

Risk-Based Selection of Design Fires to Ensure an Acceptable Level of Evacuation Safety

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ABSTRACT

In a performance-based (P-B) fire safety design, the level of fire safety of a building achieved by the design depends upon the design fire scenarios and acceptable safety criteria used. In other words, their essential role is to keep the fire risk of a building below an acceptable level. However, the relationship of the design fire with the acceptable fire risk is not clearly recognized, which often causes fire performance gaps between a P-B fire safety design and the existing building fire code. It is thought to be vital for a P-B fire safety design method to incorporate fire risk concepts for its sound development. In this paper, consideration for determining acceptable fire risk in the context of fire safety design is made and a methodology for selecting such a design fire as to ensure the risk of evacuation in fire be under the acceptable level is proposed.

KEYWORDS: fire risk, acceptable risk, design fire, fire growth factor, performance-based fire safety design, evacuation safety

NOMENCLATURE LISTING

A	floor area (m^2)	Greek	
C	number of occupants (person)	α	fire growth factor (kW/s^2)
\bar{C}	number of occupants unable to evacuate (person)	$\bar{\alpha}$	mean of α
C_0	total number of occupants (person)	$\phi(\alpha)$	probability density function of α
F	occupants' factor ($m^2/person$)	λ	$= 1/\bar{\alpha}$
P	probability of scenario	subscripts	
p	probability	a	acceptable
p''	fire incidence rate per unit area	c	critical
\dot{Q}_f	heat release rate of fire source (kW)	H	dwelling house
q	occupants' density ($person/m^2$)	hf	hazardous fire
R	evacuation risk	cas	casualty
R_a	acceptable evacuation risk	sm	smoke control
t	time (s)	sp	sprinkler

INTRODUCTION

In Japan, the verification methods for evacuation safety and fire resistance performance were introduced in conjunction with the amendment of the Building Standards Law in 2000, which is considered to be a performance-based fire code [1]. The verification methods have defined design fires and safety criteria, based on which a building design is examined to determine if it is at an acceptable safety level.

However, the verification methods are deficient in the fire risk concept, which has caused some questionable fire safety design practices. For example, evacuation safety verifications for a room involving only a small number of occupants and for a total building involving a large number of occupants are made using the same design fire. As a result, fire safety engineers in Japan are spending far more time doing evacuation safety verifications of small rooms than for those of the fire floor or the whole building. The importance of a corridor and a staircase as the evacuation route commonly used by occupants on the fire floor and in the whole building, respectively, would be understood if we imagine such a simple example as a building with 10 identical floors each of which has 10 identical rooms. In this example, the probability of fire occurrence and the number of occupants potentially involved in a fire for a floor are both 10 times of those for a room so it follows that the risk in the floor evacuation can potentially be 100 times larger than the room evacuation. Likewise the risk in the whole building evacuation can be roughly 100 times larger than the floor evacuation, and 10000 times larger than the room evacuation.

It is considered that the considerations on fire risk are prudently incorporated in the existing prescriptive codes for building fire safety albeit implicitly and empirically. Thus the provisions imposed to escape staircases and corridors are usually rigorous unlike the requirements to ordinary rooms. For another instance, the fire safety provisions normally become stricter with the increase of size, height or occupant load of a building. It is quite natural that the greater the potential consequence of a fire event the smaller the probability of the event must be made. In a P-B fire safety design method, the probability of the event is controlled through the selection of design fire scenarios.

It is vital for the sound implementation of a P-B fire safety design method to introduce fire risk concepts into it. In this paper, a methodology to select the design fires to ensure an acceptable level of evacuation safety in fire is proposed. The methodology aims to assist building designers and fire safety engineers to rationally design evacuation safety measures.

STRUCTURE OF EVACUATION SAFETY DESIGN

In this paper, only the risk concerning evacuation in fire is addressed and the risk is discussed only in conjunction with an evacuation safety design. The fire risk assessment, in its rigorous meaning, is extremely difficult partly because the associated event probabilities are not known and partly because calculations are required for a large number of scenarios. Unlike designs of mass production goods, design of a building is tailored to that building so one cannot afford time consuming calculations. On the other hand, the assessment of the evacuation risk in the context of fire safety design does not have to be rigorously accurate but good enough to yield safe building.

Procedure of Evacuation Safety Verification

Figure 1 shows the usual procedure of fire safety verification [2]. The discussion here assumes that evacuation safety verifications would follow this procedure, i.e. the safety verification of an evacuation safety design of a building space is carried out deterministically by checking if the behaviour of the fire and occupants predicted under some prescribed design fire conditions meet the prescribed safety criteria. It will be readily understood that the more rigorous the design fire conditions and the safety criteria the higher the level of evacuation safety will be. But a higher level of safety can seldom be attained without claiming more cost for safety measures, so a certain compromise need be reached between the safety level and cost. The essential role of the design fires and safety criteria in a P-B fire safety design is to ensure that the risk

