An Engineering Approach to Determine Acceptable Risk

Fredrik Olsson
Fire Protection Engineer, Ph.D. Student
Dept. of Fire Safety Engineering, Lund University
P.O. Box 118, SE-221 00 LUND, Sweden

INTRODUCTION

Risk-based fire safety design is getting more common. But the lack of established acceptable fire risk criteria makes it difficult for the designer to determine whether his building is safe or not. The objective of this paper is to present a method as well as an case study that quantifies acceptable risk level for buildings, thus deriving risk criterion to be used when performing fire safety design in the future. The paper is based upon a report published by the Department of Fire Safety Engineering, Lund University (Olsson, 1999), which is available at http://www.brand.lth.se/english/.

Background

The introduction of performance-based building regulations in Sweden in 1994 has resulted in a number of benefits. These regulations led to the development of new solutions in fire protection. They provide better flexibility and means of implementation for each individual building. They have also led to a lowering of the total cost of fire protection installations, without compromising the safety level.

However, following the transition to performance-based regulations, the uncertainty as to whether a building is safe or not has increased. According to an evaluation performed by the Swedish Board of Housing, Building and Planning (Boverket, 1997), the uncertainty in safety level does not depend on the regulations. One of the problems is that methods for design have not been completely adopted by consultants. It is therefore necessary to continue the work on fire safety design based on calculations e.g. design by calculated risk.

Terms like “good” or “bad” in describing the safety level of building are not appropriate. These terms are subjective and non-quantitative. Those who design fire protection measures should be able to present a more quantitative measure of the safety level. The Department of Fire Safety Engineering at Lund University is involved in extensive research within the area of the fire and risk. One of the research projects, “Fire Safety Design Based on Calculations” has the objective of producing an event tree based model for risk analysis in buildings. Such a model has two primary uses; it can be used to verify whether a building fulfils the criteria for accepted risk, and it can be used to derive the combination of fire safety measures leading to the lowest cost for the accepted risk. Risk can be defined as the correlation between the frequency of an activity’s possible failures and the consequences resulting from those failures. Using this definition, risk can be expressed as a risk profile, where the risk is illustrated by a so-called FN. curve (Frequency of accidents vs. Number of fatalities.). Attempts are being made to establish acceptable risk criteria for different types of buildings such as hotels, health care facilities, shopping centers, etc.

Objectives and applications

The main objective of this paper is present a method on how to quantify an acceptable risk for a specific building category. The method is then applied to hospital buildings. By using this method to quantify acceptable risk, the society is provided with a measure on the risk, i.e. safety level that is acceptable in hospitals, when they are designed by calculations.

One application of the results of this work is in designing buildings in the future, when the acceptable risk profile could be used to guide the fire safety consultant in designing a safe building. By applying this methodology, it is possible to determine which installations actually increase personal safety in the building. The methodology could also be used to analyze the cost and benefit of fire protection installations.

FIRE SAFETY DESIGN PROCESSES

There are three main methods of performing fire safety design. These methods are all accepted by regulatory bodies and differ in their degree of detail. The methods are:

- *The standard method,* simple handbook solution, i.e. using former prescriptive regulations
- *The fire safety engineering method*, calculations on sub-levels, e.g. evaluating escape time margin
- *The risk-based verification method,* evaluation on system level with risk analysis, i.e. performing a quantitative risk analysis (QRA)

At the 2nd International Conference on Performance-Based Codes and Fire Safety Design Methods in 1998, “The Swedish Case Study – Different Fire Safety Design Methods Applied on a High Rise Building” (Jönsson & Lundin, 1998) was presented. In that study, a number of different fire safety design solutions were compared in order to find out which solution resulted in the lowest risk related to its cost. Handbook design solutions were compared with fire safety engineering solutions. One of the major conclusions from the study was that the right choice of solution, using the fire safety engineering method, could only be made by using a risk-based verification method in the evaluation process. This was also one of the findings from a recently completed Swedish study (Boverket, 1997), which concluded that misuse of the fire safety engineering method could lead to unsafe buildings. This clearly shows the benefit of and to use a risk-based verification method as a complement to a deterministic engineering method.

