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PERFORMANCE BASED FIRE SAFETY DESIGN STANDARDS AND FSE TOOLS FOR COMPLIANCE VERIFICATION

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1. INTRODUCTION

Traditionally, fire safety measures of buildings in Japan have been controlled almost entirely by the detailed prescriptive provisions stipulated in the building and the fire regulations. Some of them were leaned more or less blindly from overseas countries and others were established by empirical discretions of so-called "fire experts". Such prescriptive provisions may be convenient in a sense since particular technical competence for fire safety engineering is hardly required for designers nor building officials. On the other hand, a disadvantage is that they tend to resist any incompliance however trivial it may be from the safety point of view, thereby discouraging the use of innovative materials, products, construction technologies or novel designs.

Recognizing such problems and considering the significant progress achieved in recent years in the area of fire science and engineering, Building Research Institute (BRI) undertook a five year project called "Development of Fire Safety Design Method for Buildings" 1982 through 1987. In this project, a performance based fire safety design system was addressed. Despite of incompleteness, the design system developed in this project has gained significant popularity among building industries and design firms. It has been extensively used for fire safety design of real buildings through the approval system by Minister of Construction based on the equivalency clause set forth in Article 38 of Building Standards Law. As can be seen in Fig. 1, the number of the fire safety designs applied for the Minister's approval has remarkably increased after the five year project, while the number had been very low for an extended period: only one or two, and sometimes none per year, until the five year project.

However, the design system still has many drawbacks. As a consequence, the system can not yet be independent from the existing regulations. In other words, this can only be used for supplementing and partially rationalizing the fire safety measures of buildings which almost comply with the existing building regulations. So an effort for improving the design system was continued in a regular research of BRI, and more recently as a part of BRI's new five year project "Development of Evaluation Method of Fire Performance of Building Materials and Elements", and in Fire Safety Design Method Subcommittee in AIJ (Architectural Institute of Japan).

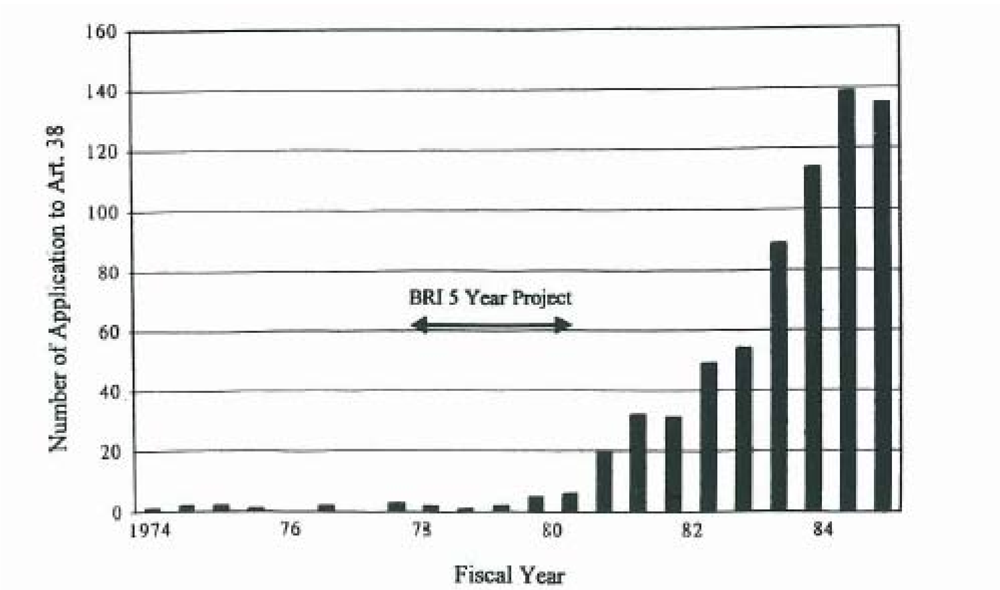

Fig. 1: Growth of number of performance-based fire safety designs of buildings

Fig. 2 illustrates the structure of the design system that has been addressed in Japan, the objectives and the functional requirements to deem to achieve the objectives are first defined, then the technical standards are provided to verify a building design to comply with each of the requirements. The technical standards may include some prescriptive type standards but predominantly consist of performance-based type ones, which are described in terms of design fires and safety criteria.

Due to such features of this design system, various FSE tools will need be involved in the verification of the compliance of the designs to the requirements.

As long as the design system is only used for a relatively limited number of buildings so by a limited number of technically competent engineers in such a case as in Japan at this moment, use of computer models as the FSE tools may not cause much problems. But in order to run this design system in a usual building control system, in which technically less competent designers and building officials are expected to be involved, simpler FSE tools will be indispensable.

In this paper, some of such simple calculation methods now being explored in Japan according to the above consideration are introduced.

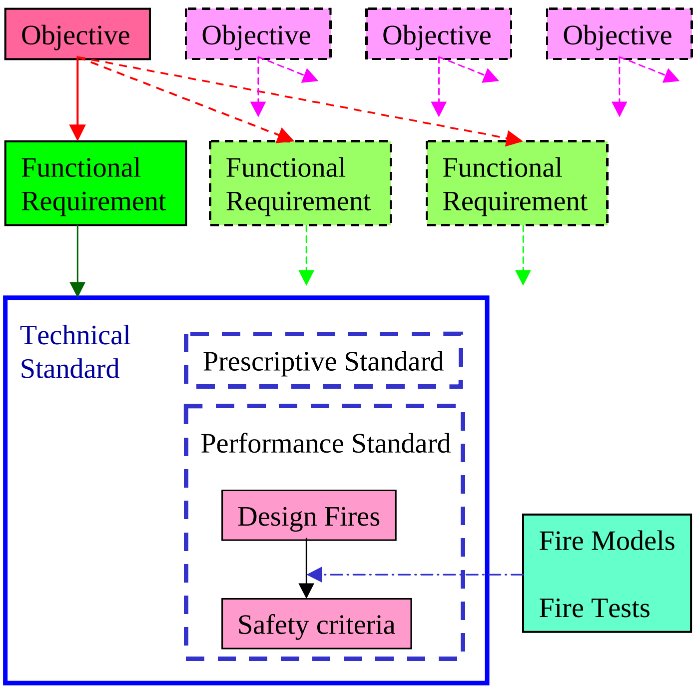

Fig. 2: Framework of a performance-based fire safety design method

2. FIRE SAFETY REQUIREMENTS AND FSE TOOLS

The performance-based fire safety design method in Japan may actually be classified into an objective based design system. In this system, compliance to the minimal requirements prescribed for fire safety is to be verified from one requirement to another basis. Every requirement must be satisfied but in return no additional requirement exists.

