A PERFORMANCE BASED DESIGN METHOD FOR FIRE SAFETY OF BUILDINGS

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1. INTRODUCTION

Traditionally, fire safety measures of buildings have been determined based on the prescriptive specifications in building and fire codes. One of the most important reasons of this may be that the progress in fire research has been too slow to keep abreast with the rapid evolution of building technologies, which have continued to produce unconventional buildings and new type of dangers due to fire as a by-product. Every time a serious fire disaster occurred, new provisions were added in these codes mostly based on the empirical judgments of "so-called experts", but old provisions were rarely eliminated even after they have already become out-of-dated. The results were the multiplication and the illegibility of the rules, the increase in the cost for fire protection, the inflexibility in designing of building etc. It has long been noticed by many fire interests that it will be much more difficult than ever to cope with the increase of scale, complexity and diversification of modern buildings by the conventional method, that is, the addition of prescriptive specifications.

Considering such circumstances and the considerable progress achieved recently in the area of fire science and engineering, the research project called "Development of Fire Safety Design Method of Buildings" was launched in Fy 1982 and carried out through Fy 1986 by Building Research Institute (BRI), Ministry of Construction (MOC) of Japan in an attempt to establish a performance based fire safety design method of buildings. The final report of this study has recently been published and the way to use this method in the design practice is now being explored among BRI staff and MOC administration. In this text, this design method is briefly outlined.

2. STRUCTURE OF THE FIRE SAFETY DESIGN METHOD

It is said that the present Building Standard Law of Japan has the following characteristics:
- it has nature of a public law, in other words, it control buildings with compulsory power,
- it provides technical standards,
- it prescribes minimum requirements,
- it operates through a system of certification for legal conformity by building authorities.

The "Fire Safety Design Method" is designed to provide minimum technical standards in the form of performance standards on the assumption that it operates in the same administration system as that of the Building Standard Law. The structure of "Fire Safety Design Method" is illustrated in Figure 1, making comparison with that of fire safety provisions in Building Standard Law.

(i) The ultimate objective

The first article of the Building Standard Law states that its ultimate goals are life safety, property protection and public welfare. Since the Fire Safety Design Method is intended to give an alternative to the fire safety provisions of the present Building Standard Law, the both of the two must share the same ultimate goals.

(ii) The safety level of technical standards

From the nature of the Fire Safety Design Method as an alternative to the Building Standard Law, which is compulsory, the level of fire safety achieved through its technical standards must be minimum.

(iii) Fundamental Requirements for Fire Safety

As for the fundamental requirements for fire safety measures of buildings, Article 35 of the Building Standard Law states that buildings must be so constructed and maintained that any hindrance is avoided with respect to evacuation safety, fire prevention and fire fighting. Since this statement is too inclusive and abstract to derive directly technical standards from it, the fundamental requirements of the Fire Safety Design Method are redefined more explicitly as follows:

(1) Requirements for Fire Safety as an Individual Building
(1.1) Precaution against outbreak and rapid spread of fire
(1.2) Assurance of life safety
(a) Control of building materials which may cause serious hindrance to evacuation in the event of fire
(b) Proper evacuation plan
(c) Assurance of safe refuge
(d) Assurance of safe egress routes
(1.3) Prevention of serious nuisance to the third parties
(a) Prevention of fire spread to buildings or a part of buildings owned by third parties
(b) Prevention of collapse of buildings
(c) Assurance of reusability of buildings of multi-ownership
(1.4) Assurance of activities of fire brigades
(a) Assurance of activities for search and rescue of occupants
(b) Assurance of fire fighting activities

(2) Requirements for Prevention of Urban Fire

The requirements for fire safety as an individual building apply for any building which is elected on the territory of Japan, while those for prevention of urban fire apply only for buildings in fire prevention districts, which are designated in the context of each city planning.

(iv) Technical standards

Most of the technical standards for fire safety in the Building Standard Law, its enforcement orders and the related Ministry of Construction orders are given in the form of prescriptive specifications, in other words, they directly specify materials, dimensions, construction methods, equipments etc. of various elements of buildings. On the other hand, in Fire Safety Design Method, attempts were made to establish the technical standards in terms of performance standard as long as possible and beneficial. It should

be kept in mind, however, that any technical standard has more or less temporary nature. Unavoidably, they have to reflect the current conditions about building construction and currently available technologies and knowledges for fire safety. So, there is a possibility that effective fire safety measures which cannot be dealt with well by the technical standards in the Fire Safety Design Method are proposed by designers etc. Such measures can be accepted as well in Fire Safety Design Method as long as they are considered to satisfy the basic requirements.

(v) Support technologies

Several fire tests are almost the only technical sources integrated into the traditional system of building control for fire safety. In order to run a performance based system, however, it is indispensable that the system is equipped with some means to predict various aspects of fire behavior so that the compliance to the technical standards can be assessed as early as at the stage of planning. So, the Fire Safety Design Method is provided with relevant calculation methods and computer codes for this purpose.

3. FUNCTIONAL DESCRIPTIONS OF THE REQUIREMENTS

The fundamental requirements of which the items are mentioned in 2. (iii) are described as follows:

(1) Requirements for Fire Safety as an Individual Building

(1.1) Precaution against outbreak and rapid spread of fire

- Proper precautions against outbreak of fire must be paid in conformity with the prescriptions of the Fire Service Law and other relevant regulations.
- The use of such materials or products that may be easily ignited or that may cause extremely rapid fire spread by a trivial misdealing of ordinary heat source is prohibited as building elements.

(1.2) Assurance of life safety

(a) Control of materials or products that may cause serious hindrance to evacuation in the event of fire

- The materials which may cause extremely rapid fire spread or which may produce extremely toxic combustion products cannot be used as building elements at the parts of buildings important for occupants' evacuation in the event of fire.

(b) Proper evacuation plan

- The evacuation plan of a building must be such that the safety of all the occupants normally expected in the building can be assured.
- The evacuation plan must be realistic as one in real fire when considering the characteristics of the occupants, use, management, operation, geometry, system of fire detection and alarm etc.
- The evacuation plan must be effective no matter when a fire may break out while the existence of occupants is normally expected.

(c) Assurance of safe refuge

A building must secure for the occupants a refuge which is free from smoke, fire, collapse, breakage or any other danger due to fire.

