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Technology Administration
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Fire Safety Design and Fire Risk Analysis Incorporating Staff Response in Consideration of Fire Progress Stage

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Abstract

The purpose of this study is to propose a framework for fire risk analysis. The method used involves modeling the fire escalation process into fire phases and evaluating the fire risk from the probability of fire phase escalation. The particular feature of this risk analysis method is that it also takes into account the actions of security staffs in the event of a fire, and the reliability of fire protection measures, both of which greatly affect the degree of damage that may result from a fire. This evaluation method may also be used in fire safety design as a systematization method of fire protection measures against a target fire phase of the building in question.

1. Introduction

Generally, the success or failure of fire protection measures and the action taken in the event of a fire can be expected to have a major effect on the spread of a building fire. However, in the conventional deterministic evaluation model of fire safety, these factors are not considered. Such considerations are usually treated in only a qualitative manner during the process of fire safety design. In the large and complex buildings in recent years, the response of fire safety personnel (security staff) in an emergency is a factor of major significance to fire safety.

The purpose of this study is to formulate a fire safety assessment method that takes into account the action of security staff in the event of a fire and also the reliability of major fire protection measures. For this purpose, we treat the spread of fire as an escalation of the fire thorough various stages (known as fire phases). The method assesses whether or not measures to prevent escalation at each fire phase can be brought into effect within a critical time of the phase being reached. In doing this, probability data of the starting time of security staff action are used. Then, fire safety is evaluated from the probability of escalation from each fire phase to the next. In this report, we propose a framework for risk analysis that incorporates security staff response based on the fire phase concept. We then look at the features of this analysis method from the perspective of fire safety design.

In addition, this fire phase-based method of risk analysis was developed as a part of the research project being carried out by Tokyo Fire Department. [1) 2)]

2. Classification of Fire Phase

Seen from the perspective of the aims of fire safety, it is useful to express the fire spread in terms of various stages. This is because the fire protection measures can be planned and organized systematically against the specific conditions that cause to escalate from a certain stage to the next. This understanding can clarify the target of fire safety design and provide alternative of fire safety measures. In this study, we define a fire as a process of escalation through various phases from the viewpoint of fire safety design.

Using this approach, the threshold of the initial stages is set from the capable condition for staff response and the performance of fire protection measures. The critical time for security staff is defined according to the condition of hindrances against human action, so that smoke layer height is adopted as the threshold. Once a room fire escalates, it spreads in units of space, such as by room, compartment, and floor. We can understand the phases as the level of fire damage. Figure 1 illustrates the defined fire phases and the thresholds for phase escalation.

It is important to remember that, depending on the particular characteristics and the success/failure of fire protection measures, fire does not always progress in order through these phases, but may skip phases.

The conditions for escalation of fire phase are analyzed using fault tree analysis, and the failure modes of these are composed fire protection measures and staff response. The fire spreading process is only considered at the point of escalation between fire phases. This makes it easier to incorporate fire safety response to a fire and the reliability of fire protection measures into the evaluation of fire safety. In this process, the dynamic aspects of fire spread are taken into account in evaluating the critical time of each fire phase.

