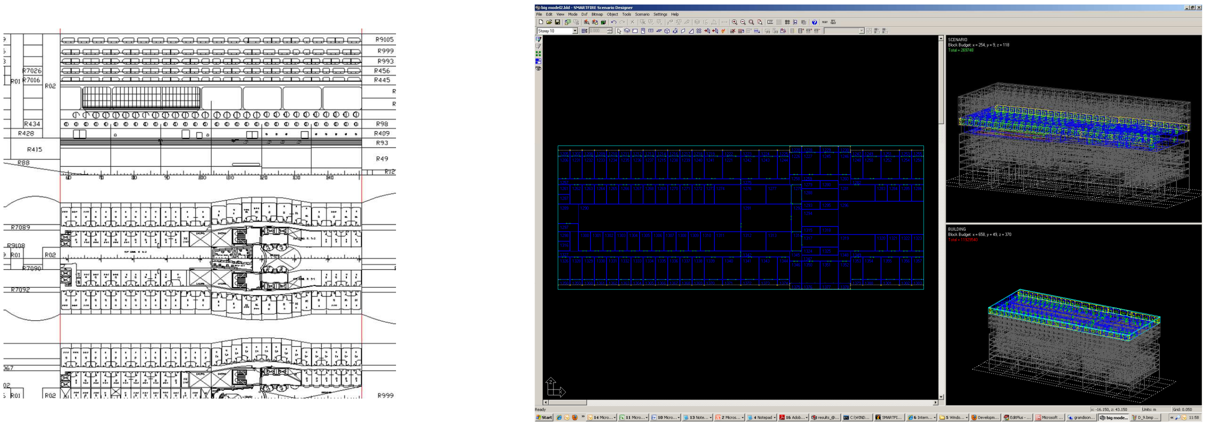

Figure 8: Generic drawings for fire analysis (left) and preparation for fire and evacuation simulation (right)

CASE STUDY

The intention of this section is to present a numerical example of the fire model developed in this paper in order to demonstrate its applicability in the RBD context. The necessary design information originates from one of the sample ships used in the course of FIREPROOF and the calculations refer to the spaces of one deck in a fire zone. The exposed population due to fire in any of the compartments is 1500 passengers and crew. Table 4 summarises the necessary information for the calculations.

The information in column (5) is obtained from the report of Themelis et al, (2010), and column (6) is calculated according to Equation 6. The data in columns (7), (8) and (9) are for illustration purposes only considering that at the time of preparation of this paper the numerical simulation results from FIREPROOF were not available. It should be noted that the fatality rates at night are assumed to be four times higher than the corresponding ones in the day case. Although this choice is arbitrary, it is included here in order to demonstrate that the increased awareness time described in (IMO, 2007) can reduce the egress efficiency from the exposed fire zone and therefore stress the importance of identifying appropriate risk metrics in such set of calculations.

Table 4: Calculations for the numerical example

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
SOLAS space	**No. of spaces**	**Space description**	**Floor area, [m^2]**	**Hist. freq. of ignition, [$s\text{-}y^{-1}$]**	$fr_{ign}(space_i)$, [$s\text{-}y^{-1}$]	$pr_{esc}(space_i)$	**Fatality rate (day)**	**Fatality rate (night)**
2	5	4 elevators & 1 staircase	11.52	0.059	1.024e-3	0.31	23.01	92.04
7	156	Cabins	11.60	0.013	7.184e-6	0.28	15.50	62.00
10	1	Electrical room	5.00	5.75e-3	1.15e-3	0.02	1.80	7.20
13	2	1 pantry & 1 provision area	52.50	0.016	1.524e-4	0.52	23.45	93.80

The resulting F-N curves for both day and night cases are presented in Figure 9 and the corresponding PLL values are 2.945e-5 and 5.333e-4 respectively.

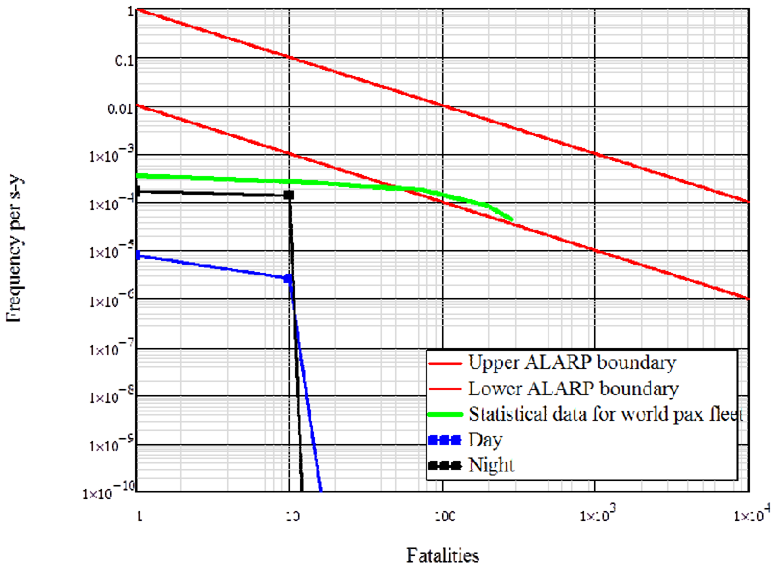

Figure 9: The obtained F-N curves for the day and night cases

The graphical representation of the calculations allows a straightforward comparison between the F-N curve of the design under consideration with respect to the ALARP region and historical fire accident data, which for this case correspond to the world passenger ships from 1982 to 2010. In this manner the approval process of a new design can be facilitated under the knowledge that (i) a holistic approach has been followed (i.e. no risk element has been ignored as the contribution to fire risk of *all* spaces onboard has been taken into consideration), and (ii) the results can be compared not only among each other (i.e. between the day and night cases in this example) but also against any threshold that can be defined on this diagram.

