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Experimental Study on Fire Hazard of Residential Fires Before and After Sprinkler Activation

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ABSTRACT

Fire experiments were conducted in a real scale room which is assumed to be a residential living room (3.8m x 3.6m x 2.4m) under the various opening conditions and locations of wood crib fire source. Concentrations of oxygen and carbon monoxide, smoke density, and temperature were measured. Response time of fire detection by several detection methods such as rate of rise heat detectors, fixed temperature type heat detectors, photo-electric type smoke detectors, residential smoke detectors, and the Intelligent Fire Detection System and activation of residential sprinklers were also examined. From the results of the experiments, the following were obtained.

(1) Maximum mass loss of wooden crib by combustion until activation of sprinklers was less than 1 kg. Therefore, the fires burnt under the fuel control condition. In this condition, it was confirmed that the residential sprinkler systems can control the wooden crib combustion.

(2) In some experiments, the smoke density and the CO gas concentration increased after activation of sprinklers because of stirring air by water discharge.

(3) In most of the experiments, it was found that the response time of all the fire detection methods used in the experiments are less than the response time of sprinklers.

1. INTRODUCTION

Every year, many lives of disaster vulnerable people like elderly, infants, and physically handicapped are lost in residential fires. For example, it is reported in the "White Book on Fire Service in Japan, 1993"[1] that 95% of fire deaths excluding incendiary suicides came from residential fires and 54% of that were elderly, infants, and ill or physically handicapped persons. Besides this fact, Japan is facing the problem of rapidly aging of a society that is expected to continue to a stage where one fourth of total population are 65 or older around in 2020. Therefore, It is earnestly desired to develop measures for reducing fires and fire deaths in homes.

From this viewpoint, the Fire Defence Agency issued a "Technical guideline on residential sprinkler system and residential detectors"[2], as of March 25, 1991. Reflecting this trend of the administration, fire protection equipment makers started the development of a quick response sprinkler head. Also, the Japan Fire Equipment Inspection Institute started experimental research[3] on test fires for establishment of approval procedures on residential sprinklers.

As the first step to study the feasibility of residential sprinklers to save persons in a room of fire origin, we carried out fire experiments using wood crib fire source in a real scale test room. We measured and examined the temperature near the ceiling, the vertical temperature distribution, smoke density, and the gas concentration as environmental conditions inside a fire room. Also, to consider conditions for a fire detection system to have capability of both fire alarm and sprinkler activator, response time was measured as for heat detectors, smoke detectors, and the multiple sensors for the fire detection system applying Fuzzy Theory 4) 5) (hereafter we call "Intelligent Fire Detection System") developed by the Fire Research Institute.

2. OUTLINE OF THE EXPERIMENTS

2.1 Fire Test Room

The area of a fire test room is 13.7 m^2 (3.8m x 3.6m), and the room height is 2.4 m. The walls and the ceilings is covered with rock wool cement board and the floor is covered with anti-water plywood. There is a slide door in the east side of a fire test room which is used to adjust the opening ratio by changing the width of a door. Next to a fire test room, there is an observation room where measurement apparatuses are located. The outline of the experiment room is shown in Fig. 1.

2.2 Fire Source and Ignition

The fire source used is wood crib whose configuration and ignition method are specified in the "Technical guideline on residential sprinkler system and residential detectors". The wood crib is assembled with 6 layers of 58 pieces of cedar crib, 0.03m x 0.035m x 0.90 m for each piece, the total weight of that is about 20kg. The wood crib was ignited by combustion of 50ml n-heptane in a heat source pan on the floor beneath the wood crib's center.

2.3 Measurement of Temperature

The temperature was measured with 1mm ϕ K- type thermocouples. Thermocouples are installed near the ceiling surface for looking into horizontal distribution and also installed in the positions as the center of the fire room (A point), south of A point by 0.9m (B point), and near the south window (D point) for looking into vertical distribution. The location of thermocouples are shown in Fig. 2 (a).

2.4 Measurement of Smoke Density and Gas Concentration

Smoke density was measured with smoke density meters of 1m light pass length. In order to see horizontal distribution of smoke density near the ceiling, six smoke density meters were placed. And, seven smoke density meters were placed along the south window in order to see the vertical distribution of smoke density.

The gases concentration was measured at the center of the fire room, 0.05m below the ceiling level. O_2 concentration was measured using O_2 gas analyzer with the range of 16% to 21% and CO gas concentration was measured using the CO gas analyzer with the range of 0% to 2%. The gas sampling position is shown in Fig. 2 (a) and positions of smoke density meters are shown in Fig. 2 (b).

2.5 Installation Position of Detection Sensors

As fire detecting sensors, a thermocouple, an analog type photo-electric smoke detector, a CO sensor are installed in a fire room in order to measure temperature, smoke density, and CO gas concentration. Also, six residential smoke detectors are installed to measure the response time in several position. The locations of the sensors, the residential smoke detectors, wood crib fire source, and sprinklers are shown in Fig. 2 (b).

