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THE DETECTION OF FIRES BY SMOKE

PART 5 : DEVELOPMENT OF A SMOKE TUNNEL FOR TESTING FIRE DETECTORS

by

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SUMMARY

A laboratory-bench scale method for measuring the sensitivity of smoke detectors is desirable. To be of value, the laboratory test must be capable of predicting the response of a smoke detector to real fires. This Note discusses how far this requirement can be met with a smoke-tunnel (0.63 m^3 volume) of simple construction. Experiments are described which simulated, in the tunnel, an important phenomenon observed in full-scale fire tests, namely, the dependence of the response of an ionisation-chamber smoke detector on the age of the smoke.

Some suggestions for future work directed towards improving the tunnel are made.

KEY WORDS: Detector, fire, smoke, specification; particle size, smoke.

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JOINT FIRE RESEARCH ORGANIZATION

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1. INTRODUCTION

In formulating a British Standard for smoke detectors it is necessary to specify methods for

(i) measuring the sensitivity of a detector to fire;

(ii) checking that this sensitivity remains substantially unchanged after the detector has been subjected to various other tests such as resistance to shock, impact, corrosive atmospheres, etc.

It is desirable, for reasons of convenience and economy, that both methods use only laboratory-bench scale apparatus. A smoke tunnel of simple construction is an attractive possibility and this note describes some experience gained with such a tunnel.

The use of the tunnel for function (ii) is relatively straightforward and is described in Section 3. Function (i) is more difficult to achieve. To predict, with a smoke tunnel, the response of a detector to real fires, the factors affecting the operation of the detector in real situations must be reproduced in the tunnel; or, at least, there must be a direct correlation between the detector's performance in the tunnel and in the many situations likely to be encountered in practice. It has been found[1,2], that the following factors influence the operation of smoke detectors:

a) the concentration of smoke;

b) the material producing the smoke;

c) the age of the smoke when it reaches the detector;

d) the velocity of the smoke-carrying gas.

The method of producing smoke and the design of the tunnel, which are described in Section 2, allow control of factors a), b), and d). Experiments which attempted to simulate the effects of age of smoke on the operation of detectors are described in Section 4. The future development of the tunnel is discussed in Section 5.

2. PRODUCTION AND MEASUREMENT OF SMOKE IN THE TUNNEL

2.1. Dimensions of tunnel

The shape and dimensions of the smoke tunnel, given in Fig 1 (a), are similar to those suggested by the IENT Laboratory at Aachen. The main frame and the centre plate of the tunnel are aluminium; the top and sides are 9 mm thick perspex. The total volume is 0.63 m^3 The positions of the circulating fan, smoke production area and detectors being tested are shown diagrammatically in Fig 1 (b). The detectors, up to 4 at a time, are mounted on a removable panel at the top of the tunnel. There are also removable panels to allow access to the smoke production area and fan.

2.2. Measurement of smoke concentration

The degree of attenuation of a light beam, expressed as optical density per metre, is taken as a measure of the smoke concentration in the tunnel. For the present experiments, the attentuation due to a 380 mm long column of smoke was measured with the lamp and photocell arrangement shown in Fig 1 (b). The light source and receiver were outside the tunnel and were mounted on a beam which was secured to the wall of the building. The tungsten lamp (28V 2.2W under-run at 15V, D.C.), the CdS photocell (Mullard ORP12) and the optical system were similar to those used to measure the attentuation by smoke produced in experimental fires[3]. The lamp and photocell were placed at the foci of 17 mm diameter, 20 mm focal length lenses. A mask with a 1 mm diameter central hole was placed over the photocell and this not only reduced the effect of ambient illumination but also excluded from the cell light scattered by the smoke in directions other than the forward direction ($180 \pm 1.5^\circ$ referred to the incident beam).

The lamp filament was at a temperature of about 1800°K. The spectral response of the lamp-photocell combination was a maximum for attenuation at a wavelength of 0.70 μm and was 10 per cent of the maximum value at wavelengths of approximately 0.52 μm and 0.90 μm.

The accuracy in measuring the optical density of the 380 mm long smoke column was $\pm$ 1% ($\pm$ 0.001 in the optical density value); this corresponds to an accuracy of $\pm$ 0.003 m^{-1} in the value of the optical density per metre.

