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THE DETECTION OF FIRES BY SMOKE:
4. PART 2. SLOWLY DEVELOPING WOOD CRIB FIRES
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## FIRE <br> RESEARCH STATION

THE DETECTION OF FIRES BY SMOKE :
PART 2. SLOWLY DEVELOPING WOOD CRIB FIRES

by<br>M.J. O'Dogherty<br>SUMMARY

Measurements have been made, at ceiling level, of the optical density per metre of smoke from slowly developing wood crib fires. Results are given for ceiling heights from 2.4 m to 7.0 m ( 8 ft to 23 ft ) above the fire, and for horizontal distances up to 9.8 m (32 ft) across the ceiling. In these experiments, the change in potential across the open chamber of an ionisation smoke detector, and the output signal from an optical-scattering smoke detector were also continuously recorded. In addition, the response times of some proprietary smoke detectors were measured.

The significance of the results in relation to a suitable sensitivity test for smoke detectors is discussed.

KEY WORDS: Detector, fire, Smoke, Optical, Ionisation, Investigation, Specification.

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## 1.. Introduction

This Note describes part of the general programme of research into smoke detection which was described in Part 1 of this series ${ }^{1}$. The work was carried out to study the detection of smoke from wood fires, and the fire used was constructed so as to develop slowly and produce smoke at an early stage in its growth with relatively little flaming.

## 2. Experimental

The fire was in the form of a wood crib constructed of 25 mm ( 1 in) square sticks which were 239 mm (9 in) long. The spacing between the sticks was $15 \mathrm{~mm}(0.6 \mathrm{in})$ and the crib had 9 layers. It was ignited by $70 \mathrm{~cm}^{3}$ of alcohol placed in a small tray at the centre of its base. The wood used was Pinus sylvestris conditioned to have a moisture content between 10 and 14 per cent.

Measurements were made of the optical density per metre of the smoke at ceiling level, the change in potential across the open chamber of an ionisation detector, and the output signal from an optical scattering detector. The response times of some proprietary detectors were measured, and air temperature. rises at ceiling level and the weight of the burning material were continuously recorded. The range of heights of the ceiling above the fire was from 2.4 m to 7.0 m ( 8 ft to 23 ft ), and the horizontal distances of the detectors and measuring equipment ranged up to $9.8 \mathrm{~m}(32 \mathrm{ft})$ from the fire.
3. Detector response time

### 3.1. Effect of ceiling height

The results for the detectors positioned above the fire, or very close to it, showed an increase in detection time which was proportional to the ceiling height. For positions at some distance from the fire, the detection times showed a rate of increase with height similar to that when the detectors were above the fire, but the curves were displaced upwards. Some results are shown in Figure 1 for an ionisation
chamber detector. These results are consistent with the concept that the smoke moves vertically and horizontally at two distinct velocities. The measurements of optical density give a time before smoke was observed at the location of the detectors, from which the average velocity of the smoke can be calculated. The overall mean values obtained for all the experiments were $6.1 \mathrm{~m} / \mathrm{min}(20 \mathrm{ft} / \mathrm{min})$ and $2.1 \mathrm{~m} / \mathrm{min}(6.9 . \mathrm{ft} / \mathrm{min})$ for the vertical and horizontal velocities respectively. Figure 2 shows the effect of ceiling height on the transit time of smoke to the detectors, and exhibits the same general form as the detection times of Figure 1. When the smoke has reached the detector, there will be a delay while it enters the sensitive chamber and builds up to a level which is sufficiently high to cause operation. Figure 3 shows the mean detection times of an optical scattering detector plotted against the smoke transit time. It is not possible for the detector to operate at a time which would give rise to a point lying below the line drawn at $45^{\circ}$ to the axes, unless it had responded to aerosols which were not detectable by the optical density meter. The line drawn through the points gives an indication of the time of response of the detector after smoke has reached it, since this time is the difference between the ordinates of a line at $45^{\circ}$ to the axes and a line through the points. This time will depend on the setting of the detector and/or its control equipment, and the design of the sensitive chamber, which determines the ease of access of smoke. For the detector shown in Figure 3, this time constant, $\tau$ (see below), is approximately 0.75 min.

The total time of detection, too, was given in Part 1 of this series ${ }^{1}$, and is:

$$
t_{0}=\frac{h}{V_{v}}+\frac{d}{V_{h}}+\boldsymbol{\tau}
$$

where $\quad$| $h \quad$ is the ceiling height |
| :--- |
| $d$ |
| $V_{v}$ |
| $V_{h}$ is the horizontal distance from the fire |
| $\tau$ |

### 3.2. Effect of horizontal distance

The detection time increases with horizontal distance in a way which suggests that it is consistent with the concept given in 3.1. above. The increase is linear, and has an intercept on the time axis which increases with ceiling height. Figure 4 shows the results observed with an ionisation chamber and Figure 5 the transit times of smoke, in both cases plotted against horizontal distance from the fire.

