

## Studies on Human Behavior and Tenability in Fire Smoke

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### ABSTRACT

This paper presents scientific basis for establishing safety evacuation countermeasures, i.e., evacuation plans and escape signs etc., in case of fire in Japan. Especially issues of physical and physiological effects of fire smoke on evacuees are addressed. This paper consists of three headings, in order of my research life: 1) visibility, 2) characteristics of human behavior, and 3) development of an “Intensive System for Escape Guidance” in fire smoke.

In Japan, since the 1960's, there have been an increasing number of people killed by smoke in fire resistant buildings. Toxic gases and/or depletion of oxygen in fire smoke are the final death causes of those victims, however many evacuees are trapped in early stage of fire by relatively thin smoke and loss of visibility is an indirect but fatal death cause. In this reason, the relations between the visibility and optical density of fire smoke were examined by experiments, and practical equations were proposed.

For further understanding of human behavior in fire smoke, many fire investigations were conducted by interviews and questionnaires to evacuees. Also experimental research were conducted with subjects under limited fire smoke conditions, and a threshold of fire smoke density for safe evacuation were examined.

Through many field investigations of fires, it is found that an effective guidance sign system is required for safety evacuation in fire smoke. Development of conspicuous exit signs, using a flashing light source was one of my first research works to improve evacuation under smoke filled conditions. A new type of the escape guidance in fire smoke by continuously traveling, flashing light sources was developed and its effectiveness was examined in a smoke filled corridor. These innovative technology for safe evacuation is now in practical use in Japan.

**KEYWORDS:** fire smoke; visibility; people behavior; tenability; exit sign; escape guidance

## **INTRODUCTION**

In Japan, since the 1960's, there have been an increasing number of people killed by smoke in fire resistant buildings. This trend has been recognized by many people concerned with the fire safety science and technology as well as fire safety authorities and has emphasized the importance of the research on fire smoke. Many full scale experiments were conducted in Tokyo metropolitan area in the years around 1965. I and my staff took part in these experiments, especially those measuring smoke density. They were the beginning of my research on the interaction between human behavior and fire smoke.

At first, visibility in fire smoke was our major concern. However, in due course, I became interested in human behavior in fire smoke. The research on human behavior was mainly conducted by interviews of and questionnaires sent to evacuees from hotel and department store fires. These interviews revealed some inexplicable human behavior in fire smoke. So, in the next research stage, I started another series of experiments on human behavior in fire smoke. These tests were directed at understanding the psychological and physiological status of evacuees in real fire situations by using test subjects. The experimental work was conducted very carefully and under very limited conditions, because very little knowledge then existed about how fire smoke might effect the subjects in serious situations. After much experimental work, I realized that, in an emergency, it is very important to have leaders who are familiar with the inside of the building.

Unless there are reliable leaders, other, substitution ways, are required. That is, an intensive system for escape guidance is required for safe evacuation. Development of conspicuous exit signs, using a flashing light source was one of my first research works to improve evacuation under smoke filled conditions. A new type of the escape guidance in fire smoke by continuously traveling, flashing light sources was developed and its effectiveness was examined in a smoke filled corridor. Recently this new type of exit sign has appeared in practical use in Japan in specific buildings and spaces such as underground shopping malls. A form of this is already found in the floor lighting of passenger aircraft cabins.

Thus my research fields can be categorized under three headings as follows, in order of my research life:

- 1) visibility,
- 2) characteristics of human behavior, and
- 3) development of an Intensive System for Escape Guidance in fire smoke.

## **PART 1. VISIBILITY IN FIRE SMOKE**

### **1.1 Research Background**

There were many research works on visibility in fog in the past. Whereas few researches have been carried out on the visibility in fire smoke. This difference is mainly owing to physical characteristics of those composite particles. Fog is composed of water mist and the shape is almost sphere. The particle size is also relatively stable in time and space. These simple characteristics enable to develop visibility model in fog.

On the other hand the characteristics of the fire smoke, i.e., composition, shape and size, depend on combustible materials and/or conditions of combustion. Also those are highly dependent on surrounding flow and temperature fields, and vary from time to time. Development of the mathematical visibility model based on such physical parameters seems to be attractive for many researchers, however it must be very complicated and it tends to be out of practical use.

My first trial was to obtain experimental visibility model by test subjects in various kinds of smoke. The smokes were generated with combustible materials under different oxygen supply rate. For evaluating the visibility, visible distance of a sign plate in the smoke was measured. In the experiments, smoke extinction coefficient, irradiance of the sign and its light contrast against surrounding background, irradiance of smoke due to light scattering were measured, then ratio ( $k$ ) of scattering coefficient and extinction coefficient was obtained under various kinds of smoke conditions.

Existing theory indicated that this value  $k$  varied in wide range with the composition and shape of smoke particles, however my experimental results showed it varied only from 0.4 to 1.0. Usually the compositions, size and shape of the particles are simplified to calculate the  $k$ . In real fire smoke, various shape and size of the particles are mixed and the variety of the smoke seems to offset the size and shape effects on the  $k$ .

The  $k$  is more sensitive to combustion condition, especially oxygen supply but not materials. The smoke generated with less oxygen supply tends to become white smoke and the  $k$  closes to 1.0. Contrary it becomes black and the  $k$  becomes smaller when more oxygen is supplied. However, the  $k$  is internal term of  $ln$  for estimating visibility as shown in Equation (1), then difference of the  $k$  between white and black smoke does not give much effects on visibility. As a result, the visibility of signs at the obscuration threshold can be expressed with a very simple formula.

