Fire Research Note No. 806

A PRELIMINARY NOTE ON THE MOVEMENT OF SMOKE IN AN ENCLOSED SHOPPING MALL

by

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FIRE RESEARCH STATION

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SUMMARY

The design of escape routes from enclosed pedestrian shopping malls in large town centre developments would be facilitated by a knowledge of the likely rate of spread of smoke should a fire occur. This note discusses the spread of smoke along a mall in the light of a tentative theory (given in detail elsewhere). Assuming the theory to be correct a fire 2 m x 2 m base area would smoke-log a mall 6 m wide and 3 m high for 70 m in both directions in about $2\frac{1}{2}$ minutes. A fire "flashing over" in a small shop could smoke-log the mall for 200 m in both directions in the same time.

Further work to verify the theory will be carried out.

KEY WORDS: Smoke, Spread, Shopping Mall, Escape Means.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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INTRODUCTION

A feature of some town centre developments is the provision of pedestrian shopping areas which may include covered malls, sometimes on the lower levels of multi-storey developments. It is envisaged that in future such malls could be a few hundred metres long. The means of escape from such developments require careful consideration but some of the information on which the design of escape routes should be based is lacking. It is important that people on an escape route should not be overtaken by smoke and hot gases from a fire and in order to estimate the possibility of this happening it is necessary to know the velocity of travel of the smoke.

Smoke and hot gases will be spread to some extent by draughts due to external winds, temperature gradients within the building (other than those associated with the fire) and forced ventilation systems; generally the most important means of spread is by buoyancy effects due to the elevated temperature and reduced density of the hot gases. This note discusses the practical implications of a tentative theory[1] which enables the buoyancy-controlled spread of smoke along a mall to be estimated. The theory was based on work by a number of authors*, particularly that of Benjamin on gravity currents, and follows established hydrodynamic principles. It is supported by the results of an experiment carried out in Japan so that figures quoted in the present note should be of at least the right order although they may be subject to some revision in the light of experiments to be carried out in future.

SPREAD OF SMOKE IN JAPANESE EXPERIMENT

The pattern of smoke spread in a mall is illustrated by the results of an experiment carried out in Japan[2], in an underground car park. This was a series of chambers connected by wide full-height openings to form the

*Full references are given in (1)

equivalent of a mall about 150 m long, 14 m wide and 3 m high. A fire (with an area 2 m x 2 m) near one end of the car park was simulated by burning alcohol and adding a chemical smoke, the duration was about 10 minutes. The smoke spread pattern is shown in Fig. 1, no distinction is made between smoke flowing outwards from the fire and that circulating back towards it.

At first the smoke and hot gases were confined to a relatively shallow layer which in 2 min had extended to about 40 m from the fire. The rate of advance of the smoke decreased with time but the depth of smoke increased until after 10 min the car park was smoke-logged almost from floor to ceiling for a distance of 70 m from the fire.

These results are directly applicable only to the situation and size of fire with which they were obtained; the theory allows similar information to be obtained for other situations and fire sizes.

FLOW OF HOT GASES IN A MALL

Because a mall is much longer than it is wide, the smoke is generally spreading in two dimensions only; "radial" flow in three dimensions, as from a fire in the centre of a large shop, is unlikely to conform to the description given here.

The pattern of smoke spread observed in the Japanese experiment may be explained as follows:

The hot gases and flames rising from a fire entrain the surrounding air, contaminating it with smoke and hot gases and lifting it to the ceiling. A layer of hot gases forms beneath the ceiling and circulation is set up within the mall; close to the ceiling smoke and hot gases move away from the fire and beneath them cool air moves towards the fire (Fig. 2a). The depth and velocity of advance of the layer of hot gases may be calculated from the dimensions of the mall and the size and heat output of the fire.

The driving force for the layer of hot gases is its buoyancy resulting from its elevated temperature and since the layer becomes cooler as it travels away from the fire it will move more slowly and consequently become deeper. The changes in depth and velocity of the outward moving layer may also be estimated; Fig. 3 shows a comparison between the calculated velocity and that observed in the Japanese experiment.

Some smoke may mix into the cool air flowing towards the fire from near the leading edge of the outward flowing hot gases, but at first the cool air will be virtually uncontaminated. As the hot gas layer becomes deeper the top part of the cool air flow becomes increasingly smoke-logged (Fig. 2b) although near the floor the air will be nearly clear. This corresponds to the situation after about 4 min in the Japanese experiment.