In order to identify what the key FSE tools indispensable to run this system are, a matrix showing the relationship between each of the requirements and the FSE tools considered to be used for its compliance verification is provided in Table 1. As can be seen in Table 1, such key FSE tools used for compliance verifications consist of predictive methods for fire source behavior, evacuation, smoke hazard, structural stability, heat conduction, radiation and window flames, and compartment fire behavior, which is the common base for the latter four tools. Although multiple FSE tools need be combined to make compliance verification to a requirement, the same or similar FSE tools can be used for the verifications of multiple requirements. So the actual number of FSE tools needed seem to be rather limited.

Table 1: Fire safety requirements and corresponding FSE tools

FSE TOOLS / REQUIREMENTS	FIRE SOURCE (Fire Plumes) (Flame Radiation)	EVACUATION (Escape time) (Number of Queue)	SMOKE HAZARD	COMPARTMENT FIRE BEHAVIOR			
				STRUCTURAL STABIITY	FIRE/HEAT SP	READ BEYOND	FIRE ROOM
					Heat Conduction	Radiation	Window Flames
PREVENTION OF FIRE	x (Ignition of linings)	-	-	-	-	-	-
HUMAN SAFETY							
Assurance of Safe Refuge	-	-	x (Tenability)	x (Bldg structure)	-	-	-
Assurance of Safe Escape Routes	-	x (at Doorway)	-	-	-	-	-
Avoid Excessive Queue	x (Tenability)	x (Escape time)	x (Tenability)	-	-	-	-
Safety from Smoke	-	-	-	-	x (Wall temp rise)	x (to Evacuees)	-
Safety from Heat	-	-	-	x (Escape routes)	-	-	-
Structural Stability							
PREVENTION OF DAMAGES TO OTHERS							
No Collapse onto Other Buildings	-	-	-	x (Bldg structure)	-	-	-
No Fire Spread to Other Buildings	-	-	-	-	-	x (to Other bldg)	-
No Fire Spread to Other's Spaces	-	-	-	-	x (Wall temp rise)	x (to Other's Spaces)	x (to Other bldg)
Reuse of Multi-Owner Buildings	-	-	-	x (Bldg structure)	-	-	x (to Upper floor)
ASSURANCE OF FIRE DEPARTMENT OPERATION							
Bases of Operation	-	-	x (Tenability)	x (Bldg structure)	x (Wall temp rise)	x (to Fire Brigade)	-
Access to Bases of Operation	-	-	x (Tenability)	x (Access routes)	x (Wall temp rise)	x (to Fire Brigade)	-
Limitation of Fire Sizes	-	-	-	x (Integrity of walls)	x (Wall temp rise)	x (to Adjacent space)	x (to Upper floor)

3. HEAT TRANSFER TO INTERIOR LININGS FROM FIRE SOURCES

Prediction of the heat transfer become necessary in conjunction with "Prevention of Fire Occurrence", one of the objectives of this "Fire Safety Design System". Gennerally, building materials are not significantly responsible for start of fires, yet a significant portion of fires are caused by inadvertent overheating of cooking oils in Japan. So preventing ignition of interior lining by such a fire source has some importance in kitchens of houses or the like. Both radiative and convective heat transfers from fire source need be estimated.

3.1 Radiative Heat Transfer

Once the source of radiation is specified, the calculation of radiative heat transfer to a target, usually a surface element on lining material is fairly straightforward. The properties of a fire as a radiation source will be characterized by the dimensions and emmisive power of the fire. In this regard, estimation of heights of turbulent diffusion flames is most important. Now that ample results are already available thanks to the progress of research in this area this is perhaps only a matter of choice. For example, the formula for flame height H_f by Zukoski et. al will be one of the best choices. This is given as [1]:

$$\frac{H_f}{D} = \begin{cases} 3.3 Q_D^{*2/5} & (Q_D^* \geq 1) \\ 3.3 Q_D^{*2/3} & (Q_D^* < 1) \end{cases} \tag{1}$$

where Q_D^* is the non-dimensional heat release rate defined using the fire source diameter D as the characteristic length as:

$$Q_D^* \equiv \frac{\dot{Q}_f}{C_p \rho_\infty T_\infty \sqrt{g} D^{5/2}} \left(\approx 0.9 \times 10^{-3} \frac{\dot{Q}_f}{D^{5/2}} \right) \tag{2}$$

where $\dot{Q}_f$ is heat release rate of fire source (Fig.3).

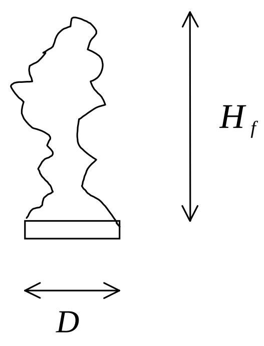

Fig. 3: Height of turbulent diffusion flames

3.2 Incident Heat Flux from Fire Plumes to Ceilings

Heat transfer from fire plumes above fire sources to ceilings may be said a mixture of radiative and convective heat transfer. It will be convenient not to separate these two modes of heat transfer in many practical applications. Based on Kokkala's experiments for heat transfer to ceilings from impinging flames [2], in the configuration as shown in Fig. 4, total incident heat flux to a ceiling $\dot{q}_C''$ [kW/m^2] may be correlated as:

$$\dot{q}_C'' = \min\left\{ 23 \left(\frac{H_f}{H_C} \right)^{7/3}, 60 \right\} \tag{3}$$

where H_C is the ceiling height from the source.

