An efficient methodology for defining probabilistic design fires

Nikos Themelis and Kostas J. Spyrou

National Technical University of Athens

School of Naval Architecture and Marine Engineering,

9 Iroon Polytechneiou, Zographou, Athens 157 73, Greece

ABSTRACT

A methodology for producing design fires for probabilistic fire safety analysis is described. Heat Release Rate (HRR) curves are the main building blocks of the various fire development stages within an enclosure. The shape of such a curve is determined by a generic formula taking into account the intensity and duration of the growth stage, restrictions of the HRR due to ventilation limits, the maximum value of HRR achieved, the possible occurrence of flashover and the duration of the “fully developed” and “decay” phases. For demonstration of the methodology, a cabin of a passenger ship has been selected.

INTRODUCTION

The trend towards implementing performance-based assessments of the maritime fire safety systems led the International Martitime Organisation to producing MSC 1002, a document that is intended to provide a basis for the technical justification of design choices deviating from the standard prescriptive requirements of SOLAS chapter II-2 (IMO 2001). More detailed guidelines for the implementation of performance – based studies focused on fire safety were concurrently published by the International Organisation for Standardization and the Society of Fire Protection Engineers [for example see ISO/TC92 (Fire Safety)/SC4 (Fire safety engineering) and also SPFE (2002)]. The guidelines contain the specification of a set of design fires whose consequences could be determined by using fire modeling tools. Design solutions could subsequently be compared against those obtained by applying the prescriptive design framework. These design fires are thus central to the assessment process and their selection could be critical for the outcome of an assessment. As a matter of fact, concern about the proper selection of design fire scenarios is not a completely new issue. For example, a method for the generation of probabilistic design fires has been presented by Hostika and Keski - Rahkonen (2003). A recent review about design fires can be found in Bwalya (2008).

However, the evolution of a fire is not based only on the parameters characterizing the ignition and growth process. It depends also on the performance of the installed systems and arrangements for fire detection, containment and suppression, on occupants reaction, etc. All these affect the course and consequences of a fire incident. To model the main fire development stages in an enclosure it is customary to use the concept of the “Heat Release Rate curve” (HRR), see for example NPFA 204 (2002). These HRR curves play nowadays a very important role in fire safety engineering. They describe the characteristics of the incipient stage of the fire, the growth, the stage of full development; and finally the decay. The selection of a specific HRR curve controls fire characteristics such as the temperature of hot gases. Furthermore, it integrates quantitatively critical parameters; such as the strength of the ignition source, the fuel load, and the type, size and duration of the fire.

The current work is specifically intended to elaborate on the link between the shape of an HRR curve and the parameters related with fire development; such as the type and amount of the fire load that is present in a space, as well as, to introduce the effect of geometrical and ventilation characteristics of the enclosure to the shape of the HRR curve. The shape of an HRR curve is determined by a generic formula taking into account the various stages of fire development and considering the intensity and duration of the growth stage, restrictions of growth due to ventilation limits, the maximum value of HRR achieved, the possible occurrence of flashover and the duration of the “fully developed” and “decay” phases. The values of these variables depend mainly on the fuel available, the geometry of the space and the size of the openings. Due to uncertainty, mainly for the amount, type and growth characteristics of the combustible materials in a space as well as the size of the fire, the current approach addresses these dominant parameters as random variables. The specification of suitable probability distributions for these parameters is one of the laborious tasks of the current methodology, since relevant data from the maritime industry is not always available. Nevertheless, a set of HRR curves could be generated probabilistically: by defining the critical conditions, such as the occurrence of flashover, the corresponding HRR curves could be utilised as the basis of selected design fires in a fire risk assessment framework.

FIRE DEVELOPMENT IN AN ENCLOSURE IN TERMS OF ENERGY RELEASED

In Fig. 1 are presented the fire stages from the viewpoint of energy released. The main assumption is that, the fire initiates from a fuel package and then its growth can result in full enclosure involvement (Quintiere 2000). Nonetheless, a more complex arrangement could also be assumed, for the case where successive ignition of fuel packages has occurred, which is the case of the fire development in a large enclosure.