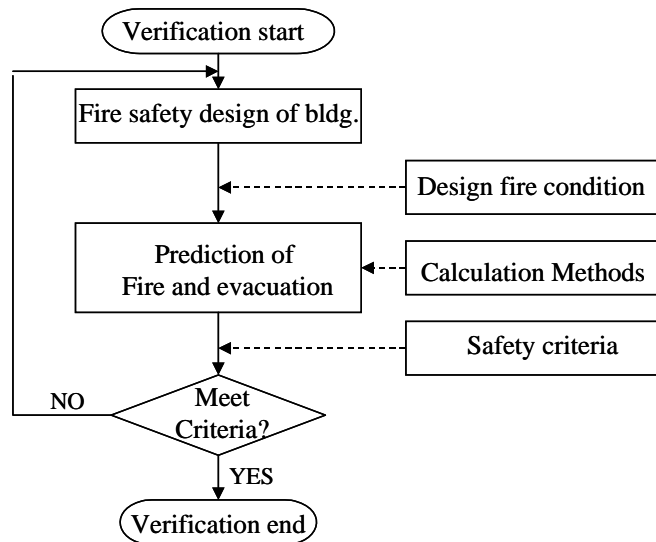


Fig. 1. Procedure of fire safety verification .

is below a socially acceptable level.

Design Fire for Evacuation Safety Assessment

In the current P-B fire safety design practices, the design fire shown in Fig. 2 in terms of heat release rate(HRR) is widely employed. The same design fire is assumed in this paper too. The HRR of the design fire increases proportionally to time-square at the initial stage and levels off after having reached a maximum value controlled by the conditions of ventilation of the fire room, fuel items or a sprinkler system. Incidentally, it is assumed here that the maximum HRR for the sprinkler controlled fire can be determined based on the minimum HRR to actuate a sprinkler head [3]. The value of the fire growth factor α , which determine how fast the HRR increases at the initial stage, depends on the properties of the ignition source, so it is probabilistic in general. The duration of the maximum HRR depends on the amount of the fuel, so probabilistic too.

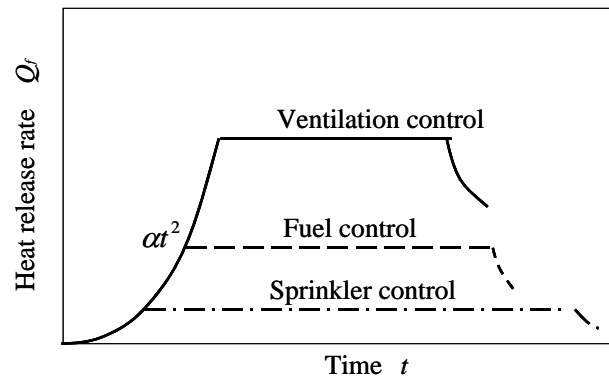


Fig. 2. HRR with time of the design fire.

Design Elements Affecting the Evacuation Safety Assessment

The interest of building designers or engineers in P-B fire safety designs is how cost effectively, as well as safely, they can design the fire safety systems of a building. Regarding evacuation safety, such designs include:

- exits and escape routes
- smoke control system
- fire walls and doors, and
- sprinkler system

Obviously, whether or not the prescribed safety criteria can be satisfied depends on how the capacities, arrangements, performances etc. of these elements are determined. The first priority for designers and engineers is to design them rationally with affordable cost. In addition, a certain degree of redundancy of the safety system need to be taken into account since none of these elements is 100% reliable.

FIRE SCENARIOS AND ACCEPTABLE EVACUATION RISK

A P-B fire safety design is not scientific research but engineering practice. A verification of evacuation safety should be efficiently done by a limited number of deterministic calculations without the need of time consuming calculations. Taking the example of fire room evacuation for simplicity, a methodology to determine the design fires that can assure the evacuation risk to be below a prescribed acceptable level is developed. In this method, only one calculation is required for verification of each of the scenarios identified from a scenario event tree.

Scenario Events of Fire Room Evacuation and Evacuation Risk

An event tree is a useful tool to identify the scenarios involved in fire. Figure 3 shows the scenario event tree for a fire room evacuation. Note, however, that the event tree is developed in the context of P-B fire safety design, in which self-extinguish fires, smoldering fires and other insignificant fires are normally neglected and only potential growing fires become issue. The growing fires consist of (a) the fire that grows to be a fully developed room fire and (b) the fire that grows to be a developed localized fire if not controlled by sprinklers. For simplicity, only the scenario event tree for the former is shown in Fig.3 [5].

