Burning Behavior in a Poorly-ventilated Compartment Fire
-- Ghosting Fire --

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Abstract
We have investigated fire behavior in a poorly ventilated compartment using a methyl alcohol pool fire as a source in a box of 2m(W) x 3m(L) x 0.6m(H). Temperatures, gas concentrations of CO, CO_2, and O_2, fuel consumption rate were measured simultaneously. The level of the fuel surface was kept constant during the tests by means of automatic fuel supply system. The flame began to detach from the fuel surface as the oxygen concentration decreased to about 16 vol.%, it color then becoming pale blue. The flame later detached completely from the fuel and a blue "ghosting flame" was observed just under the ceiling like an aurora. The oxygen concentration measured under the ceiling in the ghosting period under the ceiling was 9 - 10 vol.%, and the CO_2 was 4.5 vol.% so that the oxygen acted as an inert gas. The CO_2 gas concentration was almost uniform with a gradient in the upper part in the ghosting period. Temperatures in the same layer decreased after ghosting occurred also with a gradient. For these fires, the air exchange rate as 1.6 - 2.4 times/hr was estimated, and the burning rate decreased finally to about 1/6 of that of the fuel controlled fire.

key words : ghosting, poor ventilation, compartment fire, detached flame

1. Introduction

We have conducted about 40 fire tests in an enclosure with low ventilation, exploring fire behavior for fuel rich conditions. These tests were carried out to improve a model compartment fires to accommodate better the condition of very low natural ventilation which obtains in some recently designed residential buildings and energy power plants. To avoid the leakage and diffusion of radiative particles from atomic power plants, small air exchange openings are provided in the plant building. It is plausible that in such a power plant a fire would become a ghosting fire in the energy rich and poor-ventilation condition [2] that obtain. It has been tacitly assumed in the past that flame (reaction zone) and pyrolyzing material (fuel) leave the compartment together, but for the ghosting fire this is not necessarily so. Therefore, for the extinction of ghosting fires in a poorly ventilated enclosure with excess fuel and energy rich as in a power plant may be extremely difficult.

2. Experiment

A model compartment 2 m width x 3 m long x 0.6 m height was made with calcium silicate boards used as outer walls and ceramic boards inside. (see in Figure 1). Two adjustable slit panels were provided on the upper area of the front wall which was 60 cm x 60 cm with a observation window. A detachable opening door was also provided in it. The door was closed and sealed during tests.

Methyl alcohol in a stainless steel pan of 30 cm diameter set 40 cm above the floor at the center of the box was used as a fire source. The fuel was supplied from a reservoir through a copper tube to keep the fuel level constant during the burning, and the consumption measured.

Temperatures were measured by 0.3mmø chromel-alumel thermocouples with stainless steel sheath cover on a vertical rake so that a vertical temperature profile could be obtained.

Concentrations of CO and CO_2 were measured by gas analyzers of non-disperse Infra-red detecting type, and oxygen was measured simultaneously by a galvanic battery type detector.

In order to find the experimental condition to obtain the ghosting fire [1], we took an unexpectedly long time to improve the sealing of the joints between the boards, and is find a suitable arrangement of its small opening and the vertical position of the fuel pan. The final procedure was; the fire source was ignited by a pilot flame and then the door was closed and sealed. After 4 min from the ignition, the total opening area of the both slits was adjusted to 150 - 160 cm^2 to avoid choking and to limit the ventilation.