Because of the flow of air displaced by the advancing layer of hot gases, the latter cannot occupy more than half the height of the mall; if this is not sufficient to accommodate the total flow any excess of hot gases will mix into the cool air flow resulting in thick smoke-logging (Fig. 2c). This corresponds to the situation after about 6 min in the Japanese experiment.

Mixing of smoke into the cool air flow may be induced locally by high air velocities caused, for instance, by forced ventilation systems or the wind blowing through doorways etc.

PRACTICAL EXAMPLES

The theory has been used to obtain tentative estimates of the travel of smoke along a typical mall 6 m wide and 4 m high with two different fire situations.

(1) Small fire

A fire 2 m x 2 m base area with flames 2 m high occurs in a small open-fronted shop. This size of fire may be of the order of that which could occur in a sprinklered shop and would have a heat output of roughly 1000 kW. At first the smoke and hot gases will spread as a 1 m deep layer at 0.7 m/s in both directions along the mall. The layer will then slow down; in one minute it will have reached 30 m and increased in depth to about $\frac{1}{3}$ of the height of the mall. Some smoke will be circulating back in the cool air flowing towards the fire but there should be a clear layer near the floor (Fig. 2b). After about $2\frac{1}{2}$ min the leading edges will have reached 70 m from the fire, the hot gases flowing away from the fire will occupy the top half of the mall and the smoke free layer near the floor will be very shallow (Fig. 2c). Subsequent smoke spread will be much slower, it will have reached 100 m from the fire in 4 min and in theory, if the fire size of 2 m x 2 m did not change, it would take $\frac{1}{2}$ hour to reach 250 m. In practice by this time the buoyancy of the layer would be so small that its flow is likely to be determined by other factors such as draughts due to ventilation systems.

(2) A "fully developed" fire

It is assumed that a fire reaches a "flashover" condition in a small shop and the shop windows having a total area of 6 m x 3 m then break. The heat output of the resulting fire would be controlled by the flow of air through the broken windows and would be about 30,000 kW. The layer of hot gases will have an initial temperature of the order of 900°C and will be deficient in oxygen. After 30 s the layer of hot gases flowing away from the fire will occupy half the height of the mall and will extend for 100 m from the fire. At this distance the hot gases will have cooled to roughly 50°C but they will still be deficient of oxygen. The air in the lower half of the mall flowing towards the fire will be smoke-logged although it should be cooler and more respirable than the outward flowing hot gases. After 2½ min smoke will have reached about 200 m from the fire.

CONCLUSIONS AND FUTURE WORK

The tentative theory may be applied to estimate the spread of smoke in a shopping mall. There is good agreement between the theory and the results of an experiment on the rate of spread of smoke in an underground car park in Japan[2].

Calculations have been made, (assuming the theory to be correct) of the spread of smoke in a 6 m wide 3 m high mall. With a relatively small fire, such as could be obtained in a sprinklered shop, exits up to 70 m from the fire in both directions would be difficult to use because of smoke in 2½ minutes.

Should a fire reach "flashover" in a small shop the mall would be heavily smoke-logged for 200 m in both directions in 2½ minutes.

Further experimental work will be carried out to verify the tentative theory and the correctness of the above conclusions.

An investigation will also be carried out of the effectiveness of measures such as roof venting which are intended to limit the spread of smoke and hot gases and reduce mixing of smoke into the flow of cool air towards the fire.

The full scale model shopping mall[3] at the Fire Research Station will be used for experiments on the possible density of smoke produced by a fire in a shop and the initial velocity and depth of the layer of smoke and hot gases and also on means of restricting the travel of smoke. It is probably too short for experiments on the deepening of the layer due to cooling and the consequent flow pattern in the mall. It is likely however that these can be carried out in a small scale model and this is being constructed.

REFERENCES

(1) HINKLEY, P.L. The flow of hot gases along an enclosed shopping mall - A tentative theory. Joint Fire Research Organization F.R. Note No. 807

(2) Report of fire test in underground car park in March 1966. Fire Protection Committee Tokyo Metropolitan Fire Brigade 1966 (In Japanese).

(3) FIRE RESEARCH 1969. To be published by H.M.S.O.