2.3. Production of smoke

For the present work, smoke from cellulosic material was produced by tightly clamping a piece of thin card on a 1 kW electrical heating element mounted in the tunnel (Fig 1b). By presetting the heater voltage a given rate of rise of optical density could be achieved. By using different areas of card in contact with the heating element the maximum optical density could be varied. The smoke was circulated with a fan which gave an air velocity adjustable from 200 to 600 mm s^{-1}. (The average horizontal velocity of smoke from slowly burning wood crib fires is known[2] to be 35 mm s^{-1}).

The rates of rise of optical density with time, obtained by using an index card of length 15 mm and two different heater voltages, are compared in Fig 2 with optical density-time curves observed with experimental wood fires in a building[2]. The curves for the experimental fires represent the envelope of all rate-of-rise curves observed with fast and slowly developing wood crib fires, and petrol fires, under a 7.0 m ceiling and at horizontal distances up to 9.8 m from the fire. (Both sets of curves have been shifted to zero on the time axis; thus they do not show the time taken for smoke to reach the measuring instrument in the experimental fires, nor the delay in first observing smoke in the tunnel). In Fig 3, the maximum optical density obtained in the tunnel is plotted against the index card area which is proportional to the mass of material burned. The reproducibility of any given optical density is seen from Fig 3 to be approximately $\pm$ 0.005 m^{-1} and this may also be taken as a guide to the reproducibility of the curves in Fig 2.

Instead of varying the area of the index card and allowing the card to burn completely, a given final optical density could also be produced in the tunnel by switching off the heater when the optical density had reached approximately the desired level. This was the method used for the experiments to be described in Section 4. However, because the optical density was monitored at some distance from the heater, some experience was necessary to obtain reproducibly a given smoke level. This would make the procedure somewhat unsuitable for routine testing although this difficulty could probably be overcome by additionally monitoring the optical density near the heater.

3. CHECKING DETECTOR SENSITIVITY

3.1. Requirement

In order to use the tunnel as a routine method of checking detector sensitivity (eg before and after environmental tests), it is essential that the method of producing smoke can be programmed in a simple manner to give a desired rate of rise of optical density. The reproducibility necessary will depend on the effect of variations in the rate of increase of smoke concentrations on the operation of the detector being tested. The permissible errors in the measurement of detector sensitivity will be determined by the limits specified for the permissible variation of detector sensitivity after an environmental test. For example, if it is specified that the sensitivity of the detector should not change after an impact test by more than ± 25% of its original value, it must be possible to measure the sensitivity to within ± 5%, or, at worst, ± 10%. (Any inherent variation in the sensitivity of an individual detector should be taken into account by repetitive measurements).

3.2. Optical scattering detectors

Experiments were carried out to see if the rate of rise of smoke concentration affects the optical density per metre at which an optical scattering type of detector gives an alarm signal. In these experiments, four detectors were mounted in the tunnel to form a 2 x 2 square pattern. The position of each detector was varied from test to test so that some information was obtained on the effect of detector position on sensitivity.

The results indicate that there may be a correlation between the optical density required for an alarm and the rate of rise of optical density. Fig 4 shows this correlation for one particular detector. The rate of rise of optical density was taken as the optical density (m^{-1}) divided by the time, after switching the heater on, at which the detector gave an alarm signal. It would appear from this curve that low rates of rise are less suitable for testing detector sensitivity. However, it has since been found that the detectors used for these experiments had a high intrinsic scatter of optical density at operation, and further experiments will be required to decide on the optimum conditions for performing a test of this kind.

3.3. Ionisation-chamber detectors

The ionisation-chamber smoke detectors were found to operate in a short time after the heater was switched on and at a correspondingly low value of the optical density. In some cases, the optical density was approximately 0.007 m^{-1} when the detector alarmed. This value is too low to measure accurately at present. Among the possibilities for rectifying this situation are:

a) a more sensitive method of measuring optical density;

b) replacing the optical density measurement with a measurement using a standardised form of ionisation chamber or a condensation nucleus counter[4];

c) the use of smoke which has been aged instead of freshly-produced smoke (see Section 4);

d) the use of an artificial aerosol instead of combustion smoke.