2.6 Sprinkler Installation and Water Discharge Condition

Sprinkler heads with the nominal release temperature of 72℃ were installed at the center of a fire room (A point), and at the two positions (F point and G point), 0.8m away south and north respectively from A point, as shown in Fig. 2 (a). The conditions of water discharge of sprinkler heads were as follows.

(1) In case that only the sprinkler at A point is available.

Water discharge flow : 28 l/min. Water pressure : 1.08 ~ 1.17 kgf/cm^2.

(2) In case that the sprinklers at F point and G point are available, but the sprinkler at A point is not available.

Water discharge flow : 57 l/min. Water pressure : 1.19 ~ 1.24 kgf/cm^2.

The water discharge flow in the case when only one of F and G sprinkler activated was 34 ~ 36 l/min.

2.7 The Conditions of Experiments

The experiment conditions of the 15 fire tests are shown in Table 1. The experiment No. 1 to No. 6 in Table 1 are the cases that the fire source was placed in the center of a fire room with variety of opening ratio. The experiment No. 7 to No. 12 are the cases that the opening ratio was fixed (all closed) with variety of location of the fire source. The experiments No. 13 to No. 15 were done with no sprinklers.

3. RESULTS AND DISCUSSIONS

3.1 The Temperature Profile and The Fire Behavior

(1) The weight loss of the wood crib fire source

The weight change of the fire source for the experiments with no sprinklers, No. 13 to No. 15 are shown in Fig.3. The weight was normalized with the wood crib's initial weight. In these three cases, the weight loss curves trace nearly the same tendency. The weight loss rate became constant around 5 minutes after the ignition. From this constant weight loss rate and the heat of wood combustion, 18,900 kJ/kg, the heat release rate was estimated approximately 170kW.

At some point on the decreasing curve, the weight increases suddenly. This was caused by the water drop on the crib for suppression to prevent a fire from growing to be incontrollable state. Therefore, this sudden jump of weight should be ignored.

The data of weight loss, heat release rate, and the total heat release amount at sprinkler activation for the experiments, No. 1 to No. 12, with sprinklers are listed in Table 2. From this table, in all of these experiments, sprinklers responded in the early stage of the combustion of wood crib. This weight loss was at most 1kg. For example, when the fire source was placed in the center of the fire room, sprinklers activated at the weight loss of 240g to 280g regardless of the open ratio.

(2) The temperature near the ceiling level above the fire source

The temperature-time curve near the ceiling level for the cases that the fire source is at the center of the room (Exp. No. 1 to Exp. No. 6) traces three stages as a preheating stage of the wood crib by the burning of n-heptane where the temperature flattens after slight increase, then a drastic temperature rising stage after the ignition of wooden crib, and a cooling stage where the temperature drops due to the sprinkler's water discharge. As all of the cases followed the same pattern, the reproducibility of the crib fire is considered to be obtained, although temperature-time profiles shown in Fig.4 were the data of different opening ratio.

It is seen that there is a difference in the initial temperature rising point, ranging from 10 seconds to about 1 minute among the curves. As the preheating time of wood crib differs by the wooden crib's moisture, the room's temperature, and humidity, so the preheating time must be disregarded when the comparison of fire behavior among experiments is done.

(3) Vertical temperature distribution

The vertical distribution of temperature before sprinkler activation at the A, B, and D points for the Exp. No. 8, where the fire source was set at the north west corner and the opening was closed, is shown in Fig. 5. Between 0.4m and 2m below the ceiling level, the temperature decreases linearly as a measuring point gets closer to the floor, and the vertical distribution of temperature is nearly the same for the points A, B, and D. This indicates that the smoke layer in the room was stratified until the sprinkler activated when the opening was all closed.

The temperature near the ceiling decreased as a measuring point gets further from the fire source. This feature of the temperature near the ceiling was commonly seen in all of the experiments. Therefore, when setting a sprinkler and/or residential smoke detectors on the wall, fires could be easily detected if set at 0.2m to 0.4m below the ceiling level.

3.2 Smoke Density and Gas Concentration

The change in smoke density and gas concentration as environmental conditions of a fire room before and after the sprinkler activation is discussed here.

(1) The change in smoke density

The Fig. 6 and Fig. 7 shows the change in smoke density at points Gs, As, Bs, and Ds at the ceiling level and also vertical points at Ds (excluding Ds2) for the experiment No. 8. This experiment was done in a condition that was most unfavorable for the activation of sprinklers, because the fire source and the sprinkler location was far apart of all of the experiments in Table1.

From Fig. 6, before the activation of the sprinklers, the change of smoke density was similar among the data for the points on the ceiling except for Ds1. Four and a half minutes after the ignition, the smoke density reached 60%/m to 70%/m and then flattened. On the other hand, after the activation of sprinklers, the density at all of the points became uniform with time lapse due to the stirring effect of the air by water discharge. And the smoke density rose up to nearly 100%/m about two minutes after the sprinkler activation.