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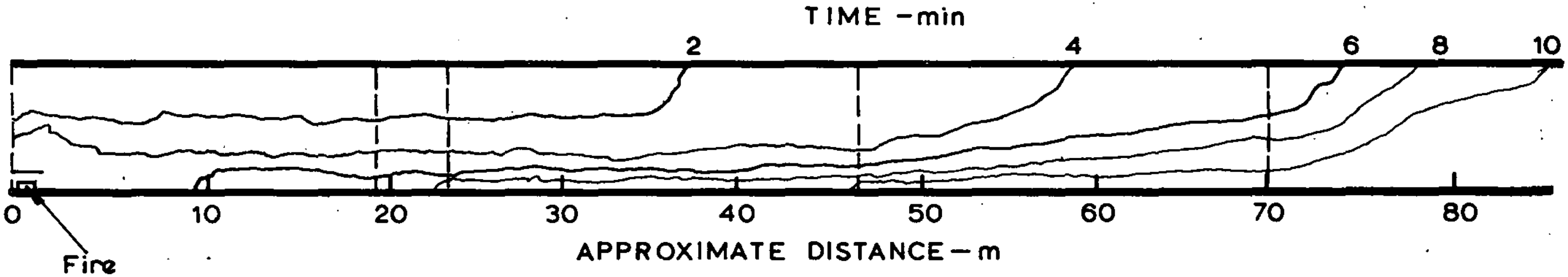
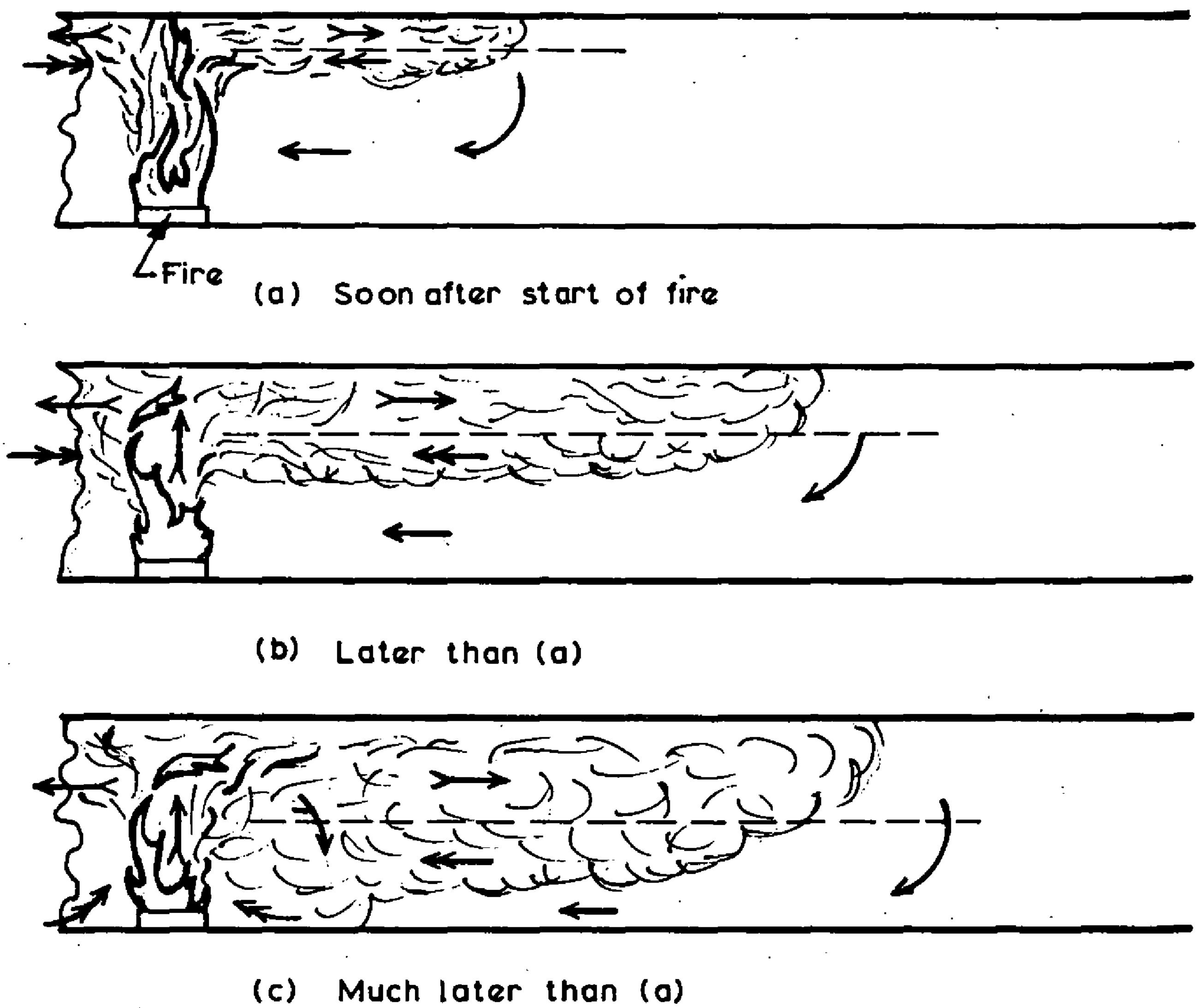