If the standard method is used, no calculations are required. But, the standard design solution could be less cost-efficient that other solutions with similar or better safety levels. If the engineer uses the fire safety engineering method he relies upon “the reasonable worst case”. He does not take into account sprinkler or detection failure, etc. The fire safety design method is preferably used when comparing, for example, different detection, suppression or alarm systems, i.e. on a sub-level. The method should not be used for the complete fire safety design system. The risk-based verification is the only method that can be used to completely analyze the consequences of a fire in a building.

A standard engineering approach to fire safety in buildings

In their Draft for Development No. 240 (1997), the British Standards Institution outlines a framework for an engineering approach to fire safety in buildings. This framework can be used to show that regulatory or insurance requirements can be satisfied. Sections 3.1-3.4 follow the methodology presented by the BSI (1997). The basic fire safety design process consists of four main stages.

- A qualitative design review
- A quantitative analysis
- Assessment against criteria
- Reporting and presentation

This basic process is illustrated in Figure 1. The BSI (1997) gives guidance in the application of scientific and engineering principles to the protection of people and property against fire. The framework presents an excellent approach on how to handle fire safety design issues. Because of its completeness, this framework is highly recommended as a fire engineering guideline.

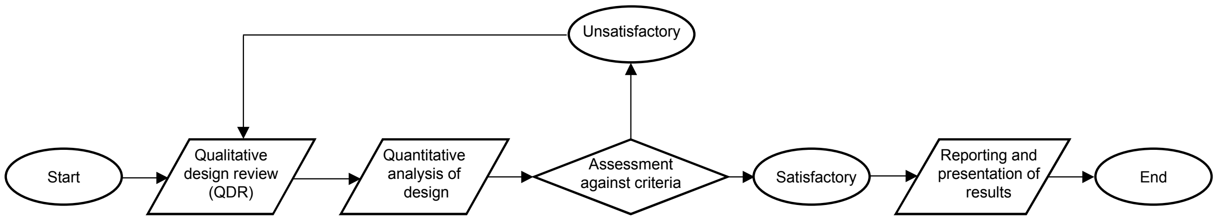

Figure 1 The basic fire safety design process.

Fire is a transient process that affects a building and its occupants in different ways at different stages. The process of fire safety design is complicated by the fact that time is one of the key design parameters. As stated by the BSI, it is important when carrying out a quantitative analysis, to recognize the role of time and the interaction of parameters within a consistent time framework. When assessing the number of people exposed to critical conditions a comparison between two time lines is made. One of these time lines represents the course of the fire, in terms of its size, rate of burning and smoke or toxic gas concentration. The other time line represents the response to the fire by the occupants. These time lines and the specific expressions used are presented in Figure 2. Note that the expressions differ between different countries.

The fire safety design process begins with a qualitative design review (QDR). During the QDR the scope and the objectives of the fire safety design are defined, performance criteria established and one or more potential design solutions proposed. Key information to be used as input in the quantitative analysis is also gathered. During the quantitative analysis the fundamentals of fire science are applied. The analysis performed using six sub-systems, which reflect the impact of a fire on people and property at different stages in its development. The sub-systems cover fire growth and development, the spread of combustion products and fire from the source, fire detection and the activation of fire safety systems, fire service intervention and the evacuation of occupants.

In performing the quantitative analysis it is necessary to assess the outcome in relation to the established performance criteria. When the report is assembled a minimum amount of information is required. This information consists of, for example, the findings of the QDR, assumptions, references, engineering judgements, methodologies employed, sensitivity analyses and comparison of the results with the performance criteria.

