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THE DETECTION OF FIRES BY SMOKE:
PART I. RESEARCH PROGRAMME AND DEVELOPMENT OF STANDARD TEST METHODS
by
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## FIRE <br> RESEARCH STATION

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## SUMMARY

This report describes the programe of research which has been undertaken to study the problem of the detection of fires by smoke. Examples are given of the information which has been obtained from the work, and how these results can be applied to the framing of standard test procedures which simulate the conditions which result from fires ooourring in buildings. The general requirements of tests for detector sensitivity and those for environmental conditions are disoussed.

KHY WORDS: Detector, Fire, Smoke, Optioal, fonization, Inveatigation, Speotifoation (standard).

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## MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE Joint fire research organization

# PART I: RESEARCH PROGRAMME AND DEVELOPMENT OF STANDARD TEST METHODS. 

## by.

M. J. O'Dogherty

## 1. Introduction

The detection of fires in buildings by the smoke they emit is dependent on a number of factors. Firstly, it depends on the materials which are burning and on the rate of burning, which may differ widely, and which determines the mass concentration of smoke particles present, together with their size distribution, shape, int ernal structure and refractive and absorption indices. Secondly, the detection of smoke is complicated by the physically unstable nature of smoke resulting from processes of coagulation, sedimentation and condensation which are continuously taking place, and by dilution with air as the smoke rises with the hot gas stream from the fire and spreads laterally across the ceiling or roof. In practice, these processes are affected by certain characteristics of the building, such as the height and shape of the ceiling or roof, by the presence of ambient thermal gradients within the building, and by air movements resulting from ventilating and air=conditioning systems. The third factor of importance concerns the characteristics of the detection system itself, such as the principle used to sense the presence of smoke, the design of the detecting chamber, the velocity and direction of flow of smoke into the detecting chamber, the setting of the detector and/or its control equipment, the detector spacing, and the depth of mounting of the detectors below the ceiling or roof.

The research programme described in this report was carried out to proyide data of use to designers and installers of smoke detection systems, and to provide a basis for the specification of suitable test procedures to examine the performance of detection systems in conditions simulating practical fire situations. Part 1 of the report describes the experimental programme, gives some typical examples of the information which the work has produced, and discusses how the results will be applied in setting up standard testing procedures. Succeeding parts of the report will describe the detailed results for each of the series of experiments described in the programme.

## 2. Experimental programme

The experiments were conducted with detectors mounted on a flat ceiling with dimensions of 15.3 m by 11.0 m ( 50 ft by 36 ft ); the general experimental arrangement is shown in Figure 1. The ef'fects of the following factors were examined:-
(1) Ceiling height.

Three heights were used in the experiments and were designated:

$$
\begin{aligned}
& h_{1}=2.4 \mathrm{~m}(8 \mathrm{ft}) \\
& \mathrm{h}_{2}=4.9 \mathrm{~m}(16 \mathrm{ft}) \\
& \mathrm{h}_{3}=7.0 \mathrm{~m}(23 \mathrm{ft})
\end{aligned}
$$

The height of the detectors above the fire was varied by raising the fire above floor level for the 2.4 and 4.9 m heights.

The fire was at ground level for the 7.0 m ceiling height.
(2) Horizontal distance.

The detectors and measuring equipment were arranged in three groups along the centre line of the ceiling. The positions in relation to the fire were designated:

$$
\begin{aligned}
& d_{1}=0 \mathrm{~m} \text { from fire (on the fire axis of symmetry) } \\
& d_{2}=4.9 \mathrm{~m}(16 \mathrm{ft}) \text { from fire } \\
& d_{3}=9.8 \mathrm{~m}(32 \mathrm{ft}) \text { from fire }
\end{aligned}
$$

(3) Type of fire
(a) $W_{1}$ : wood crib fire (slow development)

This fire was designed to develop slowly and produce smoke with no appreciable flaming up to a late stage in its growth. The construction of the crib was as follows:

| Stick size: | 25.4 mm (1 in) square |
| :--- | :--- |
| Stick length: | 229 mm (9 in) |
| Spacing between sticks: | 15.3 mm ( 0.6 in ) |
| Number of layers $=9$ |  |

The wood used was pinus sylvestris (white pine) with a moisture content in the range 10 to 14 per cent. The fire was ignited by $10 \mathrm{~cm}^{3}$ of alcohol contained in a small tray at the centre of the base of the crib.
2. Wxperimentail programme
(3) Type of fire (cont'd)
(b) $W_{2}$ : wood crib fire (f'ast development)

This fire was designed to develop rapidly so as to burn cleanly at an early stage in its growth, with a relatively low rate of smoke production. The construction of the crib was as follows:

| Stick size: | 20 mm (0.79 in) square |
| :--- | ---: |
| Stick length: | $254 \mathrm{~mm}(10 \mathrm{in})$ long |
| Spacing between sticks : | $26.8 \mathrm{~mm}(1.06 \mathrm{in})$ |
| Number of layers: 9 |  |