## 1.2 Smoke Density and Visibility

Visibility of signs through fire smoke can be expressed approximately by the following equation [1]

$$V \approx \frac{1}{C_s} \ln \left( \frac{B_{EO}}{\delta_c k L} \right) \quad (1)$$

- where  $V$  : visibility of signs at the obscuration threshold (m)  
 $C_s$  : smoke density expressed by the extinction coefficient (1/m)  
*\*(hereafter, smoke density will be expressed by the extinction coefficient in 1/m)*  
 $B_{EO}$  : brightness of signs (cd/m<sup>2</sup>)  
 $\delta_c$  : contrast threshold of signs in smoke at the obscuration threshold.  
 (0.01 ~ 0.05)  
 $k = \sigma_s / C_s$  (0.4 ~ 1.0)  
 and

$$C_s = \sigma_s + \sigma_{ab} \quad (\sigma_s : \text{scattering coefficient} ; \sigma_{ab} : \text{absorption coefficient})$$

$$L : 1/\pi \text{ of mean illuminance of illuminating light from all directions in smoke}$$

$$(1\text{m/m}^2)$$

For placard-type (reflecting) signs Equation (1) can be modified to

$$V \approx \frac{1}{C_s} \ln\left(\frac{\alpha}{\delta k}\right) \quad (2)$$

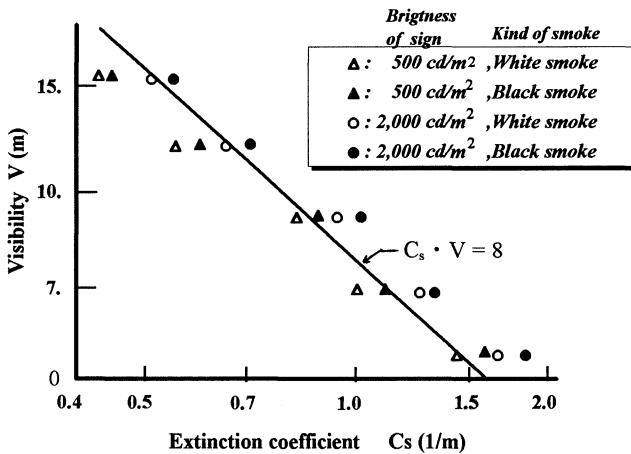
where  $\alpha$  : reflectance of sign.

The signs in a smoke-filled chamber were observed from outside through a glass window. The results are shown in **FIGURE 1**. This shows the relation between the visibility of light-emitting signs at the obscuration threshold and the density of smoldering smoke (white) or flaming smoke (black). In the range of the visibility of 5~15 m, the product of the visibility ( $V$ ) at the obscuration threshold and the smoke density ( $C_s$ ) is almost constant.

The visibility in black smoke is somewhat better than in white smoke of the same density; this remarkable difference in visibility is not recognized among smokes from various materials. For reflecting signs, the product of the visibility and smoke density is almost constant, too. The product depends mainly on the reflectance of the sign and the brightness of illuminating light. The visibility ( $V$ ) at the obscuration threshold of signs is found to be,

$$V = (5 \sim 10) / C_s \text{ (m)} \quad \text{for a light-emitting signs,} \quad (3)$$

$$\text{and} \quad V = (2 \sim 4) / C_s \text{ (m)} \quad \text{for a reflecting sign.} \quad (4)$$



**FIGURE 1.** Relation between the visibility of light-emitting signs at the obscurity threshold and smoke density (Extinction coefficient)

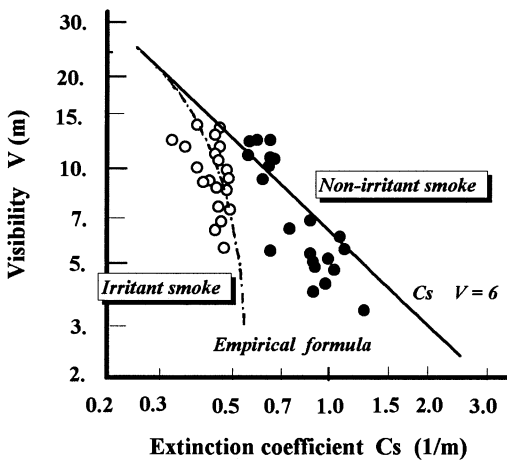
The visibility of other objects such as walls, floor, doors, stairway, etc. in an underground shopping mall or a long corridor varies depending on the surrounding reluctance and contrast condition, however, the minimum value for reflecting signs may be applicable.

### 1.3 Visibility of Signs through Irritant Smoke and Walking Speed

A 20-meter long corridor was filled with smoke corresponding to an early stage of fire; a highly irritant white smoke was produced by burning wood cribs with narrow spacing between the sticks, and a less irritant black smoke was produced by burning kerosene. The subjects were instructed to walk into the corridor from one end, or to record the places at where they saw a lighted FIRE EXIT sign at another end, or to read the words on the signs[2]. For the obscuration threshold of the sign, the following relation can be found  $C_s \cdot V \approx \text{constant}$ . However, for visibility at the legible threshold of words, this relation can only apply to non-irritant smoke as shown in **FIGURE 2**.

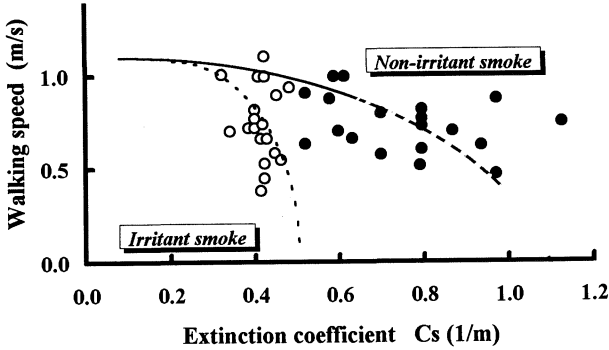
The visibility in irritant smoke decreases sharply at the smoke density exceeding a certain level. In the thick irritant smoke, the subjects could not keep their eyes open for a long time, and tears ran so heavily that they could not see the words on signs. Even in this case, when the exit signs are so simple or familiar with occupants to understand at a glance, this irritant effect of smoke may not cause a trouble so much to recognize the exits.