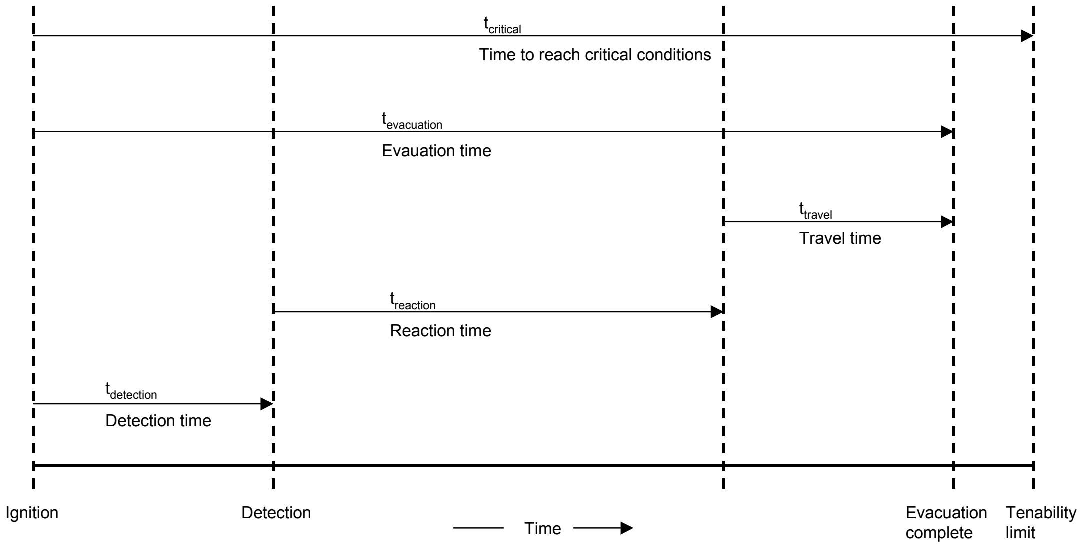

Figure 2 Example of a time line comparison of fire development and evacuation.

The risk-based verification method

The risk-based verification method should be considered as the quantitative analysis that is described in the basic fire safety design process. The method uses so-called event tree technique where an initial event results in a number of sub-scenarios, pending the outcome of each event, Figure 3. Fire is chosen as the initial event and the sub-scenarios are formed when considering the function of fire protection installations and staff response.

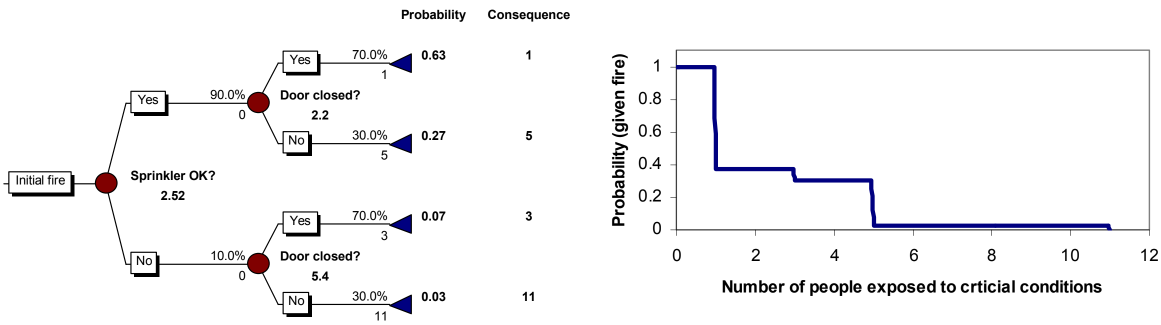

Figure 3 An illustrative example of an event tree and the belonging risk profile. The risk profile should be interpreted that e.g. the probability of two or more people exposed to critical conditions is 0.37.

The most crucial part is to construct the event tree. The engineer must be careful so that he includes all events that need to be taken in consideration. Such events could be open or closed doors, different fire growth rates, blocked escape routes, staff response etc. The probability and the consequence are calculated for each sub-scenario in the event trees. Finally, the risk is presented as a risk profile where the number of people exposed to critical conditions are put against the cumulative frequency of occurrence, Figure 3. When analyzing and evaluating the calculated risk profiles, acceptable fire risk criteria are derived.

ACCEPTABLE RISK

When a risk analysis has been performed for a given activity, and the calculated risk has been considered acceptable, it is important to discuss “who is the risk acceptable to”? If you have an economic interest in an activity you are likely to accept higher risks than if you are one of those personally affected by the risk. Another element of importance in the evaluation of risk is whether you are affected by the risk yourself or not. A risk could be acceptable from a societal point of view, but we all think that others should carry it.

The risk perception of today’s society is complex. Some carry out high-risk activities voluntarily, e.g. smoking and mountain climbing, while we are very reluctant to accept other risks. Such a risk may be the establishment of a new process industry in our neighborhood. Decisions in risk matters must be based on a common public opinion, using objective judgement, keeping public as well as individual interests in mind.