- A refuge must be planned in a free space, such as public way, except when it is difficult to complete the evacuation to outside of the building within a reasonable time.
- More than one refuges can be planned so that the most proper one can be chosen depending on the location of the room of origin, provided that it

does not complicate the evacuation plan.

(d) Assurance of safe evacuation routes

- For any part of building which is frequented by the occupants in normal use, a continuous evacuation route to the refuge with proper capacity, geometry, materials and equipments must be provided for the evacuation of the occupants.
- Evacuation routes of a building must be so planned that no matter where the room of origin may be, as long as the possibility of fire occurrence in the space is not negligibly small, at least one safe evacuation route can be secured for any potential occupant normally expected in the building.
- Proper measures must be taken so that, in the part of building of which the loss due to fire may totally jeopardize the safe evacuation routes for the occupants, the possibility of outbreak of fire or the effect of fire to the occupants is made negligible.
- Any part of an evacuation route must be designed so that the occupants are kept free from smoke, heat, collapse, breakage and any other danger due to fire during the time of their evacuation.

(1.3) Prevention of serious nuisance to the third parties

(a) Prevention of fire spread to buildings or parts of a building owned by the third parties

- Proper measures must be taken so that a fire occurred in a part of a building does not spread to the buildings or the parts of a building which are owned by the third parties or of similar character.

(b) Prevention of collapse of a building

- A building must not collapse due to fire when this may cause serious nuisance to the third parties.

(c) Assurance of reusability of a building of multi-ownership

- A building of multi-ownership or of similar character must be reusable after fire.

(1.4) Assurance of activities of fire brigades

(a) Assurance of activities for search and rescue of occupants

- A building must provide proper means for safe and prompt search and rescue by fire brigades of occupants who might have failed to escape at early stage.

(b) Assurance of fire fighting activities

- A building must provide proper means for safe and effective fire fighting activities by fire brigades.

(2) Requirements for Prevention of Urban Fire

- The buildings elected in the zone designated in view of prevention of urban fire must have a performance to prevent fire spread to and from neighbor buildings to the extent that the purpose of the zone is satisfied.

4. TECHNICAL STANDARDS FOR THE CONFORMITY TO THE FUNDAMENTAL REQUIREMENT

Since the descriptions of the fundamental requirements given in the above are only qualitative, it is indispensable to provide to each of them the technical standards in order to make it possible to examine if a concrete design of a building satisfy the requirements. These standards must be established at a level acceptable to the interested society because the level of safety depends on how much cost the society is prepared to pay and also it is impossible to attain perfect safety. On this regard, the standards in a performance based design method should be so determined that the level of safety realized by the existing fire safety regulations can be

reproduced, at least for the first time, because it is considered that this level is the easiest to be accepted by the society concerned.

The technical standards in the Fire Safety Design Method consist of specification standards and performance standards. The former type of standards still remain, to less extent than in the existing building codes, because there are some standards of which the conversion to performance is premature or not necessarily beneficial.

4.1 The performance standards

The performance based technical standards mentioned in the above are classified into the two types as follows:
(a) Standard fire conditions
(b) Standard safety criteria

In concept, these respectively correspond to design loads and allowable stress in structural design, which is already being carried out in performance based method. With these standards, a proposed fire safety design method is examined for the conformity to the basic requirements through the procedure illustrated in Figure 2 for the case of the design of evacuation routes.

To operate a performance based design method, the relevant means to predict the various aspects of fire are indispensable in order to evaluate the proposed fire safety measures at the stage of designing. The standard fire conditions are given as input data to such prediction methods and the results are compared with the standard safety criteria to judge if the proposed fire safety design is acceptable.

4.2 Character of the prediction methods

In general, it is very difficult to develop the prediction methods for complex objects as a building, whether the method may be for structural behavior or for fire behavior. Accordingly, it is inevitable that such prediction methods are considerably simplified in the course of modeling. In addition to this, fire scenarios considered in the assessment will have to be significantly simplified. And these simplifications make it difficult to evaluate the discrepancy between what is predicted to be necessary and what is actually needed. Fortunately, however, constructing buildings has long been almost an everyday practice of men, so, for ordinary buildings, we have considerable knowledge on what are needed for fire safety by experience. This saying may sound that theories are useless but does not mean it. Empirical knowledges work well only where the experiences exist. They are powerless when we try to adopt unconventional way of building. It can be said that theories are the pilot when we tread in an inexperienced field, such as when we try new designs or unconventional fire protection means.

In many engineering designs, since the theories and the conditions considered are considerably simplified, some adjustments are usually needed to compensate the discrepancy between theories and empirical knowledges. The safety factors in structural design(as large as 3 for buildings and sometimes 8 for civil engineering structure in Japan) may be a good example of this. This concept of the harmonization of theories and experiences is illustrated in Figure 3. Once we have managed to find how to adjust

theories and experience for where our experience exist, we will be able to extend this to inexperienced region. In a strict sense, it is not validated that the same technique for the adjustment in the experienced region is still valid for an inexperienced region, but this will be the risk we have to accept in conjunction with the benefit we can enjoy by introducing unconventional designs or methods.

4.3 Meaning of technical standards

As mentioned in the above, the technical standards of performance based design method consist of (a) standard fire conditions and (b) standard safety criteria. It is possible to harmonize theories and experiences by adjusting the values of the former and/or the latter of them so that a necessary level of safety can be attained.

In this particular case of the Fire Safety Design Method, however, since the safety criteria for men or building elements, such as human endurance against heat, ignition temperature of materials can be better defined than the design fire condition, it will be a good idea to let the standard fire conditions bear the principal role of the harmonization.

The standard fire conditions consist of scenarios of fire as well as the size of fire and their meanings are illustrated in Figure 4, in which a fire condition is simplified as the size of fire. The solid curve stands for the conceptual relationship of the size of fire and the frequency(or probability) of the appearance of fire. According to the general characteristic of accidents, the frequency of the appearance of fire is high when the size is small, but decreases dramatically as the size increases. Needless to say, the larger the size of fire, potentially the more dangerous, but the level of danger depends also on the fire safety measures provided. Generally speaking, a space having better safety measures can cope with severer fire conditions. The essential significance of the standard fire condition is to keep the probability of the appearance of fire of the size which may cause serious danger to occupants or other objects below an acceptable level by means of demanding to provide fire safety measures needed in order to clear the danger represented by the standard fire condition. In other words, when the condition of the fire occurred happens to be severer than that of the standards, the safety is not guaranteed. If we want to increase the level of safety, we can do it by raising the standards, but often this is accompanied by the increase of fire cost. Therefore, the standard fire conditions must be so determined that the fire safety measures can be provided for an acceptable cost for the society and yet the society is not disturbed by the remaining risk.