The smoke irritation reduces the visibility of evacuees moreover and subsequently there will be a possibility to give them needless unrest or panic. The smoke hazards of notice are found not only in such psychological aspects[3][4], but also in their actions, especially walking speed.



**FIGURE 2.** Visibility of the FIRE EXIT sign at the legible threshold of the words in irritant and non-irritant smokes.

**FIGURE 3** shows an example data of the experiment of walking speed in the smoke conducted before. Both smoke density and irritation affect the walking speed apparently. This figure shows that the walking speed in the none irritant smoke decreases gradually as increasing the smoke density. However, in the irritant smoke the speed decreases rapidly in the region over certain smoke density level as same as the visibility dose. From the observation of this experiment, this sharp drop of walking speed is explained by the subjects' movement; they could not keep their eyes open, then they walked inevitably zigzag or step by step along the side wall.



**FIGURE 3.** Walking speed in fire smoke

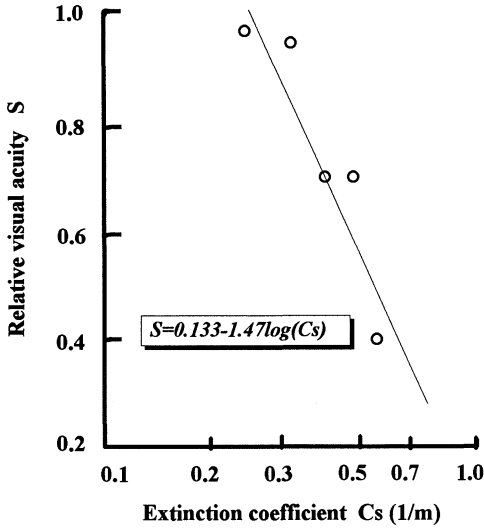
#### 1.4 Decrease of Visual Acuity in Irritant Smoke [2]

Further laboratory studies were conducted with universal Landolt's ring test chart in the high irritant smoke-filling room to obtain the relation between the visual acuity and the smoke irritant effect. Weber-Fechner's Law gives the relationship between an impact on a human sensitivity and its response; the response of human sensitivity is logarithmically proportional to the impact intensity[5].

This well known theory is applied to the series of experiments, that is,  $S = A - B \log C_s$ , where  $S$  is the relative visual acuity as the response,  $C_s$  the extinction coefficient as the impact and  $A$ ,  $B$  is experimental constant respectively. The relative visual acuity  $S$  and  $C_s$  data are plotted on a semi-log chart as shown in **FIGURE 4** in the region of  $C_s$  over 0.25 1/m. The plotted data in this figure indicate approximately linear relationship, then the decrease of visual acuity due to the smoke irritant effect is expressed,

$$S = 0.133 - 1.47 \log C_s \quad (5)$$

The drop of visual acuity through smoke seems to be caused by two factors mainly. One is the apparent decrease of the visual acuity due to the physical effect of smoke particles intercepting the objects. Another is the physiological irritant effect of smoke. Thus the visibility through smoke is expressed by the next approximations.



**FIGURE 4.** Decrease of relative visual acuity due to smoke irritant effect.

$$V_1 = C/C_s \quad (0.1 \leq C_s < 0.25 : \text{in none irritant region}) \quad (6)$$

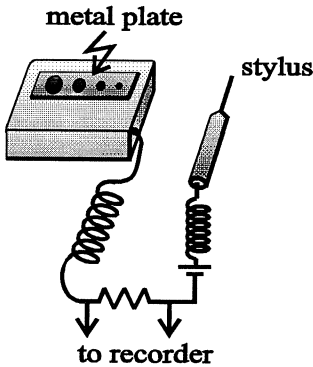
$$V_2 = C/C_s (0.133 - 1.47 \log C_s) \quad (C_s \geq 0.25 : \text{in irritant region}) \quad (7)$$

Experimental constant of C in the equations depends on the several experimental conditions; the brightness of objects and its surroundings, the contrast between them and the kinds of contents on the objects. The obtained relationships of Equation (6) and (7) are applied to the series of experiments on the visibility through the smoke, and then the results are presented in **FIGURE 2** with dash and dotted line. The theoretical curves approximately agree with the experimental data when the constant value is set to be 6.0. The visibility through other kinds of smoke besides the irritant white smoke from the smoldering wood may be considered to vary in the intermediate region between the equation (6) and (7).

## **PART 2. EXPERIMENTAL STUDIES OF HUMAN BEHAVIOR IN FIRE SMOKE**

### **2.1 Emotional Instability in Fire Smoke [3]**

An attempt was made to monitor the subjects' emotional fluctuations using a steadiness tester which is often employed in psychological studies. The test room had a floor area of five by four meters, no windows, and a floor level illumination averaging 30 lx at the start of the experiment. White smoke was produced by putting a wood chip in an electric furnace. The smoke generating rate was adjusted such that the extinction coefficient increased at the rate of 0.1 1/m per minute.