Risk can be evaluated and risk criteria established using four different principles (Det Norske Veritas, 1997). *The principle of reasonableness* says that an activity should not involve risks that by reasonable means could be avoided. Risk that by technically and economically reasonable means could be eliminated or reduced are always taken care of, irrespective of the actual risk level. *The principle of proportionality* means that the total risk that an activity involves should not be disproportionate to its benefits. By using *the principle of distribution*, risks should be legitimately distributed in society, related to the benefits of the activity involved. Single persons should not be exposed to disproportionate risk in comparison with the advantage that the activity affords them. *The principle of avoiding catastrophes* says that it is better that risks are realized in accidents with a lower number of fatalities. When discussing risk reduction, terms such as *ALARP (*As Low As Reasonably Practicable) and *ALARA* (As Low As Reasonable Achievable) are frequently used.

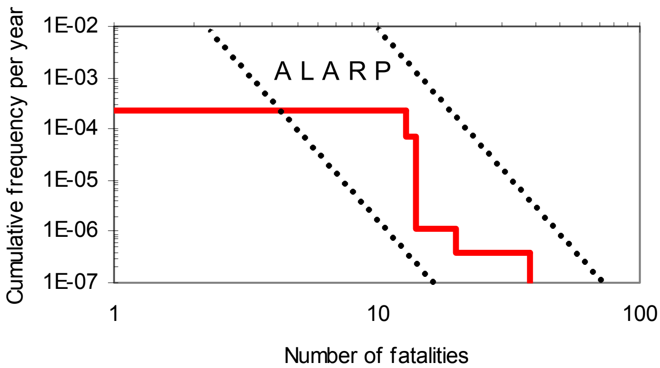

Figure 4 Schematic illustration of the ALARP zone in an FN diagram.

The acceptable risk can be defined as limit lines in the FN diagram, Figure 4. Risks that are below the lower line are tolerated and they do not have to be reduced. Risks in the zone between the two lines are in the acceptable ALARP area. Risks in this zone should be reduced if it is practicable and does not involve disproportionate costs. Risks that are above the upper line are not acceptable and should be subjected to a risk reduction process.

THE ENGINEERING APPROACH

Legislative and regulative bodies are indeed responsible for providing engineers with regulations, recommendations and guidelines. Included in their responsibilities is the task to determine what levels of risk that should be considered acceptable. In doing so many questions would arise that need to be considered by experts in the field i.e. fire protection engineers.

As stated before, the main objective of this paper was to find a way to establish acceptable fire risk criteria for hospitals. In order to do so a number of questions must be discussed: When is a risk considered acceptable? Are there any differences in risk perception and risk reluctance at a hospital? How is it possible to quantify an acceptable risk?

It is believed that a risk is considered acceptable only when society accepts it. Risk communication is a complicated matter and should not be ignored. Perhaps there should be a higher risk reluctance at hospitals as the patients are often “helpless” and under the responsibility of the hospital staff. Risk communication often fails when a hazardous incident has occurred. These failures are frequently related to differences in the interpretation of risk. The problem can also be related to the fact that methods for risk calculation and risk presentation are not well established, and also that the methods of risk evaluation are not commonly accepted. It is easy to give the risk a value such as one incident per 1000 year, but it is a fact that people react more to how the precipitate the risk than on the actual number. We are therefore more willing to accept the risk of a traffic accident, than the risk of a nuclear power plant breakdown, despite the fact that the number of people killed in traffic accidents far exceeds the number of fatalities in nuclear power accidents. It is the elevation of the limit lines in Figure 4 that represents risk aversion. The sharper the elevation the higher the aversion towards risks.

Acceptable risk has been established here by using the following arguments:

- All Swedish buildings are regulated by the Swedish performance-based building regulations (BBR, 1998). This code as been adopted by parliament and is applied to the construction of new buildings as well as renovations.
- The code contains mandatory provisions and general recommendations for building safety in the case of fire.
- Buildings that designed and built exactly according to the regulations must be considered to have an acceptable safety level.

If risk analyses are carried out on buildings that fulfil these regulations, the risk profiles could be used to quantify the acceptable risk criteria. To illustrate this approach a case study of a building category, namely hospitals has been carried out.