4. EFFECT OF AGED SMOKE ON DETECTOR OPERATION

4.1. Initial experiments

In real fires there is a time delay between the production of smoke and its arrival at the detector, and it has been found[1,2,] that the length of this delay affects the operation of detectors, a greater effect being apparent with detectors of the ionisation chamber type. Experiments were carried out in order to determine whether this effect could be simulated in the tunnel. In the initial experiments three ionisation chamber detectors, mounted in the tunnel, were covered with polythene bags. The bags were attached to metal rings which were held against the top plate of the tunnel by means of small magnets outside the tunnel. By removing a set of magnets, one of the detectors could be uncovered. In each experiment, smoke was generated in the tunnel until the optical density had risen to a predetermined value in the range 0.04 to 0.065 m^{-1}. At this point the heater and circulating fan were switched off. The smoke in the tunnel at this time was taken to be unaged. At three subsequent times after this zero, the fan was restarted and one of the detectors exposed to smoke. The times between exposure to smoke and the alarm signal from the detectors are plotted for the three detectors against the age of the smoke in Fig 5. From this graph it would seem that, for an optical density in the range 0.04 to 0.065 m^{-1}, the age of the smoke was more important than the optical density in determining the time to operation of the detectors. In fact, it was found that the optical density, measured while the smoke was being circulated with the fan, did not change materially from its initial value as the smoke aged. (This observation is in agreement with the work of Bowes[5]).

Similar experiments to those just described were performed with a commercial optical-scattering type smoke detector. The results, given in Fig 6, suggest that this type of smoke detector is not conscious of the age of the smoke.

With smoke of low concentration, it was more convenient to monitor the change of voltage across the ionisation chamber. This change in voltage was amplified with a field-effect transistor, and the change in FET source-drain current was monitored. (When this current reached a value of 1.4 mA approximately the detector gave an alarm signal). The change in FET current is plotted against age of smoke in Fig. 7 for three different smoke concentrations.

4.2. Ionisation chamber: hysteresis effect

Although it provides a good simulation of the conditions the detectors would encounter in real situations, the procedure outlined in Section 4.1 is somewhat tedious. It is more convenient to leave the detectors uncovered while the (circulating) smoke ages. First, however, it was necessary to establish that the response of a detector to smoke of a given age was not influenced by the fact that the detector had been continuously exposed to smoke up to that time. Trapping of smoke particles in the ionisation chamber or its inlet, for example, might make the response of the detector dependent on the total time of exposure to smoke.

The absence of any hysteresis effect was checked at three different smoke concentrations. At each concentration two sets of data were taken; for one set the detector was continuously exposed while the circulating smoke aged; for the other the detector was initially covered but was uncovered when smoke of the given concentration had aged for different times in separate experiments. Plots of FET current against age of smoke were substantially the same for both procedures at a given smoke concentration. One such plot is shown in Fig 8.

4.3. Ionisation chamber: further experiments

The results of three further experiments on the effect of age of smoke on the ionisation chamber response are shown in Figs 9, 10 and 11 in which optical density and FET current are plotted against time for the three experiments. The detector was continuously exposed in these experiments. The different final smoke concentrations (optical density per metre) were obtained by a suitable combination of heater voltage and index card area.

It is evident from these graphs that allowing the smoke to age had little effect on the optical density measurement but reduced the output from the ionisation chamber. On the other hand, while the smoke was being produced, the ionisation chamber was giving a substantial output before any change in optical density was observed.

5. DISCUSSION OF RESULTS

5.1. Testing the sensitivity to fire of smoke detectors

The work described in Section 4 has shown that it is possible to produce an ageing effect on smoke in the tunnel. Furthermore, the observation that the age of the smoke affects the response of an ionisation chamber type detector but not of an optical-scattering type detector is in qualitative agreement with the sensitivities of these detectors to experimental slowly-burning wood fires[12]. However, considerable work remains to be done in order to relate quantitatively the operation of the detectors in the tunnel to their operation in full-scale fire tests.