One subject at a time sat at a table on the enclosure and manipulated the steadiness tester on the table. The tester is faced with a metal plate in which there are four holes having progressively graded diameters as shown in **FIGURE 5**. The subject was told to thrust a metal stylus into holes in a specified order, trying not to touch the hole edges with the stylus. The smaller the hole size, the more concentration the subject needs to avoid contact. As the smoke density in the test room increased, fear of smoke and irritations to his or her eyes and throat hampered concentration more seriously, causing an increasing frequency of contact between the stylus and hole edges. 49 subjects employed in the test consist of researchers, who staff the Fire Research Institute (former name of National Research Institute of Fire and Disaster), and other people, most of whom are housewives.

**FIGURE 5.** Sketch of a steadiness tester to monitor the subjects' emotional fluctuation.

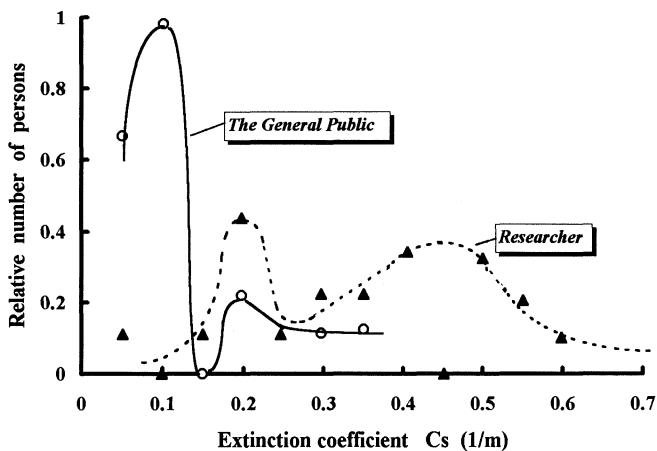
**FIGURE 6** is the result of an attempt to determine the subjects' emotional fluctuation on the basis of the number of stylus contact on the steadiness tester. Curves with two peaks as shown were obtained for both groups of the subjects. Each of these peaks seems to attest to the following facts: In the group of subjects other than the Institute researchers, most people begin to be emotionally affected when the smoke density has reached 0.1 1/m but in few other people emotional fluctuation begins to be pronounced when the smoke has become as dense as 0.2 ~ 0.4 1/m in extinction coefficient. In contrast, most researchers begin to show fluctuation only when the smoke density has reached 0.35 ~ 0.55 1/m although a small number of them begins to fluctuate at the lower smoke density of 0.2 1/m.

Interviews with some subjects were held after the experiment. Comments by many of the subjects representing the general public could be generalized like this: "Smoke itself didn't scare me much when it was thin. But irritation to my eyes and throat made me nervous, and when I thought of the smoke still getting thicker and thicker, I was suddenly scared of what's going to happen next." In other word, these people were more afraid of what's coming next than they were physiologically unable to withstand the smoke.

Hence, the author believes that the data obtained from these people could reasonably be treated as equivalent to those which would be obtained from a group of unselected people who are unfamiliar with the internal geometry of a building on fire. The smoke density of 0.15 1/m, at which most of the subjects analyzed in **FIGURE 6** began to feel uneasy, could be determined as the maximum smoke density for safe evacuation of a building to which the public have access.

In contrast, the Institute researchers used as the subjects said in the interview, "Irritation to my eyes was rather acute but the smoke didn't scare me because I had heard in the pre-test briefing that it was harmless. But as the smoke grew denser, I began to feel more acute irritation in my eyes and throat, and when I got the signal to end the test (smoke density 0.5 ~ 0.7 1/m in light extinction coefficient), irritation and suffocation were near the limit I could physiologically





**FIGURE 6.** Number of emotionally affected subjects vs. smoke density at the rapidly increase point of number of contacts

stand. Toward the end of the test, visibility in the test room was so limited that I saw only a small floor area around my feet, and this made me a little nervous when I walked through the smoke.”

Even though these researchers had some knowledge of smoke by pretest briefing and were well informed of the geometry in the test room, most of them began to be emotionally affected when the smoke density exceeded 0.5 1/m. It would be possible to reason that emotional instability of these subjects during the test resulted from physiological, rather than psychological, reasons.

These facts made the author believe that the results of this experiment using the Institute researchers as the subjects can be treated as the data of those who are well informed of the inside geometry of a building on fire. This means that the smoke density of 0.5 1/m, at which **FIGURE 6** indicates most of the researchers began to lose steadiness, can be determined as the threshold where escape becomes difficult even for persons who are well familiar with the escape route in the building. Visibility at these smoke densities is listed in **TABLE 1**, which indicates that those who know the inside geometry of the building on fire need a visibility of 4 meters for safe escape while those who do not need a visibility of 13 meters.

**TABLE 1.** Allowable smoke densities and visibility that permits safe - escape

Degree of familiarity with inside building	Smoke density (Extinction coefficient)	Visibility
Unfamiliar	0.15 1/m	13 m
Familiar	0.5 1/m	4 m

## 2.2 Correct Answer Rate and Emotional Instability in Thick Fire Smoke [6]

An experimental study was conducted in order to clarify a degree of human emotional instability under thick and hot smoke condition. Mental arithmetic and walking speed were adopted as indices of the emotional instability, and furthermore an annoyance of smoke and heat was investigated by questionnaire.

The corridor was filled with white smoke generated by smoldering Japanese cedar crib chips in an electric furnace before starting each experiment. At the beginning of the experiment, a smoke density expressed by the extinction coefficient was adjusted to 1.2 1/m and two or three subjects entered into the corridor individually under same smoke density condition. Temperature inside the corridor was about 20°C. At the inner point of A and B, the heat was radiated to subjects with an electric radiator (at A :12 kW, B :3 kW) installed at a ceiling. A maximum heat flux density was 2,030 Kcal/m<sup>2</sup>h at A-point of 1.5 m height from the floor level and 1,370 Kcal/m<sup>2</sup>h at B-point of the same height. Mean Radiant Temperature measured with a glove thermometer was about 82°C at A-point and 75°C at B-point.