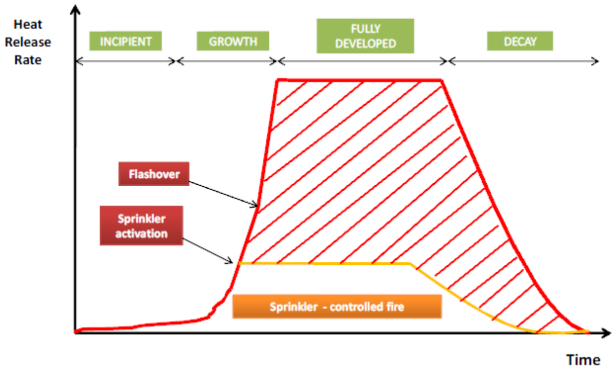


Fig.1 Development of fire in an enclosure in terms of HRR (from ISO 1999).

A short description of each stage of fire development follows:

Ignition

Before fire growth is established, an incipient phase normally occurs, whose duration and type depends on the strength and type of ignition source as well as the fuel source. For example, a piloted ignition is usually followed by flaming combustion and quicker flame spread resulting in fire growth. On the other hand, spontaneous ignition, which results in accumulation of heat in the surface or a low energy ignition source (e.g. a cigarette), will lead to smoldering combustion and not to so quick fire growth. However, toxic gases and smoke may be produced at this phase, while due to the smoke generation the incident may be detected before fire growth. Such time lag before the actual fire growth should be considered in the model. Fitzgerald (2004) noticed that a heat release rate of 20 kW, corresponding to flame of 25 cm height, can be assumed as a reference for the established burning phase.

Fire growth

After ignition and supposing that sufficient oxygen exists, the fire grows approximately following a power law with respect to time (Karlsson and Quintiere 2000). The growth rate depends mainly on the type and amount of the available fuel and type of combustion (usually flaming combustion is faster). This phase is usually governed by the amount of fuel and, in the presence of sufficient oxygen, it is called “fuel surface controlled”.

Flashover

This phenomenon occurs when there is a transition to a total surface involvement in a fire of combustible material within a compartment (ISO 1999). This transition leads to the fully developed stage, while the most common criterion demands the temperature to reach to 500 – 600 ^{0}C, or the radiation to the floor of the compartment to be 15 – 20 KW/m^2 (Karlsson and Quintiere, 2000). Flashover is a key event from the perspective of fire safety. Therefore it is common to distinguish between pre-flashover fires which are related with human safety (within the space origin of flashover occurrence) and post-flashover fires which can affect structural safety. The occurrence of flashover depends on the fire load, the geometry of the enclosure, the ventilation openings and the thermal properties of the boundaries.

Fully developed fire and decay

At this stage the released heat reaches an almost steady value, which is usually limited by the amount of oxygen in the compartment. In this case, the fire is characterised as “ventilation controlled”. The rate of air entering the space through openings controls the mass loss rate. If the space is well-ventilated, the maximum heat release rate will be determined by the amount of fuel. As soon as the full amount of the available fire load has been consumed the decay stage has started. This can be, in turn, also fuel surface controlled.

FRAMEWORK FOR SPECYFING HRR CURVES

The shape of a HHR curve could be determined by the following key parameters:

- Actual time until growth begins.
- Maximum heat release rate achieved.
- Time to reach this maximum.
- Restriction of the HRR growth due to ventilation conditions, occurrence of a steady phase and its duration.
- Time of starting the decay phase.

The following formula could define the shape of the HRR curve:

$$\dot{Q}(t)=\begin{cases}\dot{Q}_{ign}\cdot t/t_0\,, & 0\le t\le t_0\\ \alpha\cdot(t-t_0)^2+\dot{Q}_{ign}\,, & t_0\le t\le t_g\\ \dot{Q}_{max}\,, & t_g\le t\le t_d\\ \dot{Q}_{max}e^{-\frac{t-t_d}{\tau}}\,, & t>t_d\end{cases}\qquad(1)$$

$\dot{Q}[kW]$ is the heat release rate, $\alpha\left[kW/s^2\right]$ is the fire growth coefficient, $t_0[s]$ is the time until established burning occurs and τ is the coefficient governing the decay phase.