CASE STUDY OF A BUILDING CATEGORY – HOSPITALS

Fire safety is one of the greatest challenges facing the designers and operators of health care facilities. This is particularly true where patients are highly dependent on members of staff, for example, the elderly, the mentally ill, those in intensive care units, etc. The lack of alertness, lack of mobility and high dependency on fixed equipment have obvious implications for patient safety in the event of fire (Charters, 1996).

The case study is performed by choosing a representative hospital building that is equipped with a number of fire safety design alternatives. A so-called event tree technique was used to perform the quantitative analysis. Event trees were drawn for each of the three fire safety design solutions. Each design solution was evaluated by using the three design fires given in Section 6.8. The probability and the consequences for each sub-scenario were calculated. The risk is presented as a risk profile. These profiles are later evaluated and acceptable risk criteria are established. Computer-based models were used to calculate the time taken to reach untenable conditions, i.e. the safe egress time. A simple hand-calculation model was derived to assess the escape time. When using the event tree technique the sensitivity of different parameters is automatically examined.

Building, environment and occupant characterization

The building considered in this work consists of three stores and a basement. On the entrance floor there is a daytime medical reception, a pharmacy, waiting hall and a cafeteria. The first and second floors consist of two hospital wards each. The floor is divided into three fire compartments (heavy lines in figure 6.1). The two wards are separate fire compartments as well as the protected lobby. All doors between patient rooms and the corridor are assumed to be closed. The door between the protected lobby where the elevators and stairwell are situated is normally closed (self-closing device). According to the regulations (BBR, 1998) walls between fire compartments are separated with class EI-60 and doors with class EI-30. Patient rooms are not separate fire compartments, but it is assumed that no smoke can leak directly from one room to another. It is possible to evacuate patients from the hospital ward via a stairwell located at the end of the corridor. This stairwell is of course its own fire compartment. All stairwells have natural smoke ventilation devices installed in the ceiling. All surface finishes and claddings are of materials that provide negligible contribution to the spread of fire. The ceiling and walls are covered with gypsum plasterboard and the floor is concrete.

The hospital is located in Sweden, where there is an average temperature of –2 °C in winter and 15 °C in summer. The wind conditions are assumed to be normal, i.e. an average wind speed of 4 m/s. In winter there will be snow for approximately three months. The climate conditions may affect the performance of smoke and heat ventilation systems. As a hospital requires a well-ventilated environment, the inside air has a temperature of 23 °C. The HVAC system provides five total air exchange per hour. The air movement within the building is designed so that smoke spread is minimized.

The number of staff depends on the time of day. During the daytime there are seven nurses available on each ward and at night, there are only three. The staff is trained in fire safety. The training includes evacuation tactics and the use of portable fire extinguishers. If a fire occurs the staff will most likely be able to put it out. As the alarm system is well maintained the staff relies upon it and is alert to any alarm. On each ward there is a maximum of 36 patients. All patients need assistance to evacuate. They are able to walk when supported by staff. Patients are assumed to be sleeping at night and to be awake during the day. The patients are not familiar with the building.

Fire safety objectives

The main objectives of the fire safety design is to; limit the probability of outbreak of fire, ensure safe evacuation of occupants, prevent large property losses and protect the environment. In this study only the first two objectives have been studied. Organizational fire safety is the key factor in ensuring that a fire does not break out. Regular fire safety inspections and the training of staff are two other key elements in fulfilling the objective. Fire safety design solutions must ensure that the total escape time is shorter than the available safe egress time. A risk-based fire engineering method will be used to analyze this very important objective.

Evacuation strategy

The main evacuation strategy is to move people from the ward where the fire is located to safe places, e.g. another ward or the protected lobby. Horizontal evacuation is the key tactic. However, if the escape route to the protected lobby is blocked, patients are evacuated via the stairwell located at the end of each corridor. Evacuation to safe places must be carried out without the assistance of the fire service. If it is necessary, people can continue to perform total evacuation to the outside. The time frame discussed here means that the occupants must, in the worst case, have completed total evacuation approximately thirty minutes after the fire breaks out. The time is dependent on the fire class of the door to the adjacent fire compartment.