The link between tunnel tests and full-scale fire tests is the optical density per metre at which the detector gives an alarm signal. But the optical density per metre required for an alarm depends on the rate of rise of optical density,on the type of smoke and its concentration and velocity; various combinations of these four factors will occur in practice. However, the transition from experimental fire test to tunnel test would be considerably simplified if it could be decided in advance what real conditions a tunnel test is required to simulate. Thus, it might be decided that the response of a detector to the experimental fast and slowly-developing wood fires shown in Fig 2 is a fair test of detector performance. In that case, the detector in the tunnel should be exposed to smoke of an appropriate age and with a concentration-time curve given by the lower curve of Fig 2 to simulate the slowly-burning fire;

a fast burning fire would be simulated by smoke of a rather lower age and with a concentration-time curve given by the upper curve of Fig 2. The velocity of the smoke in both cases would also have to be reproduced in the tunnel. It is not necessary that the detectors in the tunnel give an alarm at the same optical density per metre as they would under the real conditions being simulated; it is only required that there is a direct correlation between their performance in the two cases and that this correlation is independent of the type and manufacture of the detector.

5.2. The nature of aged smoke

It is relevant here to speculate on the changes which occur in smoke when the smoke ages. One possibility is coagulation. Suppose n_1 particles per cm^3, of radius r_1, coalesce to form n_2 particles of radius r_2. Then, to conserve mass it is necessary that

$$n_1 r_1^3 = n_2 r_2^3 \qquad \text{..........} (1)$$

The attenuation of light by particles absorbing and scattering is expressed as

$$I = I_o \exp (-KL) \qquad \text{..........} (2)$$

in which I_o is the incident light intensity and I is the emergent light intensity, the light having traversed a path length L of the smoke medium.

The extinction coefficient, K_o, for a cloud of n particles each of radius r, is defined for a given wavelength as

$$K_o = n\, C(r)\, \pi r^2 \qquad \text{..........} (3)$$

in which $C(r)$ is the efficiency factor for extinction by a single particle. Combining equations 1 and 3, the ratio of the cloud's extinction coefficients before and after coagulation is seen to be

$$\frac{K_{o_1}}{K_{o_2}} = \frac{r_2}{r_1} \; \frac{C_1(r_1)}{C_2(r_2)} \qquad \text{..........} (4)$$

Smoke from fires is known[6,7,8] to have a distribution of particle sizes with a median diameter in the range 0.2 to 0.4 μm.

The efficiency factor for extinction can be calculated using the Mie theory, if it is assumed that smoke has the optical properties of amorphous carbon. Such calculations have shown[8,9], that when the parameter $2\pi r \lambda^{-1}$ is less than approximately 1 (where λ is the wavelength of incident radiation), the efficiency factor decreases rapidly with particle diameter. For the range of mean particle diameters in smokes, $2\pi r \lambda^{-1}$ is in the range 0.9 to 1.5 for a wavelength of 0.7 μm. Thus the smaller particles in the distribution could coagulate without appreciably affecting the light-attenuating properties of the smoke.

When $2\pi r \lambda^{-1}$ is greater than 2 approximately, the efficiency factor tends towards a value of 2, and is independent of the diameter of the particle. Since the measured optical density in the tunnel, and the response of the light-scattering detector, were found to be independent of the age of the smoke, it would seem, in view of equation (4), that the larger particles in the smoke do not appreciably coagulate. Alternatively, it is conceivable that the combined effects of the reduction in extinction, due to the coagulation of the larger particles, and the increase in extinction, due to the coagulation of particles having diameters in the range for which $2\pi r \lambda^{-1}$ is just less than 1, may be such as to maintain constant the extinction coefficient during ageing.

In the case of the ionisation chamber detector, the current i_o which flows in the absence of smoke is reduced to a value i in the presence of smoke where i is given by[10]

$$i = i_o \exp\left(\frac{-k}{u} nr\right) \qquad \text{.......... (5)}$$

The quantities k and u are determined by the chamber geometry and the applied voltage.

As regards its effect on the current in the chamber, smoke has an extinction coefficient K_i which is directly proportional to nr.

The ratio of the ionisation extinction coefficients of the smoke before and after coagulation is

$$\frac{K_{i_1}}{K_{i_2}} \doteq \frac{r_2^{\,2}}{r_1^{\,2}} \qquad \text{..........} \; (6)$$

assuming, as before, that n_1 particles of radius r_1 coagulate to n_2 particles of radius r_2. Thus, coagulation of the smaller particles in an actual smoke would give a greater reduction in the response of the ionisation chamber than in the response of an optical detector.