In this experiment, a mental arithmetic method was adopted to estimate the degree of emotional instability under thick and hot smoke condition. The rate of correct answers to simple arithmetic questions was expected to decrease continuously with increasing the human emotional instability to a certain extent. This rate was therefore adopted as an index of the emotional instability. The mental arithmetic questions were recorded in an endless tape and 10 questions were continuously imposed to the subject by a loud speaker at each five answer points (A to E). 31 adults aged 20 to 51 (male 14, female 17) participated in this experiment. These females were mainly house wives and males were undergraduate students.

At the beginning of each experiment, the condition of the smoke density was not the same. The values varied in the range of  $C_s = 0.92 \pm 0.21$  1/m. In the first experiment trial with thicker smoke, 17 subjects (male 6, female 11) could reach the deepest A-point, and other 14 subjects

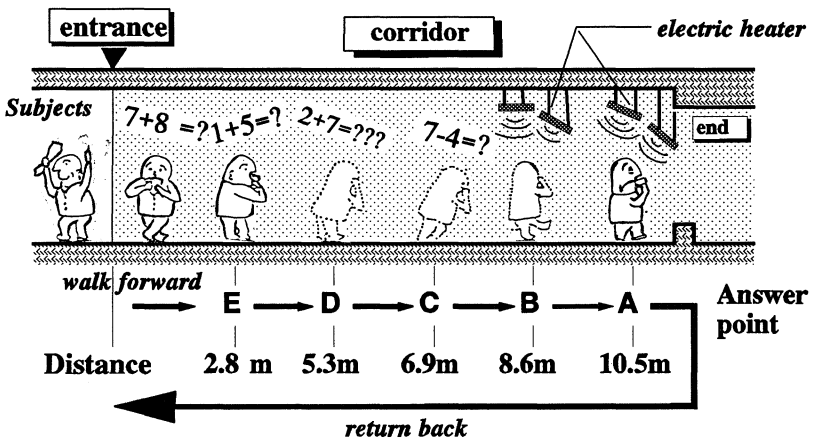
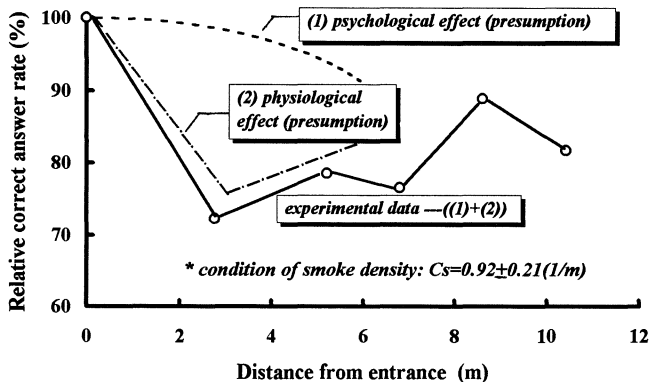


FIGURE 7. Outline of experiment.



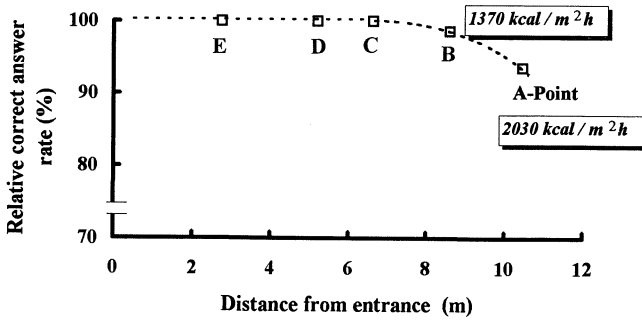
**FIGURE 8.** Relation between distance from entrance and correct answer rate: 17 subjects (6 males, 11 females) reached at the end of corridor in the first trial.

(male 8, female 6) returned back with interruption. 17 subjects were able to reach the end of the corridor in the first trial under thicker smoke. A solid line of **FIGURE 8** shows the relation between the attainable distance from the entrance and the correct answer rate. This average rate of 17 subjects falls down at the lowest just after entering the corridor (at E-point) and it tends to rise up at deeper points.

However, in inquiries conducted after experiment, the subjects pointed out that they felt more unrest when they walked forward. Experimental results of walking speed decreases in proportion to distance from the entrance. From these facts, the relative correct answer rate caused by psychological factors is considered to decrease under a certain conditions, which is unknown in this experiment, when subjects walk forward as shown in **FIGURE 8** with long dashed line. From the view point of physiological aspects, the abrupt decrease of correct rate just after entering the corridor can be explained by the smoke which attacks the subject's eyes and throat. As this discomfort is lightened with the lapse of time, the correct answer rate may rise when subjects walk forward as shown in **FIGURE 8** with dashed and dotted line. The heat radiation effect is involved at A and B-point.

The obtained experimental data as shown in **FIGURE 8** with solid line appears to be composed of two kinds of smoke effect, the physiological and psychological effect on subjects. The relation between these two effects i.e., whether a simple algebra of addition can explain the data or not, is a task for further investigations.

**FIGURE 9** presents the mental arithmetic results under no smoke condition. The data at A-point drop to 10 % lower than those of other points. This decrease is caused by the heat radiation from electric heat radiators installed at the ceiling. The same drop at A-point is also apparently recognized under smoke condition presented with normal line in **FIGURE 8**. Nevertheless, no fall is found at B-point. The maximum heat flux intensity was 2,030 Kcal/m<sup>2</sup>h



**FIGURE 9.** Relation between distance from entrance and correct answer rate with electric heater and without smoke: the electric heater is installed at A and B-point.

at 1.5 m height from the floor of A-point and 1,370 Kcal/m<sup>2</sup>h at B-point. So the threshold value of heat flux reduces human thinking power is in the range of between 2,030 Kcal/m<sup>2</sup>h and 1,370 Kcal/m<sup>2</sup>h.