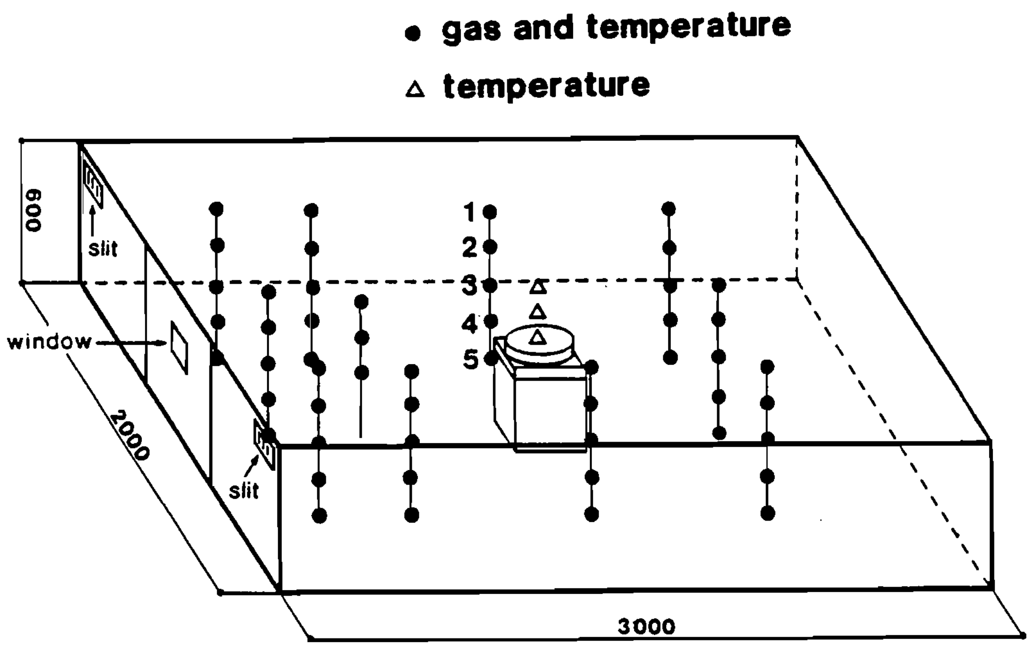

Figure 1-(a) Outline of the experimental box for the ghosting. Numbers correspond to the height from the floor, as 1:600mm, 2:450mm, 3:300mm, 4:150mm, and 5:5mm.

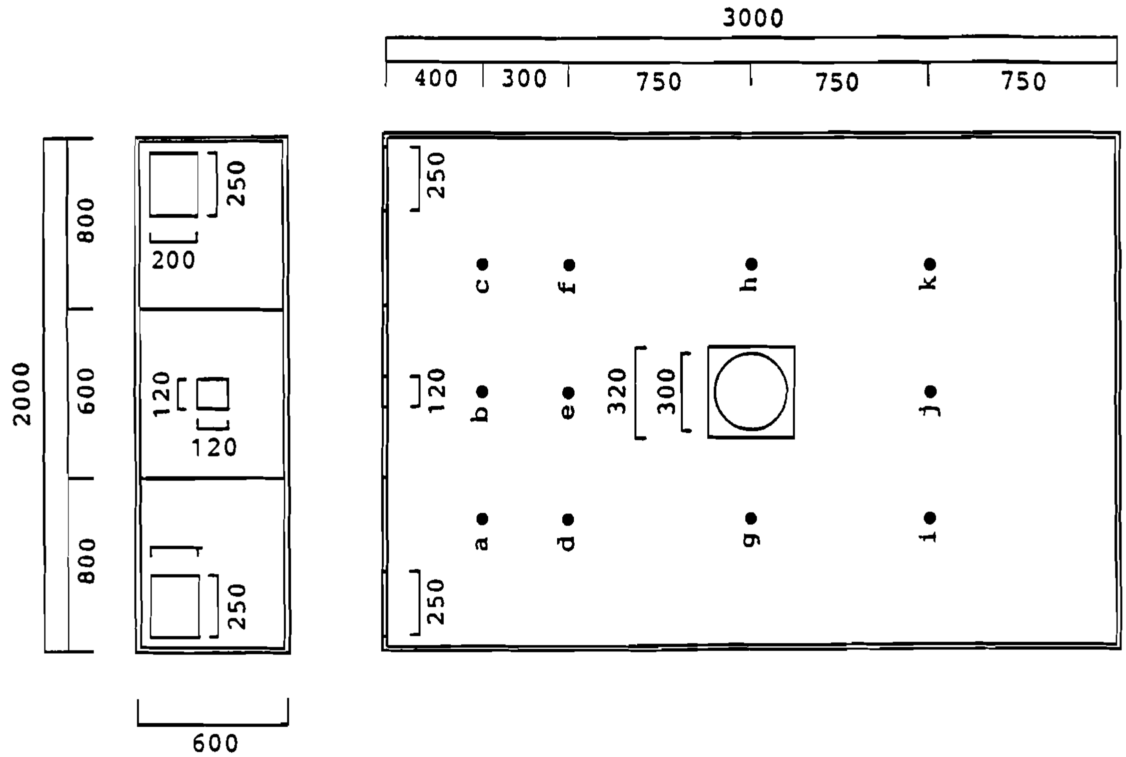

Figure 1-(b) Measuring positions in the enclosure. Length unit is mm.