From Fig. 7 for measuring points on the Ds vertical line, before the activation of sprinklers, the smoke density rose with lapse of time in the order of higher position of points since the smoke layer lowered at the same period. Although the smoke density, except for the point Ds7, was in the stable state after the increasing state before the sprinkler activation, the smoke density at Ds7 was still in the increasing state. Thus, the smoke boundary layer at this point can be estimated to be in between Ds6 and Ds7. This result corresponds with the results from Fig. 8 which is mentioned in the next paragraph. After the sprinkler activation, the smoke density at all of the points, regardless of the height, became uniform as time elapsed due to the stirring effect of the room's air by discharged water, and then it became almost 100%/m two minutes after the sprinkler activation.

(2) The change of the height of the smoke boundary layer

The Fig. 8 shows the height changes of the smoke boundary layer by time for the three cases (Exp. No. 7, 9, and 12) where the sprinkler head was only one in the center of a fire room and the fire source was not in the center of the room and one case (Exp. No. 14) without sprinklers. For the Exp. No. 14 without sprinklers, which was the case when the fire growth was quite rapid, 4 minutes after the ignition the smoke layer boundary lowered to 0.4m above the floor level, and reached the floor level after 7 minutes. For the three cases with sprinklers, whose data are presented up to the sprinkler activation, the smoke layer boundary linearly lowered and reached around 0.6m above the floor level at the sprinkler activation time.

(3) The change of the gas concentration (O_2, CO)

For the cases shown in Table 1, as the fire source was placed in the center of the room, the response of sprinklers were quick and the fire was extinguished in the fairly early stage, so the O_2 concentration was 19% to 20% and CO concentration was 200ppm before the sprinkler activation and was 500ppm after sprinkler activation which was not a so large value. Therefore, we introduce the data of the Exp. No. 8 which was done in a condition that was most unfavorable for the activation of sprinklers in Fig. 9, because the fire source and the sprinkler head were the most apart among all of the experiments in Table 1.

In this experiment, the sprinkler was activated 7 minutes after the ignition, and the water discharge up to 13 minutes after the ignition controlled he fire. However, when the slide door at the east side of the room was opened 15 minutes after the ignition, the fire started to grow again. This indicates that the imperfect combustion state was thought to continue even after the sprinkler activation. CO gas concentration rose drastically 7 minutes after the ignition, the time that the sprinkler was activated, and it became 2000ppm just before the stop of water discharge by a sprinkler (13 minutes after ignition), and reached 3500ppm at the end of the experiment (15 minutes after the ignition).

These values of CO gas concentration were close to the level as the lethal concentration for 30 minutes exposure, 4000ppm. Although this result is for the case most unfavorable among the all experiments in Table 1, we should note that in some unfavorable cases for the activation of sprinklers, persons in a room of fire origin could be involved in a critical condition for survival. Also, the high smoke density after sprinklers activation should be remarked, when we consider the environment condition of a fire room along with the unification of smoke and gas by the stirring effect of the air by water discharge.

3.3 Detection Method and Detection Time

Here, we will discuss the fire detection system that has the capability of the fire alarm and the sprinkler activator. We examined the response time of the heat detector, the smoke detector, residential smoke detectors, and the Intelligent Fire Detection System applying the Fuzzy Theory by the Fire Research Institute[13][14] based on the output signals of multiple sensors such as heat sensors , smoke detectors, and the CO gas sensors.

(1) Each detection methods

We simulated fire detection methods of the rate of rise heat detector, the fixed temperature detector, the photo-electric smoke detector, and the Intelligent Fire Detection System applying the Fuzzy Theory.

The detecting time for the rate of rise heat detector, the fixed temperature detector, and the photo-electric smoke detector was calculated using the alarm conditions shown in Table 3. The response sensitivity for the detectors were set at the same level as those set in general buildings. The response time to identify a fire by the Intelligent Fire Detection System applying the Fuzzy Theory was estimated by using the defuzzification rules for judging a fire/non-fire in Table 4 after first calculating each certainty factor based on the four judging rules as follows;

*Flaming fire judging rule
*Smoldering fire judging rule
*Steam judging rule
*Cigarette judging rule

The calculation of the certainty factor was done by combining the fuzzy membership functions[4][5].

(2) The detection time by detection method

The detection time for the various detection methods and the activation time of sprinklers are shown in Table 5. Also, the output signal of the sensors and the detecting point of the various detecting methods for the Exp. No. 12 are shown in Fig. 10. From Table 5, the approximate trend can be seen as the following.