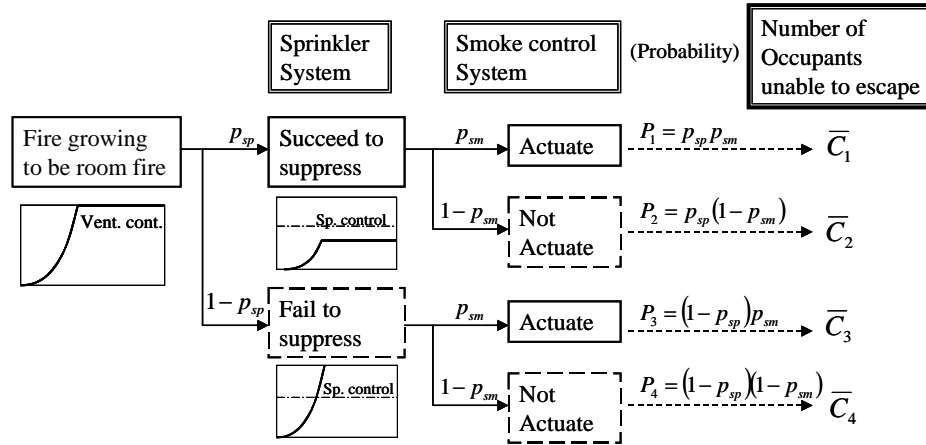


Fig. 3. Scenario event tree for a fire room evacuation.

The fire safety systems involved in the fire room evacuation are usually exits, sprinkler system and smoke venting system. Of these, exits necessarily exist but the others are up to necessity, so the scenarios yield corresponding to the success and fail of sprinkler and smoke control systems. Here, success of sprinkler is defined that the HRR of the fire is reduced to under the maximum HRR of the sprinkler control fire in Fig. 2. The success of smoke control is simply defined to be the mechanical activation of the system regardless of the capability of smoke management, which is the matter of design of fan and ducts.

Letting P_i and \bar{C}_i be the probability of scenario event i to occur and the number of evacuees who fail to evacuate safely in the event, respectively, the evacuation risk R in the fire room evacuation is defined as

$$R = \sum P_i \bar{C}_i \quad (1)$$

Incidentally, in the context of P-B fire safety design,

$$\sum P_i = 1 \quad (2)$$

since only growing fires are considered as mentioned above.

Acceptable Evacuation Risk in the Context of Evacuation Safety Design

Since 100% safety does not exist, a certain risk needs to be accepted in a P-B fire safety design, i.e., letting R_a be the acceptable value of evacuation risk,

$$R = \sum P_i \bar{C}_i \leq R_a \quad (3)$$

Note again that R_a is the acceptable evacuation in the context of P-B fire safety design. In P-B evacuation safety design or verification,

- only hazardous fires are considered

- evacuation failure includes not only fatalities but also injuries, because safety criteria are prescribed in terms of clear height or slight exposure to smoke [1, 2]
- a space is fully loaded by occupants

Therefore the value of R_a has to be consistent with such characteristics of the verification method.

Acceptable Evacuation Risk based on House Fire Statistics

There must be a lot of dispute on how to determine the value of R_a . Here, it is sought from statistics of dwelling house fires because:

- annual number of dwelling house fires is large and stable,
- dwelling houses are relatively uniform in size,
- virtually no evacuation provision applies to dwelling houses,
- fire statistics for other occupancies is informative but usually very limited [4].

According to the statistics of dwelling house fires in Japan:

- annual fatality is about 1,300 and injury is 5 times of this [6], so the total number of casualties, fatality + injury, is $1,300 \times 6 = 7,800$.
- annual number of fires is about 19,000, of which one half is insignificant fires [7], so the number of hazardous fire is about 9,500, hence
- casualty per hazardous fire is $7,800/9,500 = 0.8$ (injury by insignificant fires neglected)

These numbers have been stable for a long time and have raised no particular concern so can be regarded acceptable by the society of Japan.

Furthermore:

- the average number of family members in a dwelling unit in Japan is about 2.4 person [9],
- if one half of the family members on average, i.e. 1.2 persons, happen to be in the house at the time of fire, the casualty rate from hazardous fires per occupant, $p_{cas,H}$ is $p_{cas,H} = 0.8/1.2 = 2/3$,
- the average size of dwelling houses in Japan is about 100m^2 [8], for which the occupant load, $C_{0,H}$, is assumed roughly to be $C_{0,H} = 5-6$ in a P-B evacuation safety verification [1],

Therefore, the above accepted number is translated into the acceptable evacuation risk on the P-B fire safety design base, R_a , which is approximately as follows:

$$R_a = p_{cas,H} \times C_{0,H} \approx \frac{2}{3} \times 6 = 4 \text{ casualties/hazardous fire} \quad (4)$$

There must be significant room of dispute in many parts of the method proposed in this paper. One may argue that acceptable fire risk of buildings differ one use to another but the difference may be attributed to the code requirements prescribed without rational considerations on acceptable fire risk.