5. THE TECHNICAL STANDARDS FOR EVACUATION SAFETY

The technical standards for a performance based design method need to be given by calculable or measurable values so that the conformity to the standards can be examined without ambiguity. Here, the technical standards for assurance of safe refuges and evacuation routes are outlined as an example of those of the Fire Safety Design Method.

5.1 Assurance of safe refuges

Traditionally, final refuges of occupants of buildings in the event of fire

have been taken on public ways or some sites of equivalent character. In such places as public ways, people can escape freely whenever dangers due to fire become imminent, so virtually no check is necessary for the safety. Public ways and such will continue to remain as the most important refuges in future as well for most of the buildings.

Although considered to be rare, refuges may have to be planned on a building site having no outlet to public ways in conjunction with the plan of the evacuation routes within the building. This type of refuges need check for safety against certain potential dangers from the buildings under fire.

As for refuges within buildings, we have not ample experience, yet in case of buildings which cannot be evacuated in reasonable time for some reasons, for example, high-rise buildings and hospitals, there may be cases where securing refuges within the buildings or protecting some parts of a building so as to be practically used as refuges are a better solution. In such a case, however, a sufficient level of safety must be assured against any conceivable hazard due to fire, which may attack the refuge through open air as well as through indoor spaces. The potential causes of danger for evacuees staying in a refuge consist of smoke, heat, air contamination, structural collapse etc. as shown in Figure 5.

The standard fire conditions for safe refuges are summarized in Table 1. In principle, any space of a building must be considered as a potential room of origin. However, in order to save work in design practice, the spaces which meet the conditions given in Table 1 are exempted. In particular, if the designer of a building can find the space which gives the severest case, it follows that it is the only space that must be considered as the room of origin in the process of designing the refuge. In the room of origin, a fully developed fire is assumed and the existence of sprinkler is ignored. The area of fire is limited within a compartment adequately enclosed by fire resistant walls. This implies that compartmentation of buildings becomes to be one of the safety measures for refuges because this reduce the impact of fire on refuges.

The standard safety criteria for refuges are determined to assure safety against each of the potential dangers to the evacuees in refuges as shown in Table 2. A couple of criteria were given for certain items so that designers can choose any of them according to their convenience.

5.2 Assurance of safe evacuation routes

Obviously, it is the evacuation routes that plays the most important role for the safety of occupants of the building in the event of fire. Naturally, in the existing building codes as well, stresses are given to the provisions on dimensions, materials, fire resistant ratings, exit signs, smoke control systems of the parts of buildings expected to function as evacuation routes. While the existing regulations directly give prescriptive solutions for evacuation safety, it is necessary for the establishment of performance standards to analyze the potential causes and mechanism of dangers due to fire on the occupants in the course of evacuation. As are shown in Figure 6, while the direct hazards for the evacuees are smoke, heat, collapse and breakage, it can be seen that the factors causing hindrance on the egress routes play an important role to induce or accelerate the direct dangers. The standard fire conditions for the assurance of safe evacuation routes are

summarized in Table 3. The standards are given to evacuation routes in the room of origin, on the floor of origin and on the floor of non-origin for the clarity of designing. Any space must be considered as a potential room of origin unless exempted by the conditions shown in the table, but it is possible to reduce the number of spaces to be examined as in the case of refuges. The standard fires for evacuation in the room of origin and on the floor of origin are defined as illustrated in Figure 6. In sprinklered rooms, their maximum heat release rate is limited to the maximum rate which does not actuate the sprinkler heads, which is determined as a function of ceiling height, spacing and actuation temperature in case of ceiling mounted sprinklers. The standard fire for evacuation on the floors of non-origin is a post flashover fire of which the behavior is determined considering the ventilation condition of the room of origin.

As for the occupants conditions, the number of occupants in each space are calculated from the density of occupants specified according to the use of the space. The evacuation start time is taken as the shortest of the times at which occupants recognize the danger of fire by means of cues by smoke, other occupants and the detection and alarm system of the building.

The standard safety criteria concern with the allowable condition of the spaces which have to be protected against the potential dangers due to fire during the time of evacuation. In some cases, more than one solutions are given so that designers can choose the most convenient one.

6. AVAILABLE PREDICTION MODELS

A performance based evacuation safety design method of building is possible only when relevant prediction means for occupants' evacuation and smoke behavior are available. The followings are the computer models developed in our research project:

(a) Evacuation Model

This model predicts the numbers of occupants in each space and of crowdings at each opening on the designed evacuation routes at arbitrary time after the start of evacuation, assuming that occupants in each space start orderly movement of egress with uniform walk speed in the direction predetermined by the designer. The evacuation start time is given as input data for each of the spaces. This model agrees with the results of the field measurements of the evacuation times of an evacuation drill and the egress from several theaters in non-emergent condition within 10% of error(10).

(b) Smoke Propagation Models

Two computer models are currently available, that is:

- One layer zone smoke propagation model
- Two layer zone smoke propagation model

One layer zone model predicts the smoke propagation throughout a building assuming that smoke and air are uniformly mixed in each of the indoor spaces of the building. This model still remains as the most appropriate model when the behavior of smoke throughout a high-rise building or a large scale building need to be dealt with, although inadequate when we have to consider such a scenario as that occupants evacuate from a space involved in fire before the smoke layer descend to a hazardous level. The model can deal with transient as well as steady state flow of smoke(2).

Two layer zone model assumes an upper layer and a cold layer in each of the indoor spaces of a building. Theoretically, this model can deal with buildings with arbitrary number of floors, but considering the general behavior of smoke in tall buildings and the calculation time needed smoke filling in the room of origin, on the floor of origin, buildings with atriums etc. may be the most appropriate objects of the application of this model. At least for some simple geometries, the predictions by this model agree reasonably well with the full scale test results(3),(4).

In addition to these models, several simpler models, which are more or less limited in application but are thought to be still useful in design practices are also available(5),(6).