Acceptance criteria

According to the regulations (BBR, 1998), satisfactory escape shall be effected in the event of fire. The following design criteria are established. *Visibility* - Level of fire gases not lower than 1.9 m from the floor. *Thermal* - A maximum short-term radiation intensity of 10 kW/m^2. *Temperature* - Air temperature not higher than 80 °C. If the gases are well mixed, the following criterion will be valid: The visibility should not be less than 10 m, i.e. a visibility reduction of 1 dB/m.

These criteria define untenable or critical conditions. In a deterministic study evacuation should be completed before these conditions arise. Probabilistic criteria are those specifying individual risk and the risk of more than 10 and 100 fatalities. Since it is the objective of this study to establish such acceptable risk criteria for hospitals, they can not be given in advance. This project does not include any property loss studies and the financial criteria are therefore ignored.

Identification of fire hazards

The most relevant fire hazards are arson, technical malfunction and forgotten stove, etc. Fire by arson may occur in storerooms, nursing rooms, stairwells etc. Technical malfunction includes fire in medical devices, televisions, etc. Kitchen devices such as a hot plate on a forgotten stove, coffee machine, etc. may also result in a fire. Malfunctioning fluorescent tubes are also a common source of ignition.

Fire safety designs

As described in the objectives of this paper, three alternative fire safety designs were used to find acceptable criteria for the risk to occupants in a hospital. The first fire safety design solution (FSD1) is a design based on the standard method for hospitals, given by following the general recommendations in the building regulations. FSD1 is the so-called normal protection design. FSD1 consists of smoke detectors placed throughout the ward and an alarm bell to notify occupants of fire. The second fire safety design solution (FSD2) is a design based on active protection by the use of sprinklers, which lowers risk to occupants and property. FSD2 consists of sprinkler, designed to extinguish the fire and smoke detectors placed throughout the ward. The third fire safety design solution (FSD3) employs an alternative approach to lower the risk to occupants. FSD3 uses alternative active protection to minimize the consequences of a fire. The main components in FSD3 are smoke and fire separating doors in the corridors, smoke detectors placed throughout the ward and an alarm system that also notifies staff on adjacent wards so that they can assist in evacuation

Fire scenarios for analysis

Based on data from previous hospital fires, most fires start on the wards. The following fire scenarios were analyzed:

- Arson in a nursing room. A wastebasket, cloths, curtains, etc. could be set on fire
- Ignition in medical equipment in a nursing room
- Ignition caused by malfunctioning fluorescent tubes in a storeroom
- Fire in a coffee machine or the electric stove in the staff room
- Fire in the television set in the day room
- Unauthorized smoking in nursing rooms
- Fire in the cafeteria kitchen
- Arson in stairwells, basement, garbage rooms etc
- Electrical failure, causing a fire in a shaft

Naturally, there are additional scenarios to those listed above. The following scenarios will be analyzed in detail using expert judgement in the next step – the quantitative analysis; the nursing room fire caused by smoking in bed, the staff room fire caused by electrical failure in a coffee machine and the cafeteria fire caused by fire in the deep-frying pan

Quantitative analysis

The event tree consists of a number of events (questions) where two answers are possible, “Yes” or “No”. The questions are put so that the answer “Yes” results in a better outcome, i.e. lessening the consequences. A positive answer thus leads to longer available safe egress time or shorter evacuation time. A large number of sub-scenarios are derived from the event trees.

The following events were included in the event trees:

Initial fire?	Daytime fire?	Non-flaming fire?
Fire suppressed by staff?	Automatic detection?	Door to room closed?
Staff response correct?	All escape routes accessible?	Door closed after fire?
Fire separation sufficient?	Sprinkler successful?	Staff back-up available?
Fire & smoke separation successful?		

The computerized two-zone model CFAST (Peacock et al., 1994) has been used to calculate the time elapsed before critical conditions are reached. (Critical conditions are defined by the building regulations.) The most relevant criterion is that regarding smoke interface height. In the model hospital the critical conditions occur when the interface reaches a height of 1.9 m above the floor. The evacuation phase consists of three steps that are here assumed to be independent. These are detection, reaction and travel. Detection time is calculated by using the computerized model Detact-T2 (Evans et al., 1985). The reaction time is estimated by using reference literature and depends on time of day and fire location. The travel time is calculated by a simple formula where the ratio between patients and members of staff is a key parameter.