Some questions were asked to each subject after the experiment. One was a question on uncomfortable factors of smoke: "What are the uncomfortable factors of smoke ? Select three factors concerned with fire smoke from following items in order !". **TABLE 2** shows the result. Some variances between male and female are found. Physiological factors were mainly selected by males. Eyes and/or throat irritation was the first or the second selected item. "Obstruction of inhalation" was selected as the second or the third uncomfortable factor. In comparison with the above males' answers, females tended to feel psychological discomfort. As well as physiological annoyance the obstruction of visibility was selected as the first cause of discomfort of females along with irritation and inhalation problems. This obstruction of visibility was also cited as the second cause. This experimental result indicates that the emotional instability in thick fire smoke is not necessarily caused by the same factors for males and females. Under thin smoke conditions, the smoke irritation and heat flux are selected as the first or the second factor without distinction of sex.

**TABLE 2. Uncomfortable factor of fire Smoke :** Question "Select three discomfort factors of fire smoke from following items !"

selection Items	male (total 14 subjects)			female (total 18 subjects)		
	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>
a. foul smell	1 (7%)	2(14%)	3(21%)	1 (6%)	0 (0%)	1 (7%)
b. smoke irritation	8(57%)	4(29%)	1 (7%)	7(41%)	6(35%)	2(13%)
c. obscuration of inhalation	5(36%)	4(29%)	5(36%)	4(24%)	3(18%)	6(40%)
d. obscuration of visibility	0 (0%)	3(21%)	3(21%)	5(29%)	6(35%)	5(33%)
e. heat	0 (0%)	1 (7%)	0 (0%)	0 (0%)	1 (6%)	0 (0%)
f. feeling of isolation	0 (0%)	0 (0%)	1 (7%)	0 (0%)	1 (6%)	1 (7%)
g. others	0 (0%)	0 (0%)	1 (7%)	0 (0%)	0 (0%)	0 (0%)

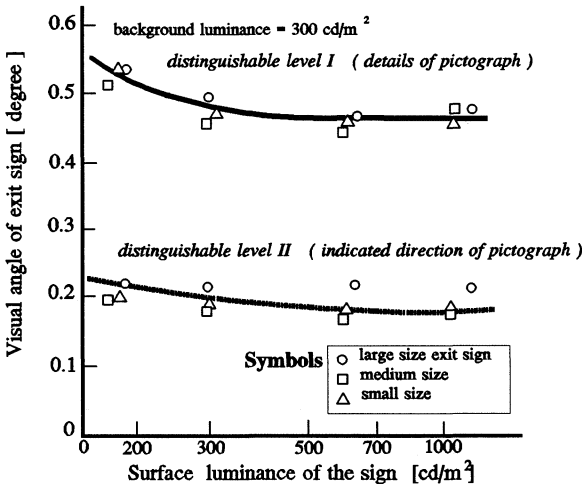
### PART 3. INTENSIVE SYSTEM FOR ESCAPE GUIDANCE

#### 3.1 Improvement of Conspicuousness of Exit Sign by Flashing Light Source [7]

An emergency exit sign, which indicates a location and/or direction of emergency exit and leads evacuees to a safety place swiftly, is important in case of fire or other emergency. In Japan, we are currently using three sizes of emergency exit sign. However, the conspicuousness of the exit sign in a background with many other light sources was not known. In the first experiment, we measured the conspicuousness of the ordinary type exit sign in an underground shopping mall in business hours. These experimental variables were the observation distance, size and luminance of the exit sign. In the second experiment, the conspicuousness of self-flashing type exit sign (flashing the lamp in the sign) was compared with that of ordinary type exit sign.

#### Visibility and Conspicuousness of Exit Sign

Prior to this experiment study, another experimental study on visibility of exit sign had been done. In that experiment, the original type exit sign was observed in a background without other light sources. **FIGURE 10** shows one of the results concerned with the relation between visibility expressed by visual angle and surface luminance of ordinary exit sign. In this figure visibility is represented on two discrimination levels; one is the level in which person can distinguish the details of a pictograph and the other is the level in which only a direction of the running person (pictograph) is distinguishable. This result indicates that visibility is almost constant when luminance of white part of the exit sign is over 300  $\text{cd/m}^2$ . This observation is true for every size of the exit sign. When visibility is expressed in terms of the visual angle (height of pictograph) it is independent of the size of the sign.

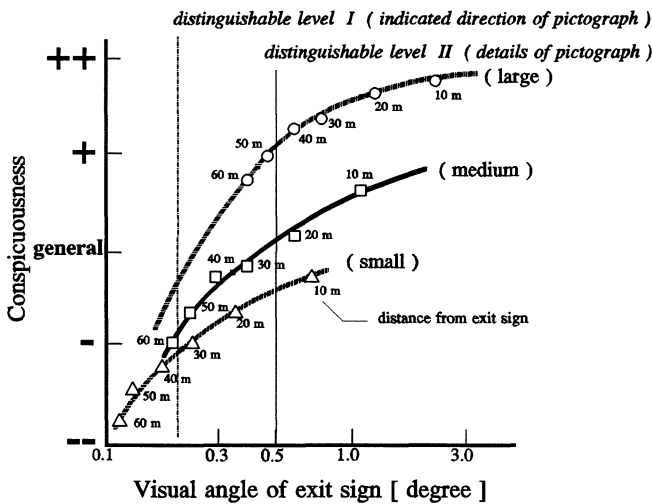


**FIGURE 10.** Relation between surface luminance of ordinary exit sign and visual angle associated with visibility.

**FIGURE 11** shows the relation between conspicuosity of ordinary type exit sign and the visual angle and **TABLE 3** gives categories for the evaluation[8]. The larger size exit sign is more conspicuous than smaller size one when the visual angle is the same. This indicates that the conspicuosity depends on the relative scale of exit sign against the surrounding lights. In this sense, the visibility expressed in terms of visual angle does not always correspond rationally to conspicuosity.