Acceptable Evacuation Risk for Arbitrary Use and Area

Needless to say, P-B fire safety designs have to deal with buildings of various uses and sizes. The fire incidence rates and casualty rates of buildings differ from one another depending on the use and size. For the evacuation risk of an arbitrary building space, K, to be below that of dwelling house, H, assumed as the societal acceptance, the following relationship should be satisfied:

$$\left(p''_{hf,K} A_k \right) \left(p_{cas,K} C_{0,k} \right) \leq \left(p''_{hf,H} A_H \right) \left(p_{cas,H} C_{0,H} \right) = \left(p''_{hf,H} \times 100 \right) \cdot (4) \quad (5)$$

where p''_{hf} and A are the incidence rate of hazardous fire per unit area and the area of the space, respectively. Incidentally, K and k, the subscripts of the arbitrary space, denote that the parameter value of

the space is determined by the use and by the area, respectively. Then it follows from Eq.(5) that the evacuation risk on the design base, $R_{D,k}(=p_{cas,K}C_{0,k})$, in other words, the conditional risk on the premise that a hazardous fire has occurred, must satisfy

$$R_{D,k}(\equiv p_{cas,K}C_{0,k}) \leq \left(\frac{P''_{hf,H}}{P''_{hf,K}} \right) \left(\frac{A_H}{A_k} \right) (p_{cas,H}C_{0,H}) = 4 \times \left(\frac{100}{A_k} \right) \left(\frac{P''_{hf,H}}{P''_{hf,K}} \right) \quad (6)$$

The maximum value of is of course the acceptable evacuation risk of the space, $R_{a,k}$, i.e.

$$R_{a,k} = 4 \times \left(\frac{100}{A_k} \right) \left(\frac{P''_{hf,H}}{P''_{hf,K}} \right) \quad (7)$$

Therefore, the acceptable evacuation risk of an arbitrary space, k, can be calculated if the incidence rate of hazardous fires in the space use per unit area relative to dwelling house is known from fire statistics. Although sufficient fire statistics is not readily available, construction of such data is attempted in **Appendix** and a sample acceptable risk is calculated for an office space in **Example 1** in **SUPPLEMENTAL NOTES**.

SELECTION OF DESIGN FIRES FOR FIRE ROOM EVACUATION

Now that the acceptable evacuation risk of an arbitrary space, $R_{a,k}$ (R_a for simplicity), can be determined, the next issue is how to select the design fires. The design fires should be such that R_a is automatically satisfied once the evacuation safety has been verified by the deterministic calculations under the design fires. It will be wise to begin this consideration with fire room evacuation, as the most simple evacuation issue.

Probability Density Function of Fire Growth Factor

The fire growth in the early stage of a design fire is expressed in terms of HRR, \dot{Q}_f , as

$$\dot{Q}_f = \alpha t^2 \quad (8)$$

where α is the fire growth factor and t is the time from ignition [10].

Since fire room evacuations occur at a relatively early stage, a safe or unsafe outcome is almost determined by the value of α . For very small α , no room is dangerous but for extremely large α , no room is safe. The question is, what value of α is appropriate to judge if a specific space is safe or not with regard to evacuation.

The value of α in an actual fire situation is considered to vary depending on the property, size etc. of the ignited combustible so it has a probabilistic nature in general. It is not well known what type of probability density function of α , $\phi(\alpha)$, is appropriate. It may be log-normal type distribution but here an exponential distribution [11] is tentatively adopted for convenience of calculation as

$$\phi(\alpha) = \lambda e^{-\lambda\alpha} \quad (9)$$

where the parameter λ is given using $\bar{\alpha}$, the mean value of α as

$$\lambda = 1/\bar{\alpha} \quad (10)$$

The value of $\bar{\alpha}$ is considered to depend on the conditions of live combustible reflecting use of a space so it is an important parameter to characterize building spaces with regards to fire hazards.

Fire Growth Factor of the Design Fire for Single Scenario Event

Figure 4 illustrates the conceptual relationship between α and $C(\alpha)$, the number of occupants who fail to evacuate safely under the fire that grows as $\dot{Q}_f = \alpha t^2$. Safe evacuation is easy for small α but becomes increasingly difficult as α gets large. Where α is very small $C(\alpha)$ will be zero, but at a certain point, $\alpha = \alpha_c$, it will start to increase and, as further increases, eventually reach C_0 , the number of the whole occupants.

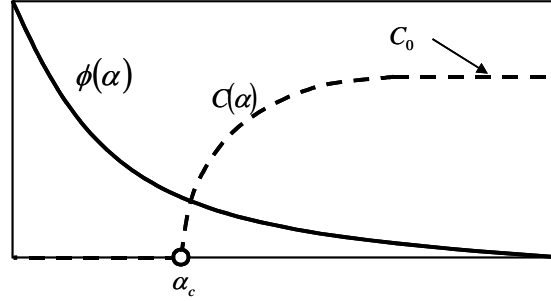


Fig. 4. Number of occupants unable to escape safely $C(\alpha)$ vs. fire growth factor α .