FIG.1 SPREAD OF SMOKE IN JAPANESE EXPERIMENT



Boundary between forward and reverse flow — — — — — —

Hot gases

Cool air

Smoke contaminated air

(Vertical scale greatly exagerated)

FIG. 2 SUGGESTED FLOW PATTERNS DUE TO A FIRE IN A MALL

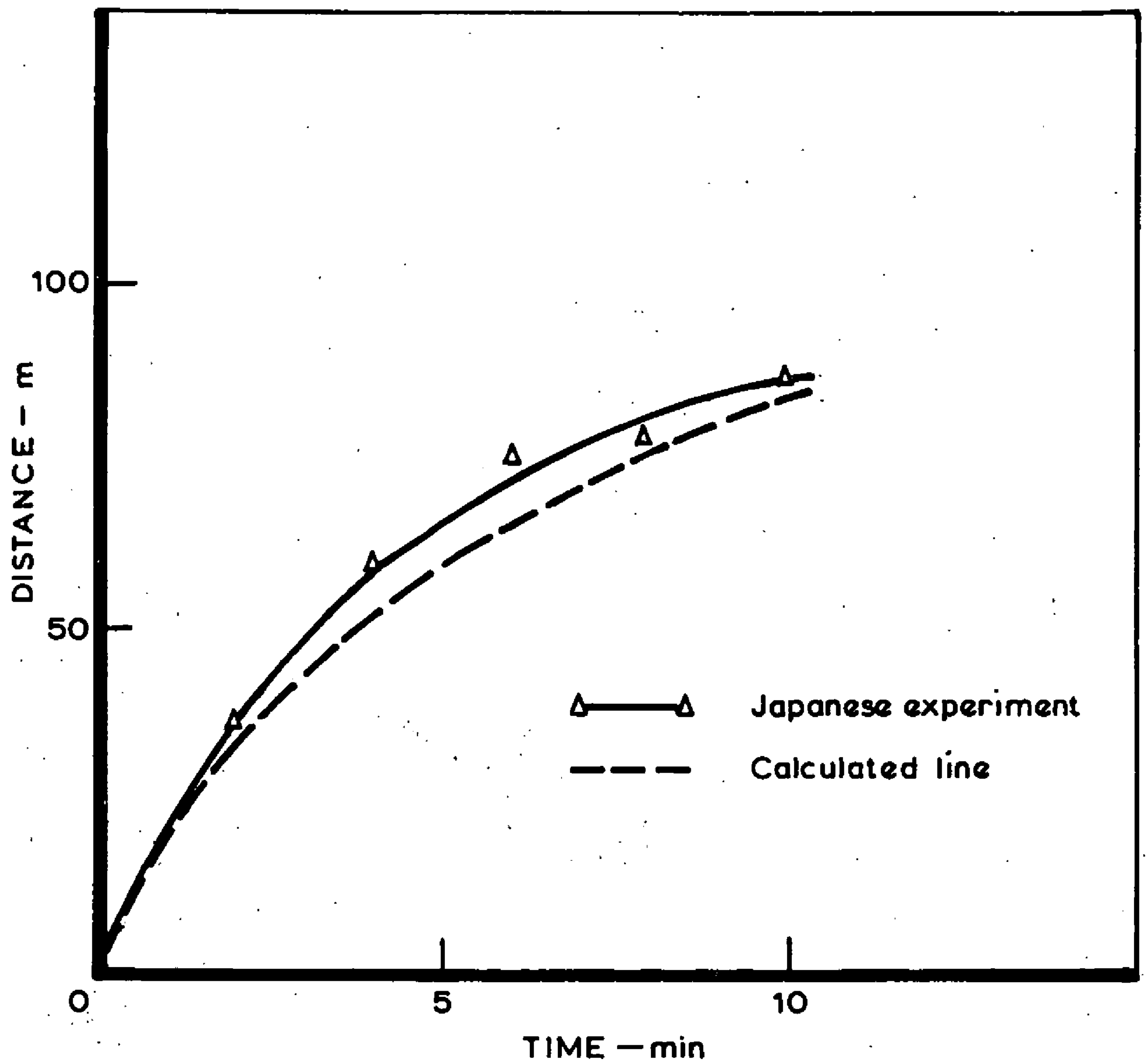


FIG.3 COMPARISON BETWEEN THEORETICAL SPREAD AND THAT OBSERVED IN JAPANESE EXPERIMENT