The parameters describing fire characteristics (e.g. fire growth, fuel and fire load) should be related with the parameters that control the shape of the HRR curve in a probabilistic way. To achieve this, appropriate distributions for the next few parameters should be defined:

- The fire load density distribution $Q\left[MJ/m^2\right]$ for the enclosure.
- The fire growth coefficient α, which determines the intensity of the growth.
- Maximum HRR density $\dot{Q}''_{max}\left[kW/m^2\right]$ obtained by the amount and type of fuel.
- The fuel area $A_f\left[m^2\right]$
- The required HRR for flashover $\dot{Q}_F\left[kW\right]$, which depends on the enclosure geometry, thermal properties and ventilation openings.
- The maximum HRR $\dot{Q}_V\left[kW\right]$ that can be achieved in ventilation control burning, which is determined by the ventilation conditions.
- The time t_d where decay starts calculated assuming that a percentage of the fire load Q has been consumed.
- The decay parameter τ which is estimated by integrating the HRR and equal with the total fire load Q.
- The duration period if the incipient phase t_0.

The growth phase is described as a t-squared fire, the fully developed or steady phase has a constant heat release rate value, while the decay phase obeys an exponential law. Each phase will be analyzed next.

Before continuing with the analysis of each phase separately, it should be mentioned that an incipient phase has also been included. The incorporation of this phase should allow for a more realistic modeling, as at this stage the temperature rise is insignificant as the released heat is very low, while the generation of smoke may lead to the fire detection before rapid development starts. In the case of smoldering combustion, the duration of the incipient phase increases significantly. For example, Babrauskas (1985) mentioned that for upholstered furniture and due to cigarette ignition the respective time can approach 20 – 30 minutes. However, during this time period the toxic gas production is much more prominent and life threatening. The integration of this phase, in fact the calculation of the duration of the incipient phase given the type of fuel and ignition source, is currently under development and will be presented in a forthcoming paper.

CALCULATION OF RELATED PARAMETERS

Fire load density

The total fire load $Q\left[MJ\right]$ that corresponds to a compartment is a measure of the energy that can be released from the combustion of all combustible material in the enclosure (Karlsson and Quintiere 2000). Thus, knowledge of the fire load of a space provides an indication about the duration of the fire. For a better account of the fire load located in an enclosure, the fire load density $Q''\left[MJ/m^2\right]$ is commonly used. Notably, in the majority of such estimations, instead of the total enclosure surface area, the floor area is preferably considered. However, for large ship spaces characterized by their large height, the enclosure surface area could be a better choice. The FLD[1] for a space is calculated as follows:

$$Q''\left[MJ/m^2\right] = \frac{\sum m_i h_i}{A_f} \quad (2)$$

where $m_i\left[kgr\right], h_i\left[MJ/kgr\right], A_f\left[m^2\right]$ are the mass, the calorific value of the i object and the floor area of the space. Various studies for the calculation of FLD can be found, see for example Zalok et al (2009). Their methodology is based on surveys and statistical analysis of the objects that one could associate with a specific type of space [both fixed (e.g. construction and lining materials) and movable], in terms of their mass and the type of combustible material.

Here, the basic idea for estimating FLD is to assume that each space encloses a group of combustible materials and the total mass of combustible materials in the enclosure, which is usually called fuel load (FL), can be represented as a distribution of the mass per unit floor area. It should be noticed that, as the framework of our analysis is intended to be probabilistic, the amount and type of combustibles inside a space are considered as random variables. However, they can be specified also in a deterministic way, an option that can be regarded as a single case of the probabilistic analysis. FLD distributions can be derived as follows:

- By specifying the fuel load (FL) distribution (kgr/m^2) for the examined space. IMO MSC/Circ. 1003 provides some reference maximum values for accommodation and service spaces (e.g. cabins: 15 – 35 kgr/m^2).
- Selecting some generic groups which characterize the type of materials in the space. For example textiles, wood – based etc. Each group will be represented by a representative calorific value.
- Estimating the contribution of each group to the total combustible mass. Due to same reasons mentioned above, a range of values can be taken into account for each group. In other words, a number of different designs, in terms of material content, will be considered.

From the above, the FLD will be determined as follows:

$$Q''\left[MJ/m^2\right] = FL\sum \frac{m_i}{m_{total}} h_i \quad (3)$$

Fire growth coefficient α

It has been assumed that, in the pre-flashover stage of a fire the HRR grows proportionally with the time squared. Another power law can also be used, however the “time squared” fires are well established as representatives of

---

[1] FLD is the abbreviation of Fire Load Density

HRR curves For example NPFA 92B (2000) have proposed the next expression:

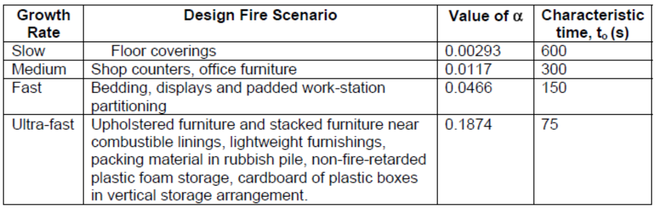
$$\dot{Q} = \dot{Q}_0 \left(\frac{t}{t_g} \right)^2 \qquad (4)$$

Where $\dot{Q}_0[\mathrm{kW}]$ is a reference HRR (proposed 1055 kW) and $t_g[s]$ is the required time to reach this HRR. In addition, a similar type for describing the *t*-squared fire is (e.g. Karlsson and Quintiere 2000, Janssens 2000):

$$\dot{Q} = \alpha \cdot t^2 \qquad (5)$$

The relationship of $\dot{Q}_0, t_g$ and α. is quite obvious, in terms that when specifying the first two, α can be calculated by $\alpha = Q_0 / t_g^2$. ISO (1999) and NFPA 92B (2000) are using a rank concerning the intensity of the growth, where ultra – fast, fast, medium and slow categories are selected and quantified as Fig.2 shows.

The value of the fire growth coefficient α depends mainly on the type of fuel materials and generally, it is characteristic of the enclosure space (e.g. occupancy). Various recommendations have appeared towards specifying characteristic values for various space types based on the type of fuel load (see Fig. 2 and Fig. 3). On the other hand, testing procedures for the estimation of burning attributes of real materials is another way to calculate the fire parameters. An excellent review is provided in the *SPFE Handbook of Fire Protection Engineering* (2002). It is noteworthy that, there is a tremendous variance in key characteristics, such as the growth coefficient α even for the same type of furniture (for example chairs).



Growth Rate	Design Fire Scenario	Value of α	Characteristic time, t_o (s)
Slow	Floor coverings	0.00293	600
Medium	Shop counters, office furniture	0.0117	300
Fast	Bedding, displays and padded work-station partitioning	0.0466	150
Ultra-fast	Upholstered furniture and stacked furniture near combustible linings, lightweight furnishings, packing material in rubbish pile, non-fire-retarded plastic foam storage, cardboard of plastic boxes in vertical storage arrangement.	0.1874	75

Fig.2: Categories of t – squared fires adapted from ISO 1999.

Type of Occupancy	Growth Rate α
Dwellings, etc.	medium
Hotels, nursing homes, etc.	fast
Shopping centers, entertainment centers	ultra fast
Schools, offices	fast
Hazardous industries	Not specified

Fig. 3: Growth rates for various types of occupancies (adapted from Karlsson and Quintiere, 2000).

Fig.4 shows a comparison of the *t* – squared fires generated for the aforementioned growth coefficients with relation to fire tests of various materials. Keeping in mind that the purpose is a generic methodology for generating HRR curves, the uncertainty regarding the objects that exist in a space and the lack of exact fire data for the objects which can be obtained only experimentally, it is proposed to use probability distributions for α , defined by considering some range of the fire growth times of the objects inside a space, taking average values and some variance. For example, one could assume that for upholstered furniture inside a passenger cabin the respective growth time can be varied from fast to slow with the majority of values around mean (300 sec according to Fig.2). By specifying such a distribution a number of scenarios can be generated as it will be shown in the demonstration of the methodology. Besides it should be noted that the exact type and shape of the distribution is an issue of discussion, as it is not realistic to know the exact shape. Nevertheless this procedure aims to ensure that the generating a sufficient number of scenarios, one will meet inevitably what would constitute the set of HRR curves.

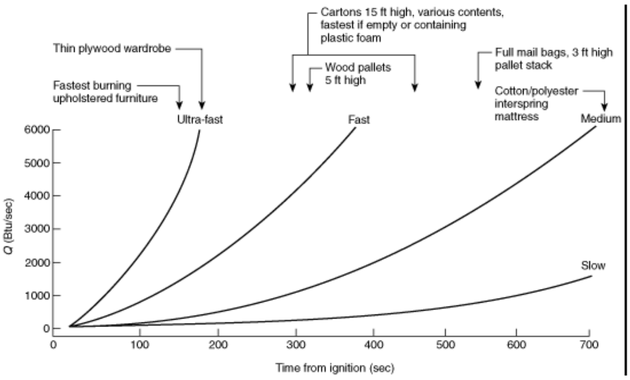


Fig. 4: Relation of t – squared fires with fire tests, adapted from NFPA 204 (2000)