### 3.3. Size of fire at detector operation

Each fire was weighed continuously and a curve plotted relating its weight to time; a typical example is given in Figure 6. By determining the slope of this curve at a number of points, a curve relating the rate of weight loss to time was obtained; an example is shown in Figure 7. These curves enable the rate of weight loss (rate of burning) at the time of detection to be found, and this can be used as a measure of fire size, as discussed in Section 6 of Part 1. ${ }^{1}$

The rate of burning of the fire at detection showed similar variations with ceiling height and distance from the fire as were observed for the times of detection. This result is confirmed by the fact that the rate of burning is approximately proportional to time over the range of times in which the fire was detected. Figure 8 shows the results obtained for an ionisation chamber detector plotted against ceiling height. The sizes of fire ranged from rates of burning of about $10 \mathrm{~g} / \mathrm{min}(0.35 \mathrm{oz} / \mathrm{min})$ to $140 \mathrm{~g} / \mathrm{min}(4.9 \mathrm{oz} / \mathrm{min})$ within the range of ceiling heights and distances examined.
4. Optical density of smoke

The optical density of the smoke was found to increase with time according to a power law, with a mean exponent of 1.66 . There was a delay period before smoke was recorded which increased with ceiling height and distance from the fire. These delay times give a measure of both the vertical and horizontal velocity of smoke movement, and the mean values are given in Section 3.1.

Figures 9 and 10 show the effects of ceiling height and distance from the fire on the optical density per metre. The points are mean values for the replications and represent conditions at 5 min after ignition of the fire. The results show a practically linear fall in optical density with increasing ceiling height, over the range examined. As the distance from
the fire increases the optical density decreases progressively, but at a decreasing rate so that the curves flatten out at greater distances. This result is in agreement with earlier work, which showed similar relationships ${ }^{2}$, 3 。

The optical density per metre recorded when the detectors reached the alarm condition showed a wide variation. The ionisation chambers operated at low values when situated very close to the fire, generally at less than 0.01 per metre, and in some cases at a level which was not measurable. At 4.9 m and 9.8 m from the fire the optical densities at detector operation were generally higher, lying between 0.01 and 0.1 per metre, and ranging up to. O. 2 per metre in a few cases. There was no evidence of a significant difference between the results at 4.9 and 9.8 m . In the case of the optical scattering detector most of the results lay between 0.01 and 0.1 per metre, with only two values of less than 0.01 per metre.

The optical density per metre of the smoke immediately over the fire was examined to see if there was a correlation with the rate of weight loss of the fire. It was found that there was a good correlation between the two quantities, although there was considerable variability in the optical density for a particular rate of weight loss for different fires. The rate of weight loss recorded before smoke was evident on the optical density meter ranged between 6.0 and $24.0 \mathrm{~g} / \mathrm{min}(0.21$ to $0.85 \mathrm{oz} / \mathrm{min})$. A typical result is shown in Figure 11. The rates of burning to give a particular smoke density were small. For an optical density of 0.1 per metre the mean rates of burning ranged from 19.1 to $54.8 \mathrm{~g} / \mathrm{min}(0.67$ to $2.2 \mathrm{oz} / \mathrm{min})$, the rate increasing with the height of ceiling.

## 5. Sensitivity testing

In order to establish a realistic test procedure for smoke detectors, it is necessary to subject them to an increasing concentration of smoke which is representative of the conditions which result from a fire in a building. Figure 12 shows two curves of optical density plotted against time which represent the envelope of all the curves obtained in the experiments; Figure 13 shows similar curves for the response of the proprietary ionisation chamber used. These curves represent the range of conditions for the wood crib fire, from a position immediately above the fire for the 2.4 m ceiling height, to the maximum nominal distance from the fire of 9.8 m for the 7.0 m ceiling height. The curves do not show
the time taken, in actual fire conditions, for smoke to reach the detectors. Curves of this type may form the basis of test curves for the comparison of the performance of detectors in a simple smoke tunnel test. Such a test will only be valid if it represents the actual response of detectors in fire tests, and further.work is required to establish whether a tunnel test alone is likely to give an adequate assessment of detector sensitivity under fire conditions.