The rate of rise heat detector was likely to respond earlier than the photo-electric smoke detector and the fixed temperature detector. The reason for this is thought to be that the fire source used in the experiments was flaming fire of wood crib's combustion and so the volume of smoke generated was fairly small. In comparison with sprinklers activation, the rate of rise heat detector responded quicker than sprinklers, but the photo-electric smoke detector responded later than sprinklers in some cases (for example, Exp. No. 5). The fixed temperature detector some times did not respond, but this was because the activation of sprinklers lowered the room temperature.

The Intelligent Fire Detection System judged adequately all of the cases as a flaming fire. The detection time was not as quick as that of the rate of rise heat detector, but was quicker than activation of sprinklers. The detection time of the residential smoke detectors were not consistent among J0 to J5.

4. CONCLUSION

Fire experiments were conducted in a real scale room using a wooden crib fire source, and measured smoke density, the gas concentration, and the temperature before and after activation of sprinklers to look into environmental conditions for survivors in a room of fire origin. Also, fire detection time for the various fire detection methods and the response time of residential sprinklers were measured and compared. The result were as follows.

1) The maximum mass loss of wooden crib by combustion until the activation of sprinklers were less than 1 kg. The air inside a fire room was enough for the combustion of this size of level wood crib fire, so then did not become ventilation control fire.
2) In some cases, the smoke density and CO gas concentration increased after sprinkler activation because the air inside the room was stirred by the sprinkler's water discharge.
3) It was found that the rate of rise heat detector method, the fixed temperature detector method, the photo-electric smoke detector method, and the Intelligent Fire Detection System responded quicker than the activation of the sprinklers.
4) In all of the experiments, the control of a fire by sprinklers were confirmed.

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4) Satoh, K : "Intelligent Fire Detection System Based on Fuzzy Theory – Introduction of Fuzzy Expert System and CO gas Sensor – ", proceedings of '94 Asian Fire Science Seminar, Bali Indonesia, Dec. 1994.
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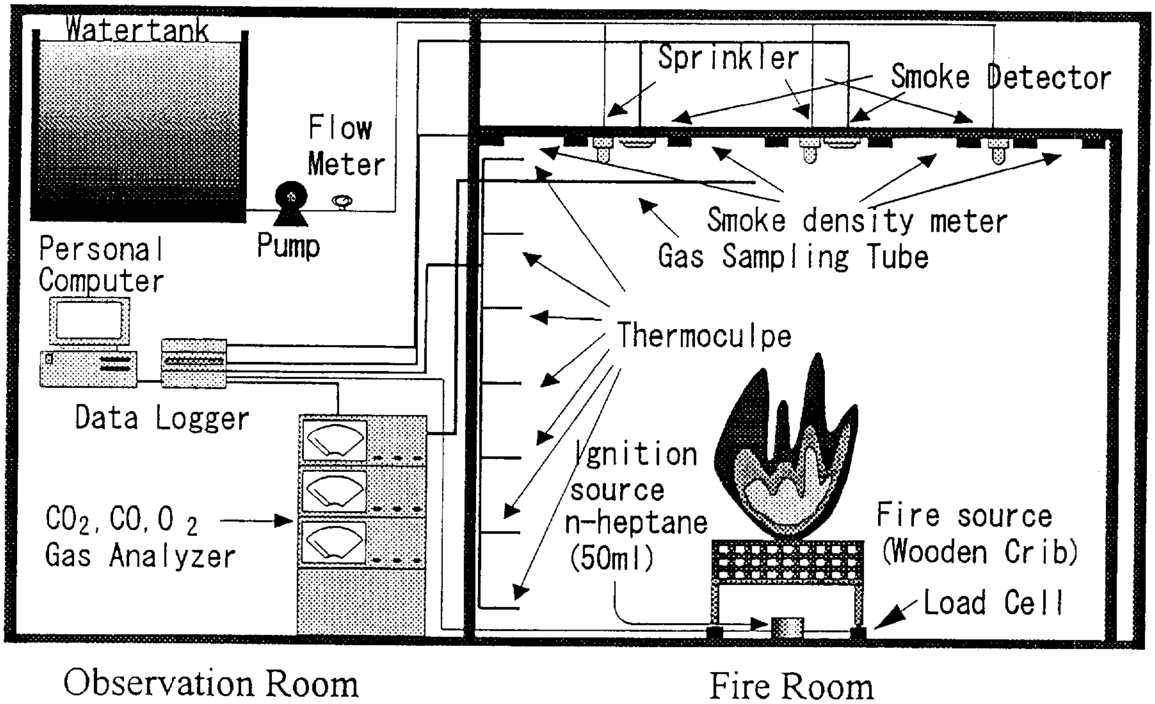


Fig.1 Schematic diagram of fire test room.

Table 1 Experimental conditions.