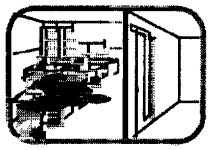
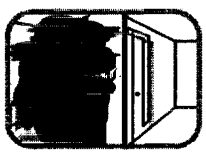
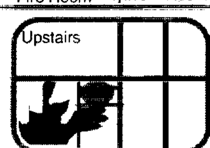
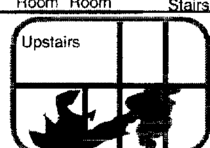
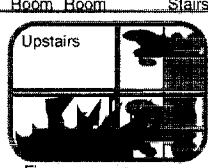
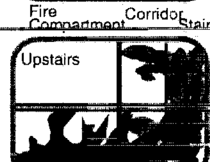
Fire Phase	Image of Fire Phase	State of Period of Fire Phase	Threshold of Fire Phase Escalation	Combination of Fire Prevention Actions
Phase I	 Fire Room Adjacent Room	Fire occurs and is growing up. It is able to be extingished by fire security staffs.	$Min.(T_{950}\ T_{Ph2})$ T_{950}: Heat Release Ratio Reaches 950kW	Cntrol automatic Detection System Emergency Elevator Fire Extinguisher Standpipe System Sprinkler System
Phase II	 Fire Room Adjacent Room	Fire is growing and is not able to be extiguished by fire extiguisher. Heat smoke layer forms under the ceiling of the fire room.	T_{Ph2} Limitation of the Critical Egress Time of Fire Room Smoke Layer Height < Human Height	Standpipe System Sprinkler System
Phase III	 Fire Room Adjacent Room	Fire is growing and people cannot stay in the fire room. Temperture of the fire room is growing up.	T_{Ph3} Temperture of Smoke Layer of Fire Room Reaches 600 •• (incombustible) 300 •• (combustible) •@	Closing the doors of the Fire Room Starting Smoke Exhaust System Turning off Air Conditioning System
Phase IV	 Fire Room Adjacent Room	Fire spreads over the fire room (flashover) , and keep buring in the fire room.	T_{Ph4} Fire Resistance Time of Fire Room (door and wall)	Fire Brigade Action Emergency Elevator Vestibule
Phase V	 Upstairs Fire Room Adjacent Room Corridor Stairs	Fire spreads out to adjacient rooms	T_{Ph5} Fire Resistance Time of wall or Door of Fire Room	Fire Brigade Action
Phase VI (= phase V)	 Upstairs Fire Room Adjacent Room Corridor Stairs	Fire spreads to corridors.	T_{Ph6} Fire Resistance Time of Corridor (Compartment)	Fire Brigade Action
Phase VII	 Upstairs Fire Compartment Corridor Stairs	Fire spreads to lobbies.	T_{Ph7} Fire Resistance Time of Compartment (Vestibule)	Fire Brigade Action
Phase VIII	 Upstairs Fire Compartment Corridor Stairs	Fire spreads to upstairs.	T_{Ph8} Radiant Heat of Flame Flame Height Reach to Upper Floor	Fire Brigade Action

Figure 1: Fire Phase and Threshold Classified from the Perspective of Fire Safety Design [2) 3) 4)]

3. Framework of Fire Phase Escalation

3.1 The concept of fire phase escalation assessment

Figure 2 outlines the concept of the assessment of fire phase escalation. The starting time of proper action and the critical time of each fire phase are compared in the respective fire phases. If the required response for a certain fire phase is not carried out within the critical time, the fire phase will progress further, whereas if the response is carried out in time, further escalation will be successfully prevented. Further, the critical time in each fire phase depends on fire protection measures and sequence of fire phase escalation.

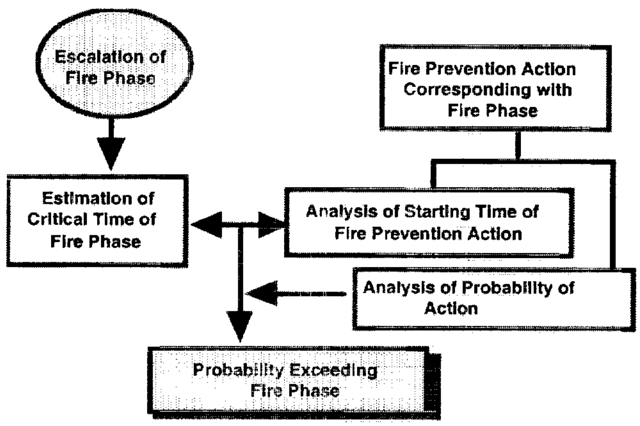


Figure 2: Framework of Assessment of Fire Phase Escalation

3.2 Calculation of Critical Time

The critical times of fire phases are calculated using analytical methods under the condition of the success or failure of fire protection measures in a deterministic way. Further, after the outbreak of a room fire, the fire resistant performance of the compartment is taken as an index of the critical time for a case where the doors are closed. Therefore, if the fire duration time is greater than the fire-resistant time of the doors or walls, the resistant time of the doors/walls is the critical time of the phase. If all doors of a compartment are not closed, the fire will spread immediately to the next compartment. Figure 3 illustrates the analytical models of fire and smoke behavior used. We adopted the BRI models.

3.3 Evaluation Procedure

In evaluating fire phase escalation, we can calculate the exceeding probability index of escalation of a certain fire phase by using the probability of the starting times of staff response in that phase and the probability of occurrence of that phase. This procedure is repeated for each phase. Evaluation of overall risk is carried out using expected value of burnt area, and we can obtain a full understanding of the characteristics of fire safety performance via risk curve represented in the form of the exceeding probability of each fire phase. The probability density functions are applied to analyze the data of the fire safety response action, and the reliability of fire protection measures is used in the condition for calculating the critical time of each phase.