7. CONCLUDING REMARKS

For the establishment of a performance based design method for evacuation safety of buildings, the followings are considered to be of central importance:

- Availability of models for the prediction of occupants' evacuation and smoke behavior in building spaces. These do not have to be perfect. We should develop the design method taking into account their limitations.
- The objectives of fire safety measures of buildings must be clearly defined. Life safety is the objective common for all the societies, but property protection and prevention of urban fire depend.
- The requirements to the fire safety measures of buildings for achieving the objectives must be defined.
- The technical standards must be given in calculable or measurable forms so that wether or not the requirements are satisfied can be examined by designers, building official etc without ambiguity.
- The technical standards should be so determined that the level of safety attained through the standards becomes equivalent with that realized by the standards prescribed in the existing codes, at least for the first step. In future, the level of safety might be more rationalized taking into account the probabilistic aspects of fire.
- The design method must be sufficiently logical and simple so that it can be dealt with by designers, building officials etc. without causing excessive work load.

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	BLDG. STANDS. LAW	FIRE SAFETY DESIGN METHOD
Ultimate Goals	a) Life Safety b) Property Protection c) Public Welfare	a) Life Safety b) Property Protection c) Public Welfare
Level of Requirements	Minimum	Minimum
Principle for Fire Safety	Article 35 etc.	Fundamental Requirements for Fire Safety
Technical Standards	- Bldg. Stands. Law - Enforcement Orders - Minist. of Const. Orders (Specification Stands.)	(Performance Stands.) - Stand. Fire Condition - Stand. Safety Criteria (Specification Stands.)
Support Technologies	Fire Tests	- Fire Tests - Means of Fire Prediction - Computer Codes

Figure 1. The Structure of The Fire Safety Design Method in Comparison with the Building Standard Law of Japan