Let's consider the simplest single scenario case: the case where a fire grows to be a developed room fire in a space with neither sprinkler and nor smoke control. In this case, the probability of this scenario to occur, P , is unity, i.e. $P=1$, and the evacuation risk is calculated as

$$R = P\bar{C} = 1 \cdot \int_0^{\infty} \phi(\alpha)C(\alpha)d\alpha \quad (11)$$

Noting that $C(\alpha)=0$ for $\alpha < \alpha_c$, the right hand side of Eq.(11) can be written as

$$\begin{aligned} \int_0^{\infty} \phi(\alpha)C(\alpha)d\alpha &= \int_0^{\alpha_c} \phi(\alpha)C(\alpha)d\alpha + \int_{\alpha_c}^{\infty} \phi(\alpha)C(\alpha)d\alpha \\ &= \int_{\alpha_c}^{\infty} \phi(\alpha)C(\alpha)d\alpha \end{aligned} \quad (12)$$

The concrete shape of function $C(\alpha)$ for $\alpha > \alpha_c$ cannot be known since it depends on many factors such as room dimension, exit conditions etc. However, since

$$\int_{\alpha_c}^{\infty} \phi(\alpha)C(\alpha)d\alpha < C_0 \int_{\alpha_c}^{\infty} \phi(\alpha)d\alpha = C_0 \int_{\alpha_c}^{\infty} \lambda e^{-\lambda\alpha} d\alpha = C_0 e^{-\alpha_c/\bar{\alpha}} \quad (13)$$

the evacuation risk R is

$$R < C_0 e^{-\alpha_c/\bar{\alpha}} \quad (14)$$

Therefore, R is conservatively $R < R_a$ if the following relationship is satisfied.

$$C_0 e^{-\alpha_c/\bar{\alpha}} \leq R_a \quad (15)$$

Eq.(15) can be solved for α_c as

$$\alpha_c > \bar{\alpha} \ln \frac{C_0}{R_a} \quad (16)$$

The important implication of Eqs.(14)-(16) is that the evacuation risk, R , is conservatively proved to be below the acceptable risk, R_a , if it is verified by a proper deterministic calculation that all the occupants in the room can evacuate safely under the design fire prescribed as follows:

$$Q_f = \alpha_c t^2 \quad \text{where } \alpha_c = \bar{\alpha} \ln \frac{C_0}{R_a} \quad (17)$$

A sample calculation of α_c is shown in **Example 2** in **SUPPLEMENTAL NOTES**.

Fire Growth Factors of the Design Fires for Multiple Scenario Events

The number of scenario events for fire room evacuation increases if a sprinkler system and/or a smoke venting system is installed. If the both systems exist, 4 scenarios have to be considered corresponding to success and failure of those systems, as already illustrated in Fig. 3. The goal of the fire safety design of such a space is

$$R = P_1 \bar{C}_1 + P_2 \bar{C}_2 + P_3 \bar{C}_3 + P_4 \bar{C}_4 \leq R_a \quad (18)$$

In Eq.(18), letting p_{sp} and p_{sm} be the probabilities of successful operation of the sprinkler and smoke venting systems, respectively, the probabilities of the scenario events, P_i ($i=1, 2, 3, 4$), in Eq.(18) are given as

$$P_1 = p_{sp} p_{sm}, \quad P_2 = p_{sp} (1 - p_{sm}), \quad P_3 = (1 - p_{sp}) p_{sm}, \quad P_4 = (1 - p_{sp}) (1 - p_{sm}) \quad (19)$$

Also note that the number of the occupants who unable to evacuate safely differ from one scenario to another depending upon the conditions in the scenarios so \bar{C}_i for an arbitrary scenario is generally expressed as

$$\bar{C}_i = \int_0^{\infty} \phi(\alpha) C_i(\alpha) d\alpha \quad (20)$$

Since $C_i(\alpha)$ is up to the design of the exit and the fire safety measures for the room, there is flexibility to arbitrary set the partial acceptable evacuation risk for each scenario event, $R_{a,i}$, i.e., it is possible to let

$$P_1 \bar{C}_1 \leq R_{a,1}, \quad P_2 \bar{C}_2 \leq R_{a,2}, \quad P_3 \bar{C}_3 \leq R_{a,3}, \quad P_4 \bar{C}_4 \leq R_{a,4} \quad (21)$$

provided that the

$$R_{a,1} + R_{a,2} + R_{a,3} + R_{a,4} \leq R_a \quad (22)$$

The design fires corresponding to Eq.(21) in terms of the fire growth factors like Eq.(17) can be obtained as follows:

$$\alpha_{C,1} = \bar{\alpha} \ln \frac{P_1 C_0}{R_{a,1}}, \quad \alpha_{C,2} = \bar{\alpha} \ln \frac{P_2 C_0}{R_{a,2}}, \quad \alpha_{C,3} = \bar{\alpha} \ln \frac{P_3 C_0}{R_{a,3}}, \quad \alpha_{C,4} = \bar{\alpha} \ln \frac{P_4 C_0}{R_{a,4}} \quad (23)$$

Needless to say, the evacuation risk R is conservatively verified to be $R < R_a$ if the number of the occupants who fail to evacuate safely in each scenario is made zero under the corresponding design fire. Sample calculations of $\alpha_{c,i}$ are shown in **Example 3** and **Example 4** in **SUPPLEMENTAL NOTES**.