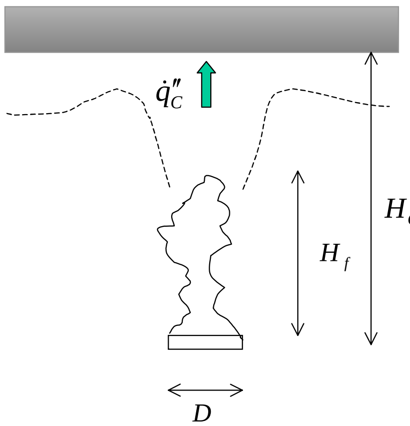

Fig. 4: Ceiling heat transfer from impinging fire plume

4. EVACUATION

Adequacy of escape route is not only the matter of its capacity, such as width of doorways, corridor, stairway etc., but also depends on various design features, such as legitimate and recognizable signs and proper texture of floors etc. too. However, the purpose of the calculation of evacuation here is confined to assessment of the adequacy of the capacity of escape routes, since it is considered that the issues associated with design features are beyond the capacity of mere calculations, so should be covered by means of proper prescriptive standards. In building fires, most people die either trapped by smoke or stuck at narrow doorways. Hence the calculation method needs to enable to assess escape time and maximum queuing to see if people can escape from a space before the space has become untenable by smoke and if no excessive queuing will be formed at any doorway or other bottle neck on the escape routes. Note, however, that the maximum escape time and the maximum queuing may not always take place under the same evacuation scenario, in which case each has to be assessed under different scenarios.

Some of the sophisticated computer evacuation models incorporate the behavior of evacuees responding to smoke or incapacitation of occupants. However, it should be bear in mind that at the stage of the design of escape routes the designers do not intend to expose occupants to hazardous smoke but seek for designs of exits which enable building occupants to evacuate safely and orderly. The central interest in building design practices is to know whether or not the capacity and arrangement of exits in a specific building are acceptable to achieve safe evacuation. Considering the purpose of the calculations, the following simple methods will be sufficient.

4.1 Room Evacuation

In the prediction of room evacuation, it is assumed that occupants are uniformly distributed in the room at the beginning, start to escape simultaneously and travel to doorway exits. In rooms with furniture, like office rooms, it is assumed that occupants cannot get straight to an exit but have to make a certain number of turns before arriving at the exit.

4.1.1 A room with only one exit

The calculation of evacuation of a room may become significantly complex depending on the geometry of the room, even in the simplest case where the room has only one exit as shown in Fig. 5, but the following formulas give a conservative estimate both for evacuation time t_E and maximum queuing $C_{\max}$ [3].

$$t_E = \begin{cases} \dfrac{P}{NB} + \dfrac{1}{2}\dfrac{NB}{pv^2} & \{NB < pv(l_1 + l_2)\} \\ \dfrac{l_{\max}}{v} & \{pv(l_1 + l_2) \le NB\} \end{cases} \qquad (4)$$

and

$$C_{\max} = \begin{cases} P\left[1 - \dfrac{NB}{pv(l_1 + l_2)}\right] & [NB < pv(l_1 + l_2)] \\ 0 & [pv(l_1 + l_2) < NB] \end{cases} \qquad (5)$$

where P and p are the total number and the density of occupants in the room, B and N are the width of the doorway and its occupant flow efficiency, v is the travel velocity, $l_{\max}$ is the maximum travel length, and l_1 and l_2 are shorter sides of the two pseudo rooms which are generated by dividing a room perpendicularly at the doorway:

$$l_1 = \min\{ra, b\}, \quad l_2 = \min\{(1-r)a, b\}$$

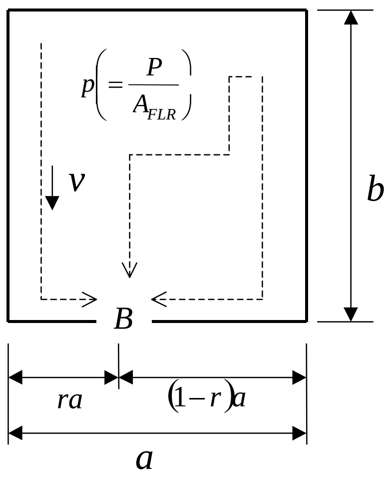

Fig. 5: Evacuation from a room with a single exit

4.1.2 A room with multiple exits

In case of a room which has multiple exits and within which occupants can move freely, occupants will seek the exit which enable them get out most quickly, as illustrated by Fig. 6. This scenario will be the more plausible the severer the situation. Hence, assuming that all the exits are cleared at the same time, the escape time t_E is given by:

$$t_E = \frac{P}{N\sum_{i=1}^{n} B_i} + \frac{1}{2}\frac{N}{pv^2}\frac{\sum_{i=1}^{n} B_i^2}{\sum_{i=1}^{n} B_i} \qquad (6)$$

and it follows that each exit is used by the number of people given as follows:

$$P_k = \frac{B_k}{\sum_{i=1}^{n} B_i}\left\{P + \left(\frac{1}{2}\frac{N^2}{pv^2}\right)\left(\sum_{i=1}^{n} B_i^2 - B_k\sum_{i=1}^{n} B_i\right)\right\} \qquad (7)$$

then assuming n pseudo rooms each of which having only one exit and the area $(P_k / P)A_{FLR}$ corresponding to the allocated number of occupants, the evacuation time t_E and maximum queuing $C_{\max}$ can be calculated in similar manner with "*A room with only one exit*" in the above.

However, in case of rooms in which free movement of occupants is restricted, it will be better to assume the pseudo rooms according to the distance to the nearest exit.

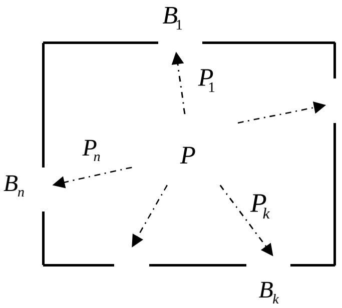

Fig. 6: Evacuation from a room with multiple exits

4.2 Floor Evacuation

An escape route on a floor usually consists of consecutive multiple spaces connected by doorways, such as "an office room - a corridor a stair vestibule". Such an escape route no seldom involves merging and branching. The evacuation time and maximum queuing become to be a function of travel distance and doorway widths along the route.

4.2.1 Escape route having no merging or branching

In the simplest case where an escape route consisting multiple spaces has no merging or branching as shown in Fig. 7, the escape time to an arbitrary location on the route $t_{E,l}$ can be simply given by:

$$t_{E,l} = \frac{l}{v} + \frac{P}{NB_{\min}} \tag{8}$$

where l is the distance of the location from the origin of the escape and $B_{\min}$ is the smallest width of the doorways in the upstream of the occupants' escape flow. The maximum queuing at an arbitrary doorway $C_{\max,k}$ in this case can be calculated by:

$$C_{\max,k} = P\left(1 - \frac{B_k}{B_{ntk}}\right) \tag{9}$$

where B_{ntk} is the width of the doorway which is the narrowest of all the doorways in the upstream which are wider than doorway k. If there is a doorway narrower than doorway k in the upstream, no queue is formed at doorway k.