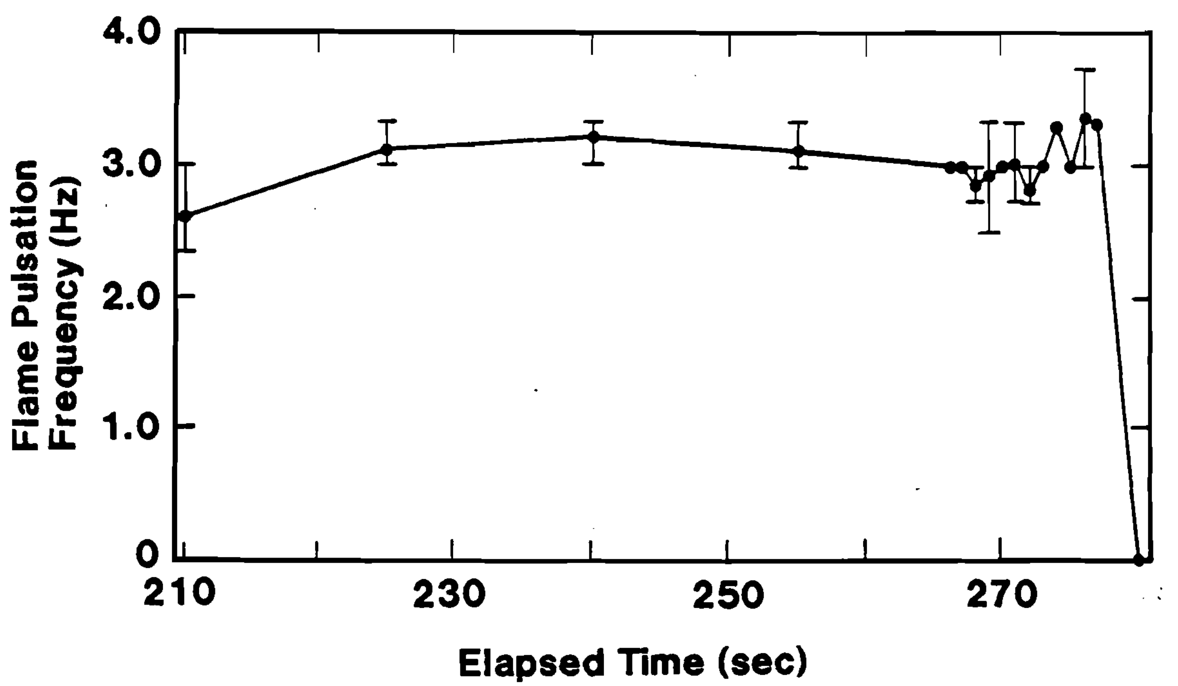

Figure 2 Time history of flame pulsation frequency of the methyl alcohol pool fire under poor ventilation.

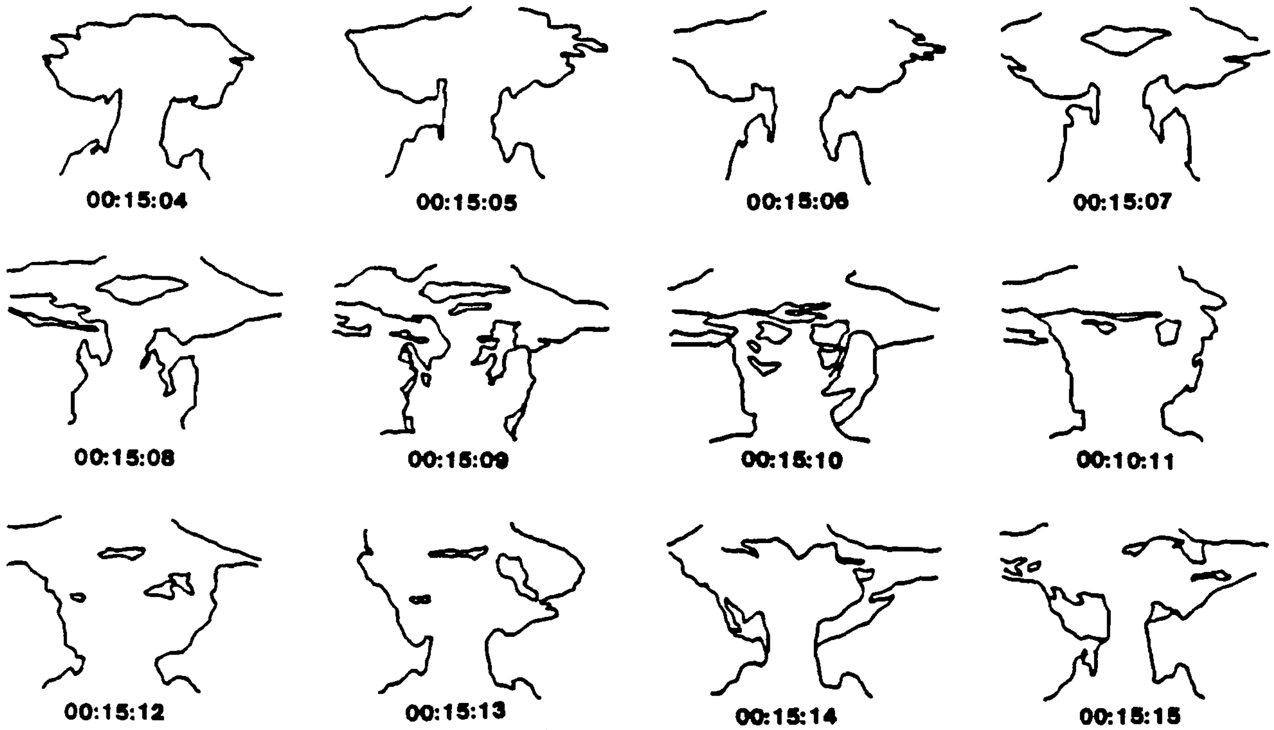

Figure 3 Typical one cycle of flame pulsation before ghosting.