The wood used and method of ignition was as for fire $W_{1}$.
(c) $L$ : petrol fire

This fire was constituted of regular grade leaded petrol contained in a square tray having an area of $0.093 \mathrm{~m}^{2}\left(1 \mathrm{f}^{2}\right)$. The quantity of petrol used was approximately $850 \mathrm{~cm}^{3}$.
(d) and (e) $R$ and $P$ : rubber and plastics fires

These fires will consist of rubber and polystyrene strips, which will be built up into the form of a crib. The details of the design will be given in the individual parts of this report concerning these materials.

For each fire and ceiling height, three repljcations were made, designated by $r_{1}, r_{2}$ and $r_{3}$. Hence each measurement made has a specific reference : for example $W_{2} h_{1} d_{3} r_{2}$ denotes measurements made with the rapidly developing wood fire, for a ceiling height of 2.4 m at 9.8 m from the fire, and represents the second replication.

At each measuring position $\left(d_{1}, d_{2}\right.$ and $\left.d_{3}\right)$ continuous measurements were made of the change in potential across the open chamber of an ionization chamber, the output from an optical scattering detector, and of the optical density over a $1 \mathrm{~m}(3.28 \mathrm{ft})$ path fength using a tungsten filament light sofrce and a cadmium sulphide photocell. In addition, the response times' of some proprietary detectors were measured. The air temperature rise at each position was measured continuously using fine wire chromel/alumel thermocouples. The fire was weighed continuously, using a supporting platform incorporating an electrical resistance strain gauge bridge, so that the rate of burning of the material could be determined at any time by a differentiation of the weight-time characteristic curve.
3. Optical density and ionization chamber measurements

Some typical results for the measurements of optical density are shown in Figures 2 and 3 for fires $W_{1}$ and $L$. The curves for fire $W_{1}$ show that the optical density increases with time according to a power law, the exponent of time being approximately two. There is a time delay before smoke is observed, and this enables the mean vertical and horizontal velocity of the smoke to be calculated. The form of the optical density curves for fire $L$ is different, and increase at a less rapid rate after an initial rapid increase as the fire spreads over the liquid surface and reaches a relatively steady rate of burning. The units of measurement of optical density and their relationship to the commonly used measure of percentage obscuration are discussed in detail in Appendix 1.

Some typical results of measurements of the change in potential across an open ionization chamber are shown in Figure 4, for fire $W_{2}$ at various distances from the fire. This graph shows the very rapid response function of an ionization chamber to the freshly formed smoke immediately above the fire, and the slower response at a distance from the fire. Curves of this type enable the response time of such a detector to be determined for various "triggering" voltages of the device.
4. Response time of detectors

The results analysed to date show that the time of deteotion of a fire by smoke is largely made up of the time taken for smoke to reach the detector, which is particularly important for slowly developing fires when the smokevelocity is low. For example, for fire $W_{1}$, the vertical velocity of the smoke was estimated at $6.1 \mathrm{~m} / \mathrm{min}(20 \mathrm{ft} / \mathrm{min})$ and the horizontal velocity across the ceiling at $2.1 \mathrm{~m} / \mathrm{min}(7 \mathrm{ft} / \mathrm{min})$. Figure 5 shows the time required for smoke to reach the measuring positions, assuming these velocities, and how this time is dependent on ceiling height and horizontal distance from the fire. These times largely determine the response times of smoke detectors, which show very similar variations with ceiling height and distance from the fire.

When smoke has reached the detector it will then take a certain time to give, a warning of fire, which will depend on the time taken for the smoke concentration to build up in the detector to a level which produces the alarm signal. This time will depend on the physical design of the sensitive chamber (which affects the ease of smoke access), and on the setting of the detector and/or its control equipment.
4. Response time of detectors (cont'd)

The response time, $t_{0}$, can be expressed as:

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

Where $h$ is the ceiling height
d is the horizontal distance from the fire
$\mathrm{V}_{\mathrm{v}}$ is the vertical velocity of smoke movement
$V_{h}$ is the horizontal velocity of smoke movement
and $\tau$ is a time constant of the detector which is dependent on the factors discussed in the previous paragraph.

