

## DESIGN FOR FIRE SAFETY

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### ABSTRACT

Fire safety is currently dealt with through statutory means for established design solutions and through a performance-based approach for alternative design and arrangements not in line with prescriptive regulations. The latter is today undertaken in a manner consistent with 'traditional' risk assessment approaches. Whilst this takes place at qualitative level in the first instance, quantitative analysis focuses thereafter on fire consequences (fire engineering) analysis for a limited number of representative scenarios. In this respect, the fire risk contribution to the total risk of a ship design is not being quantified and hence consistent risk summation is not possible for design, operation and regulatory purposes. Deviating from established normality, efforts within SAFEDOR and industry-funded projects led to developing a probabilistic framework for fire that is consistent with that for flooding, hence suitable for using within a holistic approach such as risk-based design to address fire safety (hence also ship safety) most effectively. The paper presents the formulation of the framework and some early results to demonstrate the potential afforded from this new development.

### 1 Introduction

The adoption of the provisions for alternative design & arrangements for fire safety (IMO, 2000) heralded the beginning of risk-based design and regulation and the advent of indoor promenades and atria in passenger ship design. It is rather well accepted however, that these provisions are rather open-ended in nature, and may result in ambiguity and eventually in an undefined control of safety.

In 2006, a balcony fire onboard *Star Princess* rapidly escalated leading to loss of life and extensive material damage to the ship. The furniture in and partitions between the balconies were of readily combustible material, a fact overlooked during the design and construction of the ship, because the safety requirements at the time did not cover spaces "outside" the superstructure; this may have been a reasonable assumption in the 1980s or even early 1990s,

where cabin balconies were technically inside the superstructure and did not feature extensively on the design, as is the case with today's cruise vessels. This accident led to immediate amendments in SOLAS and the FSS code demonstrating that it takes approximately 10 years for the regulatory regime to catch up with the pace of design innovation. Following the *Star Princess* incident, the International Council of Cruise Lines (ICCL) recommended to its members to undertake fire risk assessments of external areas (ICCL 2006).

In the light of today's trend for bigger, more complex and safer ships, it becomes obvious that in addition to the current regulatory regime, a more systematic and rational design framework is needed to assist the design team to undertake pro-active fire risk screening as part of the early design iterations, in the same way as damage stability is addressed, so that better-informed decisions can be made when design decision-making is still cost-effective. This is particularly relevant when the design concept includes features that need to be evaluated under the alternative design and arrangements framework.

It was in this context, that the idea of a similar formalised framework for fire safety was conceived during the SAFEDOR project, Guarin, Majumder et al. (2006). The primary goal in this undertaking was to achieve consistency in the way in which the risk associated with flooding and fire (the two main contributors to risk) onboard passenger ships is quantified and evaluated, as discussed by Jasionowski and Vassalos (2006). Ultimately, this will allow risk quantification and evaluation to be carried out efficiently within the constraints of the design process, one of the fundamental principles in risk-based design.

This paper presents the concept of a probabilistic framework for fire safety being developed along the lines of the probabilistic framework for damage stability to support the quantification of the overall ship safety level. The latter is a goal which becomes progressively obvious in the light of increasing ship size and the introduction of the casualty threshold concept for passenger ships, which already made its way into SOLAS 2009.

## 2 Aim, objectives and approach

The primary goal of the work outlined in this paper was to develop a systematic methodology for quantifying the risk due to fire for a passenger ship. It is also aimed to use this methodology during early design stages for performing fire risk screening, an approach which becomes useful for identifying the ship areas (special spaces, fire zones, etc) where vulnerability to fire has to be addressed with greater rigor during the design process and appropriate risk management strategies developed for safe operation after delivery.

To this end, an extensive review of historical accident and incident data has been carried out in order to establish the factors that influence the likelihood and the severity of the consequences of a fire event, onboard passenger vessels. This knowledge was translated into the development of a space-specific fire risk model, which takes design and operational parameters as input including relevant passive and active fire mitigation measures and provides an estimate of the risk associated with fire escalation from the evaluated space (sections 3 to 5).

The developed risk model was utilised to develop a preliminary aggregate measure of fire risk, along the same lines of the current A-Index for damage stability. The existence of such a measure would allow a designer to pursue a simple numerical goal towards achieving the requisite level of fire safety. This would also make the design process amenable to systematic optimisation and simplified decision-making when it comes to testing alternative design arrangements not complying with the prescriptive provisions for fire safety.

## 3 Fire Risk modelling

The risk associated with fire onboard a ship relates to loss of human life (fatalities or injuries) and/or damage to the ship and its cargo as well as impact on the environment. In this work, the risk is quantified in terms of the frequency of statistical fatalities (societal risk) and is estimated by adding the risk contribution associated with each space onboard. Thus, the fire risk for a ship is calculated as follows:

$$R_F = \sum_{i=1}^n dR_i$$

where  $n$  refers to the total number of spaces onboard. The risk contribution from a space  $dR_i$  is assumed to be associated with possible fire escalation outcomes. Fire escalation (E) refers to failure to contain, control and suppress fire and explosion in the compartment of origin, which is one of the main safety objectives implicit in SOLAS II-2. As can be implied from Figure 1, the value of  $dR_i$  is the product of the frequency  $f_i$  of a fire scenario ( $i$ ) and the expected value of fatalities associated with all possible fire escalation outcomes ( $k$ ):

$$dR_i = f_i \times \sum_k \left( P(E)_{i,k} N_{i,k} \right)$$

The frequency of fire occurrence in a space is a function of floor area and use of space and is calculated as described in Section 4. The second term of the expression is evaluated using various post-ignition models as described in Section 5. The conditional probability of a fire escalation outcome  $P(E)_k$  largely depends on alarm, detection and suppression arrangements, fire growth potential and insulation class of boundaries, among others. The associated number of fatalities  $N_k$  depends on the number of people exposed to the resulting fire hazards; hence it depends on the use, occupancy profile and location of the space, the capacity and occupancy of the fire zone, as well as the evacuation arrangements.