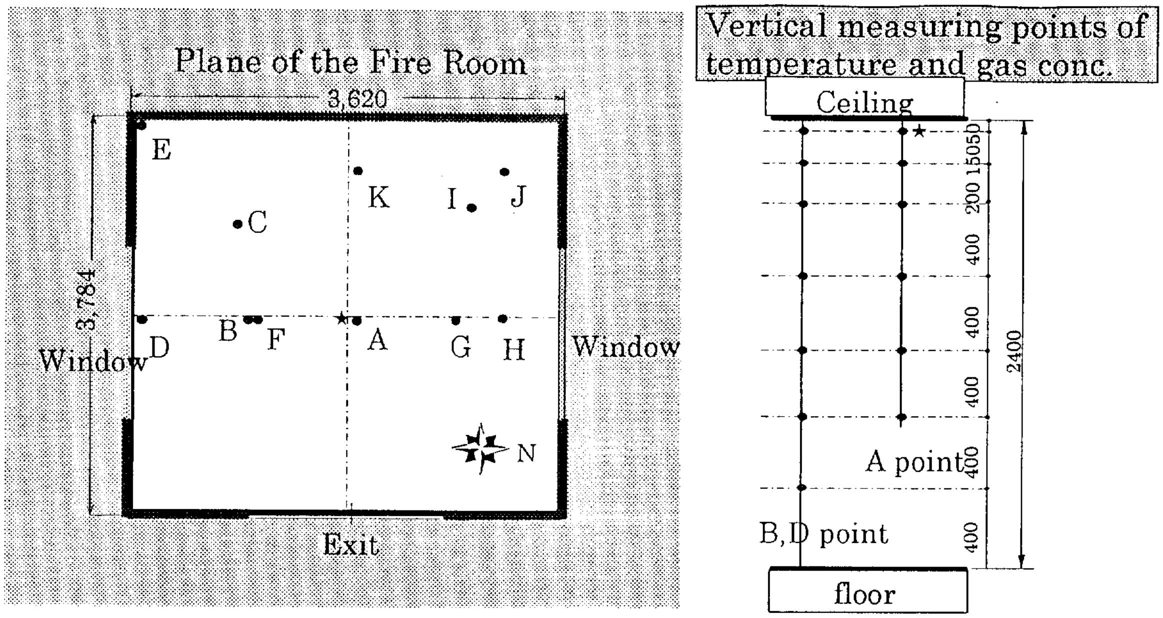
Exp. No.	Locations of sprinkler heads	Location of fire source	Ventilation conditions	Wooden crib's moisture content (%)
1	A	A	1/2 opened	17.8
2	F、G	A	1/2 opened	16.4
3	F、G	A	1/4 opened	17.3
4	F、G	A	1/8 opened	14.2
5	F、G	A	1/16 opened	12.6
6	F、G	A	Closed	13.0
7	A	J	Closed	13.4
8	F	J	Closed	12.5
9	A	K	Closed	10.1
10	F、G	K	Closed	12.5
11	F	H	Closed	10.8
12	A	I	Closed	13.1
13	No Sprinklers	J	Closed	14.3
14	No Sprinklers	J	Closed	13.3
15	No Sprinklers	J	CLosed	13.4

Wooden crib's moisture percentage(%) represents the average of four measurements.

Table 2 Weight loss, Heat release rate and total heat release amount at sprinkler response.

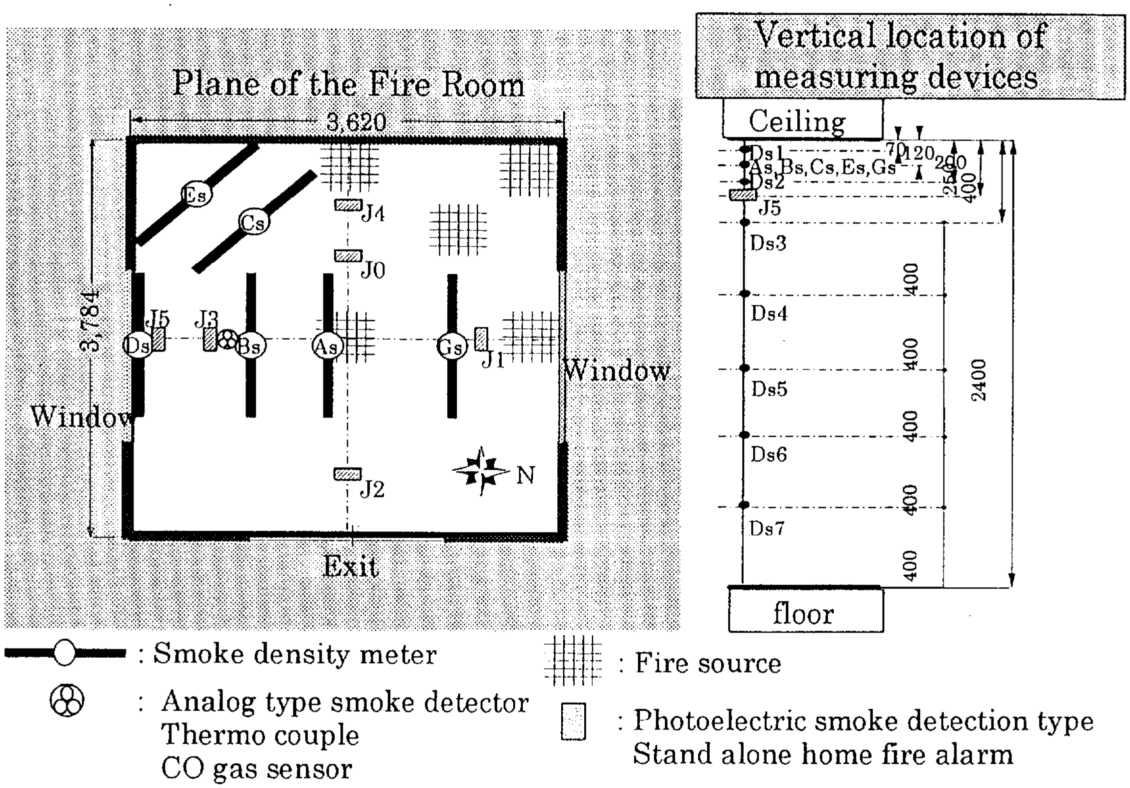
Exp. No.	Weight loss (%)	Heat release rate at sprinkler response (kW)	Total heat release amount at sprinkler response (kJ)
1	0.7	33	2,800
2	1.4	57	5,900
3	1.2	47	5,200
4	1.4	57	6,000
5	1.2	57	5,400
6	1.2	57	5,100
7	2.8	90	11,000
8	4.3	100	18,000
9	2.8	85	12,000
10	3.3	99	14,000
11	4.4	130	18,000
12	2.6	90	11,000