Note, however, minor modification is necessary in Eqns.(8) and (9) when the space immediately in the upstream of doorway k does not have enough space to accommodate the maximum queuing $C_{\max,k}$.

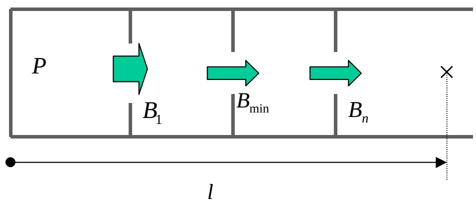

Fig. 7: Escape route with no merging or branching

4.2.2 Escape route with merging

As a fire floor evacuation scenario, it is conceivable that multiple escape flows merge at a doorway, such as when occupants issued to a corridor from multiple rooms arrive at a doorway to a staircase, as illustrated in Fig. 8. A number of arriving patterns can be possible depending on the time of evacuation start from each room. The worst of the scenarios with respect of heavy queuing, therefore important for escape route designs, will be that all the escape flows merge at the doorway simultaneously. This imply difference in escape start time from any room ranges within the difference of the times needed for the occupants to travel from the remotest and nearest room to the doorway. Then a practical formula for the escape time of the occupants on the floor can be given by:

$$t_E = \frac{l_{\max}}{v} + \frac{\sum_{i=1}^{n} P_i}{NB_a} \tag{10}$$

where B_a is the width of the doorway to which the occupants' flows merge. A practical formula for the maximum queuing in front of the doorway is given by:

$$C_{\max} = \sum_{i=1}^{n} P_i \left(1 - B_a \Big/ \sum_{i=1}^{n} B_i\right) \tag{11}$$

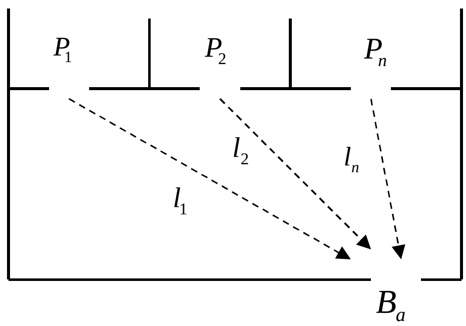

Fig. 8: Escape route with merging

4.2.3 Escape route with branching

Another possible scenario is that the occupants' flow through a doorway happens to enter a space having multiple exits, as illustrated in Fig. 9. In this case, it is assumed that the occupants exit from the room so choosing an exit as to minimize the evacuation time from the room, frantically trying to flee from the hazardous situation as fast as possible. Note, however, it is not always optimal for the fastest evacuation to use all the exits. For example, if the width of the exit nearest to entrance is larger than the width of entrance, the fastest is to use this exit since no time delay due to queuing take place. Therefore evacuation time has to be checked incresing the number of exits used. In general form, the equation of the evacuation time t_E is given by:

$$t_E = \min .\left(\left. \frac{P_O + N\sum_{i=1}^{k} B_i \left(l_i / v \right)}{N\sum_{i=1}^{k} B_i} \right| : k = 1,2,...,n \right) \quad (12)$$

where P_O is the number of occupants entering the space, and l_i is the travel length from the entrance doorway to exit i.

The number of occupants who use k-th exit Q_k is given by:

$$P_k = NB_k \left(t_E - \frac{l_k}{v} \right) \quad (13)$$

and the maximum queuing at exit k is given by:

$$C_{\max} = P_O \left(1 - \frac{B_k}{B_O} \right) \quad (14)$$

where B_O is the width of the entrance doorway originating the occupants' flow in the space.

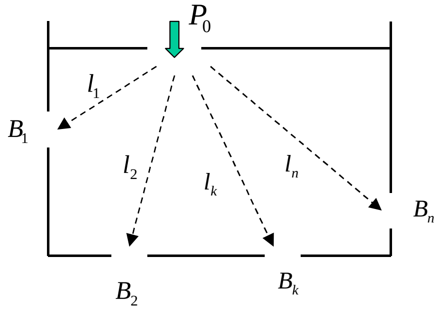

Fig. 9: Escape route with branching

4.3 Total Building Evacuation

A stairway can be considered as a vertical corridor from the evacuation point of view, so similar formulas as Eqns.(10) and (11) apply for predicting the travel time and maximum queuing.

5. SMOKE HAZARD

When multiple rooms or other complex conditions are involved, prediction of smoke behavior by hand calculation is often too difficult so there is no choice but to use computer smoke movement model. However, if specific objectives are given and a certain degree of conservative simplification is allowed in building design practice, not negligible problems may be solved by simpler hand calculations.

5.1 Smoke Filling

The objective of predicting smoke filling in practical applications is often related to assess available egress time under given fire source and space geometry. The fire source is now being simplified into design fires such as a t^2 (t –square) fire in the consideration of performance-based fire safety design system ongoing worldwide. The space geometry may be significantly complex in real buildings but may also be so simplified as to yield conservative predictions. Then, the formulas below are practical for estimating smoke filling times in the room of origin.

5.1.1 Plume mass flow rate after Zukoski [1]

Considerable work has been done for establishing plume flow rate above fire source. Most of the formulas for the plume flow rates take the same form although the coefficient may be different to some degree depending on the investigators. According to Zukoski for the coefficient, the plume flow rate $\dot{m}_p$ is given as:

$$\dot{m}_p = 0.21 \left(\frac{\rho_\infty^2 g}{C_p T_\infty} \right)^{1/3} \dot{Q}_f^{1/3} z^{5/3} \approx 0.07 \dot{Q}_f^{1/3} z^{5/3} \quad (15)$$

where $\dot{Q}_f$ and z are heat release rate of a fire source and height from the source, respectively.