Estimating the required HRR for flashover

The required HRR rate for generating flashover is important because the occurrence of flashover will bring about the surface burning of all the combustibles within the enclosure space. Thus the whole fire load located in the space will be involved in the fire development. The necessary rate depends on the space geometry (floor area and height), the ventilation openings and thermal properties of the boundaries. Various methods for predicting the required HRR for flashover in compartments have been developed. A review has been provided by Walton and Thomas in SPFE (2002) Handbook (section 3, chapter 6: Estimating temperatures in compartment fires). The basic principle for the calculation is the energy and mass conservation for the hot upper layer. Specifically, the energy added to the hot upper layer by the fire should be equal to the energy lost from the hot layer and the rate of change of energy within the hot upper layer. So the methodologies firstly target the estimation of the compartment's hot layer temperature and then, given that the flashover occurs when the temperature of the hot gas layer reaches about 600^0C, the necessary HRR is estimated.

An important factor that governs the process is the ventilation factor $A_0\sqrt{H_0}$, where A_0 is the area of opening and H_0 is the height of opening. In the majority of the available methods, it is assumed that free ventilation will supply sufficient air for the combustion. It is widely accepted that the mass flow rate of air into the compartment through an opening is (Babrauskas 1980, Karlsson and Quintiere 2000)

$$\dot{m}_a = 0.5 A_0 \sqrt{H_0} \qquad (6)$$

In the current stage, our approach has incorporated two methods for the necessary HRR for flashover occurrence; one proposed by Thomas (1981) and another by Babrauskas (1981). Both are semi empirical and rely on experimental data.

Method of Thomas (1981):

Assuming that flashover occurs at 577^0C and taking into account experimental data, the minimum required rate of released heat is:

$$\dot{Q}_{flsh} = 7.8A_T + 378A_0\sqrt{H_0}\ \left[kW\right] \tag{7}$$

where A_T is the total area of compartment enclosing surfaces.

Method of Babrauskas (1980)

From a series of experiments, it was deduced that the minimum HRR required for flashover is about $0.44 \cdot \dot{Q}_{stoich}$, where $\dot{Q}_{stoich}$ is the so called stoichiometric HRR and calculated taking into account the maximum amount of fuel that can be burnt for a given air flow. Considering that, for most fuels, the HRR per mass of air consumed is about $3000\ \text{kJ/kg}$ and using eq. 5, it will be:

$$\dot{Q}_{stoich} = 3000 \cdot \dot{m}_a = 1500 \cdot A_0\sqrt{H_0}\ \left[kW\right] \tag{8}$$

Therefore the minimum HRR for flashover will be:

$$\dot{Q}_{flsh} \simeq 0.434 \cdot \dot{Q}_{stoich} = 650 \cdot A_0\sqrt{H_0}\ \left[kW\right] \tag{9}$$

Taking into account some refinements by fire tests (see Babrauskas 1980) the following expression is derived that accounts for wall effects:

$$\dot{Q}_{flsh} = 3.25A_T + 650A_0\sqrt{H_0}\ \left[kW\right] \tag{10}$$

In a forthcoming presentation other methods that take into account more straightforward the thermal properties of the boundaries as well as a comparison of these methods will be presented.

Maximum HRR for “ventilation- controlled” fires

In this case, the rate of heat released depends mainly on the ventilation factor $A_0\sqrt{H_0}$. As already mentioned, for stoichiometric mass burning (no excess fuel and no excess oxygen), the maximum HRR rate is given by (e.g. Janssens 2000, Drysdale 1999, Babrauskas and Williamson 1978):

$$\dot{Q}_{max,vent} = \dot{m}_a \cdot \left(\frac{\Delta h_{c,net}}{r}\right) \tag{11}$$

where $\Delta h_{c,net}\left[kJ/kgr\right]$ is the net heat of combustion of the fuel and r is a constant and represents the amount of air needed to perfectly burn a unit mass of fuel (or else is the stoichiometric air to fuel ratio). For most of fuels, the ratio $\Delta h_{c,net}/r$ is constant and about $3\ \text{MJ/kgr}$. However, when fuel and air are not present in that ratio, a correction factor ϕ or else the dimensionless stoichiometric coefficient is used (e.g. Drysdale 1999), which in terms of HRR is defined as:

$$\phi = \frac{\dot{Q}}{\dot{Q}_{stoich}} = \frac{\dot{Q}}{1500 \cdot A_0 \cdot \sqrt{H_0}} \tag{12}$$