These considerations indicate that it may be necessary to characterise smoke more precisely than by its age. For example, if coagulation is the explanation of the present observations, as has been hypothesised, then smoke flowing beneath a ceiling may coagulate in a different way to smoke ageing in the tunnel, since the solid surface areas in contact with the smoke are different in the two cases. And, whereas an empirical relationship may be found relating the performance of existing detectors in the tunnel and under experimental fire conditions, this may not hold for other types of detectors, or, indeed, for smokes from materials other than wood.

On the other hand, it may be possible to match the important characteristics of aged wood smoke with (unaged) smoke from some other fuel, or with an artificial aerosol. Thus, if the particle size distribution of wood smoke is the main factor which determines the response of existing smoke detectors, then it may be that a closely similar particle size distribution can be obtained with a hydrocarbon liquid or gaseous fuel or an artificial aerosol.

CONCLUSIONS

The next phase in the development of a tunnel test for detector sensitivity should include:

1 Modification of the tunnel so that the concentration of smoke can be increased by the addition of aged smoke rather than by the production of fresh smoke in the tunnel.

2 Measurement of detector response to conditions which simulate, in the tunnel, the extremes observed with experimental wood fires.

3 Improvement in the measurement of low smoke concentrations (either with an optical instrument, an ionisation chamber, or a condensation nucleus counter).

4 Investigation into the possible applications of smokes from other fuels and of artificial aerosols.

5. Improvement in the method of producing smoke from cellulosic materials.

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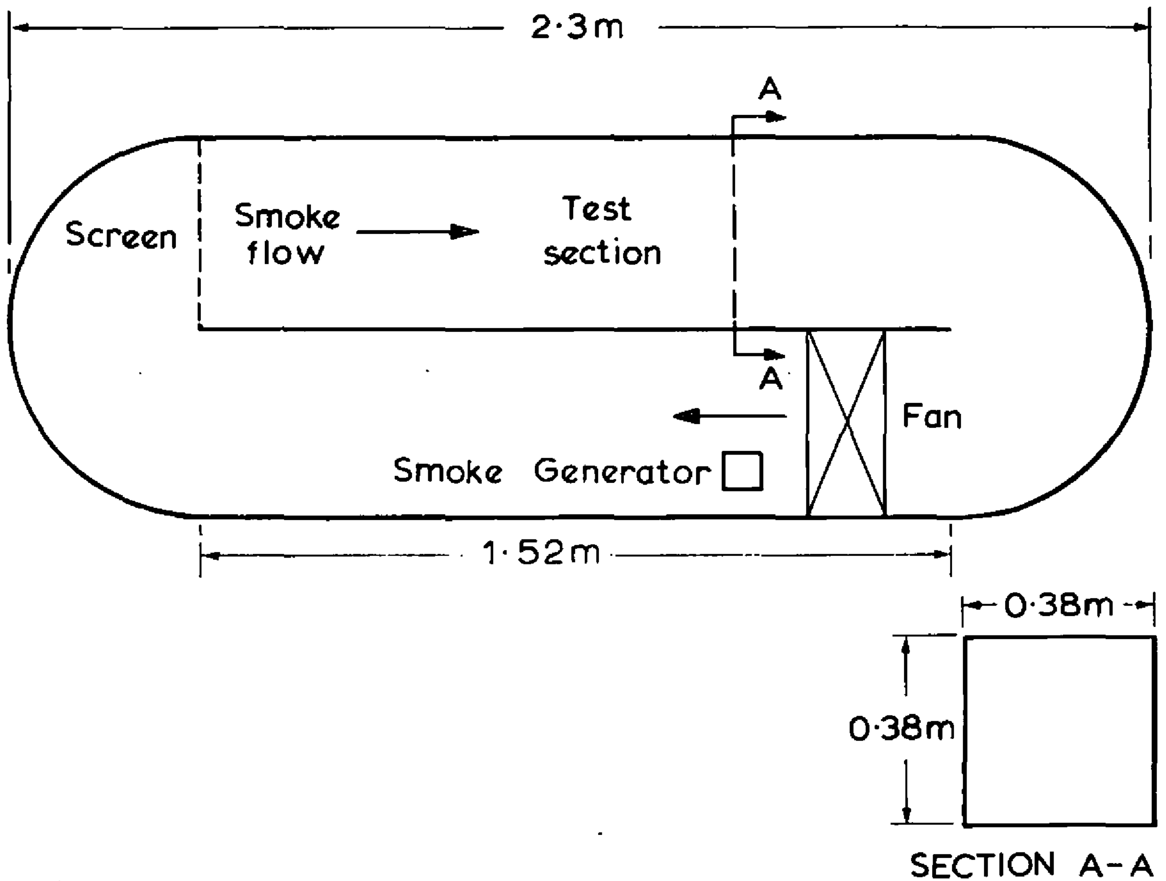
(a) Dimensions