Figure 4 illustrates the relationship between the time at which fire safety action is taken and the starting time at which the design fire model begins. We assume a smoldering stage here. The time elapsed after the fire outbreaks until the automatic fire detection system triggers is assumed to be 60 seconds, and this is the point at which the fire model starting. This time of difference depends on the type of fire detection system.

4. Starting Time of Staff Response in the Event of Fire

To determine the staring time of fire safety actions in the event of a fire, we investigated the training of fire safety center personnel. The Tokyo Fire Department conducts the training courses for such staffs. The training program includes the use of a fully equipped simulator incorporating a fire control center room with fire control console, an emergency elevator, an emergency communication equipment, a standpipe, an emergency public-address system, etc. During the training, the times at which different fire safety actions began after the outbreak of a fire were automatically recorded. Six people for a standard team and a fire room on the 22nd floor were assumed,

Fire Phase	Expression of Critical Time for Fire Phase
Phase I	$Min(T_{950}, T_{Ph\,2})$ $T_{950} = \sqrt{\dfrac{950}{\alpha}} + T_{lag}$
Phase II	$T_{Ph2} = \left\{\dfrac{5}{2}\dfrac{\rho}{k}\dfrac{A_{room}}{\alpha^{1/3}}\left(\dfrac{1}{(1.6+0.1H_{room})^{2/3}} - \dfrac{1}{H_{room}^{2/3}}\right)\right\}^{3/5} + T_{lag}$
Phase III	$T_{Ph\,3} = \begin{cases} 600 & (\text{interior finish is incombustible}) \\ 300 & (\text{interior finish is combustible}) \end{cases}$ $T_{Ph3} = 0.0236 Q^{2/3} \left(h_k A_T A\sqrt{H}\right)^{-1/3} T_\infty + T_0 + T_{lag}$
Phase IV • VII	Fire Resistance Time of Compartment
Phase VIII	$\Delta T > 350$ $\int_0^{t_p} q'' dt > 2.0 \times 10^3$

Figure 3: Calculation of Critical Time of Fire Phase Escalation for this Study [6)]

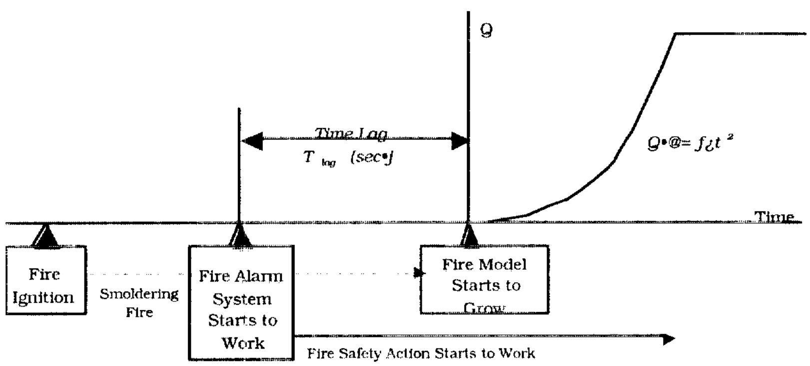


Figure 4: Arrangement between the Times of Fire model and Fire Safety [1) 2)]

and 73 teams were recorded. Three members of staff were dispatched to the fire room and the others took control of the systems in the fire control center after the fire alarm working.

Table 1 summaries these starting times of fire safety actions, Figure 5 - 11 give the distribution of the data. Table 2 shows the reliabilities of the fire safety measures applied in this study. The first step actions after the automatic fire detection system is triggered are control of console and immediate dispatch of personnel to the fire room via the emergency elevator. These personnel then, confirm the existence of the fire, communicating with the fire control center. The standard procedure thereafter is to fight against the fire using fire extinguishers and to close the doors of the fire room. Once confirmation is received by the fire control center, the fire department is contacted. In a large proportion of cases, these initial steps are successful, and there is little difference in the starting times of different teams.