In fact is very difficult to know exactly what the ratio ϕ means in terms of lack of oxygen. It is then generally assumed (see the previous references) that in the crossing of regime there is quasi-stoichiometric condition, which is a rather conservative approach. However, a reduction in the maximum HRR value might be appropriate due to incomplete combustion. It is known (see for example Karlsson and Quintiere 2000) that in real fires in an enclosure, only some amount of the mass of the fuel (about 70 – 80%) is converted to volatiles, thus the combustion is incomplete. The efficiency of the combustion is described by the following combustion efficiency factor:

$$\chi = \frac{\Delta h_{eff}}{\Delta h_{c,net}} \tag{13}$$

where Δh_{eff} is the effective heat of combustion. The maximum HRR in ventilation-controlled condition will be:

$$\dot{Q}_{max,vent} = 1500 \cdot \chi \cdot A_0\sqrt{H_0}\ \left[kW\right] \tag{14}$$

Maximum HRR for fuel surface controlled fires

In order to determine the maximum HRR resulted from fuel controlled burning we have to define a peak HRR density $\dot{Q}_{peak}\left[kW/m^2\right]$ distribution. Knowing that the decay phase starts when an amount of the fire load about (50-80) % has been consumed, then the peak of the HRR curve will be determined by the fire load available, the fire growth coefficient and the value of the percentage of fire load consumed. Then we have to define the fuel surface area $A_{fuel}\left[m^2\right]$, which is in fact the area of the fuel package. This will be a random variable expressed as percentage of the total floor area of the compartment. Thus, the peak HRR due to fuel surface controlled burning will estimated by multiplying $\dot{Q}_{peak}\left[kW/m^2\right]$ with the $A_{fuel}\left[m^2\right]$. It should be considered that the fire load assumed in any case is estimated from the fire load density and the fuel surface area of the package. In some cases the peak HRR obtained is greater than the required HRR for flashover, so for these cases the total fire load of the enclosure will be involved as mentioned before.

Finally the maximum HRR in each fire is going to be the minimum among the ventilation controlled value and the fuel surface controlled.

APPLICATION

As basis for the demonstration of the discussed methodology, a passenger cabin will be used. The geometrical and ventilation characteristics are found in Table 1. The door of the cabin is assumed open. As the fire load will be treated as a random variable, a fuel load distribution should be defined. We set a requirement of the maximum mass of combustible materials to be $15\ \text{kgr/m}^2$ and we select the gamma distribution (Fig. 5) with mean $5.69\ \text{kgr/m}^2$ and standard deviation $2.46\ \text{kgr/m}^2$. As the floor area is $12.88\ \text{m}^2$, the maximum combustible mass will be 193.18 kgr. The selection of the distribution of fuel load density implies that the most common statistical distributions for the fire load density are: the lognormal, the

Gumbel, the gamma and the Weibull (Zalok et al 2009). For the generation and sampling of the relevant results the commercial program @RISK[2] has been used.

Table 1: Geometrical and ventilation characteristics

Length [m]	4.30
Breadth [m]	3.00
Height [m]	2.10
Breadth of door [m]	0.75
Height of door [m]	2.01
A_f [m^2] floor area	12.88
Ao [m^2] opening area	1.51
At (m^2) enclosure area	54.89

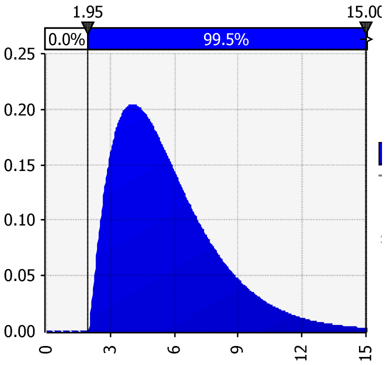


Fig. 5: Fuel load density distribution (kgr/m^2).

To generate the fire load density distribution, generic groups of materials with their average heat of combustion values have to be determined. From a similar cabin the percentage of contribution to the total combustible mass has been estimated, where due to uncertainty a range ±10% uniformly distributed to these values has been assigned. The average heat of combustion has been estimated from the respective materials that constitute the groups. Table 2 shows the groups and the required values.