Figure 6 shows response times of an ionization chamber plotted against the time taken for smoke to reach it from fire $W_{1}$, for various values of $h$ and $d$. "It is impossible for detection to occur in the region below the line $O A$, drawn at $45^{\circ}$ to the axes. The dotted line through the points gives an indication of the time constant of this detector to this type of smoke, since $\tau$ is given by the difference in ordinate between the line $O A$ and the dotted line. The results shown in the figure suggest a substantially constant value of over the range of results observed.
5. Smoke density and rate of weight loss

In experiments in which the rise in air temperature has been measured, it has been possible to correlate this with the rate of convective heat output of the fire ${ }^{1}$. The results so far obtained with developing fires in wood have shown á similar correlation for smoke density, and a representative result is shown in Figure 7. Further analysis will show whether such correlations hold for different materials and for a wide range of ceiling heights and horizontal distances from the fire, and whether general relationships can be established.
6; Sizen:of firé detected.
In assessing the size of fire detected by heat detectors and sprinklers in builidings the rate of convective heat output at the time of detection has generally been adopted as a measure of fire size ${ }^{1}$, on the assumption that 75 per cent of the heat of combustion is convected upwards. The size of fire can also be expressed in terms of the rate of burning of the material expressed in weight loss per unit time. Figure 8 shows the rate of weight loss of fire $W_{1}$
at the time when it was detected by an optical scattering device. Results of this nature enable the sizes of fires detected by smoke detectors, in a variety of circumstances, to be compared with those detected by other forms of detection system, such as heat detectors, sprinklers and infra-red detectors.
7. Performance testing of smoke detectors

The research programme described above is intended to provide a basis for test methods which are representative of the range of conditions to which a smoke detector may be subjected when a fire occurs in a building, and which provide a realistic assessment of the different types of detector in current use. The test apparatus will probably take the form of a re-circulating tunnel in which smoke is generated in a controlled manner, at specified ambient temperature conditions and at a flow rate representative of practical smoke velocities. Test curves will be specified to represent the limits of conditions which can be met in practice, and Figure 9 shows some suggested curves for increasing optical density with time, based on experimental results for the range of heights and horizontal distances examined for the wood fires $W_{1}$ and $W_{2}$, and the petrol fire L. A draft standard test for smoke detectors is at present under consideration in the revision of British Standard 3116 : 1959, and will form Part 3 of the revised issue of this document. Work is being carried out to correlate the response of detectors in the smoke tunnel with that observed in the experiments in the building.

An essential part of the test specification is the inclusion of upper and lower limits of sensitivity of the detector to ensure on the one hand that it is not too insensitive, and, on the other, that it does not give false alarms when installed in industrial and commercial premises. Work is being undertaken to measure ambient conditions under normal working circumstances in industry, measuring both optical effects and ionization chamber response. Some typical results obtained in a fabricating area of a factory are shown in Figure 10. Measurements of this kind are of the utmost importance in the setting of a realistic value for the maximum sensitivity of detectors to reduce the probability of false alarms to an acceptably low level.

## 8. Environmental testing of smoke detectors

It is important that all detectors when installed in buildings should be capable of continuing to function normally in the event of a fire. They should, therefore, be capable of withstanding the range of environmental conditions which are likely to be encountered in a wide variety of circumstances. Factors which have to be taken into account in the design of a detector are:-
(1) Building vibrations.
(2) Corrosive atmospheres.
(3) Impacts on detector.
(4) Iñireot shock:..
(5) High and low ambient temperatures.
(6) Dusty conditions.
(7) High air velocities.

The revision of British Standard 3116 ("point" or "spot" heat-sensitive detectors) includes tests for building vibrations, corrosion, impact, shock and low ambient temperature, and these will form the basis of the tests to be applied to smoke detectors. Consideration is being given to tests for high ambient temperature, dust accumulations, and high air velocities for smoke detectors. In general, the philosophy of such tests is that the detector should be designed so as to be able to continue to function, within certain specified limits, after being subjected to the environmental tests.
9. Reference

1. $0^{+}$DOGHERTY, M. J., NASH, P. and YOUNG, R. A. A study of the performance of automatic sprinkler systems, Fire Research Technical Paper No. 17, H.M.S.O. 1967.

## APPENDIX I - ATTENUATTON OF LITGHT BY SMOKE

The attenuation of a light beam when passing through a suspension of particles in a disperse medium is given by the Lambert-Beer law, viz:

$$
\begin{equation*}
I=I_{0} e^{-(S+A) n l} \tag{1}
\end{equation*}
$$

where $I$ is the intensity of light transmitted
$I_{0}$ is the initial intensity of light
$S$ is the scattering cross-section area
A is the absorption cross-section area
$n$ is the number of particles per unit volume

1 is the optical path length.
The functions $S$ and $A$ depend on the wavelength of the light, and on the size, shape, internal structure and the relative refractive and absorption indices of the particles and the surrounding medium.

The optical density, $D$, of the suspension of particles, or aerosol, in the case of smoke or combustion particles, is defined as:

$$
\begin{equation*}
D=\log _{10} \frac{I_{0}}{I} \tag{2}
\end{equation*}
$$

which from equation (1) gives:

$$
\begin{equation*}
D=\frac{(S \pm A) \mathrm{n} 1}{2.303} \tag{3}
\end{equation*}
$$

so that the optical density is directly proportional to the length of the optical path.