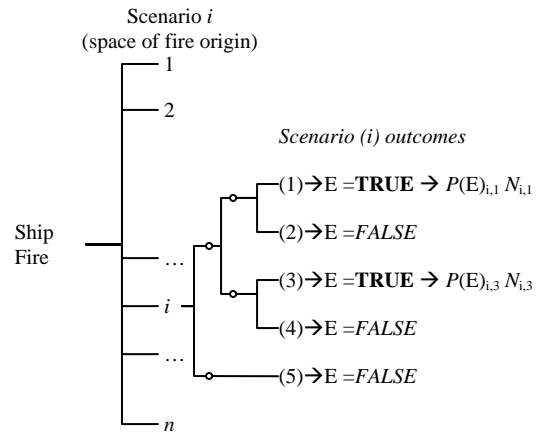


Figure 1: fire risk model for the ship

## 4 Fire Ignition model

The ignition model is aimed at estimating the frequency of a fire ignition event  $f_i$ . It can be shown that the fire incidence rate for a specific ship space is influenced by the type or 'use' of space, determining the contents of the space (materials, dimensions), presence of heat sources and exposure to a hazardous situation that could lead to fire. For the purpose of this study, typical cruise vessel ship spaces were grouped according to their specific 'use': e.g. incinerator room, laundry, cabin, casino, office, open deck, library, corridor, etc. In total 50 space "uses" were identified. Figure 2 illustrates the space types with the top-ten highest relative frequency of fire incidence.

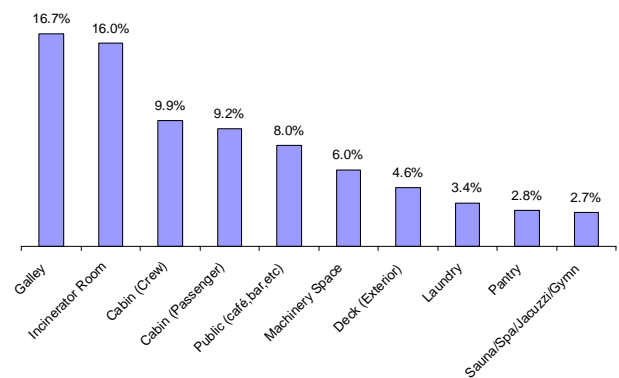
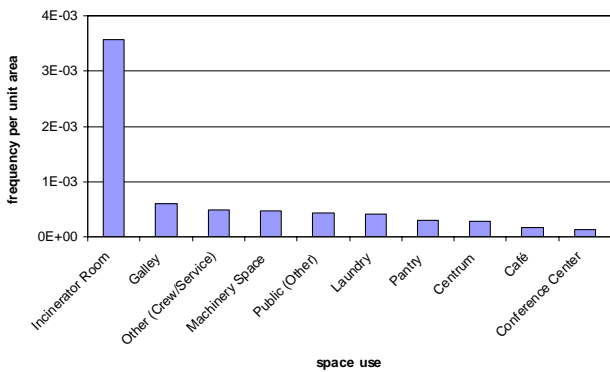


Figure 2: Relative frequency of occurrence of fire incidents; 20% of space "uses" contribute to 80% of all fire occurrences

A review of available fire incident data onboard cruise vessels indicated that the most significant fuel sources include furnishings, floor, wall and ceiling coverings, fittings and other contents (e.g. oil and waste receptacles), which has been shown (Tillander, 2004) to have a degree of correlation with the floor area of the spaces. In terms of heat sources the most significant include auto-ignition (stores), cigarettes, electrical (accommodation), hot surface (machinery, galleys), open flames (galleys), pyrotechnics (public), as well as hot work in crew and service spaces. The exposure to a hazardous situation depends on the exposure to different operational factors such as the level of occupancy, public/crew only access, time of the day, etc, all of which are associated with the actual “use” of the space. Hence, estimation of the frequency of ignition for a specific space type is based on the corresponding historical incidence rate per unit area, referred to as  $\gamma_i$ . Figure 2 illustrates the spaces with the top-ten highest values of  $\gamma_i$ .