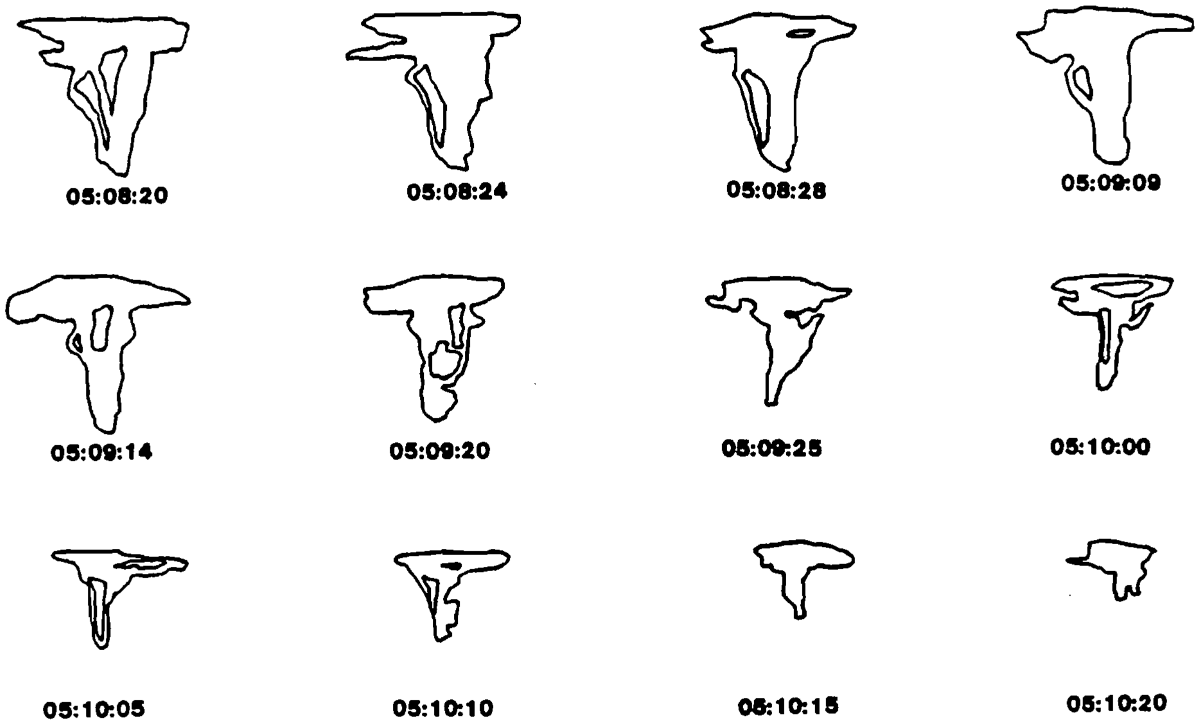

Figure 4 Flame shapes in the transition period to ghosting flame.

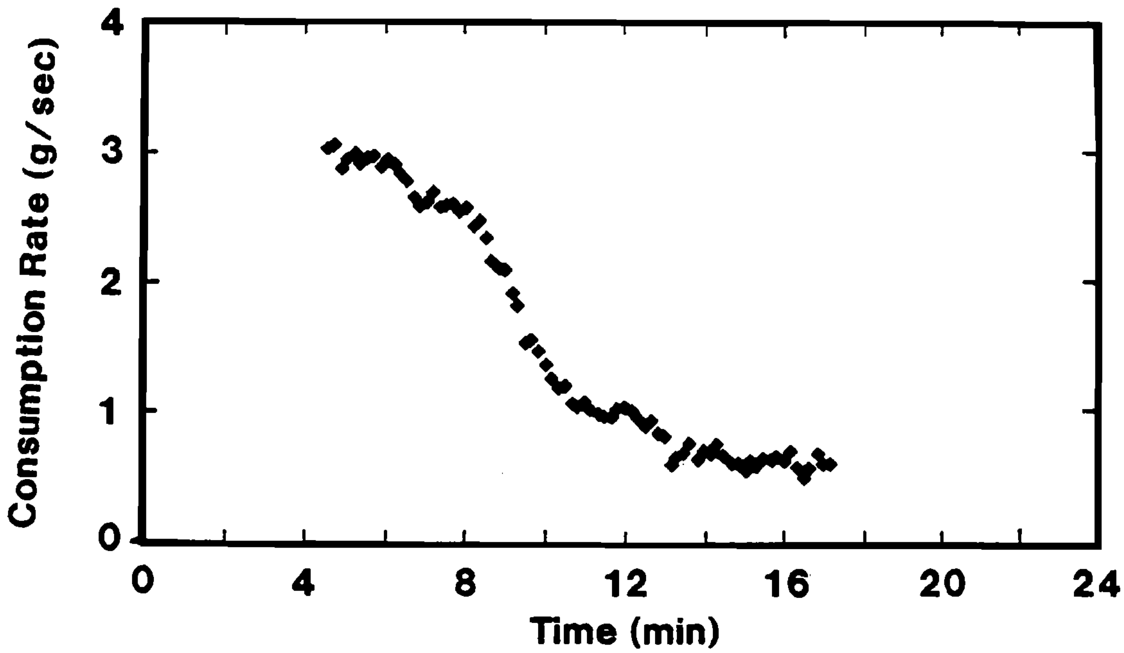

Figure 5 Time history of the consumption rate of the fuel including transition to ghosting.