It is convenient to express the optical density over a standard distance, e.g. over a one metre path length, so that the optical density $D^{\prime}\left(=\frac{D}{L}\right)$ is expressed as:

$$
\begin{equation*}
D^{\prime}=\frac{I}{L} \log _{10} \frac{I_{0}}{I} \tag{4a}
\end{equation*}
$$

where $L$ is the length of the optical path in metres. It is the practice on the continent to express optical density in units of decibels/metre,
defined by:

$$
\begin{equation*}
\mathrm{D}^{\prime \prime}=\frac{10}{\mathrm{~L}} \log _{10} \frac{\mathrm{I}_{\mathrm{Q}}}{\mathrm{I}} \mathrm{~dB} / \mathrm{m} \tag{4b}
\end{equation*}
$$

so that the values obtained by using the units of equation (4b) are ten times greater than those obtained from equation (4a).

The percentage obscuration, $p$, is often used as a measure of smoke density and is defined as:

$$
\begin{equation*}
p=100\left(\frac{I_{0}-I}{I_{0}}\right)=100\left(1-\frac{I}{I_{0}}\right) \tag{5}
\end{equation*}
$$

Hence from equation (1):

$$
\begin{equation*}
\left.p=100\left(1-e^{-(S}+4\right) n 1\right) \tag{6a}
\end{equation*}
$$

and from equation (3):

$$
\begin{equation*}
p=100\left(1-e^{-2.303 D}\right) \tag{6b}
\end{equation*}
$$

Hence the percentage obscuration is not directly proportional to the beam length, although it is approximately so at relatively low values of obscuration,

The relationship between the optical density $D$ and the percentage obscuration $p$, for a given optical path length, is shown in Figure 11 for values of $p$ up to 20 per cent. The departure from linearity is small over this range, and an approximete formula for the relationship between $D$ and $p$ is given by:

$$
\begin{equation*}
D=\frac{p}{220} \quad \text { for } \quad 0 \leqslant p \leqslant 10 \text { per cent } \tag{7}
\end{equation*}
$$

An example of the use of the graph shown in Figure 11 is as follows: Suppose that a measurement of smoke density over a 1 metre path showed a percentage obscuration of 4.5 per cent, and the obscuration over a 4 metre path was required. The curve shows that 4.5 per cent obscuration is equivalent to an optical density of 0.02 over the 1 metre path. Since optical density is directly proportional to path length, the optical density over 4 metres would be equal to 0.08 . The curve enables the percentage obscuration to be obtained, and its value is 16.8 per cent, confirming that it is not directly proportional to path length.


FIG. 1. ARRANGEMENT OF FIRE IN RELATION TO SMOKE MEASURING POSITIONS


Fire ref: $W_{1} h_{1} r_{3}$

FIG. 2. VARIATION IN OPTICAL DENSITY WITH TIME FOR WOOD FIRE



FIG. 4. RESPONSE OF AN IONISATION CHAMBER DETECTOR


Horizontal smoke velocity $=2.14 \mathrm{~m} / \mathrm{min}(7 \mathrm{ft} / \mathrm{min})$
Vertical smoke velocity $=6.10 \mathrm{~m} / \mathrm{min}(20 \mathrm{ft} / \mathrm{min})$
Fire ref: $W_{6}$ (mean of $r_{1}, r_{2}, r_{3}$ )
FIG. 5. VARIATION JN TIME TAKEN FOR SMOKE TO REACH MEASURING POSITIONS WITH CEILING HEIGHT AND DISTANCE FROM FIRE


TIME FOR SMOKE TO REACH MEASURING POSITION-min

$$
\begin{array}{ll}
h_{1}-x & d_{1}-1 \\
h_{2}-0 & d_{2}-2 \\
h_{3}-\Delta & d_{3}-3
\end{array}
$$

Fire ref: $W_{1}$ (mean of $r_{1}, r_{2}, r_{3}$ )

FIG.6. RESPONSE TIME OF AN IONISATION CHAMBER DETECTOR TO SMOKE


FIG. 7. RELATIONSHIP BETWEEN OPTICAL DENSITY AND RATE OF WEIGHT LOSS OF FIRE


FIG. 8. VARIATION OF RATE OF WEIGHT LOSS OF FIRE AT DETECTION WITH CEILING HEIGHT FOR AN OPTICAL SCATTERING DETECTOR


FIG. 9 RANGE OF OPTICAL DENSITIES PROPOSED AS A BASIS FOR TEST CURVES



FIG. 11. RELATIONSHIP BETWEEN OPTICAL DENSITY AND PERCENTAGE OBSCURAION