RESULTS AND DISCUSSION

The risk due to fire is calculated for each fire safety design solution and is presented in Figure 5 below. The mean risk is 0.27, 0.09 and 0.18 for FSD1, FSD2 and FSD3 respectively.

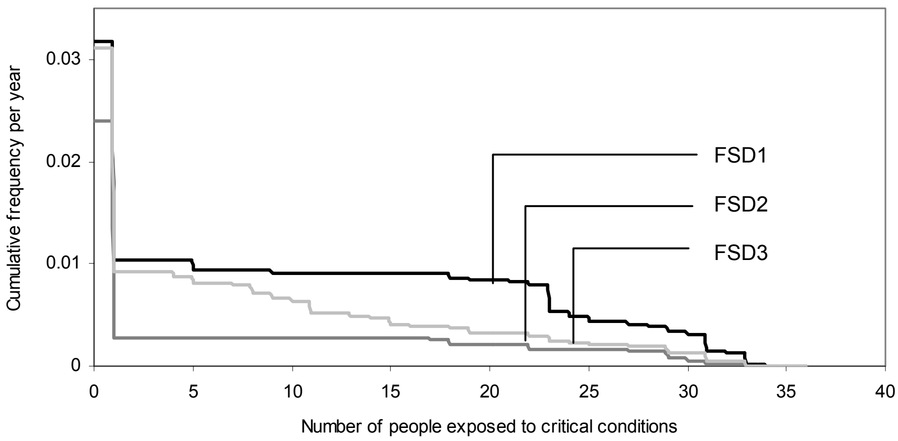

Figure 5 Risk profiles for the three fire safety designs. The upper (black) line represents FSD1, the middle (light gray) line is for FSD3 and the lower (dark gray) line is for FSD2.

Evaluation of the three fire safety design solutions

The risk profile for FSD1 illustrates that there is a relatively high risk for serious consequences, i.e. more than 20 people exposed to critical conditions. The evacuation of patients is highly dependent on the ratio between the number of patients and staff available to assist in evacuation. In order to examine the sensitivity of the ratio parameter, risk profiles were derived for a number of patient to staff ratios. The ratio during normal conditions is 6 during daytime and 12 during the night. The mean risk of being exposed to critical conditions for the normal situation is 0.27. The corresponding values for twice and 3 times the number of staff are 0.18 (-33 %) and 0.11 (-59 %), respectively. There are at least three ways for the hospital management to decrease the patient to staff ratio. First, the number of patients on the ward could be decreased. Second, the number of staff employed could be increased. Third, the number of staff could be increased in the case of an emergency using the back-up alarm system described in FSD3

The installation of sprinklers provides effective protection against untenable smoke and fire spread. The mean risk is lowered by 67 % in FSD2 compared with the standard design. However, even when sprinklers are installed there is a high-consequence low-probability tail which can not be reduced without decreasing the patient to staff ratio. The installation of sprinklers also provides effective protection to property, but is associated with high installation and maintenance costs.

Using smoke-separating doors to limit smoke spread combined with a back-up alarm system lowers the risk by about 33 %. The risk profile has a quite different appearance compared with the others. Between one and ten people exposed to critical conditions the profile corresponds well with the profile for the standard design (FSD1), but for ten or more exposed people the profile agrees with the sprinkler risk profile.

The most cost efficient way to reduce the risk of people being exposed to critical conditions in the case of fire is to install an alarm system which alerts members of staff on adjacent wards so that they can assist in the evacuation process. Installing smoke-separating doors in the ward minimizes smoke spread and therefore lessens the consequences of a fire. This measure is associated with low costs, but the smoke doors available today do not have a sufficient reliability. The installation of sprinklers may be regarded as an option where there is a possibility to fight the fire every minute around the clock. This system protects lives and property, but is associated with high costs. It is clear that the building regulations of today do not provide for sufficient safety for patients in hospitals. The key factor for hospital safety is the patient to staff ratio. If the fire safety engineering method had been used, the fire safety level would have been acceptable. However, in cases of human error and the failure of protection installations the risk is obvious. One recommendation the regulations incorporate codes on how to improve the patient to staff ratio in the case of fire.