5.1.2 Smoke filling in a space with uniform horizontal section area

Smoke filling in a room with a uniform horizontal section area, as shown in Fig. 10, is considered here as one of the simple yet practical smoke filling problems. For a t^2 fire, which is the fire whose heat release rate $\dot{Q}_f$ grows proportionally to square of time, that is $\dot{Q}_f = Q_0 t^2$ where Q_0 is the growth coefficient of heat release rate, smoke layer interface height z at a given time after ignition can be estimated by [4]:

$$z = \left\{ \frac{2}{5} \left(\frac{0.07 Q_0^{1/3}}{\rho_s A_R} \right) t^{5/3} + \frac{1}{H_R^{2/3}} \right\}^{-3/2} \qquad (16)$$

where A_R is the floor area, H_R is the ceiling height of the room and ρ_s is the smoke layer density. Or in terms of time as a function of layer height z:

$$t = \left\{ \frac{5}{2} \left(\frac{\rho_s}{0.07 Q_0^{1/3}} \right) \left(\frac{1}{z^{2/3}} - \frac{1}{H_R^{2/3}} \right) \right\}^{3/5} A_R^{2/3} \qquad (17)$$

as long as the horizontal section area of the room of origin is the same as A_R indifferent of the height from the floor.

Similarly, for a constant fire, which is expressed as $\dot{Q}_f = Q_0$, the smoke layer interface height is given as:

$$z = \left\{ \frac{2}{3} \left(\frac{0.07 Q_0^{1/3}}{\rho_s A_R} \right) t + \frac{1}{H_R^{2/3}} \right\}^{-3/2} \qquad or$$

$$t = \frac{3}{2} \left(\frac{\rho_s}{0.07 Q_0^{1/3}} \right) \left(\frac{1}{z^{2/3}} - \frac{1}{H_R^{2/3}} \right) A_R \qquad (18)$$

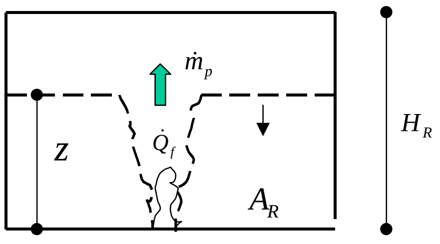

Fig. 10: Smoke filling in a room with t-square fire

5.2 Smoke Venting

In building design practices, the objectives of predicting smoke behavior under naturally or mechanically smoke vented conditions are most often to find out an appropriate size of smoke vent or rate of mechanical smoke extraction to keep smoke layer above a certain height. In such cases, the fire source may be simplified into a constant fire conservatively assumed. A couple of examples of hand calculations for such applications are shown here [4].

5.2.1 Natural smoke vent size

Considering a steady state fire under two layer configuration as illustrated in Fig. 11, the area of natural vent, installed on an upper part of a space, necessary to keep the smoke layer above a critical height z_c can be assessed by following the procedure as follows:

1. plume flow rate $\dot{m} = 0.07 \dot{Q}_f^{1/3} z_c^{5/3}$ (19.1)
2. smoke layer temperature (19.2)
   $T = T_\infty + \dot{Q}_f / \left[C_p \dot{m} + h\{A_C + L(H_R - z_c)\} \right]$
3. smoke layer density $\rho = 353/T$ (19.3)
4. floor level pressure difference
   $\Delta p = \dot{m}^2 / 2\rho_\infty (\alpha A_D)^2$ (19.4)
5. vent area required (19.5)
   $A_E = m / \alpha \sqrt{2\rho\{-\Delta p + (\rho_\infty - \rho) g (H_E - z_c)\}}$

where ρ, T are smoke layer density and temperature, ρ_∞, T_∞ are the ambient density and temperature, A_C, L are the ceiling area and perimeter length of the room, A_E, H_E are the area and the height from the floor of the smoke vent, $A_D, \Delta p$ are the area of air inlet and the pressure difference at the level of the floor, α is opening flow coefficient and g is the acceleration due to gravity.

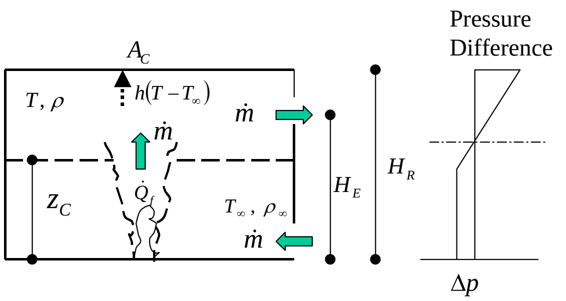

Fig. 11: Natural smoke venting

5.2.2 Rate of mechanical smoke extraction

To achieve the same criterion for smoke layer height by means of mechanical ventilation, the required extraction rate $\dot{m}_e$ is simply given by:

$$\dot{m}_e = 0.07 \dot{Q}_f^{1/3} z_c^{5/3} \qquad (20)$$

Note, however, it will be not practical to attempt to keep layer interface at high level because the required extraction rate may easily exceed the capacity of usual fans.

5.3 Pressurization Smoke Control

Vestibule pressurization smoke control, often combined with elevator shaft pressurization, is now increasingly popular in Japan, particularly for office buildings. This smoke control system can be employed to support fire floor evacuation by preventing smoke penetrating into corridor as well as to support whole building evacuation. The example here is shown only for the latter, which is most important for life safety.

The objective of the calculation is to find the air supply rates to the vestibule and the elevator shaft required to prevent smoke from infiltrating into staircases or elevator shaft thereby to assure the building evacuation and fire fighting. Fig. 12 illustrates a simplified floor plan of typical office buildings in Japan. The procedure for calculating the air supply rates based on average pressure difference concept is illustrated for this example as follows [5]:

1. Pressure differences necessary to prevent smoke infiltration to lobby and elevator shaft

(lobby - corridor) $\Delta p_{LC} = \frac{4}{9}\Delta\rho_{LC} g H_{LC}$ and

(elevator - corridor)

$$\Delta p_{EC} = \frac{4}{9}\Delta\rho_{EC} g H_{EC} \qquad (21.1)$$

where $\Delta\rho, \Delta p, H$ stand for density difference, pressure difference and doorway height, respectively, and subscripts LC and EC stand for between "lobby and corridor" and "elevator shaft and corridor", respectively.

2. Flow rates corresponding to the above pressure differences

(flow rate from lobby to corridor)

$\dot{m}_{LC} = \alpha A_{LC}\sqrt{2\rho_L \Delta p_{LC}}$ and

(flow rate from elevator to corridor)

$$\dot{m}_{EC} = \alpha A_{EC}\sqrt{2\rho_E \Delta p_{EC}} \qquad (21.2)$$

where ρ_L, ρ_E are densities of the lobby and the elevator shaft, respectively. A_{LC}, A_{EC} are the areas of the doorways between "lobby and corridor" and "elevator shaft and corridor", respectively.