**Figure 3: Frequency of occurrence of fire incidents per unit area**

Thus, the frequency of fire ignition in a specific space type of given area  $a_i$  and “use” type, is calculated as follows:

$$f_i = \gamma_i a_i$$

**5 Post-Ignition models**

Post-ignition models are aimed at quantifying the probability of fire escalation  $P(E)$  for a given scenario/space type ( $i$ ). The adopted risk model is illustrated in Figure 4, the elements of which are described below:

- **Fire growth:** this model estimates the probability of failure of first-aid fire suppression  $P(A)$ , which would lead to fire growth. It depends on the automatic and/or manual first-aid fire suppression arrangements. Successful first aid means that the fire is not allowed to grow and the outcome of the fire event is only minor. The fire does not escalate.
- **Loss of containment:** this model estimates the probability of insulation failure  $P(B)$  – due to failure of fire fighting, which is assumed to be equivalent to loss of containment. It depends on the fire growth potential of the contents in a given space, the timing and effectiveness of the fire

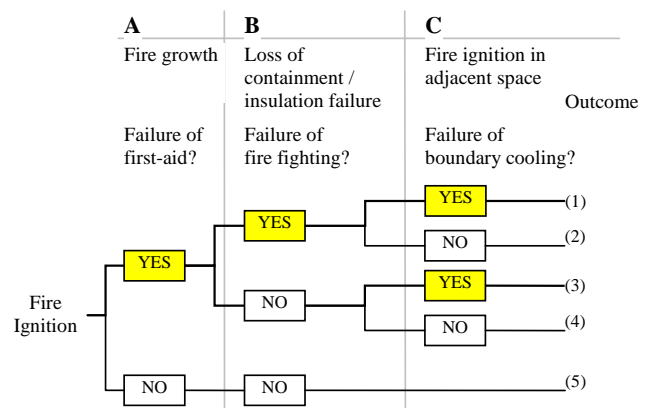
fighting activities as well as the insulation class of boundaries.

- **Fire Spread:** this model estimates the probability of fire ignition in an adjacent space  $P(C)$ . It depends on the contents of the adjacent space and on the timing and effectiveness of boundary cooling (access and capacity) if relevant.
- **Injury / Fatalities:** this model estimates the expected number of fatalities  $N$  for a given escalation outcome. It incorporates factors affecting the egress time of the occupants and the time to reach untenable conditions (due to smoke toxicity, heat and optical density) inside the space of fire origin and in spaces within the same fire zone.

As illustrated in Figure 4, the risk contribution associated with fire escalation from the space of fire origin ( $i$ ), is related to outcomes ( $k=1$ ) and ( $k=3$ ) and is estimated as follows:

$$dR_i = f_i \times [ P(1)_i N_{i,1} + P(3)_i N_{i,3} ]$$

where  $P(k)_i$  and  $N_{i,k}$  are the probability of outcome  $k$  and the corresponding number of expected fatalities, respectively. The human life loss associated with outcomes 2, 4 and 5 is assumed to be limited to minor injuries; hence these outcomes do not contribute to risk.



**Figure 4: Fire risk model for a space type ( $i$ )**

**5.1. Failure of first aid (A)**

Fire suppression first-aid failure can occur if fixed automatic and manual fire suppression failed. The corresponding failure model leads to the following expression for estimating the probability of first-aid failure:

$$P(A) = P(A_1) \cdot [ P(A_2) + P(A_3) - P(A_2)P(A_3) ]$$

Where  $P(A1)$  is the probability of failure of the automatic (fixed) suppression system,  $P(A2)$  is the probability of failure of manual first-aid and  $P(A3)$  is the probability of failure of first-aid by an on-duty staff (manual first aid using portable or available fixed system).

### Failure of automatic first-aid

The value of  $P(A1)$  is determined by the reliability of the automatic suppression system, the activation time which, in turn, depends on the type of fitted automatic fire detector, the fire suppression capability of the system (capacity, heat absorption, etc) and the fire energy at the time of activation. Thus, the probability of automatic first-aid failure is expressed as follows:

$$P(A_1) = 1.0 - [P(\text{system}) \cdot R_{\text{system}} \cdot P(\text{suppress}|\text{system})]$$

Where,  $P(\text{system})$  is the probability that the *system* is present ( $P=1$  system present,  $P=0$  otherwise),  $R_{\text{system}}$  is the *system* reliability and refers to reliability of the detection and activation mechanism, and  $P(\text{suppress}|\text{system})$  is the conditional probability of successful suppression by the system and it is calculated on the basis of the ratio between the available and required capacity of the fire suppression system; the latter is estimated with an empirical formulation developed by Davis (2004). The formulation is a function of the following parameters:

- Extinguishing medium (water, mist, CO<sub>2</sub>)
- Detection threshold (Temperature if heat detector, height of smoke detector head)
- Extinguishing medium suppression capacity (flow rate)
- System reliability
- Extinguishing medium heat absorption rate and efficiency

The probability of automatic suppression strongly depends on the fire energy at the time of activation, referred to as time to first-aid  $t(A1)$ , which is assumed to be equivalent to the detection time. The detection time is derived from the corresponding time histories of temperature and/or smoke layer height (for heat and/or smoke detector, respectively) obtained on the basis of empirical formulations developed by Cooper (2002). These variables are influenced by space attributes such as the floor area, the height of the space and the fire growth factor, among others. The automatic detection time will trigger the response by the bridge command; hence it will influence the value of  $P(A3)$ .