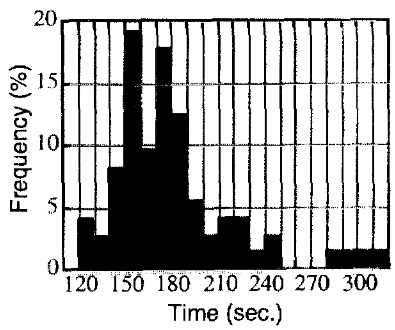
Table 1: Summary of the Starting Times of Fire safety Actions [1) 2)]

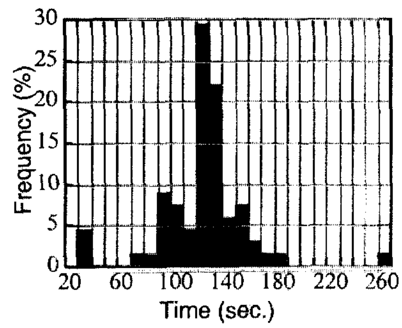
Action	fÊ (sec)	fÐ (sec)	p (%)	Estimation Curve Type
E0・E1	120.5	19.8	93.2	Log-Logistic
E0・E2	189.4	28.0	82.2	Lognormal
E0・E3	57.2	4.2	98.6	Log-Logistic
E0・E4	116.0	84.5	87.7	Weibull
E0・E5	179.1	102.7	80.8	Weibull
E0・E6	138.6	78.2	100.0	Lognormal

Index	Meaning	Index	Meaning
E0	Arrival at Fire Floor	E5	Turning off Air Conditioning System
E1	Use of Fire Extinguisher	E6	Fire Department Notification
E2	Use of Fire Hose Station	fÊ	Average of Starting Time
E3	Fire Door Closing for Compartment	fÐ	Standard Deviation of Starting Time
E4	Starting Smoke Exhaust System	f±	Probability of Action

Table 2: Reliability of Fire Safety Measures Established [2)]

Fire protection measure		Reliability	Reference
Automatic sprinkler system		0.972	Fire data of Tokyo Fire Department (1987-1996)
Automatic fire detection system		0.945	same as above
Fire extinguisher		0.996	same as above
Standpipe system		0.971	same as above
Smoke extraction system		0.974	Annual Inspection Data (1989-1997)
Emergency generating system		0.998	Investigation by Kakegawa [7)]
Fire door	Automatically closing	0.97	Established by Tokyo Fire Department based on investigations
	With inter-locking device	0.91	same as above
Fire shutter		0.91	same as above





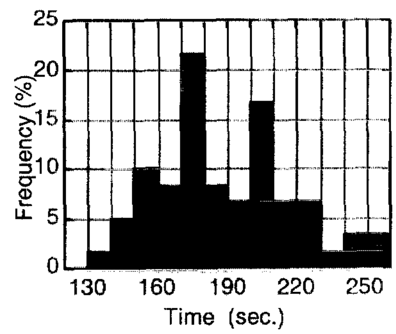
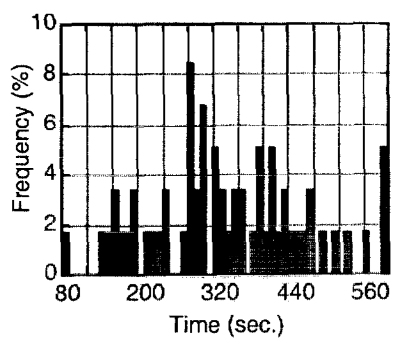
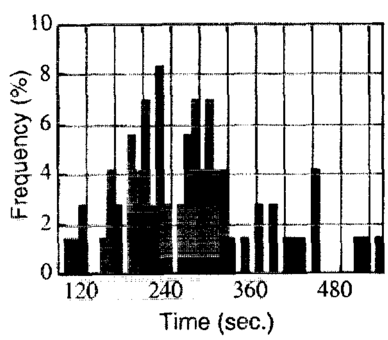


Figure 5. Arrival Time at Fire Floor Figure 6. Time of Fire Extinguisher Usage Figure 7. Time of Standpipe System Usage