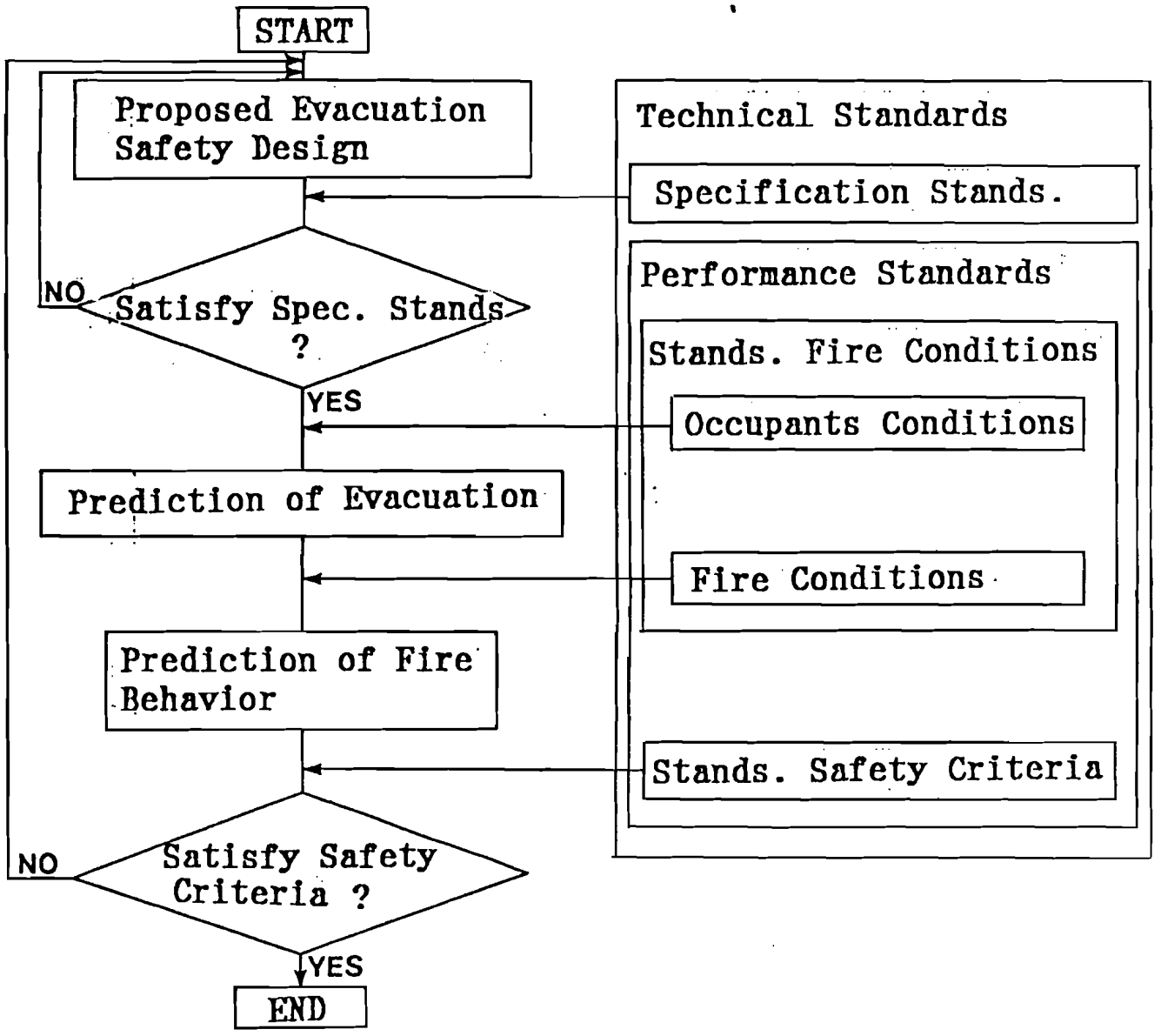


Figure 2. The Procedure of The Evacuation Safety Design

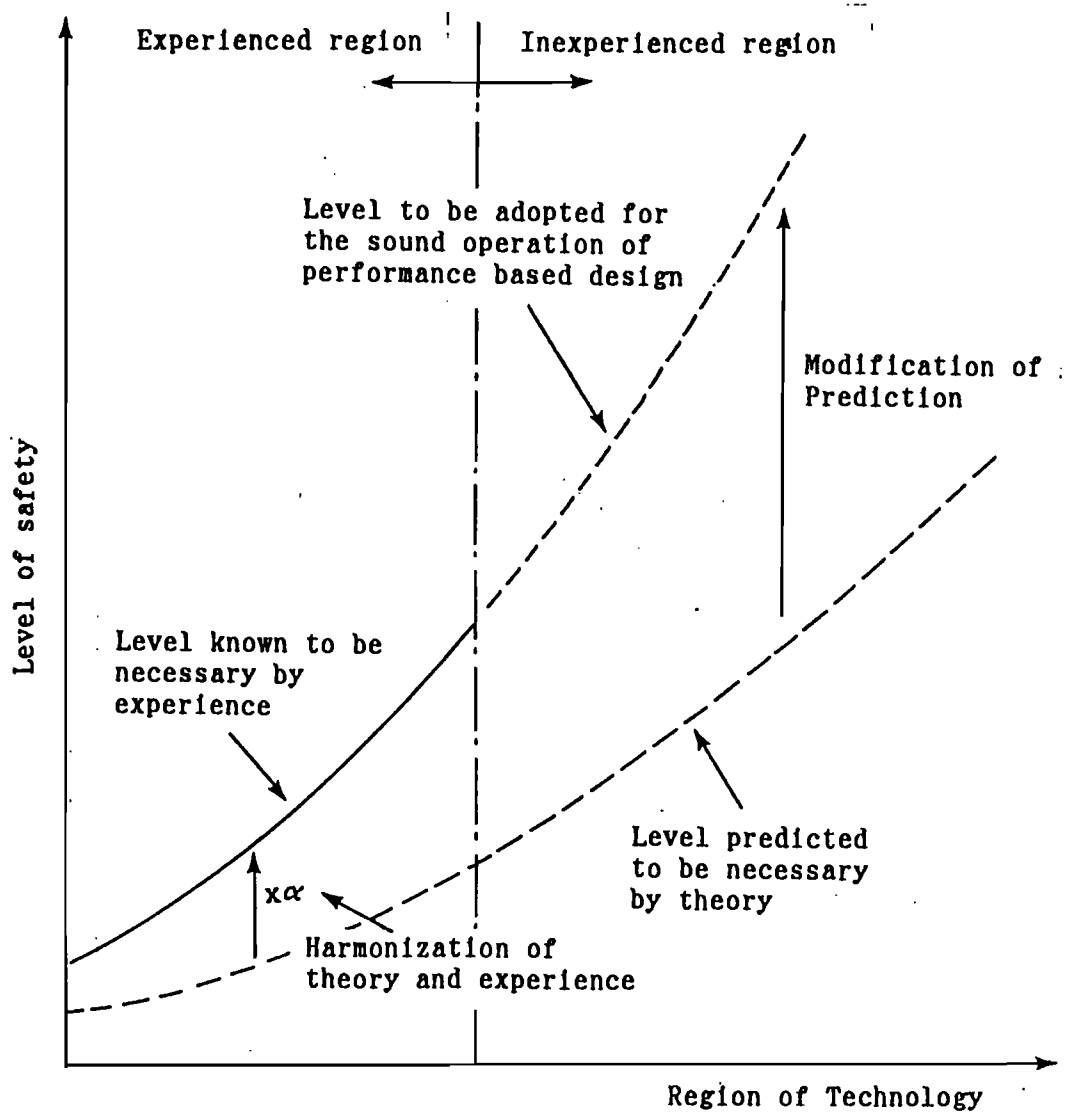


Figure 3. Concept of harmonization of theories and experiences

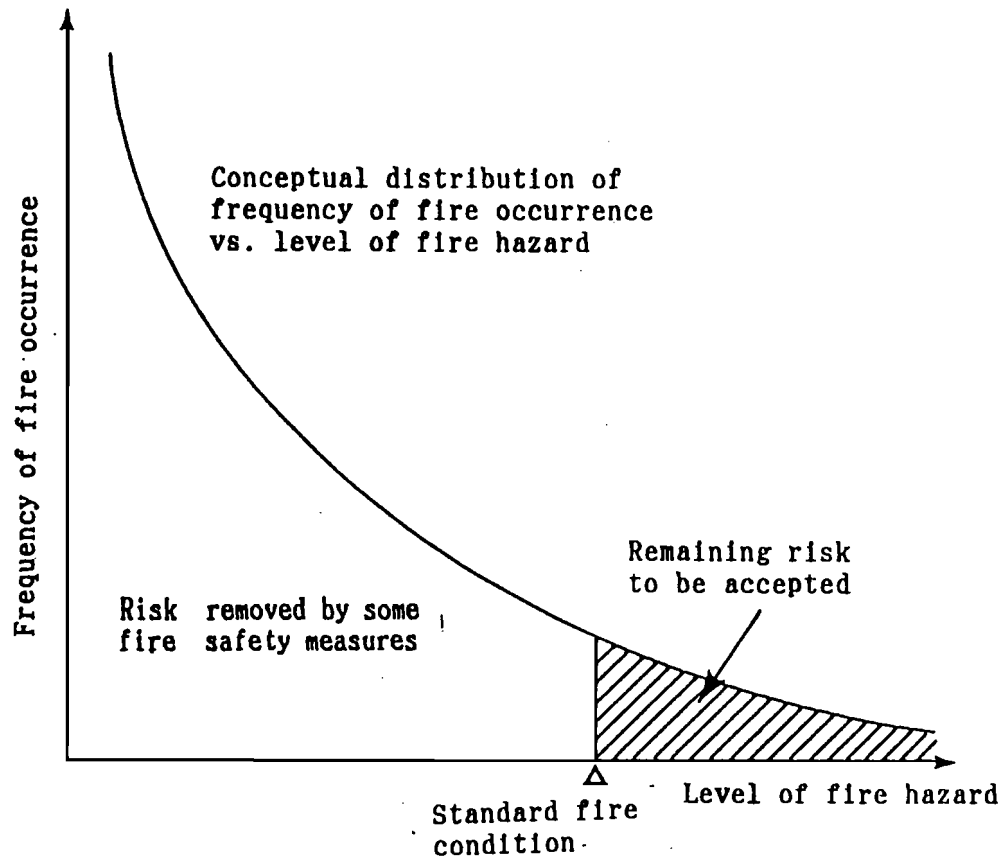


Figure 4. Meaning of standard fire condition

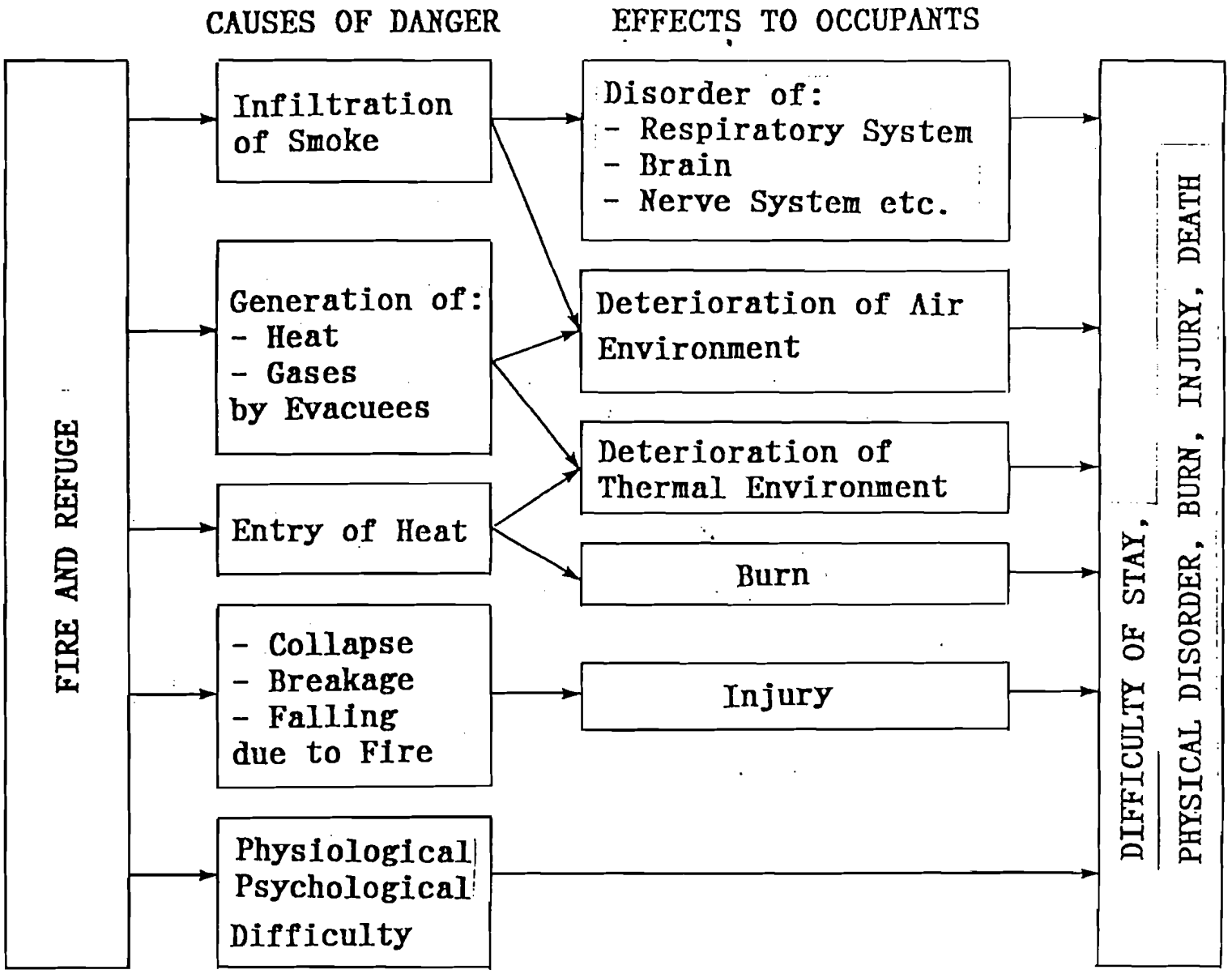


Figure 5 FIRE HAZARDS IN REFUGES

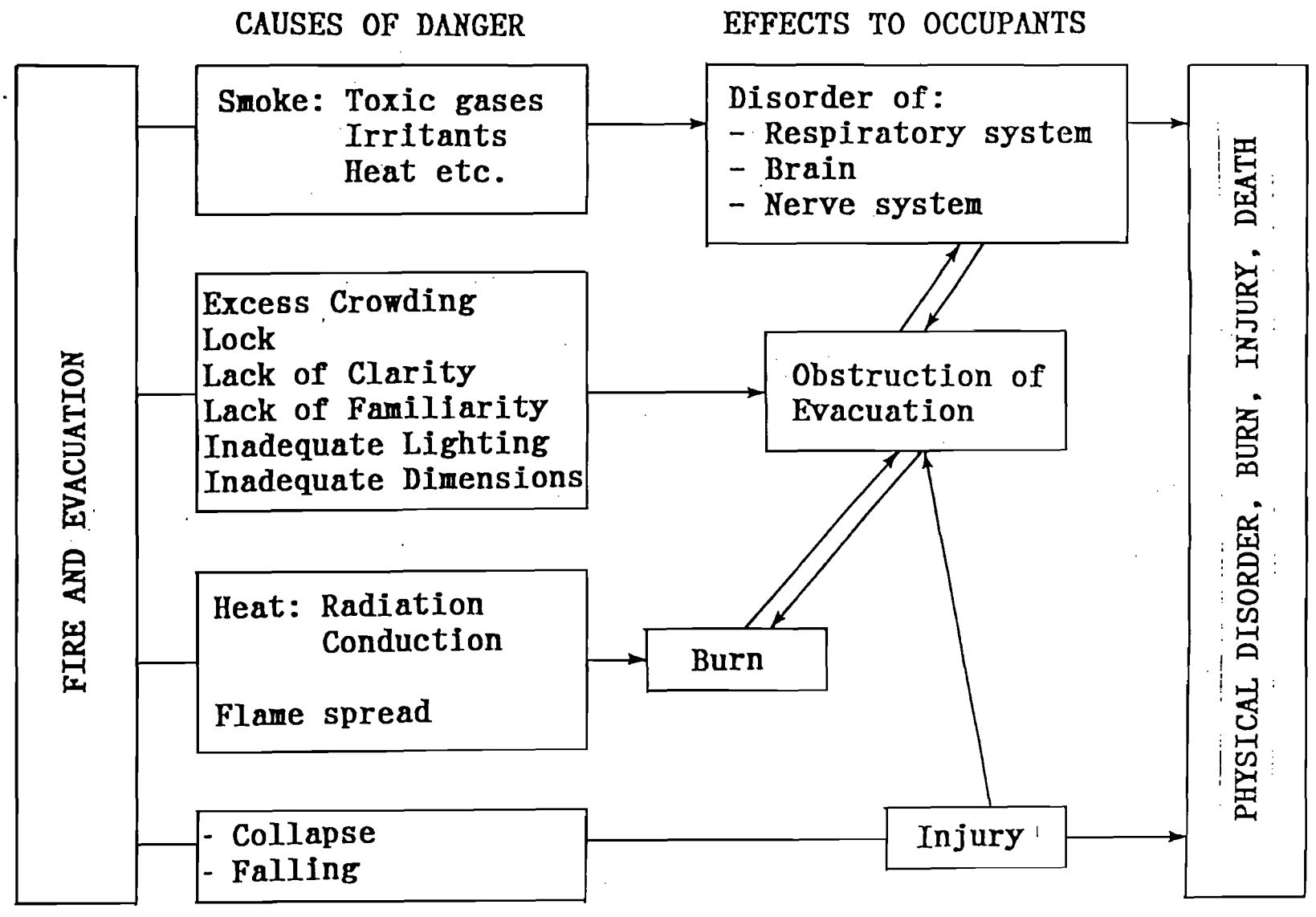
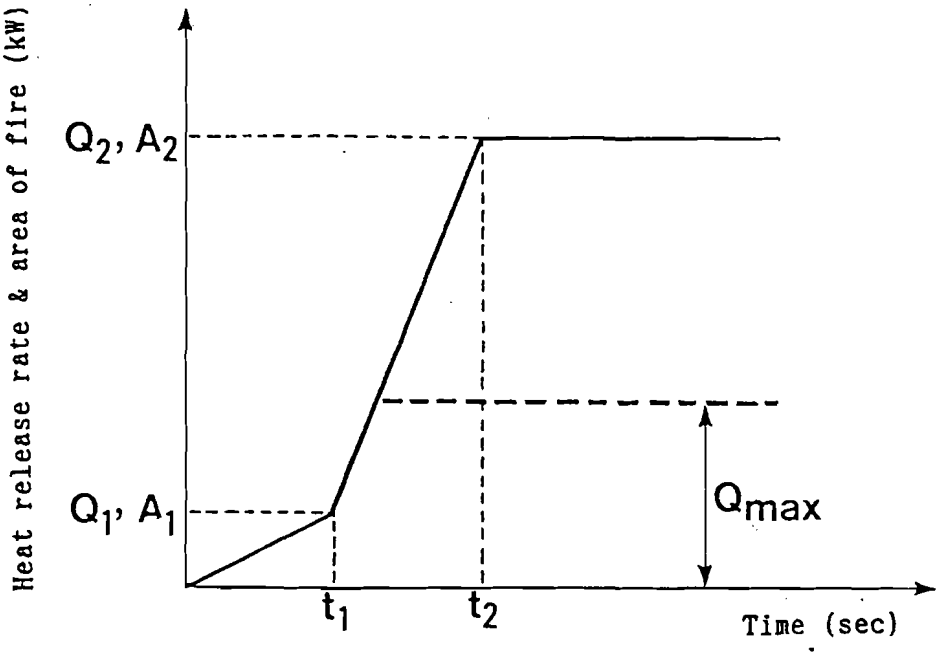


Figure 6 FIRE HAZARDS IN EVACUATION ROUTES



Occupants' condition	Quantity of Contents	Time (sec)		Heat release (kW)		Area (m^2)	
		t_1	t_2	Q_1	Q_2	A_1	A_2
Wake	Large	120	240	300	3,000	1.7	1.7
	Small	120	320	750	25,000	0.5	17.0
Sleeping		480	720	200	1,000	2.5	2.5

note: For spaces in which ceiling mounted sprinklers are installed, the maximum heat release rate Q_{max} is given by

$$Q_{max} = 0.08\ r\ \{(T_c - T_o)H\}^{3/2}$$

where H : ceiling height (m)
r : maximum horizontal distance between a sprinkler and the axis of fire plume (m)
T_c : critical temperature of sprinkler actuation (K)
T_o : ambient temperature (K)

Figure 7. Standard fire for evacuation routes in the room of origin and on the floor of origin