### Failure of manual first-aid

The probability of failure of manual first-aid  $P(A2)$  depends on whether the space in question is occupied (by passengers or crew), and if so, it is influenced by the probability of the occupant taking first-aid fire suppression, the timing of his/her reaction, the fire energy at the action time, and the reliability and suppression capacity of the manual equipment available in the space. First-aid manual equipment includes portable fire extinguishers, fire blankets, etc. The probability of manual first-aid failure is expressed as follows:

$$P(A_2) = 1.0 - [P(\text{occup}) \cdot P(\text{attempt}|\text{occup}) \cdot P(\text{suppress}|\text{attempt}|\text{occup})]$$

Where  $P(\text{occup})$  is the probability that the space is occupied ( $P=1$  space occupied,  $P=0$  otherwise),  $P(\text{attempt}|\text{occup})$  is the conditional probability that the occupant would attempt manual first-aid fire suppression. This probability is assumed to be 99% if the space is occupied by a crew member and 50% if occupant is a passenger;  $P(\text{suppress}|\text{attempt}|\text{occup})$  is the conditional probability of successful manual suppression by the occupant. It depends on the medium used to suppress the fire, the energy of the fire at the time of activation of the manual suppression equipment and the equipment suppression capability. In this case, the activation time, referred to as time to first-aid  $t(A2)$ , is the time at which any of the occupants (crew or passenger) is likely to start first-aid fire suppression and is calculated as follows:

The activation time  $t(A2)$  depends on the reaction (perception) time, i.e. the occupant's delay in becoming aware of the fire, the time to make a decision, and the time to take action (to reach to and prepare the nearest portable equipment). Thus, the activation time will depend on the time of day and level of training of the occupant. Estimates of the different times have been made for passengers and crew members on the basis of cruise vessel experience. The occupant may activate the fire alarm, which will also trigger the response by the bridge command; hence it will influence the value of  $P(A3)$ .

### Failure of manual first-aid by on-duty staff

If the space in question is not fitted with an automatic suppression system or the space is not occupied, the probability of failure is determined by the time for detection and alarm of the fire by other means such as CCTV or other (smell of smoke outside space of origin) and the time it takes the bridge (or command) to react to the alarm; in addition the time it takes an on-duty staff being sent to investigate the alarm, to arrive at the space in question, find the ignition source and take first-aid action will need to be considered. Available fire suppression can be fixed (e.g. CO<sub>2</sub>) or manual (portable fire extinguishers). Accordingly, the probability of automatic first-aid failure is expressed as follows:

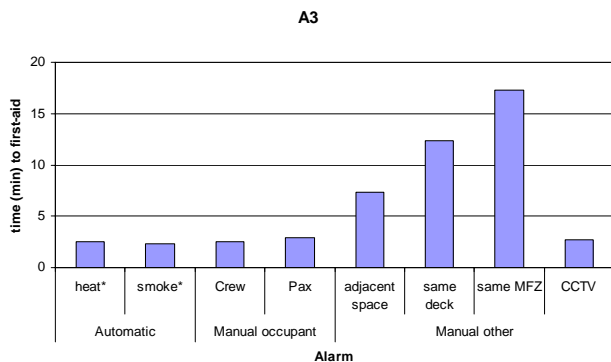
$$P(A_3) = 1.0 - [P(\text{attempt}) \cdot P(\text{suppress}|\text{attempt})]$$

Where,  $P(\text{attempt})$  is the probability that the crew responding to the alarm decides to attempt first-aid fire suppression. This probability is calculated on the basis of the reliability of the available and relevant suppression method. If manual portable equipment is available, the probability depends on the fire energy at the time of attempted action. There is a heat threshold (in KW) above which manual fire fighting is unlikely to be attempted. Finally, the conditional probability of successful suppression is referred to  $P(\text{suppress}|\text{attempt})$ . This probability depends on the fire energy at the time of attempted first-aid suppression  $t(A3)$ .

The first-aid time  $t(A3)$  is calculated by adding the time at which the alarm is received, with the bridge (command)

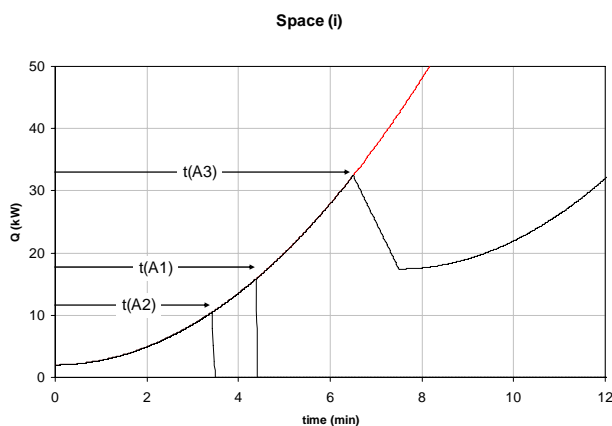
reaction/decision time delay and the responding crew member reaction, travel and assessment time delay.

These time delays have been estimated on the basis of cruise vessels experience and depend mainly on the time of day, the frequency of fire patrol teams, and generally on the level of training and the effectiveness of fire contingency plans. Figure 5 illustrates average times to first-aid  $t(A3)$  for various scenarios of alarm. As can be observed, first-aid response by the fire patrol or any on-duty staff is on average less than 3 minutes in passenger accommodation spaces. Note that time to first aid for automatic alarm must include the detection time (\*); not included in Figure 5.



**Figure 5: Estimated time to first-aid by on-duty staff instructed by the ship's Command**

Figure 6 illustrates the impact of first-aid on the rate of heat release from fire. Failure of any of these actions (see A3) would result in fire growth to flashover situation.