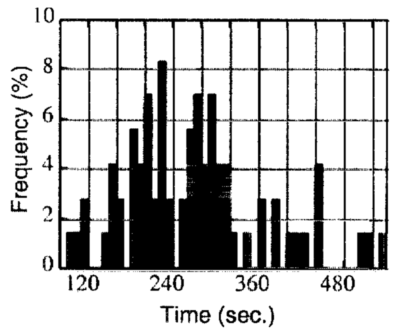


Figure8. Start Time of Smoke Exhaust System after Arrival Time

Figure9. Time of Turning off Air Conditioning System after Fire Detection

Figure10 Time of Fire Department Notification after Fire Detection

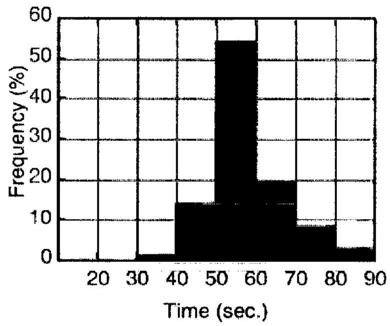


Figure 11: Time of Closing Door of Fire Room after Arrival Time

Subsequent actions include using the standpipe, using the emergency public-address system, operating the smoke extraction system, and stopping the air conditioning system, etc. However, the ratio of implementation of response in these steps begins to fall off, and there is considerable difference among teams. The ratio of standpipe use is 82%, and that for operating the smoke extraction system is 88%. There is large divergence in ratios of different teams. (Note: the emergency public-address system is used in 93% of cases, and also its use usually late.)

5. Case Study

As a case study, we applied the new evaluation method to the building shown in Figure 12. Based on the data mentioned above, the time taken for the fire department to arrive at the fire floor was calculated. As a result, the exceeding probability of each fire phase is shown in Figure 13.

In cases where the sprinkler system is not installed, or where the sprinkler system fails (assumed to be a probability of 0.03), the followings can be understood (the case of improved fire prevention systems without SP). The exceeding probability of escalation beyond Phase 2 is 0.4. Because the room is small, the fire grows quickly to the critical condition for staff response, and initial fire extinguishing (phase 2) will not be successful. Then, the probability of the fire reaching Phase 2 is 0.7, and the probability that the fire spread further in the room is 0.4 (that is Phase 3). The probability of fully developed fire in the room the exceeding probability of escalation beyond Phase 3 is 0.15. However, the probability of reaching Phase 5, in which the fire has an impact on the corridor, is 0.03 in exceeding Phase 4, since the probability of closing doors is 0.996.

Equipment that required human intervention tends not to be worked to its full potential. For example, efforts to extinguish fires using standpipe systems are actually quite ineffective. In cases where the smoke exhaust system also requires manual operation, its availability in terms of life safety is limited because it tends to be switched on late. This tendency is particularly notable in the type of building which are comprised of small rooms without fire compartment. A consideration of how this kind of emergency action is actually implemented leads to the conclusion that there is a need to rethink emergency response to match the characteristics of each particular building in question.

Figure 14 illustrates the effectiveness of fire protection measures elucidated from a parametric study of expected value of burnt area in the cases where various fire protection measures are in place or absence. It is clear that sprinkler systems are highly effective. Automatic fire detection systems also have a considerable effect on how much a fire spreads, and implementation of closing door of the fire room also is effective. It is because these lead to success of other fire safety actions in the initial stages. Architectural fire protection measures are not particularly effective in terms of expected value of burnt area, but, from the viewpoint of preventing escalation beyond phase 4, compartmentalizing is highly effective. This parametric study obtains quantitatively the characteristics of the fire safety measures and fire prevention activities.

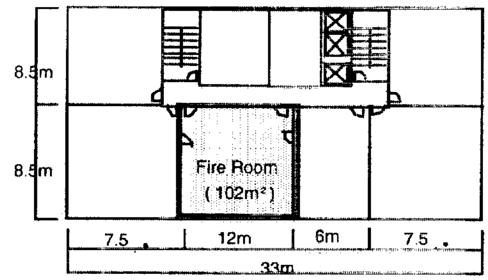


Figure 12: Model Plan of Case study

6. Conclusion

6.1 Effect of Delayed Response

From the analysis carried out here, late response, low implementation ratio of response and wide proportion of distribution of the response time cause to serious fire spreading. In particular, the times of using the extinguisher and the standpipe system and operating smoke control system are found to be late in cases where a fire spreads from a small fire room.