Weight Loss (%) represents the percentage of the weight lost from the initial weight.



★ : Setup location of gas sampling
● : Setup locations of the thermo couples

(a) Setup locations of thermocouples and gas sampling



(b) Setup locations of Smoke density meter, Analog smoke detector and Fire alarm

Fig.2 Set up locations of thermocuples, gas sampling, smoke density meters, analog smoke detector and fire alarms.

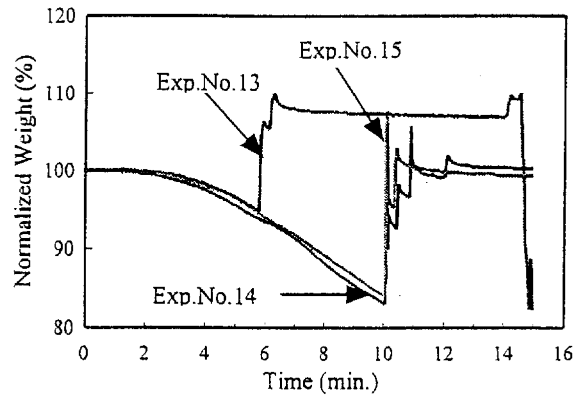


Fig.3 Change of Nomalized weight expressed by percentages as the initial weight is to be 100%

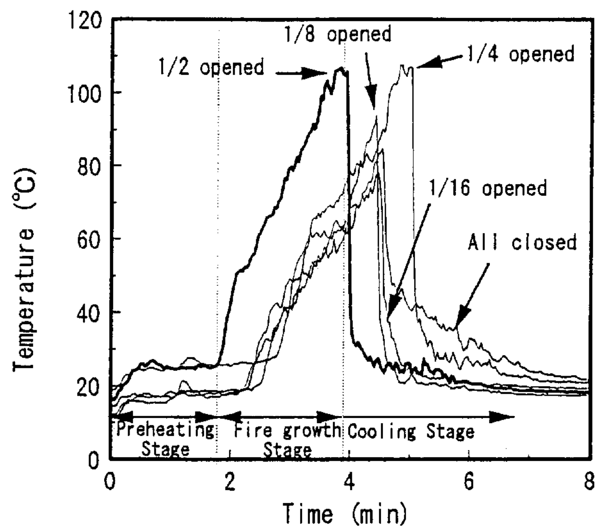


Fig.4 Relation between temperature near the ceiling level above the fire source and elapsed time.

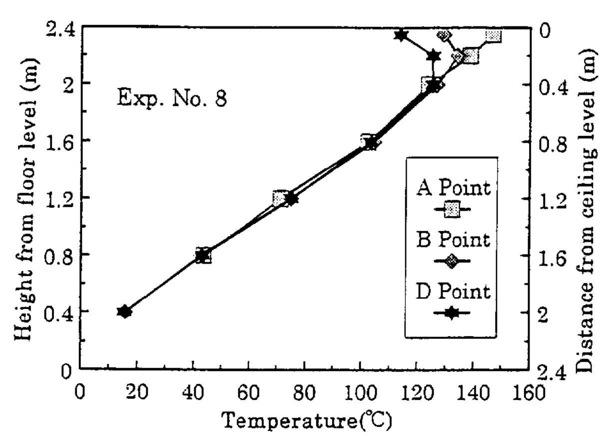


Fig.5 Vertical distribution of temperature in the fire test room for the experiment No8.