Even if more scenarios have to be considered, the same procedure can be followed, i.e., (a) choose arbitrarily the partial acceptable risk for each scenario as

$$P_i \bar{C}_i \leq R_{a,i} \quad \text{provided that } \sum R_{a,i} \leq R_a \quad (24)$$

and (b) verify that, in each scenario, no occupant fails to evacuate under the corresponding design fire given by

$$\alpha_{C,i} = \bar{\alpha} \ln \frac{P_i C_0}{R_{a,i}} \quad (25)$$

Note, however, that the efficient choice of the values of the partial acceptable risk belongs to the expertise of designers and fire safety engineers. Any fire safety system, such as sprinkler, smoke venting, exit etc. has its own advantage and weakness in managing evacuation risk. Without the sufficient knowledge of them, it will be difficult to take advantage of the freedom in determining the partial acceptable risk.

It may be worth to stress again that just once verification using deterministic means is only necessary for each scenario since the design fire is selected taking the probabilistic aspect of fire into account.

SCREENING FOR EVACUATION SAFETY DESIGN TARGETS

Not all the building spaces but only particularly important ones are objects of usual P-B evacuation safety designs/verifications. Virtually no requirement on evacuation safety applies to small building spaces such as dwelling houses. This is thought to be because the evacuation risk, i.e. (probability of a fire to occur) x (number of occupants involved in the fire), is acceptably small considering the rarity of fire in a specific space. Screening out such low risk spaces has practical importance to save time and labor for evacuation safety verifications.

Recall that the risk of an arbitrary space has to satisfy Eq.(5). Using $A_H=100 \text{ m}^2$ and $C_{0,H}=6$ as the design base area and occupants load of dwelling houses as the reference in Eq.(5), we have

$$C_{0,k} \leq 6 \times \left(\frac{100}{A_k} \right) \left(\frac{p''_{hf,H}}{p''_{hf,K}} \right) \left(\frac{p_{cas,H}}{p_{cas,K}} \right) \quad (26)$$

that is, any space k, in which the number of occupants, $C_{0,k}$, satisfy Eq.(26) need not be subject to the safety verification.

The number of occupants may be calculated based on prescribed occupant density [1], q [person/m²] or occupant load factor [12], $F (=1/p)$ [m²/person], so that $C_{0,k} = qA_k = A_k/F$, in which case the condition of Eq.(26) can be rearranged in terms of space area as

$$A_k \leq 24.5 \sqrt{\frac{1}{q} \left(\frac{p''_{hf,H}}{p''_{hf,K}} \right) \left(\frac{p_{cas,H}}{p_{cas,K}} \right)} \quad \text{or} \quad A_k \leq 24.5 \sqrt{F \left(\frac{p''_{hf,H}}{p''_{hf,K}} \right) \left(\frac{p_{cas,H}}{p_{cas,K}} \right)} \quad (27)$$

Therefore, the maximum number of occupants or space area for which evacuation safety verification is waived can be obtained if the ratios of fire incidence rates per unit area, $p''_{hf,H} / p''_{hf,K}$, and casualty probabilities, $p_{cas,H}/p_{cas,K}$, relative to those of dwelling houses are known. Sample calculations are shown in **Example 5** in **SUPPLEMENTAL NOTES**.

CONCLUDING REMARKS

In this paper, a methodology to select design fires in P-B evacuation safety design methods, or verification methods, is proposed. The ultimate goal of the study is to rationalize the determination of the design fires in P-B fire safety design practices, which seems to lack sufficient consideration on fire risk. Only the evacuation from the room of origin is discussed in this paper as the first step toward a risk-based fire safety design. The results up to now are:

- The acceptable risk in the context of P-B evacuation safety design is defined and established based on the fire statistics of dwelling houses in Japan. The fire statistics in Japan classifies the fires into 'whole building burn', 'partial building burn' and 'insignificant burn'. The last is defined as a small fire, self-extinguished or put out at very early stage, with only trivial property damages based on the criteria set by the Fire Defense Agency. Although such small fires take a large portion in the total fires, fire safety designs normally disregard them since no particular safety measures can be drawn from such fires.
- The methodology is for the selection of the design fires to be set for examining the adequacy of the designs of fire safety measures such as exit, sprinkler, smoke venting system etc.

- The methodology employs an event tree to identify the scenario events to take place due to the success and fail of sprinkler and smoke venting system, although the probabilities of the system operations have to be given in advance.
- The methodology allows to verify the safety of evacuation by only one deterministic procedure for each scenario.
- The evacuation risk can be verified to be conservatively below the acceptable risk once it is proved that nobody fails to escape safely under the determined design fire by the method. This can be accomplished by proper designs of exits, arrangement of sprinkler, smoke venting rate etc.,

As said in the above, this study is still at the beginning stage. Further considerations are needed particularly as to the issues such as follows:

- The current probability density function is only tentative so it is necessary to see if there is any better one.
- The fire statistics used in this paper is never complete. Further investigations into the available fire data to support the system may be necessary.
- The methodology has to be extended further to fire floor and total building evacuations.