It was observed that the ionisation chamber had a rapid response to smoke when situated close to the fire, and could result in detection of the fire at very low values of optical density of the smoke. This is shown in the steep gradient of curve A in Figure 13, and illustrated in Figure 14 where the change in potential across the ionisation chamber is plotted against optical.density of the smoke per metre. These results raise the question of whether it is possible to specify the performance of a smoke detector in terms of optical criteria only, especially taking into account the fact that smoke is freshly formed in a tunnel test when it reaches the detector. Further work is required to establish whether a measure of optical density is practicable for judging ionisation chamber performance, and comparative measurements are required, with an ionisation chamber designed as a standard of measurement, of the effects of smoke particles. In addition, some further measurements are required to establish the lower limit curve shown in Figure 12, for a ceiling height of at least 12 m ( 39.6 ft ). Consideration may also have to be given to artificially ageing the smoke used in a tunnel test to give a closer simulation to practical conditions.

## 6. Conelusions

The time required to detect a fire by sensing the smoke emitted was found to be proportional to ceiling height for detectors placed above the fire. For detectors at 4.9 and 9.8 m from the fire the detection times also increased linearly with ceiling height, but were greater than those for detectors above the fire by a constant factor dependant on the horizontal distance. The time for detection was found to be made up of the time taken for smoke to ascend to the ceiling and move horizontally across it, plus a time constant while the smoke entered the detector and reached a level sufficient to cause operation. The smoke velocities were estimated at 2.1 and $6.1 \mathrm{~m} / \mathrm{min}$ for the horizontal and vertical directions respectively.

The detection time was found to increase linearly with the horizontal distance from the fire，with an intercept on the time axis which was proportional to the ceiling height．
．．．The sizeiof＇fixe：at＇detection showed similar variations with ceiling height and distance from the fire as the detection time．The sizes of fire detected were small and in the range 10 to $140 \mathrm{~g} / \mathrm{min}$ ．

The optical density of the smoke was found to increase with time according to a power law，with a mean exponent of 1.66 ．There was a good correlation between the optical density and the rate of weight loss of the fire，with a comparatively small fire resulting in a high density of smoke． It was found that ionisation chamber detectors operated at low values of optical density when situated above the fire，but at distances of 4.8 and 9.6 m from the fire the results for ionisation chamber detectors and an optical detector were comparable．

The results give data on which test curves can be proposed for a smoke tunnel test．It is necessary to establish whether the performance of practical detectors when subjected to a defined smoke density curve in a tunnel test is similar to that when subjected to the same smoke density curve as measured under fire conditions．

7．Acknowledgments
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FIG.1. VARIATION OF OPERATING TIME OF AN IONISATION CHAMBER DETECTOR WITH CEILING HEIGHT

CEILING HEIGHT-ft


Horizontal velocity $=\mathbf{2 . 1 3 \mathrm { m } / \mathrm { min }}(7 \mathrm{ft} / \mathrm{min})$
Vertical velocity $=6.10 \mathrm{~m} / \mathrm{min}(20 \mathrm{ft} / \mathrm{min})$
FIG. 2. VARIATION OF TRANSIT TIME OF SMOKE WITH CEILING HEIGHT

$h_{1} \times 2.44 \mathrm{~m}(8 \mathrm{ft})$ ceiling
$h_{2} \times 4.88 \mathrm{~m}(16 \mathrm{ft})$ ceiling
$h_{3} \quad \Delta 7.01 \mathrm{~m}(23 \mathrm{ft})$ ceiling

FIG.3. COMPARISON OF OPERATING TIMES OF AN OPTICAL SCATTERING DETECTOR WITH THE TIME REQUIRED TO REACH THE DETECTOR LOCATER


FIG. 4. VARIATION OF OPERATING TIME OF AN IONISATION CHAMBER DETECTOR WITH DISTANCE FROM FIRE


Horizontal velocity $=2.13 \mathrm{~m} / \mathrm{min}(7 \mathrm{ft} / \mathrm{min})$
Vertical velocity $=6.10 \mathrm{~m} / \mathrm{min}(20 \mathrm{ft} / \mathrm{min})$
FIG.5. VARIATION OF TRANSIT TIME OF SMOKE WITH DISTANCE FROM FIRE

fig. 6. VARIATION OF WEIGHT OF CRIb FIRE WITH time
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Fig.7. VARIATION OF RATE OF WEIGHT LOSS OF CRIB WITH TIME

CEILING HEIGHT-ft


FIG.8. VARIATION OF SIZE OF FIRE AT DETECTION BY AN IONISATION CHAMBER DETECTOR WITH CEILING HEIGHT


FIG.9. VARIATION OF OPTICAL DENSITY WITH CEILING HEIGHT


FIG. 10. VARIATION OF OPTICAL DENSITY WITH DISTANCE FROM FIRE


FIG.11. VARIATION OF OPTICAL DENSITY WITH SIZE OF FIRE




FIG. 14. RELATIONSHIP BETWEEN CHANGE IN IONISATION POTENTIAL AND "OPTİCAL DENSITY


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