### Improvement of Conspicuousness by Flashing the Light Sources

**FIGURE 12** shows the relation between conspicuosity of ordinary type exit sign and that of the self-flashing type exit sign. In this figure the vertical interval between the dash-dotted line and the curves corresponds to the improvement of conspicuosity by the flashing light in the sign. For the medium size exit sign, self-flashing type sign is more effective to improve conspicuosity. However, the small size exit sign of self-flashing type is not conspicuous enough when observed from the distance more than 20 m in the background with many other lights, since the exit sign is too small to be recognized as an exit sign, even though the flashing



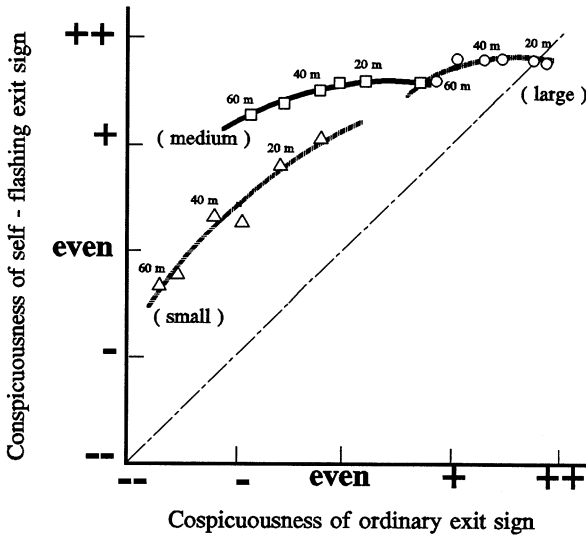
**FIGURE 11.** Relation between conspicuosity of ordinary type exit sign and visual angle.

**TABLE 3.** Categories for evaluating conspicuosity of ordinary type exit sign.

Evaluation categories	(marks in Figure 11)
(1) The exit sign is fairly conspicuous.	(++)
(2) The exit sign is slightly conspicuous.	(+)
(3) The exit sign is similar to the general level.	(general)
(4) The exit sign is less conspicuous.	(-)
(5) The exit sign is not conspicuous at all.	(--)

was expected to be much more conspicuous. The large exit sign is big enough to have sufficient conspicuousness without flashing even in the background with many competing light sources.

Besides this improvement by adding flashing light, the author promoted to develop an acoustic guiding exit sign. Adding a speaker and voice recorded IC chips to this flashing type exit sign, it enables to announce, i.e., "Here is an emergency exit", when fire is detected by sensors, i.e., smoke detectors[9].



**FIGURE 12.** Relation between conspicuosity of self-flashing exit sign and that of ordinary one.

**TABLE 4.** Categories for evaluating conspicuity of self-flashing ordinary type exit sign.

Evaluation categories	( marks in Figure 12)
As compared with the ordinary type exit sign.	
(1) The flashing exit sign is fairly conspicuous.	(++)
(2) The flashing exit sign is slightly conspicuous.	(+)
(3) The flashing exit sign has similar conspicuity.	(even)
(4) The flashing exit sign is less conspicuous.	(-)
(5) The flashing exit sign is not conspicuous.	(--)

### 3.2 Effect of Escape Guidance in Fire Smoke by Traveling Flashing of Light Sources [10]

A new escape guidance system is now developing for safety evacuation. This system indicates appropriate escape directions by making flashing of row of light sources successively away from hazardous area such as fire room. A portion of passage way (1.4 m width, 6.3 m long and 2.5 m height) filled with smoke is used for this experiment. As lighting for the experimental passageway, four units of fluorescent (40 W x 2) lamps are equipped under ceiling, which give about 200 lx at the center of the passage under non smoke condition. The flashing light unit boxes are set on the floor along the right hand side wall at a pitch of 0.5 m, 1.0 m and 2.0 m as a test guidance system.

The effectiveness of the escape guidance is evaluated by 12 subjects, who walk in a line at a side of a row of flash-traveling green light sources located on the floor under various conditions, i.e., the spacing and the traveling speed of flashing lights and smoke concentration. Under each condition, subjects walk along the system successively, however, there are only two or three people inside the passage way at a time for keep free walking speed.

The degree of effectiveness of escape guidance is classified into seven steps as follows, and the evaluations are made by filling one score from seven points into an observation sheet directly after each test run. These categories are adopted as semantic differential scale for escape guidance.

Score : 7 point --- very effective for escape guiding

5 point --- fairly effective

3 point --- a little effective

1 point --- not effective

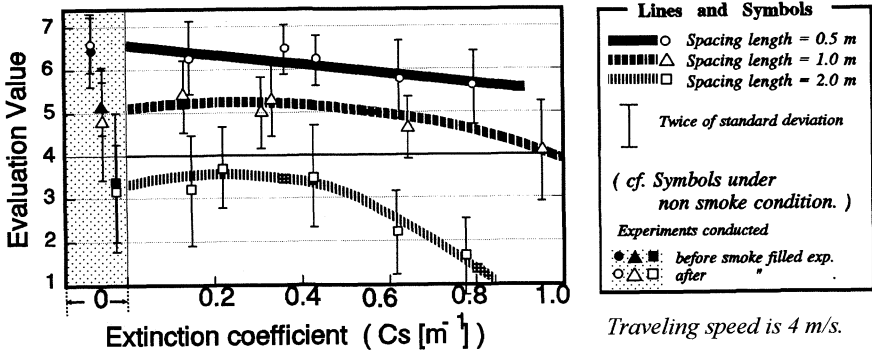
(\* 2, 4 and 6 point correspond middle point between 1 and 3, 3 and 5, 5 and 7 respectively.)