SUPPLEMENTAL NOTES

Appendix: Fire data

Table S-1 shows the data of fires for several typical occupancies, which are averaged between the years 2001 - 2003 [6]. The average areas of the occupancies are calculated from the statistics of the buildings constructed in 1996 [8] assuming that such data do not vary much by year. The number of existing facilities of respective occupancy, except dwelling house, is from Fire Service White Book 2004, in which facilities smaller than 150m² are disregarded [7]. So a certain degree of error may be present in the number of some small type occupancies. Both independent houses and dwelling units in apartment buildings are included in the number of dwelling houses.

Table S-1. Fire statistics for several typical occupancies

Type of occupancy	Number of facilities	Average area (m ²)	Number of fires/ year	Number of fires /facility (x10 ⁻³)	Number of deaths/year	Deaths/fire (x10 ⁻²)
Dwelling house	45,258,400(a)	93	19,093	0.42	1280	6.70
Restaurant, Bar	87,328	243	667	7.63	3.67	0.55
Shop, Market	142,356	616	500	3.51	4.00	0.80
Hospital, Clinic	61,586	1005	154	2.50	0.33	0.22
Hotel, Inn	75,458	942	180	2.39	3.67	2.03
Amusement	18,058	936	145	8.05	0.33	0.23
School	131,448	1131	393	2.99	1.33	0.34
Ware house	323,701	324	753	2.33	4.00	0.53
Office building	405,729	426	844	2.08	9.33	1.11
Mixed use	581,310	-	3,778	6.49	96.3	2.55

a: Number of household units

Table S-2 shows the ratio of the fire incidence rate per unit area and the casualty rate of respective occupancy relative to those of dwelling houses calculated based on the data in Table 1. However, exactly pertinent data were not always available so some of them had to be substituted by similar ones: The numbers of fires include not only hazardous fires but also insignificant fires and casualty data were not

available so fatality data were used instead. But this will not cause much errors in the ratios of the hazardous fire incidence per area, $p''_{hf,H} / p''_{hf,K}$, and the casualty per fire, $p_{cas,H}/p_{cas,K}$, in Table S-2 since the numbers of the insignificant fires and the casualty are considered to be approximately proportional to those of the hazardous fires and the fatality, respectively.

Table S-2. Ratios of fire incidence per unit area and casualties relative to dwelling house

Type of occupancy	Average area (m ²)	Number of fires/facility (x10 ⁻³) (a)	Number of fires/100m ² (x10 ⁻³) (a)	$\frac{p''_{hf,H}}{p''_{hf,K}}$ (b)	Deaths /fire (x10 ⁻²) (b)	$\frac{p_{cas,H}}{p_{cas,K}}$ (b)
Dwelling house	93	0.42	0.45	1.00	6.70	1.0
Restaurant, Bar	243	7.63	3.14	0.14	0.55	12.2
Shop, Market	616	3.51	0.57	0.79	0.80	8.4
Hospital, Clinic	1,005	2.50	0.25	1.80	0.22	30.5
Hotel, Inn	942	2.39	0.25	1.80	2.03	3.35
Amusement	936	8.05	0.86	0.52	0.23	29.1
School	1131	2.99	0.26	1.73	0.34	19.7
Ware house	324	2.33	0.72	0.63	0.53	12.6
Office building	426	2.08	0.49	0.92	1.11	6.04
Mixed use	(1,000)(c)	6.49	(0.65)(c)	(1.44) (c)	2.55	2.63

(a: Minor fires are included, b: Casualty data not available, c: Area data not available)

Example 1: Acceptable evacuation risk for an office room with area of 400m²

From Table 2, the ratio of hazardous fire incidence per area of office space is found to be $p''_{hf,H} / p''_{hf,K} = 0.92$, hence the acceptable evacuation risk for the space is calculated by Eq.(7) as

$$R_{a,k} = 4 \times (100 / A_k) \left(p''_{hf,H} / p''_{hf,K} \right) = 4 \times (100 / 400) \times 0.92 = 0.92 \text{ person/(hazardous fire)}$$

Example 2: Design fire for an office room with 50 occupants

Let's consider that the same office room as in **Example 1** accommodates 50 occupants on the design base and assume that the mean fire growth factor, $\bar{\alpha}$, which characterize the live combustibles for office use space, be $\bar{\alpha} = 0.025$. Then the fire growth factor to be set to assure the evacuation risk be below the acceptable level, i.e. $R_a=0.92$ in this particular case, is calculated by Eq.(17) as

$$\alpha_c = \bar{\alpha} \ln \frac{C_0}{R_a} = 0.025 \times \ln \frac{50}{0.92} = 0.10 \text{ kW/s}^2$$

Since neither a sprinkler nor a smoke control system is available in this single scenario case, it is necessary to make nobody fails to escape safely under this design fire by the exit design alone.

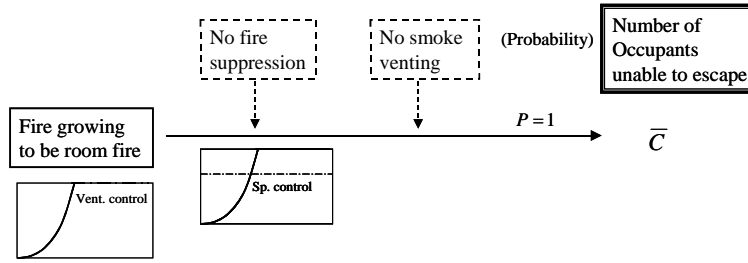


Fig. S-1. Event tree for single fire scenario in a room having neither sprinkler nor smoke venting.