3. Results and Discussion

(a) Observation

The diffusion flame from the fuel impinged on the ceiling for the first 6 - 7 min, and then flame began to detach from partly of the circular pan edge. The flame color, initially bright orange became pale blue. About 10 min after the ignition, the flame detached completely from the fuel surface and the "ghosting flame" started. It floated just under the ceiling with a thickness of about 5 cm and a diameter of about 40 cm. The thin pale blue ghosting flame looked like an aurora. This ghosting flame continued for times varying from 7 to 20 minutes in the different tests, sometimes coming down to the fuel surface forming an attached flame again. During the burning, a flame pulsation frequency of about 3 Hz was observed and it continued until just before the ghosting as shown in Figure 2. The pulsation frequency decreased abruptly about 3 sec before the ghosting began. Figure 3 shows one cycle of the pulsating flame, and Figure 4 the outline flame shapes in the transition to ghosting. Photo 1 shows the ghosting flame which appeared under the ceiling just above the pool. The last two frames show the beginning of the ghosting flame.

(b) Consumption rate of the fuel

Figure 5 shows the variation in time of the consumption rate of the fuel. In the first period of burning, the consumption rate was about 3 g/sec. The flame behavior changed as the consumption rate decreased and flame began to detach from the pan in this transition period. The consumption rate in the ghosting stage decreased finally to about 0.5 g/sec as an average value, 1/6 of that of the fuel controlled fire.