Table 1. Standard fire conditions for safe refuges

	Public ways	Refuge isolated from public ways	Refuge within buildings
Space of origin	N/A	All spaces which do not fall in any of the followings: a) The refuge is not needed in case a fire occurs in the space b) Possibility of the occurrence of fire in the space is negligible c) Safer than the case when a fire occurred for which the safety standards are satisfied	
Scale of Fire	N/A	i) Area of fire: The area within a fire can be limited by effective fire walls or confined by fire resistant compartment. ii) Condition of fire: Post flashover fire regardless of sprinkler systems	
Radiation Source	N/A	i) Fire resistant buildings a) width: width of opening (m) b) height: height of opening x2 (m) c) radiation intensity: 100 (kW/m^2) ii) Wooden houses a) width: width of the house viewed from the point of refuge (m) b) height: h (m) given by $h = -A^{1/2} + 4.5A^{2/5}$ where A is the horizontally projected area of the house	
Evacuees' Condition	N/A	i) Number of Evacuees: The number of evacuees determined by the specific evacuation plan	
			ii) Generation of heat: 400 (kW/person) iii) Generation of CO_2: 0.02 (m^3/h/person)

Table 2. Standard safety criteria for refuges

The items to be checked		Public ways	Refuge isolated from public ways	Refuge within buildings
1. Smoke	thru outdoor	N/A	$D_1 > 12A^{2/3}$	any of (1),(2),(3)
	thru indoor		N/A	any of (3),(4),(5)
2. Heat			$q_{max} < 1$ (kW/m^2)	$q_{max} < 1$ (kW/m^2) and $T_i < 10$ (K)
3. Air quality			N/A	$C_2 < 0.02$ (%) and (6)
4. Collapse of building			$D_2 > 2H_2$ (m)	any of (7),(8)
5. Falling objects			$D_3 > 4.5H_3$ (m)	N/A
6. Area of refuge			$a > 2$ (m^2/person)	$a > 1$ (m^2/person)

A : horizontal projected area of the building (m^2)
D_1 : horizontal distance of the refuge from the building (m)
D_2 : horizontal distance of the refuge from the top of the building (m)
D_3 : horizontal distance of the refuge from potential falling part (m)
H_2 : vertical distance of the refuge from the top of the building (m)
H_3 : vertical distance of the refuge from potential falling part (m)
a : effective area of refuge per person (m^2/person)
q_{max} : maximum incident radiation flux to evacuees (kW/m^2)
T_i : temperature rise of interior surface of the refuge (K)
C_2 : concentration of CO_2 in the refuge (%)