CONCLUSIONS

In an era where new technologies and innovation are among the primary drivers of the industry, the current regulatory framework retains its foundation on historical data and prescriptive approaches. In this manner, although new passenger ships are not inherently unsafe with respect to fire, yet they face difficulties during the approval process, which errs towards penalising unnecessarily arrangements which fall outside the regulation regime.

Notwithstanding this situation and stemming from the mature development and demonstrable benefits of the RBD methodology in the area of damage stability and survivability, an analytical formulation for the quantification of fire risk onboard passenger ships is presented. This approach builds on the physics of fire and the ensuing evacuation process from the outset, and because it is mathematically compatible to the corresponding formulation for damage stability, it contributes to the development of a common risk model for flooding and fire, which constitutes 90% of all serious accidents.

ACKNOWLEDGEMENTS

The research reported in this paper is partially funded by the FIREPROOF project (under Grant Agreement 218761) as part of the 7th Framework Surface Transport Programme of the European Commission, a contribution that is gratefully acknowledged by the authors.

REFERENCES

ARVIDSON, M., AXELSSON, J. and HERTZBERG T., “Large-scale fire tests in a passenger cabin, Fire Technology”, SP Report 2008:33

BS EN 1363-1, *Fire Resistance Tests – Part 1: General Requirements*, 1999

BSI, “Application of fire safety engineering principles to the design of buildings - Part 7: Probabilistic risk assessment”, British Standards, PD 7974-7:2003

FLEMING, R. P., “Automatic Sprinkler System Calculations”, SFPE Section 4, Chapter 3, 2002

GRANDISON, A., WANG, Z., GALEA, E., PATEL, M., LOHRMANN, P., THEMELIS, N., CAI, W. and MERMIRIS, G., “Scenario Generation Model”, FIREPROOF Deliverable 1.4, 2011

GUARIN, L., LOGAN, J., MAJUMDER, J., PUISA, R., JASIONOWSKI, A. and VASSALOS, D., “Design for Fire Safety”, Proceedings of the 3rd Annual Conference on Design for Safety Conference, Berkeley, USA, 2007

HASOFER, A. M., Beck, V. R. and BENNETTS I. D., *Risk analysis in building fire safety engineering*, Butterworth-Heinemann, 2007

HESKESTAD, G., and DELICHATSIOS, M. A., “Environments of Fire Detectors Phase 1; Effects of Fire Size, Ceiling Height and Material”, Volume H -- Analysis. Technical Report Serial No. 22427, RC 77-T-11, Factory Mutual Research Corporation, Norwood, MA, 1977

IMO, “Guidelines for Alternative Design and Arrangements for Fire Safety”, MSC/Circ.1002, 2001

IMO, “Consolidated text of the International Convention for the Safety of Life at Sea 1974 and its protocol of 1988 articles, annexes and certificates (incorporating all amendments in effect from 1 July 2004)”, 2004

IMO, “Guidelines for Evacuation Analysis for New and Existing Passenger Ships”, MSC/Circ.1238, 2007

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

JASIONOWSKI, A. and VASSALOS, D., “Conceptualising Risk”, Proceedings of the 9th International Conference on Stability of Ships and Ocean Vehicles, Rio de Janeiro, Brazil, 2006

JASIONOWSKI, A., “Fast and Accurate Flooding Prediction – Analytical Model”, SAFEDOR Deliverable 2.1.3, 2006

LOHRMANN, P., KAR, A. and BREUILLARD, A., “Reliability and Effectiveness Models of Passive and Active Fire Safety Systems”, FIREPROOF Deliverable 1.3, 2011

MCDANIEL, D. L., “Cultural Resources”, *Fire Protection Handbook*, Section 13, Chapter 16, 2003, National Fire Protection Association (NFPA), 2003

MERMIRIS, G., CAI, W. and AZZI, C., “Verification and Validation of Scenario Generation”, FIREPROOF Deliverable 1.5, 2011

NILSEN, O. V., “Risk Analysis for Cruise Ships”, SAFEDOR Deliverable 4.1.2, 2007

Society of Fire Protection Engineers (SFPE), *The SFPE Handbook of Fire Protection Engineering*, NFPA International, 3rd edition, Bethesda, MD, 2002

SCHIFILITI, R. P., MEACHAM, B. J., and CUSTER, L. P., “Design of Detection Systems”, SFPE Section 4, Chapter 1, 2002

THEMELIS, N., MERMIRIS, G. and CAI, W., “Fire Ignition Model Specification”, FIREPROOF Deliverable 1.2, 2010

THEMELIS, N. and SPYROU, K., “An efficient methodology for defining probabilistic design fires.” Proceedings, 4th International Maritime Conference on Design for Safety, October, 2010, Trieste.

THEMELIS, N. and SPYROU, K., “Probabilistic framework of fire safety assessment for passenger ships.” Submitted to the Journal of Ship Research, March 2012

TILLANDER, K., “Utilisation of Statistics to Assess Fire Risk in Buildings. VTT Building and Transport”, PhD Dissertation, 2004

VASSALOS, D., "Risk-based Ship Design (Chapter 2)", *Risk-Based Ship Design – Methods, tools and applications,* ed. Papanikolaou, A., Springer, 2009

WALTON, W. D. and THOMAS, P. H., “Estimating Temperatures in Compartment Fires”, SFPE Section 3, Chapter 6, 2002