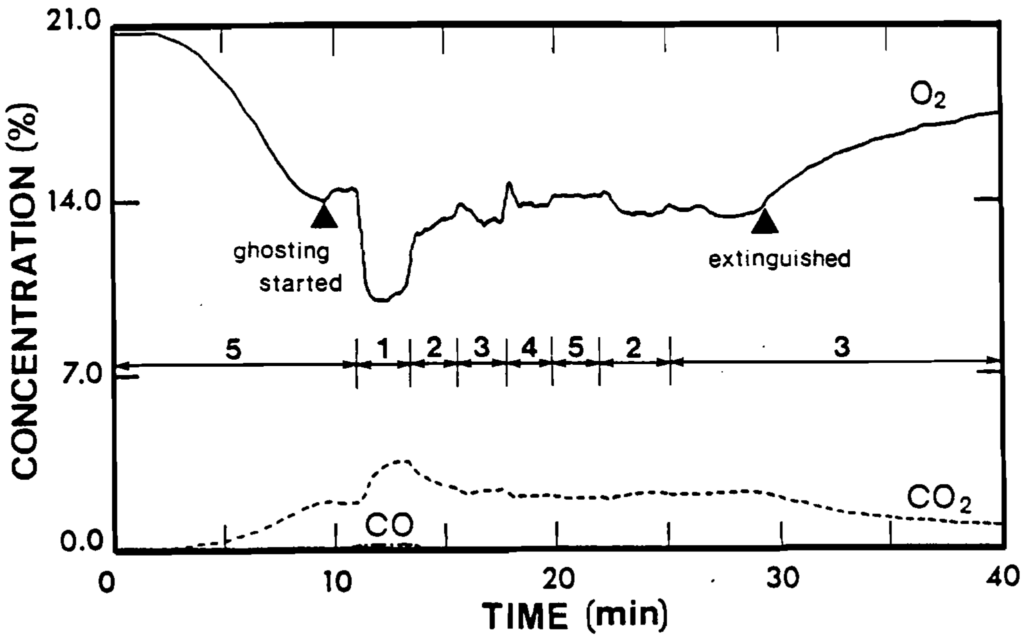

Figure 6 Time histories of typical gas concentrations for Test 46

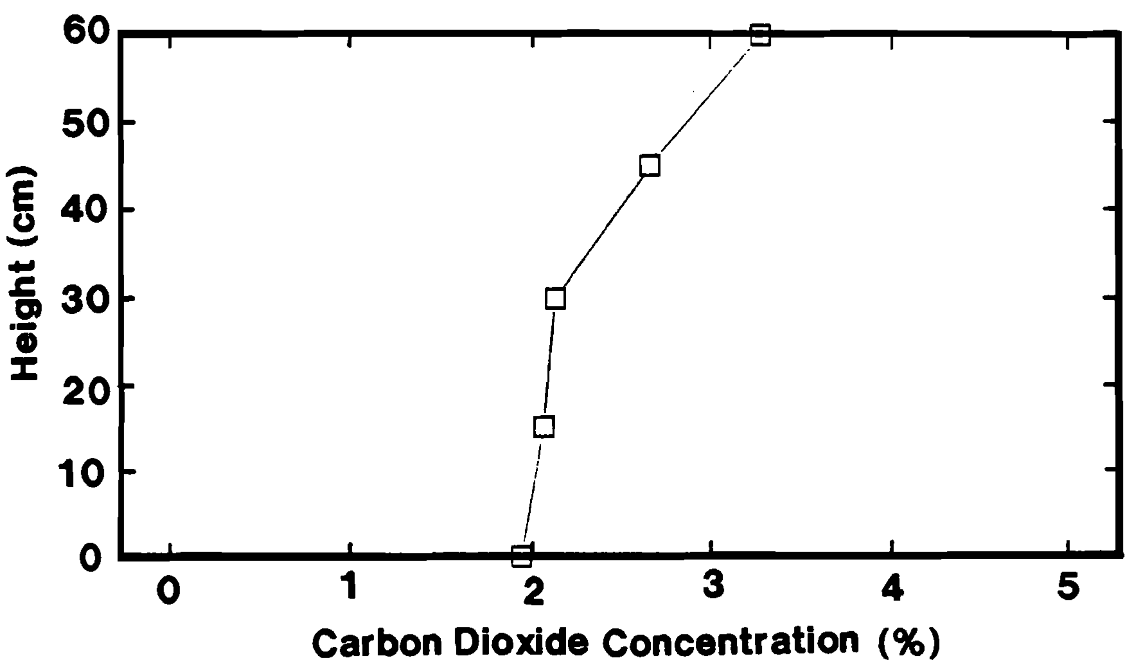

Figure 7 Vertical distribution of CO_2 gas concentration in the ghosting period. Data from Test 46.

(c) Gas Concentrations

Sample gas was sucked from the various positions a - k in the box, as shown in Figure 1, at 600 mm (corresponding to the ceiling height), 450 mm, 300 mm, 150 mm, and 5 mm from the floor. Figure 6 shows the typical variation in time of the gas concentrations and a triangle in the figure shows the start of the ghosting fire. Numbers in the figure 4 refer to the sampling positions of the rake. It is very clear that the measured carbon monoxide concentration was very low. 13 - 14 % oxygen concentration was measured in the ghosting period. The concentration of carbon dioxide varied with height and its vertical profile was almost uniform with some gradient in the upper part. Figure 7 shows the CO_2 gas concentration profile in the ghosting period. In the upper part of the layer the concentration was 2.7 - 3.5 % and it was 2 % below the mid height.

(d) Temperature

The temperature of the fuel was measured every 10 sec at the mid height for this tests and Figure 8 shows the variation in time of fuel temperatures. For both tests, the fuel temperature increased for 3 - 5 min after the ignition and then the rate of rise decreased with decrease of oxygen concentration. In test 21, the ghosting continued for only about 30 sec and then extinguished when the oxygen concentration (measured at point b) reached about 4 - 4.8 %. The experimental conditions of test 24 was the same as the test 21, however ghosting continued for about 20 min. The oxygen concentration decreased to a minimum of 5.5 % about 2 min before the ghosting started, and then increased to about 14 % in the ghosting period. Ghosting stopped when the fuel temperature reached about 45 ^oC. The quenching of ghosting may be associated both with the high fuel concentration or temperature within 10 - 15 ^oC of the