3. Corridor pressure p_C

$$p_C = \frac{\left(\dot{m}_{LC} + \dot{m}_{EC} - \dot{u}_C\right)^2}{\left\{\sum\left(\alpha A_{CR} A_{RO}\sqrt{2\rho_c \rho_R / \left(\rho_C A_{CR}^2 + \rho_R A_{RO}^2\right)}\right)\right\}^2} \qquad (21.3)$$

where ρ_C, ρ_R are densities of the corridor and the room, including the room of origin, respectively, A_{CR}, A_{RO} are the area of the doorway between "corridor and the rooms" and the opening area between "the room and the outdoor", respectively, and $\dot{u}_C$ is the smoke extraction rate in the corridor.

4. Pressures of the lobby and elevator shaft at the level of fire floor

(lobby) $p_L = p_C + \Delta p_{LC}$ and

(elevator shaft) $p_E = p_C + \Delta p_{EC}$ (21.4)

5. Air leak from lobby to staircase and elevator shaft

(lobby to staircase)

$$\dot{m}_{LS} = \frac{\alpha A_{LS} A_{SO}\sqrt{\rho_L \rho_S}}{\sqrt{\rho_L A_{LS}^2 + \rho_S A_{SO}^2}}\sqrt{2\left\{p_L + \left(\rho_O - \rho_S\right) g H_{LS}\right\}}$$

(lobby to fire elevator)

$$\dot{m}_{LF} = \frac{\alpha A_{LF} A_{FO}\sqrt{\rho_L \rho_F}}{\sqrt{\rho_F A_{LF}^2 + \rho_F A_{FO}^2}}\sqrt{2\left\{p_L + \left(\rho_O - \rho_F\right) g H_{LF}\right\}} \qquad (21.5)$$

where ρ_S, ρ_F, ρ_O are the densities of the stair, the fire elevator and the outdoor, respectively, A_{LS}, A_{LF} are the areas of the doorway between "lobby and the stair" and the leakage between "lobby and the fire elevator", A_{SO}, A_{FO} are the opening area between "the stair and the outdoor" and "the fire elevator and the outdoor", respectively, and H_{LS}, H_{LF} are the vertical distance between "lobby and the stair opening to the outdoor" and "lobby and the fire shaft opening to the outdoor".

6. Air leak from elevator shaft to the outdoor

$$\dot{m}_{EO} = \alpha A_{EO}\sqrt{2\rho_E\left\{p_E + \left(\rho_O - \rho_E\right) g H_{CE}\right\}} \qquad (21.6)$$

where ρ_E is the density of the stair, A_{EO} is the areas of the leakage between "the elevator shaft and the outdoor" and H_{CE} is the vertical distance between "corridor and the opening of the elevator shaft open to the outdoor".

7. Air supply rates to lobby and elevator shaft

Using the flow rates calculated as above, the required air supply rate for the lobby $\dot{W}_L$ and that for the elevator shaft are given as:

(lobby) $\dot{W}_L = \dot{m}_{LC} + \dot{m}_{LS} + \dot{m}_{LF}$

and (elevator shaft) $\dot{W}_E = \dot{m}_{EC} + \dot{m}_{EO}$ (21.7)

respectively.

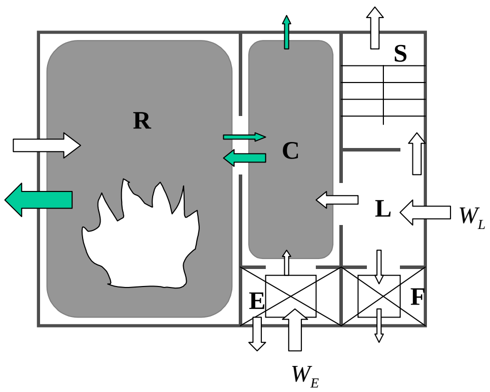

Fig. 12: Vestibule pressurization smoke control

6. COMPARTMENT FIRE BEHAVIOR

Prediction of compartment fire behavior has been one of the main topics in fire research area. It is obviously important in many practical applications since it is the basis for assessments of stability of building structures and fire spread beyond fire compartment.

6.1 Mass Burning Rate

An engineering formula for estimating mass burning rate of wood fuel in fuel control and ventilation control regimes in compartment fire, which is critical for predicting fire behavior, has been experimentally established as [6]:

$$\frac{\dot{m}_b}{A_{FUEL}} = \begin{cases} 0.1\chi & (\chi \le 0.07) \\ 0.007 & (0.07 < \chi \le 0.1) \\ 0.12\chi e^{-11\chi} + 0.003 & (0.1 < \chi) \end{cases} \quad (22)$$

where A_{FUEL} is the surface area of the combustibles in the room and χ is the parameter defined by:

$$\chi \equiv A_W \sqrt{H_W} / A_{FUEL} \quad (23)$$

where $A_W \sqrt{H_W}$ is the ventilation factor of the room. It is considered that the factor χ determines the type of burning of compartment fires. Note that the region $\chi \le 0.07$ corresponds to under-ventilated fires where mass burning rate is known to be proportional to ventilation factor, while the region $0.07 < \chi$ corresponds to over-ventilated fires, where mass burning rate asymptotically get closer to its value in an open space as ventilation factor becomes larger as illustrated by Fig. 13.

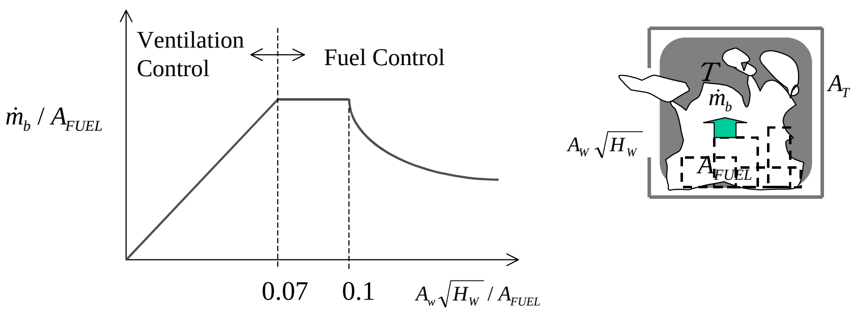

Fig. 13: Mass burning rate in compartment fire

Using the mass burning rate given by Eqn.(22), fire duration t_D can be calculated as:

$$t_D = wA_{FLR} / \dot{m}_b \quad (24)$$

Incidentally, a method for estimating the surface area of live combustibles in building spaces in real use has been proposed as:

$$A_{FUEL} = \phi W \quad (25)$$

where W stands for total weight of live combustibles (kg) and ϕ stands for surface area ratio and may be estimated based on field fire load survey as:

$$\phi = \begin{cases} 0.54w^{-2/3} & (office\ room) \\ 0.39w^{-2/3} & (hotel\ room) \\ 0.61w^{-2/3} & (apartment) \end{cases} \tag{27}$$

where w stands for fire load density [7].