In general, the effectiveness decreases with increasing smoke. However, expect a few cases having relatively low evaluation value under non smoke condition, the evaluation values are over "4 point" in the smoke concentration of 0.4 1/m. The evaluation value of "4 point" stands for less effective than "fairly effective" and more than "a little effective", so we consider that the value is a threshold where practical effectiveness of escape guidance is secured.

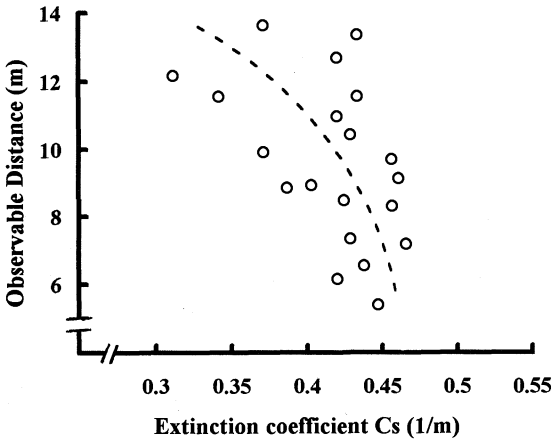
The correlation between smoke concentration and the effect of escape guidance is shown in **FIGURE 13**. This indicates that this system is useful for evacuees to escape in thick smoke of 1.0 1/m when the spacing length is 0.5 m and flashing speed is 4 m/s. When the spacing length is set to be 1.0 m, the effectiveness decreases but it is still useful in smoke under 0.8 1/m. However the spacing length gets wider than 2.0 m, not so much effectiveness is expected even under no smoke condition and it decreases as increasing smoke optical concentration. In the left side meshed box, these are evaluation values prior and post smoke inhalation test under no smoke condition. It shows stability of the evaluation, and no assimilation effects are observed. The effectiveness of flashing traveling signs in ambient atmosphere can be maintained under 0.4 1/m smoke density condition.

This result is very important for evaluating the escape guidance system from the view point of





**FIGURE 13.** Relation between smoke concentration and the effect of escape guidance with variation of flashing light sources under smoke condition.



**FIGURE 14.** Relation between smoke concentration and visibility of exit sign.

safe evacuation. Because visibility (observable distance) of normal exit sign drops rapidly from over 10 m to 5 m and then lose the guidance effectiveness in that range of smoke concentration.[1] This relation between the visibility of exit sign and the smoke concentration is expressed in **FIGURE 14**. Comparing with the visibility drop of normal exit sign, decreasing rate of the effectiveness of the guidance system seems to be small, so the new system is expected for maintaining high and stable effectiveness of escape guidance even in relatively high smoke concentration. It is known that threshold of smoke concentration required for safety evacuation in a building without indication emergency signs is almost under 0.5 1/m for evacuees who are familiar with the building, and 0.15 1/m for strangers.[3]

The effectiveness of this escape guiding system can be also recognized in the former experiments' observation mentioned in 2.2, i.e., 7 subjects out of total 31 participants could not proceed beyond just 2.8 m away from exits and 3 for 5.3 m, 6.9 m for respectively in thick smoke ( $C_s=0.92 \pm 0.21$ ) filled corridor. Many evaluation values at 0.2 l/m smoke concentration give higher values than those under non smoke condition. It is considered that surrounding light noises are weakened with the smoke, then evacuees can more concentrate to the flashing light. Therefore also in thinner smoke at the very beginning of fire, this type of the guidance system can be expected for having high effectiveness for safety evacuation as well as in thick smoke.

As a result, the spacing length between flashing light sources is very important factor to keep appropriate guiding effectiveness. Especially, high effectiveness is expected, when the spacing is set to be less than 1 m. The relation between effectiveness and flashing light conditions under smoke is found to be almost the same as the relation under non smoke condition.

## CONCLUSION

The followings are major knowledge and technology developed in my research activities for dedicating to life safety in case of fires.

1. Relation between smoke density and visibility in fire smoke was examined under various kinds of smoke, and simple equations were proposed for practical use.
2. The visibility in fire smoke depends on irritating effect as well as optical smoke density. Especially this irritating effect causes highly drop of visual acuity. A modification due to irritating effect was made for the visibility vs. smoke density equation.
3. Evacuees begin to feel emotional instability in relatively thin smoke, however the threshold of the smoke density varies by subjects. Through experiments and investigations, it was found that the level depended on the degree of evacuees' familiarity of the internal geometry of a building on fire. Evacuees in unfamiliar building tend to feel emotional instability in thinner smoke.
4. Ability of thinking of evacuees in fire smoke decreases with increasing smoke density. Generally, this is caused by both psychological and physiological effects on evacuees. Also in due course, hot smoke enhances decrease of thinking ability.
5. Conspicuousness of the ordinary exit sign was improved by adding flashing light sources. This effectiveness was examined under conditions where there were many other light noises.
6. A new type of the escape guidance in fire smoke by traveling flashing light sources towards exits was developed and the effectiveness was examined under smoke filled corridor. This new system is expected for maintaining high and stable escape guidance even in relatively thick smoke.

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