Table 2: Composition of generic groups

type	percentage	Δh_c (MJ/kgr)
A: textiles	26%	18.27
B: wood	12%	17.00
C: plastics	44%	24.81
D: foams	18%	24.50

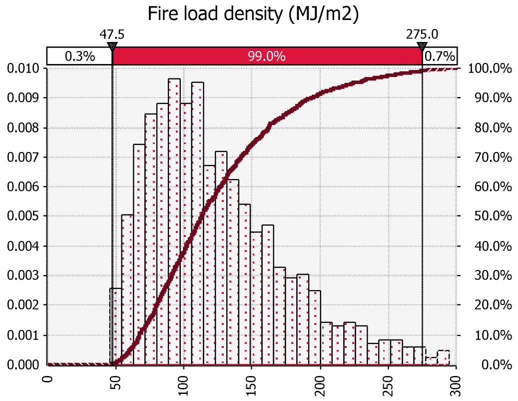


Fig. 6: Fire load densities with the cumulative ascending overlaid. The mean value is $124\ MJ/m^2$ and the standard deviation $50\ MJ/m^2$

The treatment of the other random variables described in the previous section follows. Regarding the fire growth characteristics, we have selected a range from fast to slow growth potential (see Fig. 2 for the characterization of the fires), where the values are uniformly distributed. The percentage of fire load consumed until decay lies uniformly within the range 50-80%, while the combustion efficiency is 0.7 – 0.85, also uniformly distributed.

The required HRR for flashover is estimated as the mean value from eq. 6 and 9 and it is 1405 kW. On the other hand, the maximum value of HRR due to ventilation restriction ranges from 2251 to 2731 kW. The range comes as a result of the combustion efficiency definition.

Fig. 7 shows the derived distribution for the peak HRR due to fuel surface controlled fires, which is estimated according to the previously described methodology.

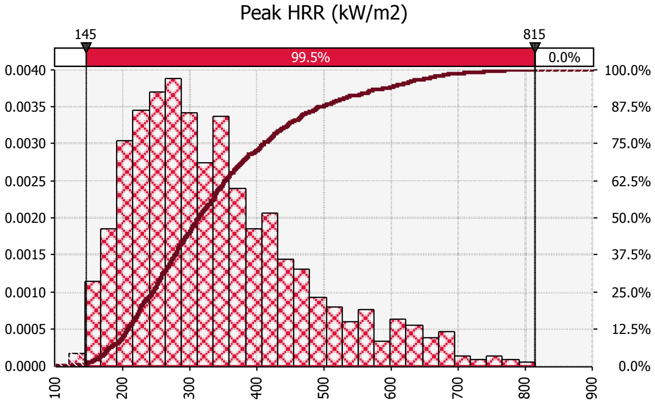


Fig. 7: Probability density functions of the peak HRR due to fuel controlled fires.

The last parameter that should be defined is the surface area of the fuel package, which was adjusted to the range 10 – 40 % of the floor area. A uniform distribution has also been selected. The reason of this selection is that, for demonstration purposes we only want to generate cases within these ranges, without favouring specific values (e.g. those around the respective means).

In total, 200 scenarios have been generated. The estimated maximum HRR and the time for reaching these values are

---

[2] @RISK is a product of Palisade Corporation, Newfield, NY

shown in Fig.8. The flashover limit has been included also and it was found that 22% of the fires have reached flashover and beyond. The probabilistic HRR curves generated are shown in Fig. 9.

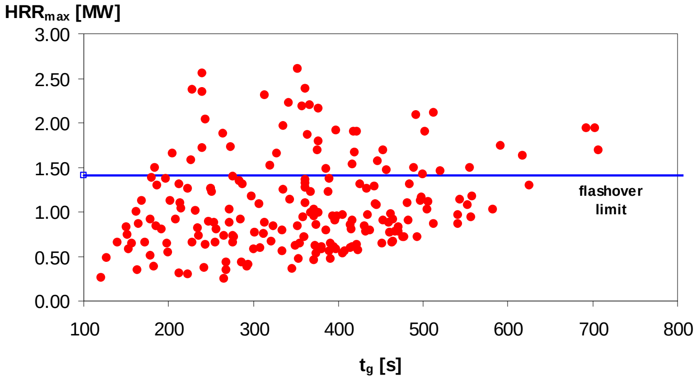


Fig. 8: Maximum vales of HRR and respective times.