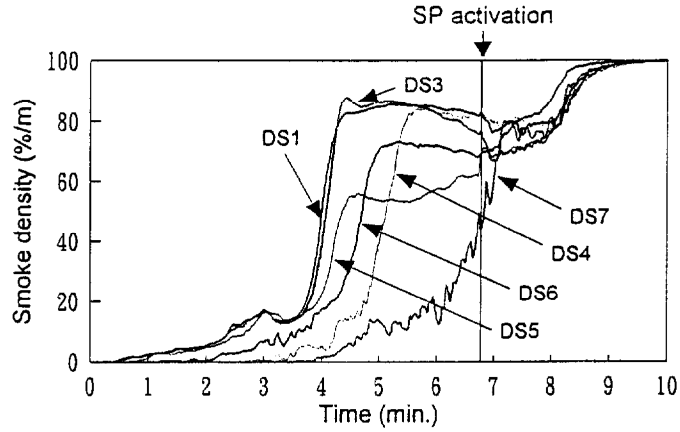


Fig.6 Smoke density at different points on the ceiling in lapse of time for the experiment No8.

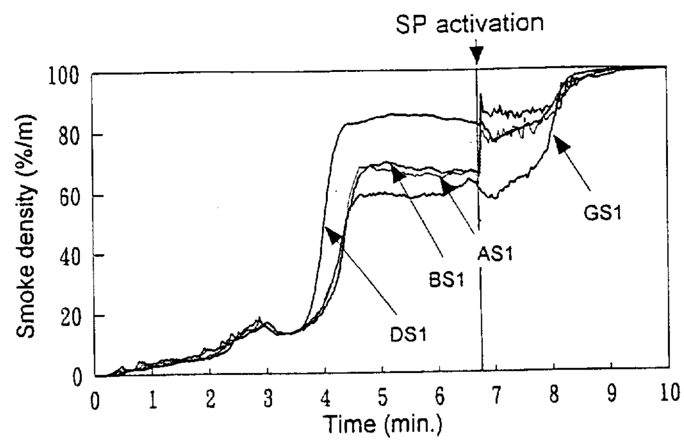


Fig.7 Smoke density at different points on the wall in lapse of time for the experiment No8.

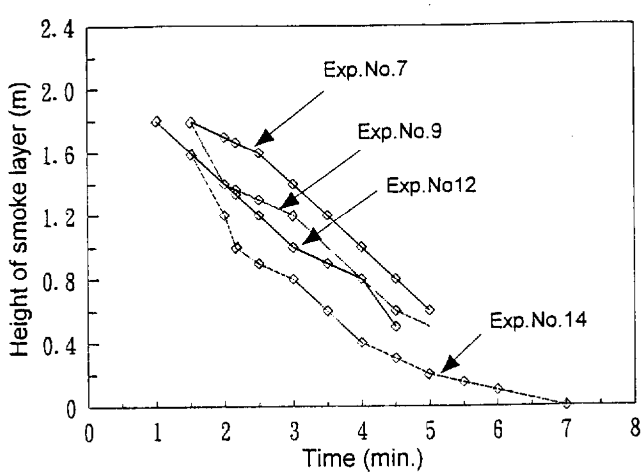


Fig.8 Height of smoke layer from the floor in lapse of time.

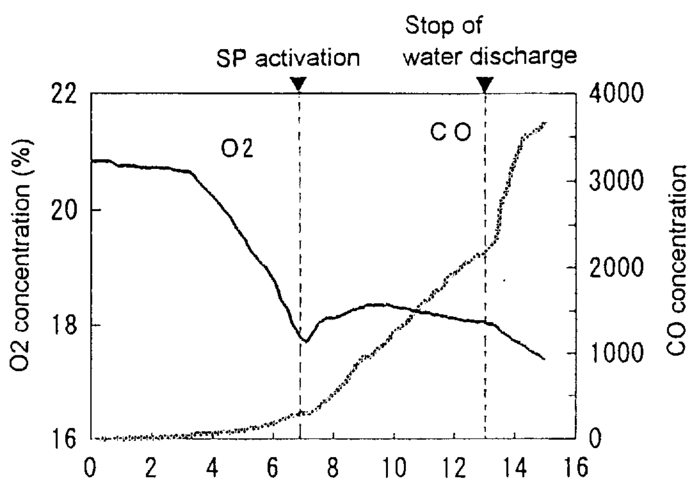


Fig.9 O_2 and CO concentrations in lapse of time for the experiment No.8.