Example 3: Design fires for an office room equipped with smoke venting system

Let's consider that the same office room as in **Example 2** is equipped with a smoke venting system. In this case, two scenarios are considered depending on the success and failure of the system as shown in Fig. S-2. The success of smoke venting system means that it simply operates, indifferent of how much smoke in the fire is exhausted. If the success probability of the smoke venting system, p_{sm} , is tentatively assumed to be 0.9 the scenario event probabilities are $P_1=0.9$ and $P_2=0.1$, respectively. The partial acceptable risks corresponding to the two scenarios, $R_{a,1}$ and $R_{a,2}$, can be set arbitrarily provided that $R_{a,1}+R_{a,2} < R_{a,2}$, so if 0.5 and 0.4 ($0.5+0.4 < 0.92$) happen to be selected, the design fires corresponding to the scenarios are calculated as

$$\alpha_{c,1} = 0.025 \times \ln \frac{0.9 \times 50}{0.5} = 0.112 \quad \text{and} \quad \alpha_{c,2} = 0.025 \times \ln \frac{0.1 \times 50}{0.4} = 0.063.$$

That is, if the smoke venting system is designed to cope with a severer fire condition, the verification for the scenario for the system failure can be made under a less severe fire condition.

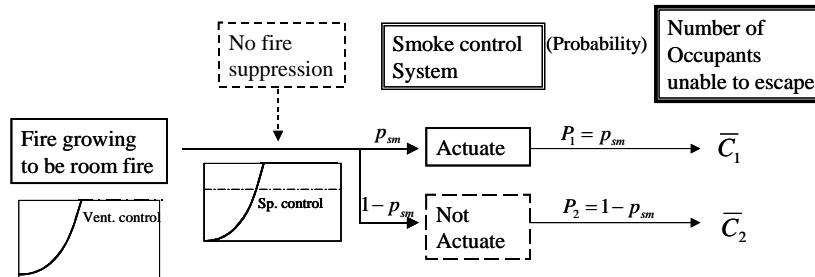


Fig. S-2 Event tree for a room equipped with smoke venting system

Example 4: Design fires for an office room equipped with sprinkler and smoke venting systems

Let's consider that the same office room as in **Example 3** is equipped with a sprinkler system as well as a smoke venting system. In this case, 4 scenarios are considered as shown in Fig.3. The success of a sprinkler system means that the HRR of the fire is controlled under the level at which the fire does not trigger the sprinkler system. If the success probability of the sprinkler and smoke venting systems, p_{sp} , is tentatively assumed to be 0.8 in addition to $p_{sm} = 0.9$ in **Example 3**, the scenario event probabilities are calculated by Eq.(19) as

$$P_1 = 0.8 \times 0.9 = 0.72, \quad P_2 = 0.8 \times 0.1 = 0.08, \quad P_3 = 0.2 \times 0.9 = 0.18, \quad P_4 = 0.2 \times 0.1 = 0.02$$

If we use a bit of expertise of fire safety engineers, it will be easy to notice that safe evacuation is easily attained when the sprinkler system works successfully since the maximum HRR is controlled at a low level. Then we may be able to find advantageous setting of partial acceptable risks, such as

$$R_{a,1} = 0, \quad R_{a,2} = 0, \quad R_{a,3} = 0.5, \quad R_{a,4} = 0.4,$$

Note that $R_{a,1}=R_{a,2}=0$ means that fire growth rate is infinity, in other words, the design fires for the scenarios of the sprinkler success are constant at the maximum HRR under sprinkler controlled condition. The design fires for the scenarios of sprinkler failure are calculated as

$$\alpha_{c,3} = 0.025 \times \ln \frac{0.18 \times 50}{0.5} = 0.072 \quad \text{and} \quad \alpha_{c,4} = 0.025 \times \ln \frac{0.02 \times 50}{0.4} = 0.023,$$

corresponding to the success and failure of the smoke venting system, respectively. The lower values of these fire growth factors imply the advantageous effect of sprinkler system.

Example 5: Maximum area for which evacuation safety verification is waived

For offices, whose occupant factor, F , is about $F=8$ m²/person, referring to Table S-2, the floor area for which evacuation safety verification is waived is calculated as

$$A_k \leq 24.5 \sqrt{F \left(\frac{P''_{hf,H}}{P''_{hf,K}} \right) \left(\frac{P_{cas,H}}{P_{cas,K}} \right)} = 24.5 \sqrt{8 \times 0.92 \times 6.04} = 165 \text{ m}^2$$

And for shops or markets, letting occupant factor be $F=2$ m²/person,

$$A_k \leq 24.5 \sqrt{2 \times 0.79 \times 8.4} = 89 \text{ m}^2$$

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