A Study for Performance Based Design of Means of Escape in Fire

TAKEYOSHI TANAKA
Building Research Institute
Ministry of Construction
1 Tatehara, Tsukuba-shi, Ibaraki-ken 305, Japan

ABSTRACT

It is important for a performance standard for fire safety of buildings to determine the safety criteria and design fires. In this study, the provisions for means of escape concerning shops in existing regulations of several countries are investigated and a preliminary consideration is made on the methodology to determine such a design fire that is able to reproduce the level of safety which have been realized for shops by complying with the existing regulations.

KEY WORDS: fire safety, performance standards, safety criteria, design fire, means of escape, department store, occupants density, exit width, maximum travel distance, available egress time.

1. INTRODUCTION

It is only after World War II that active research on building fire has begun. Nevertheless, the accomplishment in fire research to date may be said remarkable, particularly in the field of fire modeling in recent years. As a natural consequence, the fire research community has come to be more and more interested in developing a scientifically and engineering based performance standards for fire safety of buildings.

However, even though fire hazards may be understood clearer than before, it still rest on ambiguous consensus of communities to decide what level of safety is to be assured thereto. The safer, a community may be the happier, but at the same time it may resist to increase of cost of safety measures or excessive hindrance of everyday convenience. People live side by side with many kind of dangers anyway. So, a certain compromise is inevitable and in this sense the existing fire safety provisions in each country may be said an expression thereof.

By and all, direct loss by fire in most developed countries stays at an allowable level for a significant period, so it may be said that their current interest is to reduce the total cost of fire while enjoying the present level of safety. The most responsible obstacle to cost effective fire safety measures is that only limited number of solutions are allowed by existing regulations. Once performance based standards are established, a variety of solutions will be made possible so that the most cost effective one can be selected.

For developing a performance based standard, it will be important that safety criteria and design fire are so determined as to make it possible to maintain the level of safety normally realized by complying with the existing regulations.

2. INVESTIGATION INTO PROVISIONS ON MEANS OF ESCAPE

The regulations in several countries concerning means of egress of department stores are investigated. The list of the regulations studied is given in **REFERENCES**.

Although all the countries have provisions for many factors affecting life safety, the present investigation is concentrated on the provisions which might have significant impact on planning of buildings. The summary is given in Table 1. It seems that the provisions for means of escape in these countries essentially address to the following purposes:

a) adequate arrangement of exits,
b) adequate number and capacity of exits, and
c) mitigation of fire hazard to facilitate escape movement.

2.1 Arrangement of Exits

Arrangement of exits is regulated by means of "maximum travel distance", "maximum length of common path of travel", "maximum dead end length" and so forth, but all of these are not necessarily prescribed in each country. It seems that maximum travel distance is considered to be the most important of these. Most countries require this to be 30 - 40m. The second most important may be maximum length of common path of travel, which is about one half of maximum travel distance in many countries.

What is interesting and puzzling as well to note is the variety of conditions among the countries to ease these requirements. These are relaxed by automatic sprinkler in USA, multiple escape directions in UK, protection of stair case in France, and height of floor in Japan.

2.2 Number and Capacity of Exits

The number of exit may be indirectly regulated by the maximum travel distance etc. but many countries have separate provisions for number of exits. Two or more exits are required approximately from 50 - 280 m^2 of floor area.

Except Japan and Germany, occupants densities are incorporated into the calculation of the required width of exits. Dominantly, the densities are specified according to level of floor. The values thereof somewhat differ from a country to another. The capacity of exits actually required depends, however, not only on the occupants density but also on the rules of calculation of exit width, for instance, whether or not occupants loads of adjacent floors has to be taken into account makes difference.

In order to compare the widths required in the countries, sample calculations are made for a model department store having seven floors of the same area above the ground and a basement. Figures 1-3 indicate how much width of exits is required according to the floor areas. The increase of exit width due to the requirements of two way exits is neglected so as not to obscure the basic nature of exit capacity requirement, so more width may actually be required for small floor area.

Width of exits on 2nd - 7th floors: It may be said from Figure 1 that the required widths for upper floors vary considerably among countries, and the requirement in Japan looks to be most severe since this applies uniformly to all the upper floors.