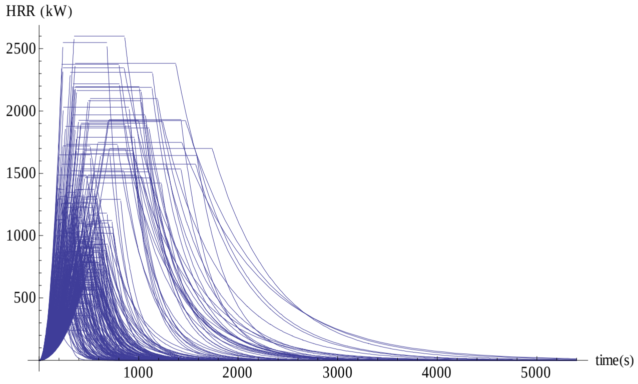


Fig. 9: Generated HRR curves.

CONCLUDING REMARKS

A rational methodology for the probabilistic generation of HRR curves has been developed. The procedure is based on the specification of the basic parameters of the problem, like the fire load and the growth characteristics. Moreover, it considers some critical events like the occurrence of flashover and the existence of ventilation restrictions. The outcome could be utilised within a risk-based design framework for fire safety in terms of fire characteristics of the assumed scenarios. A critical set of these curves, an envelope or all of them could be considered, depending on the demands of the analysis and the type and efficiency of the numerical tools available. The selection of the appropriate distribution of the basic parameters is probably the formidable task of this methodology as it depends on the availability of data.

Various issues need further consideration. One is the incorporation of some suppression system that should result in the decease of HRR, started from the time of its activation. Furthermore, more complex HRR curves could be defined, more suitable for large enclosures, where a distribution of fuel packages could be combined with successive ignition of them resulted in the phenomenon of spreadover, which is rather appropriate than flashover for large spaces. Future work will try to handle these issues.

ACKNOWLEDGMENTS

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

REFERENCES

Babrauskas, V. (1980) “Estimating Room Flashover Potential”, *Fire Technology, 16, 2, pp. 94–104.*

Babrauskas, V. and Williamson, R.B. (1978) “Post-Flashover Compartment Fires: Basis of a Theoretical Model”, *Fire and Materials, 2, 2, pp. 39–53.*

Babrauskas, V. and Krasny, J., (1985) Fire behaviour of upholstered furniture, NBS Monograph 173, National Engineering Laboratory, Center for Fire Research, National Bureau of Standards: Gaithersburg, MD 20899.

Bawlya, A. (2008) “An Overview of Design Fires for Building Compartments”, *Fire Technology, 44, pp. 167 – 184.*

Drysdale, D., *An introduction to fire dynamics*, John Wiley & Sons, 2nd edition, 1999, ISBN: 047197290.

Fitzgerald, R., *Building fire performance analysis*, John Wiley & Sons, 2004, ISBN 0-470-8632699.

Hostika, S. and Keski-Rahkonen, O. (2003), “Probabilistic simulation of fire scenarios”, *Nuclear Engineering and Design, 224, pp. 301-311.*

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

International Marmite Organisation, MSC/Circ. 1003. *Guidelines on a simplified calculation for the total amount of combustible materials per unit area in accommodation and service spaces*, London, IMO, 2001.

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

Janssens, M., *An introduction to mathematical fire modelling*, Technomic Publishing Co. INC., USA, 2000, ISBN: 1-56676-920-5.

Karlsson, B. and Quintiere, J.G., Enclosure fire dynamics, CRC press, USA, 2000, ISBN: 0-8493-1300-7.

National Fire Protection Association (NPFA), *Smoke management systems in malls, atria and large spaces*, NPFA guide, NPFA 92B, 2000.

National Fire Protection Association (NPFA), *Standard for smoke and heat venting, NPFA guide*, NPFA 204, 2002.

Society of Fire Protection Engineers (SPFE), The SPFE Handbook of Fire Protection Engineering, NPFA International, 3rd edition, Bethesda, MD,2002.

Thomas, P.H. (1981) “Testing Products and Materials for Their Contribution to Flashover in Rooms”, *Fire and Materials, 5, 3, pp. 103–111.*

Quintiere, J.G., *Fundamentals of fire phenomena*, John Wiley & Sons, Ltd, England, 2006, ISBN: 0-470-09113-4.

Zalok, E., Hadjisophocleous, G.V., and Mechaffey, J.R., (2009) Fire loads in commercial premises, *Fire and Materials, 33, pp. 63-78.*