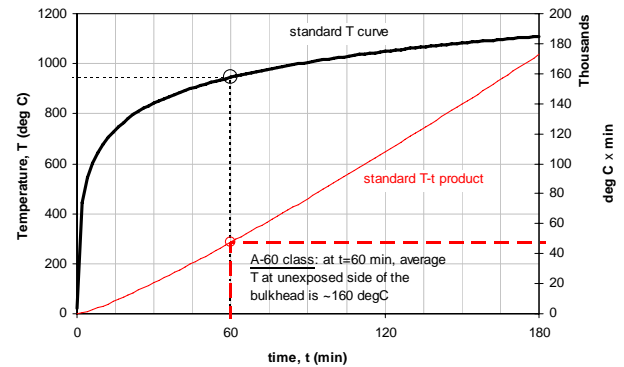


**Figure 6: Impact of first-aid on fire energy time line**

### 5.2. Failure of insulation (B)

Failure of fire insulation of boundaries is evaluated in accordance with the performance criteria implicit in SOLAS regulation 3.2, 3.4 and 3.10 for insulation class A, B and C respectively. These criteria refer to the times at which the temperature at the unexposed side of the bulkhead exceeds certain limits. If the criteria are exceeded it is assumed that loss of containment, conditional to failure of first-aid, will occur.

The standard times to failure, however, relate to the fire insulation performance in relation to the standard fire test. The standard temperature-time curve of the standard fire test is illustrated in Figure 7. As can be seen, if the actual energy released by the fire, which is proportional to the temperature-time product ( $T \cdot t$ ) is known, then it is possible to estimate the time to failure for a bulkhead with any of the SOLAS standard class insulation types.



**Figure 7: Standard fire time line**

As it can be implied from Figure 7, the fire energy depends largely on the impact of fire fighting, which in turn is highly dependent on the time at which fire fighting is initiated. The time to fire-fighting is highly influenced by the alarm time (see Figure 5) and the time it takes for a fire fighting team to assembly and to reach the space of fire origin. Estimates were made on the basis of current cruise vessel experience.

The probability of insulation breakdown (e.g. loss of containment) is calculated on the basis of the ratio ( $r$ ) between the temperature-time product of the actual fire (including the heat release reduction due to fire fighting) and the standard fire test for a given insulation class. Since boundaries of a space can be of different bulkhead insulation class, the probability of failure corresponding to the lower boundary class is used for the calculation.

### 5.3. Fire spread into adjacent spaces (C)

Fire spread into an adjacent space occurs when the temperature in any of the adjacent spaces due to heat transferred from the space of fire origin, reaches the *flashpoint* temperature ( $T_{\text{flash}}$ ) of its contents.

The heat radiated from the boundary between the space of fire origin and an adjacent space, is proportional to the temperature  $T_{\text{BHD}}$  in the unexposed side of the bulkhead, which is determined by the type of insulation fitted and the released fire energy in the space of fire origin. For example, for non-combustible material, the flashpoint temperature is approximately  $750^{\circ}\text{C}$ . If the fire energy is similar to the standard fire energy, then after 60 minutes, the average temperature in the unexposed side of an A-60 bulkhead can be expected to be around  $T_{\text{BHD}} = T_{\text{amb}} + \Delta T \approx 160^{\circ}\text{C}$ . Where  $\Delta T$  is given in SOLAS II-2 Reg. 3.2. The timing and extent of boundary cooling, if relevant, would also impact on the value of  $T_{\text{BHD}}$ .

If the probability distribution function of  $T_{\text{flash}}$  and  $T_{\text{BHD}}$  is known, then the probability of fire spread can be calculated as follows:

$$P(C) = \int_0^{\infty} F(T_{\text{flash}}) f(T_{\text{BHD}}) dT$$

where,  $f(T_{\text{BHD}})$  is the probability distribution function of the temperature in the unexposed side of the boundary and  $F(T_{\text{flash}})$  is the cumulative probability distribution of the ignition temperature of the contents in the evaluated adjacent space. In the model, it has been assumed that both  $f(T_{\text{BHD}})$  and  $F(T_{\text{flash}})$  follow a normal distribution, the parameters of which are estimated on the basis of the average temperature in the space of fire and the flash temperature of the adjacent space contents, respectively. The probability of boundary cooling and its timing is estimated subjectively on the basis of expert opinion and available typical training patterns from the Cruise Industry. It is expected that this approach would give a conservative estimate of  $P(C)$  as heat radiation from the bulkhead in question and the location of the ignitable contents is not taken into account.

#### 5.4. Injuries and fatalities

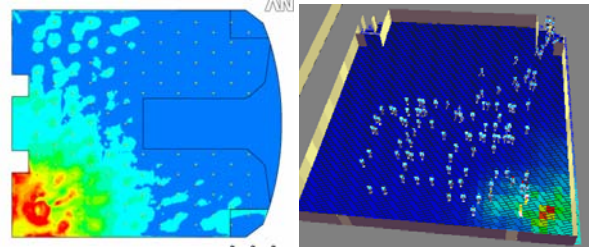
As stated earlier, the number of injuries and/or fatalities associated with a specific fire scenario outcome depends on the number of people exposed to the resulting fire hazards.