Width of exits on street floor: High occupants density may be normally expected on street floors of department stores so that the line for the UK

TABLE 1 Summary of regulatory requirements for means of escape for shops

		Australia	France	Japan	UK	LSC(USA)	UBC(USA)
Specifi-cations	Maximum travel distance	40m	a)a.p.-protected st. 40m b)a.p.-non prtd.st. 30m c)dead end-prtd.st 30m	a)>=15th flr 30m b)=<14th flr 40m	a)1 direction 18m b)>=2 directions 30m	a)no sp. 30m b)with sp. 45m	a)no sp. 30m b)with sp. 45m
	Max. direct distance				a)1 direction 12m b)>2 directions 30m		
	Max. common path length	20m		a)>=15th flr 15m b)<=14th flr 20m	a)travel distance 18m b)direct distance 12m	a)no sp. 15m b)with sp. 23m	
	Max. dead end length	(20m)	10m	10m		a)no sp. 6.1m b)with sp. 15m	6.1m
	Distance between exits	9 - 60m				>1/2 diagonal space distance	>1/2 diagonal space distance
	Min. number of exits	buildings: a)>25m b)>=7 flrs 2	a)=<50Ps. 1 b)51-500Ps. 2 c)>500Ps. $2+\frac{Ps-500}{500}$	>=2 for bldgs: a)total area >1,500m^2 b)>3 floors	>=2 for all shops except small ones	>=2 for bldgs: a)>15m b)trvl.dist.>23m c)area>280m^2 d)>3 floors	a)1-10Ps. 1 b)11-500Ps. 2 c)501-1,000Ps. 3 d)>1,000Ps. 4
Occupant density	Upper floors	0.2	a)>= 4th flrs. 0.2(x1/3) b)3rd floor 0.5(") c)2nd floor 1.0(")		Super market 0.5 Dept. store -main sales flr 0.5 -low density flr 0.14	0.18	0.18
	Street floor	0.33	2(x1/3)			0.36	0.36
	Basements	0.33	1(")			0.36	0.36
Width of exits	Corridor	a)1-100Ps. 1m b)101-200Ps. $1+\frac{Pn-100}{25}$x0.25m c)>200Ps. $2+\frac{Pn-200}{75}$x0.5m	a)1-50Ps. 0.9m b)51-100Ps. 0.9mx2 or 1.4mx1 c)101-500Ps. $(1+\frac{Pn}{100})$x0.6m d)>500Ps. $\frac{Pn}{100}$x0.6m	a)upper floors 0.27An/100 m b)street floor 0.6A0/100 m where An: area of n-th floor	a)1-50Ps. 0.8m b)50-110Ps. 0.9m c)111-220Ps. 1.1m d)>220Ps $1.1+\frac{Pn-220}{20}$x0.1m	a)upper floors $\frac{Pn}{100}$x0.56m b)street floor $\frac{P_{-1}+P_0+P_1}{100}$x0.56m	a)upper floors $\frac{Pn}{50}$x0.3m b)street floor $\frac{P_{-1}/2+P_0+P_1/2}{50}$x0.3m
	Stairs	a)1-100Ps. 1m b)101-200Ps. $1+\frac{Pn-100}{25}$x0.25m c)>200Ps. $2+\frac{Pn-200}{60}$x0.5m	Same rule as corridor, Pn being the total occupants served by the part of the stairs	0.6Amax/100 m where Amax: Max. area of upper floors	$1.1+\frac{Pnt-40(n+4.5)}{5(n+3)}$ m where n :number of floors served Pnt:number of total occupants served	$\frac{Pn}{75}$x0.56m	$\frac{P_n+P_{n+1}/2+P_{n+2}/4}{50}$m
Built-in systems to facilitate escape	Smoke control	all shops	shops>300m^2	room>100m^2			
	Sprinkler	a)building>25m b)space>3,500m^2	sales area >3,000m^2	a)>=11th flr &>100m^2 b)total area>3000m^2 & >200m^2 c)space>1,500m^2	compartment or floor>2000m^2	a)floor>1100m^2 b)total area>2200m^2 c)>=4 floors d)>23m	a)floor>1100m^2 b)total area>2200m^2 c)>= 4 floors d)>23m