Acceptable Fire Risk Criteria

The establishment of acceptable risk criteria is based on the engineering approach outlined in this paper. The aim of established risk criteria is to provide guidance for engineers in designing fire protection in buildings, including hospitals. It was stated that today's regulations do not provide for sufficient safety for patients in hospitals. Therefore, the here proposed risk criteria would be more stringent than the result of the standard design. Risk criteria should be expressed in terms of an upper and lower limit for risk tolerance and the elevation of the curve. However, it is here difficult to derive an upper limit. Therefore the acceptable risk criteria will only by established via a lower line for risk tolerance.

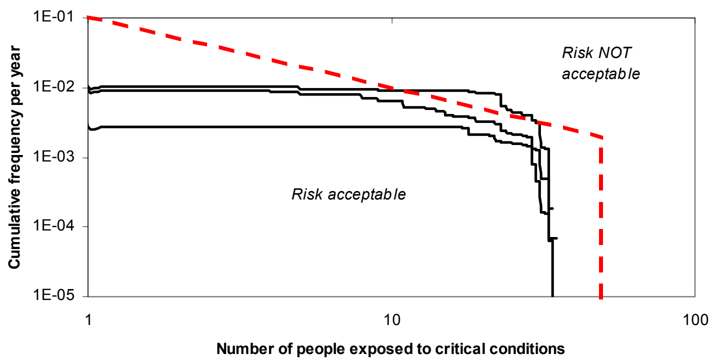

Figure 6 The lower limit of the acceptable fire risk criteria for hospitals. If the patient to staff ratio is increased, the part of the FSD1 risk profile which is above the lower limit for risk tolerance will disappear. Note that critical conditions are not the same as lethal conditions.

Having the three risk profiles for FSD1, 2 and 3 derived here in mind, the following specifications can be drawn up, Figure 6:

- Lower limit for risk tolerance $F = 10^{-1}$ for $N = 1$.
- The elevation of the curve is –1.
- There should be a vertical line for risk tolerance, saying that no more than 50 people should be exposed to critical conditions.

This is a fairly new approach in the field of acceptable risk. The method must, therefore, be evaluated. It would be useful to compare the results of this study with the ones achieved when deriving acceptable risk criteria for other activities. The results will find use in the future for checking safety levels when designing new or remodeling old hospitals, comparing future established risk criteria for other building types, and in giving politicians an idea on the safety level provided by today's regulations.

REFERENCES

BBR, *Boverkets Byggregler*. BFS 1993:57 med ändringar tom BFS 1998:38, Boverket, Karlskrona, 1998. (In Swedish)

Boverket: *Utvärdering av ändringar i byggregleringen: brand*. Rapport 1997:9, Karlskrona, 1997. (In Swedish).

BSI Draft for Development DD240: *Fire safety engineering in buildings. Part 1: Guide to the application of fire engineering principles*. British Standards Institution, London, 1997.

Charters, D., *Quantified Assessment of Hospital Fire Risks*, Proceedings of Interflam ´96, 1996.

Det Norske Veritas: Davidsson, G., Lindgren, M.m Mett, L. *Värdering av risk (Evaluation of Risk).* SRV report P21-182/97, Karlstad, 1997. (In Swedish)

Evans, D.D., Stroup, D.W., *Methods of Calculating the Response Time of Heat and Smoke Detectors Installed below Large Unobstructed Ceilings*. NBSIR 85-3167, National Bureau of Standards, Gaithersburg, 1985.

Jönsson R., Lundin J., *"The Swedish Case Study – different fire safety design methods applied on a high rise building",* Report 3099, Department of Fire Safety Engineering, Lund university, Lund, 1998.

Olsson F., *"Tolerable Fire Risk Criteria for Hospitals"*, Report 3101, Department of Fire Safety Engineering, Lund university, Lund, 1999.

Peacock, R.D., Jones, W.W., Forney, G,G., Portier, R.W., Reneke, P.A., Bukowski, R.W., Klotke, J.H., *An Update Guide for HAZARD I, Version 1.2*. NISTIR 5410, National Institute of Standards and Technology, Gaithersburg, 1994.