It is well known that when evaluating the consequences of fire effluent to human life, the basic performance criterion states that the time required for escape, normally referred to as RSET (Required Safe Egress Time) should be shorter than the time available for the fire and smoke hazards to reach untenable conditions, normally referred to as ASET (Available Safe Egress Time) – Cooper (2006).

$$\text{RSET} < \text{ASET}$$

The ASET is the interval between the time of ignition and the time at which conditions become untenable such that occupants can no longer take effective action to accomplish their own escape. Untenable conditions during fires may result from inhalation of asphyxiant gases, exposure to radiant and convective heat, and visual obscuration due to smoke. A quantitative approach to evaluate the above criterion was implemented by Guarin *et al* (2004, 2007) and it has been used in the present study to derive results for typical layout arrangements. Figure 8 illustrates an example of this assessment for a large public space carried out during the SAFEDOR project. On the left hand side, a snap shot is shown of the time history of temperature calculated with a state-of-the-art field model (Horvat *et al*, 2007). On the right hand side, egress simulations include a model for estimating the Fractional Effective Dose (FED) of heat of each occupant, based on the distribution of temperature in time and space. When the FED of an occupant exceeds the tenability criterion ( $\text{FED} > 1$ ), the occupant can be assumed to be incapacitated. The same can be followed for toxicity and visibility evaluation.

By adopting this approach, it can be shown that the actual human life loss is scenario-specific and is influenced by use of space, occupancy profile, and location of space within the main fire zone (MFZ) as well as the escape and evacuation arrangements. The criterion is evaluated in the space of fire origin and in spaces likely to be affected by smoke propagation within the same MFZ.



**Figure 8: Left: temperature at 1.5m height from floor level for a large public space after 4 minutes from ignition (Horvat *et al*, 2007). Right: Human injury analyses for the same scenario (Guarin *et al* 2007)**

In order to aggregate the risk contribution from fire and flooding, in the manner suggested by Vassalos (2007), the probability mass function (*pmf*) for the resulting fatalities of an outcome ( $k$ ) of scenario ( $i$ ) has to be assumed. The frequency of occurrence of exactly  $N$  fatalities is calculated as follows:

$$fr_N(N) = \sum_{i=1}^n \left[ f_i P(k)_i pmf(N)_{k,i} \right]$$

It can be assumed that the probability mass function of fatalities is given by the Poisson distribution with mean  $N$ , hence,

$$fr_N(N) = \sum_{i=1}^n \left[ f_i P(k)_i \frac{e^{-\lambda} \lambda^{N_{k,i}}}{N_{k,i}!} \right]$$

The parameter  $\lambda$  is the mean number of fatalities and can be estimated from regression analysis of evacuation simulation results for typical configuration arrangements and standard scenarios (night and day). Consequently the FN curve (reflecting societal risk) associated with fire, is calculated as follows:

$$F_N(N) = \sum_{i=N}^{N_{\text{max}}} fr_N(i)$$

#### 6 Aggregate fire risk measure for a ship

The fire risk model described in the foregoing can also be aligned with the concept of probabilistic damage stability if the severity of the consequences are associated only with the probability of fire escalation  $P(E)$  and human life loss is implicit only by assuming  $N_{i,k}=1$ . Thus, the risk contribution from a specific scenario becomes:

$$dR_i = f_i [P(1)_i + P(3)_i]$$

If the conditional probability of a scenario (i) is expressed by  $p_i$  and the escalation probability  $P(E)$  is denoted by  $e_i$ , then

$$dR_i = p_i e_i$$

Where,

$$p_i = \frac{f_i}{\sum_i^n f_i}$$

The aggregated risk *measure* becomes:

$$M_F = \sum_{i=1}^n p_i e_i$$

The above measure  $M_F$  follows the same logic as the A-Index for damage stability and it expresses the weighted sum of the scenario costs ( $e_i$ ), weighted by the corresponding probabilities of the scenarios ( $p_i$ ). This approach of calculating risk is rational with respect to normative utility theory, but as we shall argue in this section, this often fails to capture the societal expectations. The societal perception of loss is quite non-rational. A single incident causing a certain number of fatalities has a much higher impact than the same number of fatalities amounting from several isolated incidents, even when they are recorded over the same period of time. This is consistent with the models of risk-averse utility quantifications. Simple weighted mean aggregation – as in the A-Index, has the disadvantage that it fails to adequately reflect the real impact of very-high-loss scenarios. On account of relatively low historical frequency the high impact incidents are under-represented in the weighted sum thus making it a less realistic quantification.

Thus, if the same format is to be used, it is suggested that a more realistic formulation is used for the aggregation of fire risk. The descriptive statistics such as median and percentile loss can be used for this purpose. Another useful approach is to define an “impact function” that represents a more realistic measure of loss. An impact function could be a mathematical function of the number of fatalities, injuries and other cost factors that would assess the real cost of a given scenario. As an example, we present the case of a very simple impact function – one that over-emphasizes the cost of high casualty accidents non-linearly in comparison with low-casualty accidents, such as the following:

$$f(x) = x^r \text{ for some } r > 1.$$

This function is monotonically increasing for all positive  $x$  and grows more than linearly with  $x$ . If  $\{p_1, p_2, p_3, \dots, p_n\}$  are the scenario probabilities of  $n$  scenarios, and  $E = \{e_1, e_2, e_3, \dots, e_n\}$  are their associated cost, in this case the probability of escalation as defined earlier, then under this impact function a possible quantification of overall risk is the power mean:

$$M^r = \left( p_1 e_1^r + p_2 e_2^r + p_3 e_3^r + \dots + p_n e_n^r \right)^{\frac{1}{r}}$$