Max.:Maximum, Ps.:Persons, Pn:Number of persons on n-th floor, flr:floor, trvl:travel, dist.:distance, sp.:sprinkler

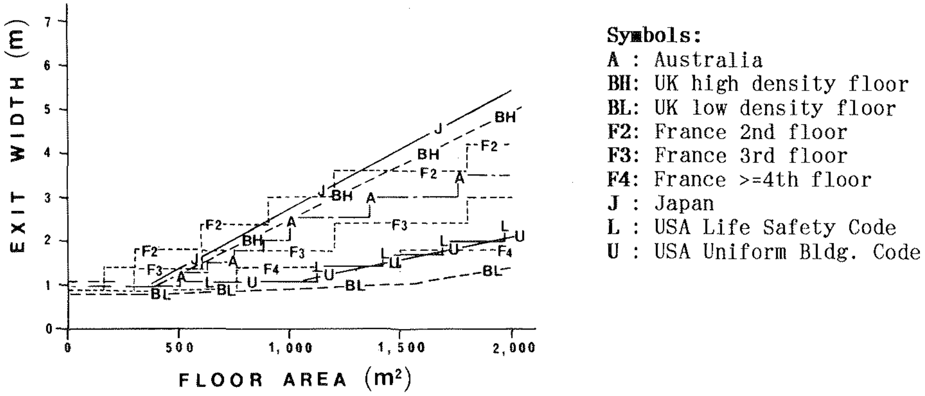

FIGURE 1 Required exit widths for upper floors of shop buildings

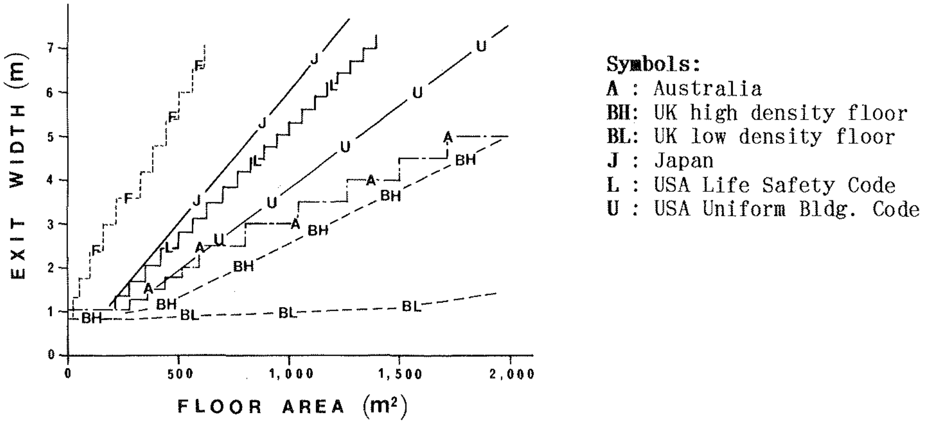

FIGURE 2 Required exit widths for street floors of shop buildings

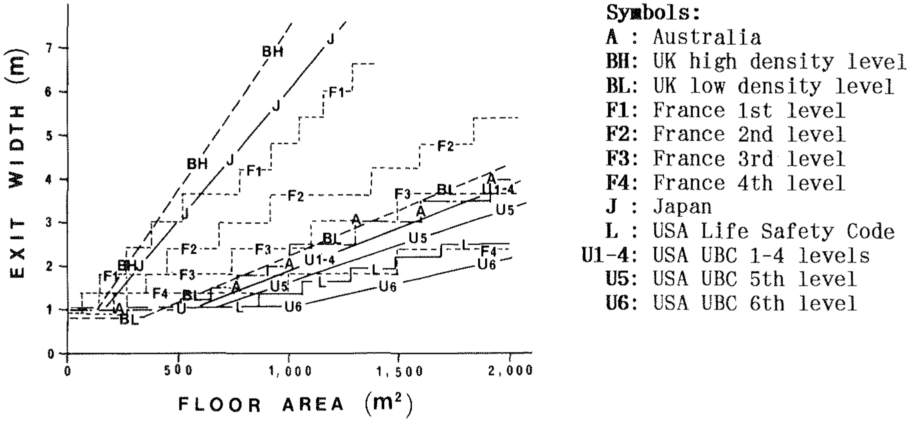

FIGURE 3 Required widths for stairs of shop buildings

requirement for low density area can be neglected from Figure 2. Even so, the difference among the countries is still significant.