6.2 Compartment Fire Temperature

Although compartment fire temperatures is usually predicted by means of a computer models, the following simple equation can be an alternative for the temperature rise ΔT_{FIRE} in fire compartments.

$$\frac{\Delta T_{FIRE}}{T_\infty} = \begin{cases} 3.0\left(\frac{A_W\sqrt{H_W}}{A_T}\right)^{1/3}\left(\frac{t}{k\rho c}\right)^{1/6} & (\chi \le 0.07) \\ 0.022\frac{\dot{Q}^{2/3}}{\left(A_T A_W\sqrt{H_W}\right)^{1/3}}\left(\frac{t}{k\rho c}\right)^{1/6} & (0.07 < \chi) \end{cases} \tag{28}$$

where t is time in second, $k\rho c$ and A_T are the thermal inertia and the total surface area of the compartment boundary.

The formula for over ventilated region ($0.07 < \chi$) is from McCaffrey et. al.[8], in which case the heat release rate $\dot{Q}$ should be calculated as:

$$\dot{Q} = \Delta H_w \dot{m}_b \tag{29}$$

where ΔH_w is the heat of combustion of wood [kJ/kg] and Eqn.(22) can be utilized to estimate $\dot{m}_b$.

The maximum possible heat release rate within a compartment in ventilation control fires, i.e. $\dot{Q} = 1{,}500 A_W\sqrt{H_W}$, has been taken into account in the formula for under ventilated region ($\chi \le 0.07$) [9].

7. STRUCTURAL STABILITY

The temperatures and duration of compartment fires predicted based on design fire differ from one to another depending on the conditions regarding ventilation and heat transfer in the compartment. On the other hand, fire performance of structural elements is tested under unique temperature condition. Heat conduction calculation could be invoked if we had all the material properties at our disposal, which is unfortunately not the case. Undeniably, it is one of the most important issues for rational and flexible fire safety designs to establish some means to translate the results from standard fire resistance tests into performance under design fire conditions.

Noting that the compartment fire temperature can be assessed by the above formula $\Delta T_{FIRE} \propto t^{1/6}$, and that ISO standard fire test temperature ΔT_{ISO} can be approximated as:

$$\Delta T_{ISO} \equiv 345\log_{10}(8t/60+1) \approx 230t^{1/6},$$

the practically convenient conversion methods can be proposed as follows:

7.1 Equivalent Fire Duration

If the equivalent fire duration t_{eq} of a duration t_{dsn} under design fire temperature ($\Delta T_{FIRE} = \beta t^{1/6}$) can be considered as the time under standard fire test condition ($\Delta T_{ISO} \approx 230t^{1/6}$) at which the heat absorbed to a specimen becomes the same as that under design fire conditions, the relationship between the two duration can be given as [10]:

$$\frac{t_{eq}}{t_{dsn}} = \left(\frac{\beta}{230}\right)^{3/2} \tag{30}$$

7.2 Superposition Method

The temperatures measured for a test specimen ΔT_{msrd} , such as temperature of a steel covered by insulation, unexposed side temperature of a fire wall etc. under the standard test can be converted to the temperatures under design fire conditions ΔT_{dsn} using superposition method as follows[11], [12]:

$$\Delta T_{dsn} = \left(\frac{\beta}{230}\right) \times \begin{cases} \Delta T_{msrd}(t) & (0 \le t \le t_{dsn}) \\ \Delta T_{msrd}(t) - \Delta T_{msrd}(t - t_{dsn}) & (t_{dsn} < t) \end{cases} \tag{31}$$

where t_{dsn} is the duration of design fire, which can be calculated as $t_{dsn} = W / \dot{m}_b$.

7.3 Parameter Estimation Method

If thermal properties can be estimated from the measurements under standard fire test, well established heat conduction computations can readily be invoked. Parameter estimation method has been developed for this purpose [13], although description of this method is omitted for shortness of paper.

8. FIRE/HEAT SPREAD BEYOND FIRE COMPARTMENT

Assessing the hazards of fire spread beyond fire compartments are related with requirements for preventing damages to third parties, assurance of fire brigade operation and so on. Since fire spreads may be caused by heat conduction through compartment boundaries, by radiation and by window flames, practical FSE tools need be provided for these three modes of fire spread.

8.1 By Heat Conduction

Temperature rise of the unexposed side surface of the compartment boundaries is usually used as the criterion for the prevention of fire/heat spread to spaces adjacent to fire compartment due to heat conduction. The methods described in "STRUCTURAL STABILITY" can be employed for this purpose as well.

8.2 By Radiation

The hazard of fire/heat spread to adjacent buildings or spaces due to radiation is assessed based on incident radiation flux to a target $\dot{q}''_{in}$, which is calculated by well established method as:

$$\dot{q}''_{in} = \phi E_f \left(= \phi \sigma T_{FIRE}^4\right) \quad (32)$$

Formulas for calculating the configuration factors are provided for a variety of geometry in a number of heat transfer books. However, in majority of practical cases, the radiation source is simplified as a rectangular shape and the target is assumed to be a plane element parallel to the source plane and on the central axis of the source as shown in Fig. 14. In this case the estimation of the configuration factor for elliptical plate as follows will be sufficiently accurate in many of the practical situations [14]:

$$\phi = \frac{ab}{\sqrt{\left(s^2+a^2\right)\left(s^2+b^2\right)}} \left(= \frac{A_{source}}{4\sqrt{\left(s^2+a^2\right)\left(s^2+b^2\right)}} \right) \quad (33)$$

where *a*, *b* are the half length of the rectangular radiation source and *s* is the distance between the source and the target surface element. It will not be so difficult for whom familiar with calculation of configuration factors to extend this formula to calculate the configuration factors for the cases where the target surface element is not on the central axis of the source plane.