Interestingly, there is a mathematical theorem (called the power mean inequality) which states that for a given dataset

$E = \{e_1, e_2, e_3, \dots, e_n\}$  if  $r < s$  then  $M^r < M^s$ . In particular,  $M^\infty$  (i.e. the power mean for an infinitely large power) is the largest element in  $E$ . Thus the more we increase  $r$  the more  $M^r$  shifts towards the higher values in the set  $E$ . The more we move towards a higher  $r$ , we not only get a greater indicative risk figure for a given scenario, but we also get a value that is more significantly dependent on the higher range of consequences. The A-Index formulation is a special case of the above with  $r=1$ .

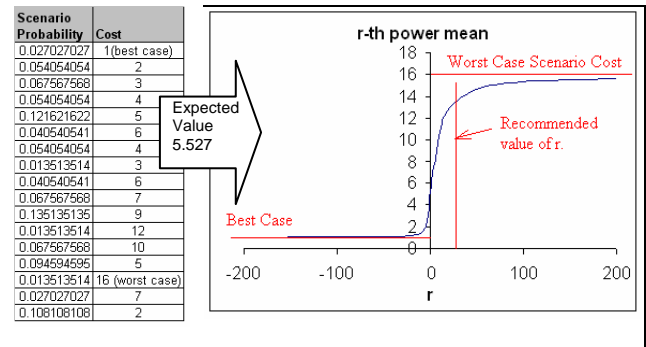


Figure 9: An illustration of the variation of  $r^{\text{th}}$  power mean

It is suggested that in order to quantify risk in a descriptive way we should use a value of  $r$  much greater than 1. Figure 9 shows the variation of  $r^{\text{th}}$  power mean with  $r$  for a sample dataset of costs.

The aforementioned is an example of a descriptive statistic that may be used in formulating fire risk aggregate. It is only one of the many possible candidate expressions for a descriptive risk statistic. Other possible expressions could be formulated based on *percentile*, *median*, *quartile*, etc. Such statistical functions can be used to design risk indices for which the larger volume of low cost scenarios can not overwhelm the relatively rare but very acute vulnerabilities.

## 7 Preliminary results

In order to run the model described in the foregoing, a set of 25 space-specific attributes has to be defined. Each attribute describes a certain aspect of the space. These range from real number inputs for the dimensions and location of the space, to Boolean options that describe the fire suppression arrangements and procedures that are specific to that particular space. Table 1 shows a selection of the important input parameters for a passenger cabin. Inputs such as location of space within the vessel, have been omitted from the table as they are heavily layout dependant.

Table 2 shows how changes in certain input parameters can affect the calculated frequency of escalation. The changes made to the input parameters can be seen to vary the result by +24% to -60% for the same basic space. The occupancy of the space only has an effect on the frequency of escalation in the case where there are no automatic detection systems (smoke/heat/CCTV) present in the space. The largest change was observed upon decreasing the SOLAS rating of the bulkhead, resulting in a 50% increase in the frequency of an escalation incident. The results for

reduced fire fighting capacity (10% capacity and 50% capacity) show the existence of a threshold capacity, below which fire fighting loses its effectiveness and the probability of escalation increases rapidly.

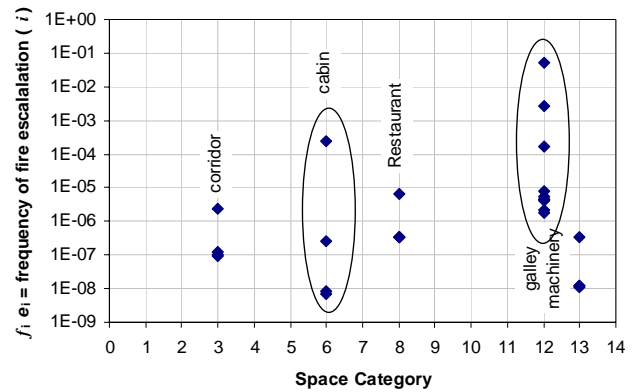
**Table 1: Basis inputs for a passenger Cabin**

Basis Inputs (Cabin)	
Bulkhead Class	B-15
Area	17m <sup>2</sup>
Height	2.7m
Occupancy (number of people)	2 pax
Fire Growth Factor, ( $\alpha$ )	0.0002 kw/s <sup>2</sup>
Smoke Detector	Yes
Heat Detector	Yes
CCTV	No
Sprinkler (water)	ON
Boundary Cooling Possible	Yes
Flow Rate of Fire Fighting Hoses	1.0 l/s
Average Ignition Temperature of adjacent space contents	200°C
Mass of combustible material in space	625 kg

Figure 10 shows some preliminary results for typical spaces when the space type is varied, and the other inputs (area, occupancy etc.) are what are deemed typical for that type of space. As can be seen, the risk associated with a specific space category can vary significantly (at various orders of magnitude) depending on the attributes and scenario-specific assumptions.