Width of stairs: It will be said from Figure 3 that the requirement of Japan is extremely high if the special floors, namely, 1st and 2nd levels, in France and UK high density floor are disregarded. Other countries seem to have similar level of requirements.

2.3 Equipments to Mitigate Hazard of Fire

Smoke control and sprinkler are considered to be the most important means to mitigate hazard due to fire so to facilitate safe escape behavior. In the USA, Japan and Australia, sprinklers are required according to height of building, area of each floor or compartment and total floor area of building. In UK and France, the requirements seem to be only on compartment area basis. Any smoke control measure is not required for floor area in the USA and Germany, nor in UK. By contrast, some sort of smoke control means are required when a space exceeds a certain area in Japan, France and Australia.

3. INTERPRETATIONS OF EXIT REQUIREMENTS IN EXISTING REGULATIONS

As was seen in the above, capacity of exits and maximum travel distance are regarded to be the most important requirements for safe escape in the event of fire. Then what level of safety is promised by these requirements? In the following this question is considered taking a floor of a department store as an example.

3.1 Scenario of Evacuation

The scenarios of the evacuation assumed here is as follows:

a)occupants locate uniformly over the floor before the start of evacuation,

b)evacuation starts simultaneously when the smoke layer descends to the height Z_1,

c)troubles arise in evacuation when the smoke layer descends to the height Z_2, and

d)heat release rate of fire Q increases proportionally to square of time, i.e. $Q = Q_0t^2$.

We learn by ample experience of fire that evacuations never start immediately after ignition of fire. Even though fire alarms are sounding, people tend to seek further information or make sure of fire. Often it is only after they have witnessed the fire or recognized the danger that they rush to escape. The smoke layer height Z_1 is the parameter which represents such a stage. This may be specified as $Z_1 = 0.9H$, H being the ceiling height. The height Z_2 represents the stage at which a hazardous situation for evacuation takes place. People might be able to escape through smoke for a short period of time, but at design stage the criteria should be such that no occupant is allowed to be exposed to smoke. So Z_2 may be specified as $Z_2 = 1.6 + 0.1H$ for instance[12]. An alternative criterion such as $Z_2 = h_d$ could be taken, h_d being the exit doorway height, when smoke should be prevented from invading stair cases through exit doorways, which are expected to be kept open during floor evacuation.

The t^2 fire $Q = Q_0t^2$, which is getting popularity over the world as a design fire for some applications, will be a reasonably adequate model representing fire at initial stage. Needless to say, the larger the value of coefficient Q_0, the faster the growth of fire.

3.2 Available Egress Time

From the scenario assumed in the above, it follows that the available egress time of a sales floor is given as the time that smoke layer descends from Z_1 to Z_2. In a space with floor area A, ceiling height H and t^n fire $Q = Q_0 t^n$, the time t that the smoke layer descends to height Z is given as[13]:

$$t = \{ \frac{n+3}{2} \frac{1/(Z+Z_0)^{2/3} - 1/(H+Z_0)^{2/3}}{k\, Q_0^{1/3}/A} \}^{3/(n+3)} \qquad (1)$$

where

$$k = 0.21 (\frac{\rho a^2 g^{1/3}}{CpTa}) \frac{1}{\rho s} \qquad (2)$$

and ρa and ρs are the densities of ambient air and smoke layer, respectively, Ta is the ambient air temperature, Cp and g are specific heat of air and acceleration due to gravity and Z_0 is the distance of the virtual point heat source.