Table 3. Standard fire conditions for safe evacuation routes

	Evacuation routes		
	Room of origin	Floor of origin	Floor of non-origin
Space of origin	All the spaces which do not fall into the followings: a) No occupant exists in normal use b) Safer than a space for which safety standards are satisfied	All spaces which do not fall into the the followings: a) No occupant who needs to escape exists when a fire occurs in the space b) Possibility of fire occurrence in the space is negligible c) Safer than the case when a fire occurs in a space for which safety standards are satisfied	
Scale of fire	Heat release rate and area of fire source i) Unsprinklered spaces: specified as in Figure 6 according to the type of space ii) Sprinklered spaces: the smaller of the followings: a) fire source specified by i) b) maximum fire which is unable to activate the sprinklers in the space		i) Area of fire: the same as in the case of refuges ii) Condition of fire: the same as in the case of refuges
Occupnts	i) Number of evacuees: specified in the form of occupants' density or some other ways according to the type of spaces ii) Evacuation ability: specified according to the type of spaces and occupants iii) Evacuation start time: The smallest of the times at which the occupants recognize the danger due to fire by means of: a) Cue by fire, smoke b) Cue by other occupants c) Through the fire detection and alarming systems		

Table 4. Standard safety criteria for evacuation routes

The items to be checked		Evacuation routes		
		Room of origin	Floor of origin	Floors of non-origin
Smoke	thru outdoor	N/A	N/A	any of (3),(4),(5) and (10)
	thru indoor	any of (9),(10)	any of (3),(4), (5),(10) and (11)	any of (3),(4),(5), (9) and (10)
Heat		(12)	(12)	(12)
Flame spread		(13)	(13)	(14)
Collapse of bldg.		N/A	N/A	any of (7) and (8)
Falling objects		functional	functional	functional
Excessive crowding		(15)	(15)	(15)
Geometry,dimension clarity etc.		specification	specification	specification

THE LIST OF STANDARDS IN TABLES 2 AND 4

(1) The refuge is out of the region enclosed by any cone having the apex on the opening of the fire room and extend upward with the angle of $\tan^{-1}0.25$ around its axis.

(2) The infiltration of smoke into the refuge is prevented by any means of the followings:

(a) air tight exterior wall which satisfy

$$\frac{\alpha A}{V} < 1.0\times10^{-6}\frac{1}{\sqrt{\Delta P}} \qquad (0< P<60 \ \ Pa)$$

(b) indoor pressurization of refuge which satisfy

$$60-P < 6.0\times10^{-12}\left(\frac{V}{\alpha A}\right)^2$$

where V : volume of refuge (m^3)
αA : area of leakage potentially exposed to smoke (m^2)
ΔP : pressure difference (Pa)
P : relative pressure of refuge (Pa)

(3) The fire products entered in the refuge are diluted to satisfy

$$C < (1/200)C_0$$

where C : fire product concentration in refuge
C_0: fire product concentration in the room of origin

(4) Smoke transported through indoor space is released at a point between the space to be protected(refuge, evacuation route) and the room of origin to an open air having no obstacle which may prevent free rise of plume in the region enclosed by the following surfaces:

(a) plane which contains the opening ejecting smoke

(b) two plane at right angle to (a) of which the distance from the edge of opening x_1 is given as

$$x_1 = 0.20Z$$

(c) a curved surface of which the distance from (a) x_2 is given as

$$x_2 = 0.6H^{2/3}Z^{1/3} + 0.20Z$$

where H : height of opening (m)
Z : height from the bottom of opening

(5) Smoke transport is prevented between the spaces to be protected(refuge, evacuation route) and the room of origin by any means of the followings:

(a) air tight partition which satisfy

$$\frac{\alpha A}{V} < 8.0\times10^{-3}\left(\frac{1}{t_s\sqrt{\Delta P}}\right) \qquad (0< P<H_1)$$

(b) building up pressure difference(positive at refuge side) which

satisfy

$$\Delta P > 1$$

(c) keeping smoke layer bottom at the height s (m) which satisfy

$$s > h + 0.1(H_2 - h)$$

where H_1 : height of non-airtight vertical shaft (m)
H_2 : ceiling height of the space at fire side of the partition (m)
h : height of opening or leakage on partition (m)
ΔP : pressure difference (Pa)
t_s : time of stay in the space (s)

(6) Thermal environment which satisfy

$$\int_0^{t_s} (\Delta T - 10)^2 dt < 4.0\times10^4 \qquad (\text{if } (\Delta T-10)<0,\ (\Delta T-10)^2)=0)$$

where ΔT : temperature rise in refuge (K)
t_s : time of stay (s)

(7) Fire resistant building prescribed in the Building Standard Law.

(8) Building which satisfy the relevant standards given by Fire Resistant Design Method.

(9) Smoke layer bottom is kept at height s (m) which satisfy

$$s > 1.6 + 0.1(H - h)$$

where H : ceiling height (m)
h : height of the floor of evacuation route (m)

(10) The smoke to which evacuees are exposed satisfy

$$\int_0^{t_e} (\Delta T)^2 dt < 4.0\times10^3$$

where ΔT : temperature rise (K)
t_e : time during which evacuees are exposed to smoke (s)

(11) Outside of the region enclosed by the surfaces defined as
(a) plane which contains the opening ejecting smoke
(b) two vertical planes at right angle to (a) of which the distance from the edge of opening is 0.4 (m)
(c) plane parallel to (a) whose distance from (a) x (m) is given as

$$x = 0.6H^{2/3}Z^{1/3} + 0.20Z \qquad (Z=1.8-Z_n \text{ or } 1.8-0.3H)$$

where H : height of opening (m)
Z_n : height of neutral plane at opening (m)

(12) Incident radiation heat flux r (kW/m^2) to evacuees satisfy

$$\int_0^{t_e} (r - 2)^2 dt < 10 \qquad (\text{if } (r - 2)<0,\ (r - 2)^2=0)$$

where t_e : evacuation time (s)

(13) The interior lining materials do not induce the combustion which violates the safety criteria of 1. Safety from smoke and 2. Safety from heat during the time of evacuation.

(14) The interior lining materials do not burn during the time of evacuation

(15) Unless in space specially protected, crowding at any opening on evacuation routes satisfy

$$n < 120$$

where n : number of evacuees in crowding per unit width (person/m)