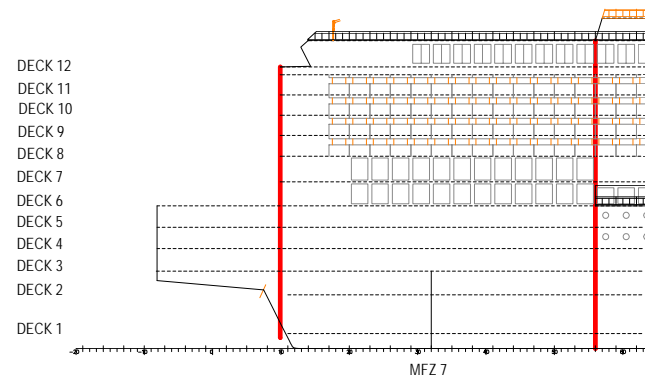
**Table 2: Effect on Escalation Frequency of changes to the Inputs for a Passenger Cabin.**

Change in Inputs from Basis	% change in Frequency of Escalation
Fire fighting capacity reduced by 90%	23.85%
Sprinkler = OFF	19.02%
$\alpha$ factor increased by factor of 2	16.38%
Automatic detection = OFF	16.32%
Space unoccupied	16.21%
Ignition Temperature of contents in adjacent space lowered by 50%	16.20%
Automatic Detection = OFF	9.53%
Boundary Cooling not Possible	0.54%
Increase Floor Area by factor of 2	0.27%
Fire fighting capacity reduced by 50	0.01%
Automatic detection = ON	0.01%
Space unoccupied	-0.07%
Lower Height of Space by 0.5m	-0.86%
Hi_FOG in place of water sprinkler	-0.86%
Bulkhead Change from B-15 to A-15	-59.64%



**Figure 10: Results for Frequency of Escalation for various space types. (SOLAS category in brackets)**

Preliminary calculations have been carried out for a hypothetical main vertical zone of a post-panamax cruise vessel as illustrated in Figure 11.

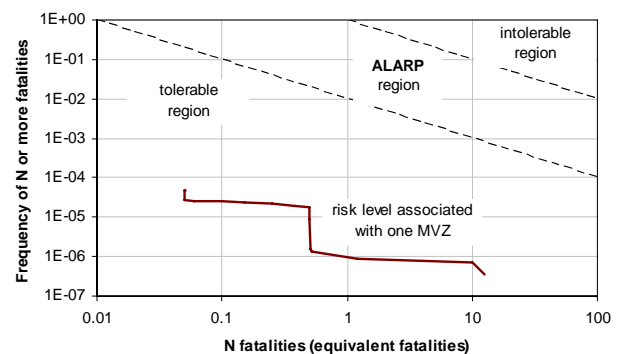


**Figure 11: Vertical fire zone of a typical post-panamax cruise vessel**

For this main vertical fire zone (MVZ) risk was estimated to be as follows:

$$R_F = 1.95 \times 10^{-5} \text{ statistical fatalities per year}$$

The corresponding FN curve (societal risk) is illustrated in Figure 12. The risk evaluation criteria developed in SAFEDOR (Skjong, 2006) are included for reference. Note that  $N < 1$  is equivalent to injuries to people not resulting in fatality. In general it is assumed that 10 serious injuries are equivalent to 1 fatality.



**Figure 12: Resulting FN curve (societal risk) for a hypothetical fire zone.**

If, instead of the actual risk value, an aggregated measure or index is used as described in Section 6, then the following results can be obtained:

$$\begin{aligned} M_F^{(1)} &= 1.34 \times 10^{-4} & r=1 \\ M_F^{(5)} &= 7.12 \times 10^{-3} & r=5 \\ M_F^{(10)} &= 1.19 \times 10^{-2} & r=10 \\ M_F^{(20)} &= 1.54 \times 10^{-2} & r=20 \end{aligned}$$

## 8 Concluding remarks

The methodology presented in this paper, although still under development, is proving to be a systematic and robust framework to undertake fire risk analysis within risk-based design. It is being implemented in a product modelling tool, where the current ship layout with geometric, topological and space attribute information will be available. This setup will allow for semi-automatic creation of the model input and for quick and efficient calculation of fire risk and the contribution to risk from all relevant scenarios.

The methodology once implemented in a standard product modelling system (such as NAPA or CATIA) can be very useful for carrying out *fire risk screening* at early design stages. Fire risk screening is a concept well known in the offshore sector UKOOA/HSE (2006). The higher the risk within a compartment/deck/MFZ the greater should be the rigor that is employed to understand and reduce that risk. Where the risk associated with an outcome is low, any inaccuracies in determining that risk will also be low in absolute terms. Hence, having the means for early estimation of risk will allow developing an optimal fire safety design and operational strategy for the ship.

Although there is still much to do in order to achieve a reasonable degree of confidence in the fire dynamic modelling implicit in the framework, it is evident that the main source of uncertainty is the calculation of human life loss. For this reason, the aggregate measure  $M_F$  does not give priority to this parameter. Further work in this respect relates to the following aspects:

- Probability of ignition: it will need a larger statistical base.
- Verification and validation of the fire dynamics modelling: the level of confidence is higher for all enclosed spaces in which zonal model calculations can be utilised. Further work is required to address open and other special spaces onboard
- Consolidation and standardisation of the procedure to quantify human life loss.

## 9 Acknowledgments

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