Since n=2 in this particular case, Eq.(1) becomes as

$$t = \{ \frac{5}{2} \frac{1/(Z+Z_0)^{2/3} - 1/(H+Z_0)^{2/3}}{k\, Q_0^{1/3}/A} \}^{3/5} \qquad (3)$$

Therefore, t_1 and t_2 being the times at which Z becomes Z_1 and Z_2, respectively,

$$t_1 = C_1 (\frac{5}{2k})^{3/5} / (\frac{Q_0}{A^3})^{1/5}, \quad t_2 = C_2 (\frac{5}{2k})^{3/5} / (\frac{Q_0}{A^3})^{1/5} \qquad (4)$$

where

$$C_1 = \{1/(Z_1+Z_0)^{2/3} - 1/(H+Z_0)^{2/3}\}^{3/5}, \quad C_2 = \{1/(Z_2+Z_0)^{2/3} - 1/(H+Z_0)^{2/3}\}^{3/5} \qquad (5)$$

So, the available egress time t_A is given as

$$t_A = t_2 - t_1 = \frac{(C_2 - C_1)(5/2k)^{3/5}}{Q_0^{1/5}} A^{3/5} \qquad (6)$$

that is, in a space with t^2 fire, the available egress time increases proportionally to the area to 3/5.

Incidentally, for a constant fire $Q = Q_0$, following the same process as in the above with n = 0, the available egress time becomes as

$$t_A = C' \{ (3/2k)/Q_0^{1/3} \} A \qquad (7)$$

where

$$C' = 1/(Z_2+Z_0)^{2/3} - 1/(Z_1+Z_0)^{2/3} \qquad (8)$$

that is, the available egress time is proportional to area.

3.3 Available Egress Time and Provisions for Exits

In the following, let's consider how available egress time is related with exit width and maximum travel distance. Assuming that occupants are located uniformly over floor area, egress time is almost controlled by the larger of the exit time through doorway t_E and travel time t_L given by:

$$t_E = pA/NB \qquad (9)$$

$$t_L = L/v \qquad (10)$$

where p, B, L, v and N are occupants density(persons/m^2), exit width(m), maximum travel distance(m), travel speed(m/s) and exit flow efficiency (persons/m/s). Equating t_A of Eq.(6) and t_E gives

$$B = (p/N)\{Q_0^{1/5}/(C_2-C_1)(5/2k)^{3/5}\}A^{2/5} \qquad (11)$$

that is, exit width should be increased in proportion to area to 2/5. Next, likewise equating t_A with t_L,

$$L = v(C_2-C_1)\{(5/2k)^{3/5}/Q_0^{1/5}\}A^{3/5} \qquad (12)$$

that is, maximum travel distance can be increased in proportion to area to 3/5. However, it may be necessary to add a safety factor taking into account that people may wander into dead ends or miss exit directions.

Incidentally, for constant fire, B and L become as follows:

$$B = (p/N)Q_0^{1/3}/C'(3/2k) \qquad (13)$$

$$L = vC'\{(3/2k)/Q_0^{1/3}\}A \qquad (14)$$

respectively. So, exit width can be constant regardless of area and maximum travel distance can be increased in proportion to area.

3.4 Consideration on Design Fire

Next, let's try to find out the fire that the prescriptive provisions assume implicitly. From Figure 1, it looks that the existing regulations consider the exit widths as shown in Table 2 are necessary for sales area of 2,000 m^2. Now, from Eq.(11) we have

$$Q_0^{1/5}/\{(C_2-C_1)(5/2k)^{3/5}\} = NB/pA^{2/5} \qquad (15)$$

TABLE 2 Required exit width for sales floor of 2,000 m^2

Country Regulation	(a) Occupant density	(b) Exit width	(c) $NB/pA^{2/5}$	(d) Available egress time ($xA^{3/5}$)
UK high density	0.5	5.0	0.717	1.39
low density	0.143	1.4	0.702	1.42
USA LSC	0.18	2.2	0.876	1.14
UBC	0.18	2.1	0.836	1.20
Australia	0.2	3.5	1.25	0.80
France 2nd FL	1.0/3	4.2	0.903	1.11
3rd FL	0.5/3	3.0	1.28	0.78
>=4th FL	0.2/3	1.8	1.94	0.52
Average(Last one omitted for big difference)			0.94	1.06

Note that the left hand side of Eq.(15) depend only on fire condition. Substituting the values in columns (a), (b), A=2,000 and N=1.5 into the right hand side of Eq.(15) yields the values in column (c). Using these values to Eq.(6), available egress time can be obtained as in column (d) in the same table. Since fire condition and the resulting available egress time should have nothing to do with occupants density, the difference in the numbers implies that the empirical provisions are somewhat inconsistent on the assumption of fire. Taking the average of the values, we have

$$\text{Left hand side of Eq.(15)} = 0.94 \tag{16}$$

This is the fire conditions that give the available egress time as:

$$t_A = 1.06A^{3/5} \tag{17}$$

Using the value of Eq.(16), the exit width for a space with occupants density p can be determined as

$$B = 0.62pA^{2/5} \tag{18}$$

The solid lines in Figure 4 show the values of B calculated using Eq.(18). Where area is small, B shown in Figure 4 may seem larger than the values of the existing provisions in Figure 1, however, the difference in practice is not as significant as it might seem since the latter usually requires two or more exits in this area.