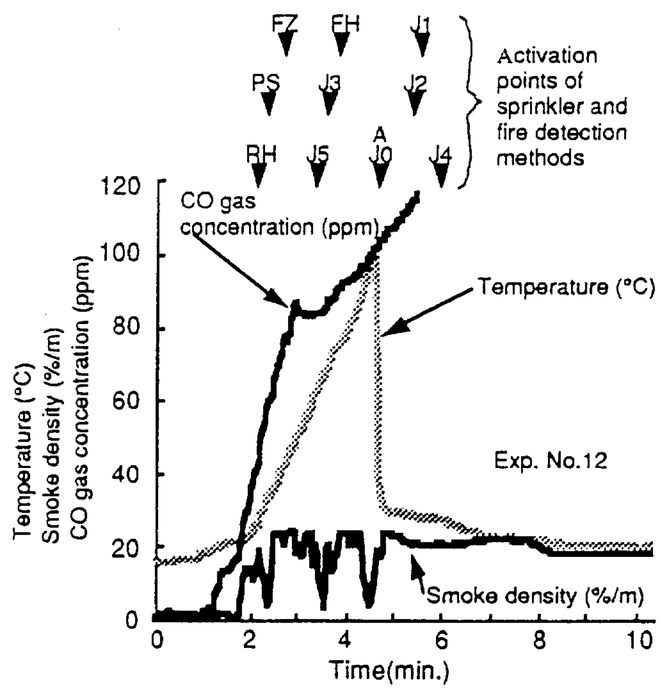


Fig.10 An example of sensor signal outputs and activation points of sprinkler and fire detection methods.

A : residential sprinkler 'A' activation
RH : rate-of-rise heat detection
FH : fixed-temperature type heat detection
PS : photoelectric type smoke detection
FZ : multi sensor with fuzzy reasoning
J0-J5 : residential smoke detectors

Table 3 Alarm condition of heat detection and smoke detection methods.

Fire detection method	Alarm condition
Rate-of-rise heat detection	15°C/min.
Fixed-temperature type heat detection	70°C response = special class
Photoelectric type smoke detection	10%/m duration = 10 sec.

Table 4 Defuzzified rules for judging a fire/non-fire.

Case 1	Value of first rank = over 90% and value of second rank = under 60% and duration = 4 sec.
Case 2	Value of first rank = over 80% and value of second rank = under50% and duration = 8 sec.
Case 3	Value of first rank = over 70% and value of second rank = under 40% and duration = 12 sec.

Table 5 Time lapse of sprinkler activation and fire detection.

Exp. No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Time lapse after n-heptane ignition (min•sec) - : no data NR : no response judgement f.f. : flaming fire	Sprinkler activation															
	F	-	NR	NR	4•27	4•33	4•33	-	6•45	-	5•31	4•50	-	-	-	-
	A	3•13	-	-	-	-	-	5•03	-	4•53	-	-	4•38	-	-	-
	G	-	3•57	5•03	4•25	4•31	NR	-	-	-	5•39	-	-	-	-	-
	Fire detection															
	Rate-of rise-heat detection method	0•36	1•54	2•50	2•16	2•20	2•18	2•20	3•00	2•14	2•32	0•58	1•58	2•20	1•10	1•50
	Fixed-temp. type heat detection method	NR	NR	4•42	4•12	NR	4•32	3•56	4•38	3•32	3•48	2•54	3•42	3•50	3•10	3•26
	Photoelectric type smoke detection method	0•56	1•24	2•32	1•50	4•52	2•30	4•56	4•16	2•16	5•20	3•26	2•02	4•12	3•54	4•40
	Fuzzy reasoning method: judgment	f.f.	f.f.	f.f.	f.f.	f.f.	f.f.	f.f.	f.f.	f.f.	f.f.	f.f.	f.f.	f.f.	f.f.	f.f.
	Fuzzy reasoning method: time	2•32	2•48	3•12	2•42	3•40	2•56	2•50	4•12	3•12	3•08	2•40	2•24	2•46	2•04	2•30
	Residential smoke detectors															
	J0	0•46	0•34	2•42	6•00	5•18	2•18	4•52	5•46	1•58	NR	4•28	4•38	2•04	3•28	4•46
	J1	-	-	-	-	-	-	6•17	-	-	-	-	5•18	2•00	6•43	4•57
	J2	-	-	-	-	-	-	5•29	-	-	-	-	5•09	3•31	3•16	4•48
	J3	-	-	-	-	-	-	3•47	-	-	-	-	3•13	4•01	3•27	4•00
	J4	-	-	-	-	-	-	5•34	-	-	-	-	5•54	1•44	6•08	5•01
	J5	-	-	-	-	-	-	4•17	-	-	-	-	3•08	2•16	2•54	3•34

Discussion

Yuji Hasemi: You measured the gas concentration near the ceiling level but I think it might have been better if you would have measured at a lower level. When you focus on the life safety of the people inside the room, then probably you should have measured the height of where people stand up or people sit down.

Ai Sekizawa: Your are right. After this paper was prepared, we started vertical direction measurement tests. As Dr. Hasemi pointed out, we started to measure the gas concentration at the level people are sleeping and also the level of people standing up.