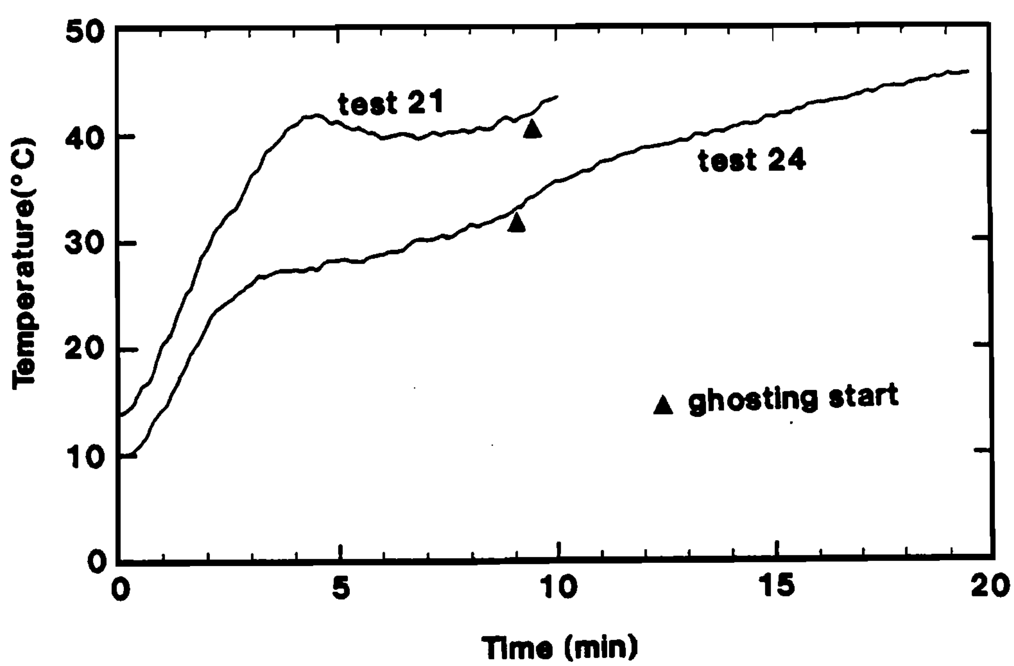

Figure 8 Time histories of fuel temperature.

boiling point and the low concentration of oxygen. In the ghosting period, the temperature just under the ceiling decreased about 100 ^{o}C as shown in Figure 9. This decrease of temperature produced less thermal radiation feedback to the fuel surface and reduced the rate of rise of the fuel temperature.

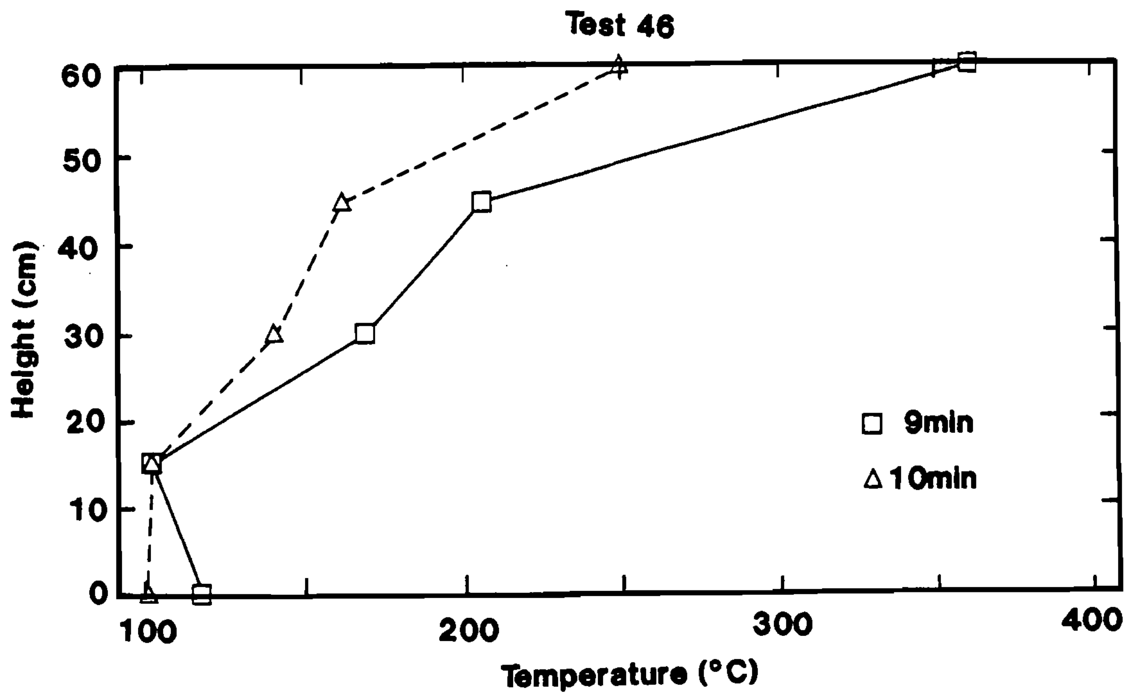

Figure 9 Typical temperature distribution for vertical direction before and in the ghosting period. Data from Test 46.

(e) Air Exchange Rate

In order to estimate the air change rate for the enclosure and the influence on it if the total leak area including the two slits, oxygen gas concentration was employed as a tracer gas after the extinction of burning. Figure 10 shows the variation in time of the oxygen gas concentration both with 160 cm^2 slit opening area (test 18 : point b) and another the slit closed (test 46 : point d): the air exchange rate was about 2.4/hr in the former case and 1.1/hr in the later. The air exchange rate condition required to start the ghosting fire was 1.1/hr and to sustain the ghosting was 2.4/hr. In the ghosting fire period, an oxygen concentration of about 14% was estimated as shown in Figure 6. Numbers in the Figure correspond to the measuring positions as shown in Figure 1-(b). Foote [1] found the "ghosting fire" using a methane diffusion burner in a full scale compartment under mechanical ventilation applying more than 5 times of air volume of the room per hour. As to be referred he found that the appearance of ghosting depended on the positions of the fire source and of the air inlet and outlet.