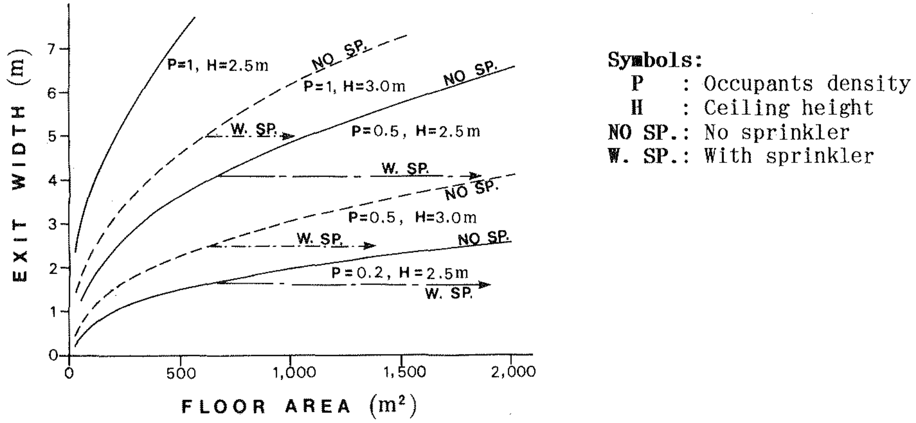

FIGURE 4 Calculated exit widths required for different conditions

Coming back to design fire issue, the left hand side of Eq.(15) is considered to indicate the fire conditions that the existing regulations implicitly assume. In a strict sense, (5/2k) in Eq.(15) is not a constant since it depends on ambient air and smoke layer temperatures, but here this is assumed to be almost constant. Calculation using Ta=293 K and Ts=373 K yields

$$Q_0^{1/5}/(C_2-C_1) = 7.33 \tag{19}$$

Note that the numerator $Q_0^{1/5}$ represents growth of fire and the denominator C_2-C_1 represents safety criteria. There is a degree of freedom in determining the two parameters. Even though one of them is arbitrarily specified, the agreement with the empirical standards is preserved as long as the ratio is kept at the value of Eq.(16) or (19). Here, C_2-C_1 is first determined since it is easier. As can be seen in Eq.(5), this is a function of H, Z_1, Z_2 and Z_0. If the values given in Case 1 and 2 of Table 3 are accepted as the standard conditions, Q_0 can be obtained as follows:

Performing calculation for Case 1, $C_2-C_1=0.1916-0.1012=0.0904$. So, Q_0 is calculated as $Q_0=(7.33\text{x}0.0904)^5=1.28\text{x}10^{-1}$. That is, it follows that the design fire Q_1 for Case 1 is

$$Q_1 = 1.28\text{x}10^{-1}t^2 \tag{20}$$

Likewise for Case 2, the design fire Q_2 is obtained as

$$Q_2 = 1.44\text{x}10^{-2}t^2 \tag{21}$$

The connotation of the difference between the two fires is that the more rigorous the safety criteria, the less severe the design fire has to be for the economy of fire safety measures.

TABLE 3 Conditions for sample calculations

Parameter	Symbol	Case 1	Case 2	Case 3
Ceiling height(m)	H	2.5	2.5	3.0
Smoke layer height at start of evac.(m)	Z_1	0.9H=2.25	2.25	0.9H=2.7
Allowable smoke layer height(m)	Z_2	1.6+0.1H=1.85	hd=2.0	1.6+0.1H=1.9
Constant for t^2 fire	Q_0	$1.28\text{x}10^{-1}$(*)	$1.44\text{x}10^{-2}$(*)	$1.28\text{x}10^{-1}$

(*)Calculated Result

3.5 Application of Safety Criteria and Design Fire

Lastly, examples are given to show how safety criteria and design fire can be applied to different conditions once the design fire has been established.