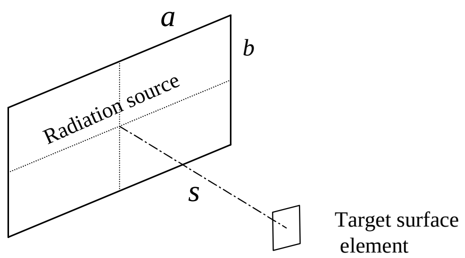

Fig. 14: Calculation of a typical configuration factor

8.3 By Window Flames

Window flames or window jet plumes are a major cause of upper floor fire spread and perhaps not a negligible cause of fire spread to adjacent buildings in densely built urban area. It is a common practice to assess the hazard of upper floor fire spread based on the estimation of axis temperature of window jet plume. However, the temperature which actually affects to fire spread is not exactly the axis temperature but the temperature to which windows on upper floors are directly exposed, which differs depending on many design features, such as geometry of window, spandrel or balcony. A practical means to take into account such design features in assessing the hazard of fire spread by widow flames may be using reduced scale experiments provided that an appropriate scaling parameter is established. In this regard, the non-dimensional temperature defined as:

$$\Theta(\xi,\psi,\zeta) \equiv \left(\frac{\Delta T(x,y,z)}{T_\infty}\right) / Q_W^{*2/3} \quad (34)$$

with $$Q_W^* = \frac{\dot{Q}_W}{C_p \rho_\infty T_\infty \sqrt{g} B_W H_W^{3/2}} \quad (35)$$

$$(\xi,\psi,\zeta) = (x/D,\ y/D,\ z/D)$$

proved to be a good practical scaling parameter for temperature at an arbitrary location (*x, y, z*) outside a window, regardless the fire room temperature and window dimension[15]. In Eqn.(30), B_W, H_W are the width and the height of the window, respectively, *D* is the characteristic length of the window jet, for which B_W, H_W or other length representing the length scale of the window jet can be used, and $\dot{Q}_W$ is the heat issued from the window, which, in practical applications, may be estimated as:

$$\dot{Q}_W = C_p \dot{m}_d \Delta T_{FIRE} \quad (36)$$

letting $\dot{m}_d$ be the mass flow rate of gases ejecting from the window.

If the temperatures at the locations of interest $\Delta T(x, y, z)$ are measured in a reduced scale experiments, the non-dimensional temperature $\Theta(\xi, \psi, \zeta)$ can be established. Then, the temperatures at geometrically similar locations in real scale building can be obtained by letting Θ be the same between the reduced scale and the real scale as long as the window jet geometry is similar.

9. CONCLUDING REMARKS

Researchers may not be attracted to such simple FSE tools as exemplified in this paper since those do not always address fundamental theories nor advanced technologies. However, they will certainly benefit the currently ongoing activities for the development of performance based design systems. We have to bear in mind that any of the most sophisticated computer models developed to date has not yet integrated all the FSE tools needed for designs of real buildings. Also, such computer models tend to conceal the calculation procedure in a black box so induce blind use of the results. Perhaps we need more engineers who have sound knowledge on fire behavior and technical skills to cope with fire hazard and risk. Simple engineering tools will certainly foster such knowledge and skills. It is, as I believe, very much needed that some portion of efforts in fire research community is devoted to the development of such practical FSE tools.

NOMENCLATURE

Symbols

A_{FLR}	floor area (m^2)
A_{FUEL}	fuel surface area (m^2)
A_C	ceiling area (m^2)
A_D	door way area (m^2)
A_E	smoke vent area (m^2)
A_{FLR}	floor area (m^2)
A_{FUEL}	fuel surface area (m^2)
A_{IJ}	area of opening between space I and J (m^2)
A_{source}	area of radiation source (m^2)
A_T	total area of compartment boundary (m^2)
$A_W\sqrt{H_W}$	ventilation factor of a window ($m^{5/2}$)
a, b	half lengths of the sides of a rectangular radiation source (m)
B	exit width (m)
$C_{\max}$	maximum queuing in front of a doorway (*person*)
C_p	specific heat of air (kJ/kgK)
D	fire source diameter, characteristic length (m)
E_f	radiative energy flux of source (kW/m^2)
g	gravitational acceleration (m/s^2)
H_C	ceiling height (m)
H_{IJ}	height of doorway between space I and J (m)
H_f	flame Height (m)
H_R	room height (m)
h	total heat transfer coefficient (kW/m^2K)
$k\rho c$	thermal inertia (kJ^2/m^4K^2s)
l	travel length (m)
$l_{\max}$	maximum travel length (m)
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}_{IJ}$	opening mass flow rate from space I to J (kg/s)
$\dot{m}_b$	mass burning rate (kg/s)
$\dot{m}_p$	mass plume flow rate (kg/s)
N	doorway people flow coefficient ($person/ms$)
n	number of rooms, doorways
P	occupant load $(= pA_{FLR})$, Total number of occupants ($person$)
P_k	number of occupants escaping through arbitrary exit k ($person$)
Δp_{IJ}	pressure difference between space I and J (Pa)
p	pressure (Pa), Occupant density ($person/m^2$)
$\dot{Q}_f$	fire source heat release rate (kW)
Q_0	growth coefficient of t-square fire (kW/s^2), heat release rate of constant fire (kW)
Q^*	non-dimensional heat release/addition rate
$\dot{q}''_C$	total incident heat flux to a ceiling (kW/m^2)
T	temperature (K)
ΔT	temperature elevation (K)
t	time (s)
$\dot{u}$	mass extraction rate of smoke (kg/s)
s	distance between radiation source and target surface element (m)
v	escape travel speed (m/s)
W	total fire load in a compartment (kg)
W_L, W_E	air supply rate to lobby, elevator shaft (kg/s)
w	fire load density (kg/m^2)
z	height, Smoke layer interface height (m)
z_c	critical smoke layer interface height (m)

Greeks

α	opening flow coefficient
ϕ	configuration factor
ρ	density (kg/m^3)
$\Delta\rho_{IJ}$	air density difference between space I a116 (kg/m^3)
Θ	non-dimensional temperature
σ	Stefan-Boltzmann constant (= 5.67x 10^{-11} kW/m^2K^4)

Subscripts

C	corridor
E	elevator shaft
F	fire elevator
L	staircase lobby
O	outdoor
R	room, room of fire origin
S	stair
∞	ambient

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