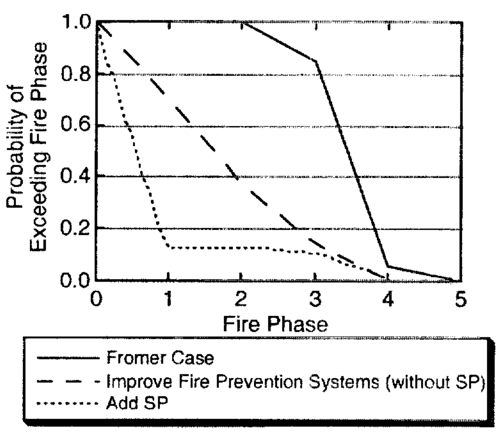


Figure 13: Risk Curve expressed as Exceeding Probability of Each Fire Phase [2)]

Case	N	I1	I2	I3	I4	I5	I6	EFDA •itF•j	Reduction Rate 0 20 40 60 80 100 (%)
1	0							94.3	•
2	1					•,		94.1	0.1%
3	1				•,			91.6	2.8%
4	1	•,						87.9	6.7%
5	1			•,				85.3	9.5%
6	2	•,			•,			85.3	9.5%
7	2			•,	•,			81.4	13.6%
8	2	•,		•,				79.6	15.6%
9	3	•,		•,	•,			75.7	19.7%
10	1		•,					69.2	26.6%
11	2	•,	•,					63.4	32.8%
12	2		•,		•,			62.4	33.8%
13	3	•,	•,		•,			56.7	39.8%
14	2		•,	•,				42.3	55.1%
15	3	•,	•,	•,				38.3	59.4%
16	3		•,	•,	•,			34.6	63.3%
17	4	•,	•,	•,	•,			30.8	67.3%
18	5	•,	•,	•,	•,	•,		16.7	82.3%
19	1						•,	12.0	87.3%
20	6	•,	•,	•,	•,	•,	•,	0.8	99.1%

Explanatory Notes N: Number of items Improved
I1: Improvement of Compartmentalization (Fire Resistance Time, Fire Door Closing)
I2: Improvement of Security Staffs' Skill
I3: Improvement of Fire Alarm System
I4: Improvement of Maintenance grade
I5: Addition of Smoke Exhaust System
I6: Addition of Sprinkler System
EFDA: Expected Value of Average Fire Damage Area

Figure 14: A Parametric Study for Response of Fire Protection Measures [2)]

These data reflect the training of fire control center personnel. These indicate the need to maintain the capability to take the correct action. Further, in most cases, a fire control center has between three and six personnel on duty. The smaller this numbers the greater the wide distribution of response time. We believe that this has a very serious impact on the life safety of evacuation except evacuation from fire room.

Generally, when evaluating fire safety performance, design fire scenarios are rarely set such as failure or delayed time of fire safety action. The results of the case study demonstrate that it is necessary to consider suitable response and their sequence for each fire phase. Also, it is important to carry out an overall assessment of automatic fire detection systems, extinguishing systems and building fire protection measures to the target of fire safety design. We believe that phasing and modeling a fire into fire progress stages from the viewpoint of preventing fire escalation is a valuable tool in the systematization of fire protection measures.

6.2 Effectiveness of Phase Escalation Concept for Risk Assessment

We believe that by applying the fire phase concept, we have achieved the following results.

By focusing on the escalation of fire progress stages, it becomes easier to incorporate the success or failure of fire protection measures and fire safety response into risk analysis. The fact that the evaluation includes human factors is the most significant feature of this study, though the methodology is still in the prototype stage.

Further, this method allows us quantitatively understand the fire safety characteristics of a building from expected value of burnt area and exceeding probability of each phase. Thus, it is possible to plan more effective fire protection measures that meet the needs and characteristics of a particular building. The technique can also be applied to assess the fire response sequence and the number of security staff required.

7. Issues Facing Systematization of Fire Safety Design

This study is simply a prototype risk analysis incorporated security staff response, so there remain the following issues facing progress development.

(1) Determination of initial lag time

In this study, we assume that there is a lag after ignition until the starting time of the fire model ($Q=kt^2$), and that smoke detector works in smoldering stage. Though this lag time depends on the type of automatic fire detection system in use and other factors, it significantly affects the success or failure of the response in the preliminary stage. It is necessary to determine these lag times through experiment or analysis of actual fire data.

(2) Setting of parameters

We have obtained some experimental data of fire safety response, but there is a need for more data to improve reliability. Further, parameters must be set so as to ensure that the data conform to actual conditions (e.g., the degree of experience of security staff, the number of security staff, etc.)

(4) Independence of fire escalation factors

This trial model of risk analysis computes probability of each fire protection measure independently. This independence of factors should be studied further, taking into account the response in the event of a fire, because there are interactions among human factors, fire stages and availability of fire protection measure.

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