In the fully developed compartment fire in the ventilation controlled regime, the oxygen in the air (21% oxygen) which flows into a compartment is consumed almost completely by chemical reaction and in the out flow oxygen concentration is nearly zero.

But in the ghosting condition, 13 - 14% oxygen was observed so that it seems that it behaves like an inert gas. When the oxygen concentration decreased under this critical value, spontaneous extinguishment was obtained.

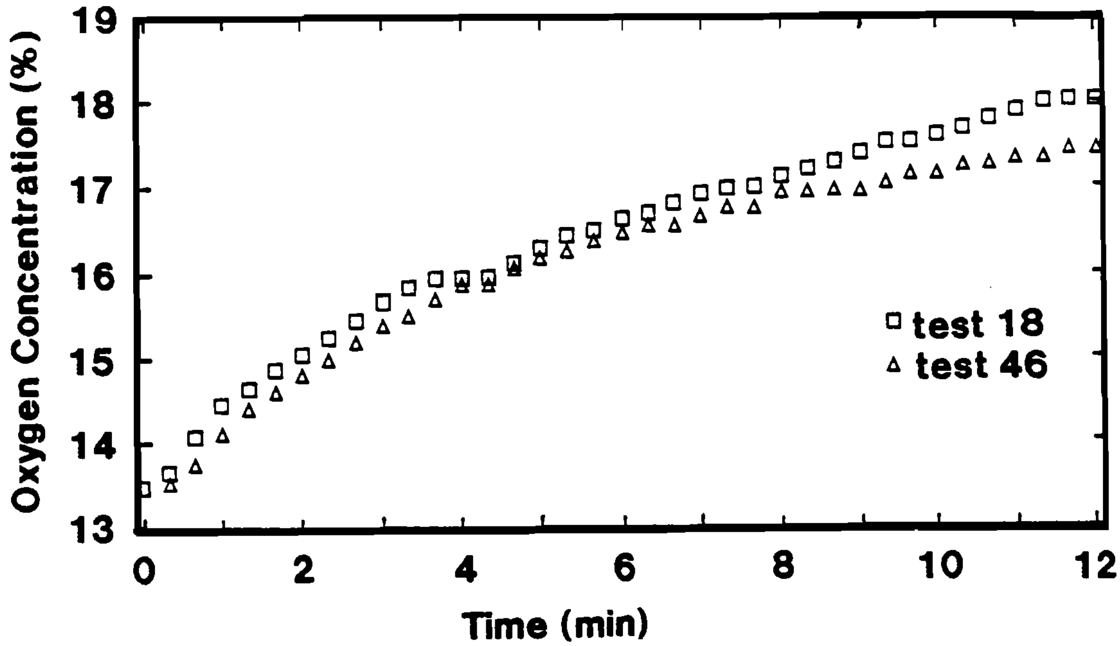

Figure 10 Time histories of oxygen concentration after extinction.

4. Conclusion

Many researchers are now interested in the pre-flashover phenomenon under the condition of enough oxygen. The computer fire codes for a two-layer zone model [3] can simulate the fire propagation from a small fire source up to flashover in a compartment. The assume that the cool lower zone is always supplied with enough air having 21% oxygen all of which could be available for consumption. But under the ghosting condition, the air in the lower zone having 13 - 14% of oxygen behaves as an inert gas. Thus the zone model seems suitable for predicting fire phenomena under the condition of oxygen starvation. It is necessary to apply a field model to predict such ghosting fire, although the mechanism of ghosting is not yet clear. Oxygen starvation may be obtained in an actual fire, some cases have been reported by the fire brigades.[4] We believe that the further study of the fire phenomenon under the oxygen starvation condition of in a compartment is essential in order to advance fire protection and fire fighting tactics for multi-story buildings.

5. Acknowledgment

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6. References

1) Foote, K.L., "1986 LLNL Enclosure Fire Tests Data Report", UCID-21236, Lawrence Livermore National Laboratory, August 5,(1987)

2) Backovsky,J., Foote,K.L., and Alvares,N.J. "Temperature Profiles in Forced-Ventilation Enclosure Fires", p315-324, Proc. of the Second Int. Symp. on Fire Safety Science, ed., by T.Wakamatsu et al., Hemisphere Publishing Corp. (1988)

3) There are several two-layer Zone Models and Codes, typical ones are;
"FIRST", "HAZARD I", "ASET A", "ASET B", Center for Fire Research, National Institute of Standards and Technology, Department of Commerce, USA
"Tanaka-Model", Building research Institute, Ministry of Construction of Japan
"ASKFRS", Building Research Establishment, UK (1988)

4) Private communication from Tokyo Fire Department

Photo 1 Ghosting flame located under the ceiling and above the fire source pool. The photo was taken by IR film with 1 sec exposure and opened iris.