(i) Space with high ceiling

Let's consider the case shown as Case 3 in Table 3, that is, the case with 3.0m ceiling height, the way to determine layer height criteria and the fire being the same as Case 1. Given the values in Case 3, calculation of Eq.(6) yields $t_A = 1.72A^{3/5}$, that is, the available egress time increases by 50 - 60% from Case 1, in which the ceiling height is 2.5m. Accordingly, the exit width B can be $B = 0.39pA^{2/5}$. This value of B for p=0.5 and 1.0 is shown by the broken lines in Figure 4.

(ii) Space with automatic sprinklers

The significance of automatic sprinklers on safety of egress is always an interesting issue to look into. According to statistics automatic sprinklers are fairly reliable to extinguish fires as long as the heat release is large enough to actuate sprinkler heads. So, only what we have to concern is relatively small fires which cannot be put out by sprinklers.

For ceiling mounted sprinklers, maximum heat release rate that cannot actuate sprinkler heads Qmax may be given as[14]

$$Qmax = 0.08r\{(Tc-T_0+dT)(H+Z_0)\}^{3/2} \qquad (22)$$

where r is the lateral distance between fire plume axis and the closest sprinkler head, Tc, T_0 and dT are the nominal actuation temperature of the head, ambient temperature and margin temperature for sure actuation, respectively. If the spacing of the sprinkler heads is 4m, $r = 2\sqrt{2} = 2.82$m is the largest distance possible, so performing the calculation for the example where H=2.5m, Tc=72 ^oC, T_0=20 ^oC, dT=20 ^oC and Z_0=1m, we have Qmax = 900 kW. Therefore, it is sufficient to assure safety for at most a 900 kW fire in this case. Also, C' is calculated using Eq.(6) as $C' = 1/(1.85+1.0)^{2/3} - 1/(2.25+1.0)^{2/3} = 0.0417$. Substituting these values into Eq.(13), the exit width needed for this space is obtained as B = 8.2p. Therefore in case of p=0.2 and 0.5, B =1.64m and 4.1m, respectively.

Incidentally, if H=3.0m, Qmax = 1,100 kW, and C' = 0.0737 so that exit width B becomes as B = 5.0p. These values are shown also in Figure 4. It can be seen that the exit width can be considerably relaxed by automatic sprinklers.

4. CONCLUDING REMARKS

In developing a performance based standards for fire safety of buildings, to establish adequate safety criteria and design fire is as important as to develop engineering tools for fire prediction. These criteria and design fire have to be so determined as to be harmonized with building economy. In this paper a preliminary consideration is made for this purpose, but more systematic studies using computer fire models will have to be carried out.

REFERENCES

1. Building Code of Australia, AUBRCC, 1988.
2. Reglement de Securite contre l'Incendie - Relatif aux Etablissements Recevant du Public, 4eme edition, Ministere de l'Interieur, 1987.
3. Securite contre l'Incendie - Etablissements Recevant du Public, Magasins, Centre Commerciaux, Journal Officiel de la Republique Francaise 1477 II.
4. La Reglementation de la Construction en Republique Federale d'Allemagne, Norex, 1987.
5. Building Standard Law, Japan.
6. Fire Service Law, Japan.
7. Tokyo Metropolitan Ordinance for Building Fire Safety, Tokyo.
8. The Building Regulations 1985 - Mandatory rules for means of escape in case of fire, Department of Environment and Welsh Office, Her Majesty's Stationary Office, 1985.
9. British Standard 5585 - Fire precautions in the design and construction of buildings, Part 2: 1985 Code of practice for shops, BSI.
10. Life Safety Code 1985, NFPA.
11]Uniform Building Code, 1988 edition.
12. Total Fire Safety Design Method of Buildings, Report of Technology Development Project, MOC, 1989. (in Japanese)
13. Tanaka, T., Yamana, T. : Smoke Control in Large Scale Spaces, Fire Science and Technology Vol.5 No.1, 1985.
14. Alpert, R.L. : Calculation of response time of ceiling-mounted fire detectors, Fire Technology, 8, 1972.