(b) Schematic

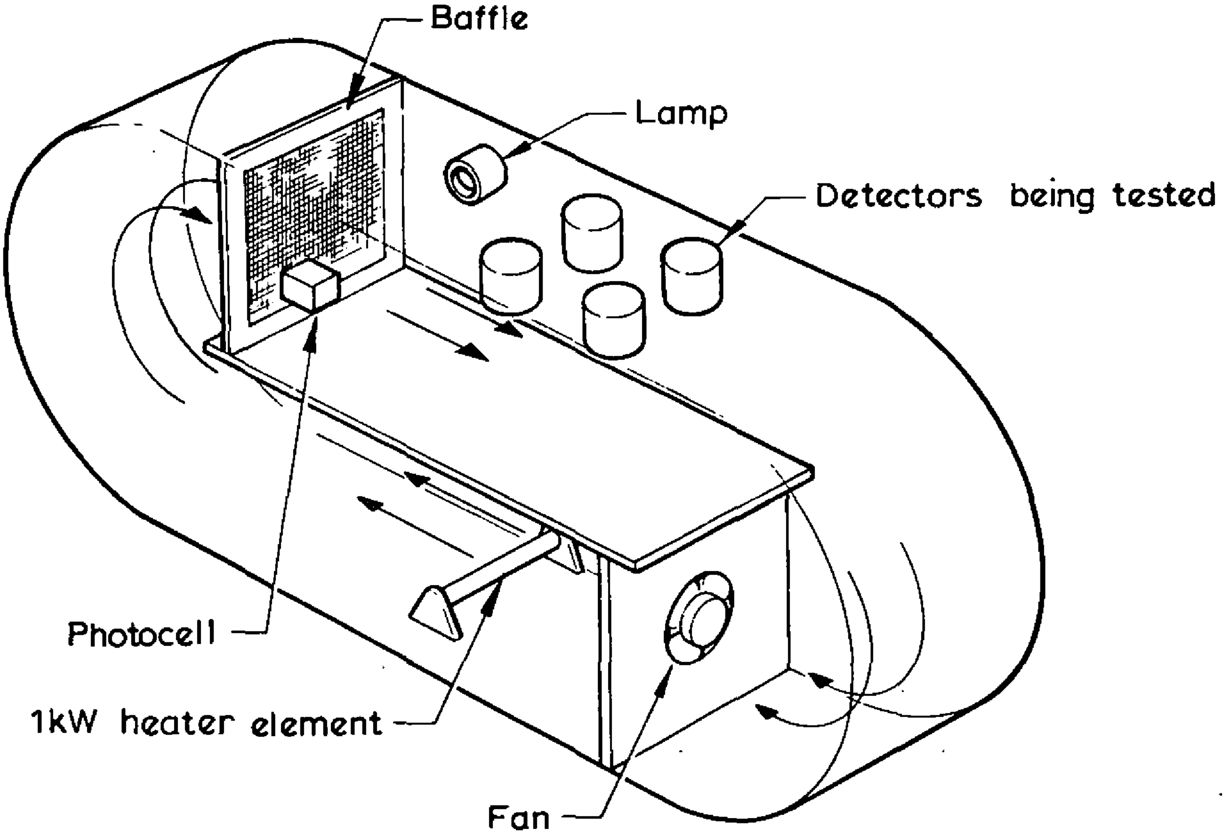


FIG. 1 RECIRCULATING SMOKE TUNNEL

Drg. No. 12071A FR 822

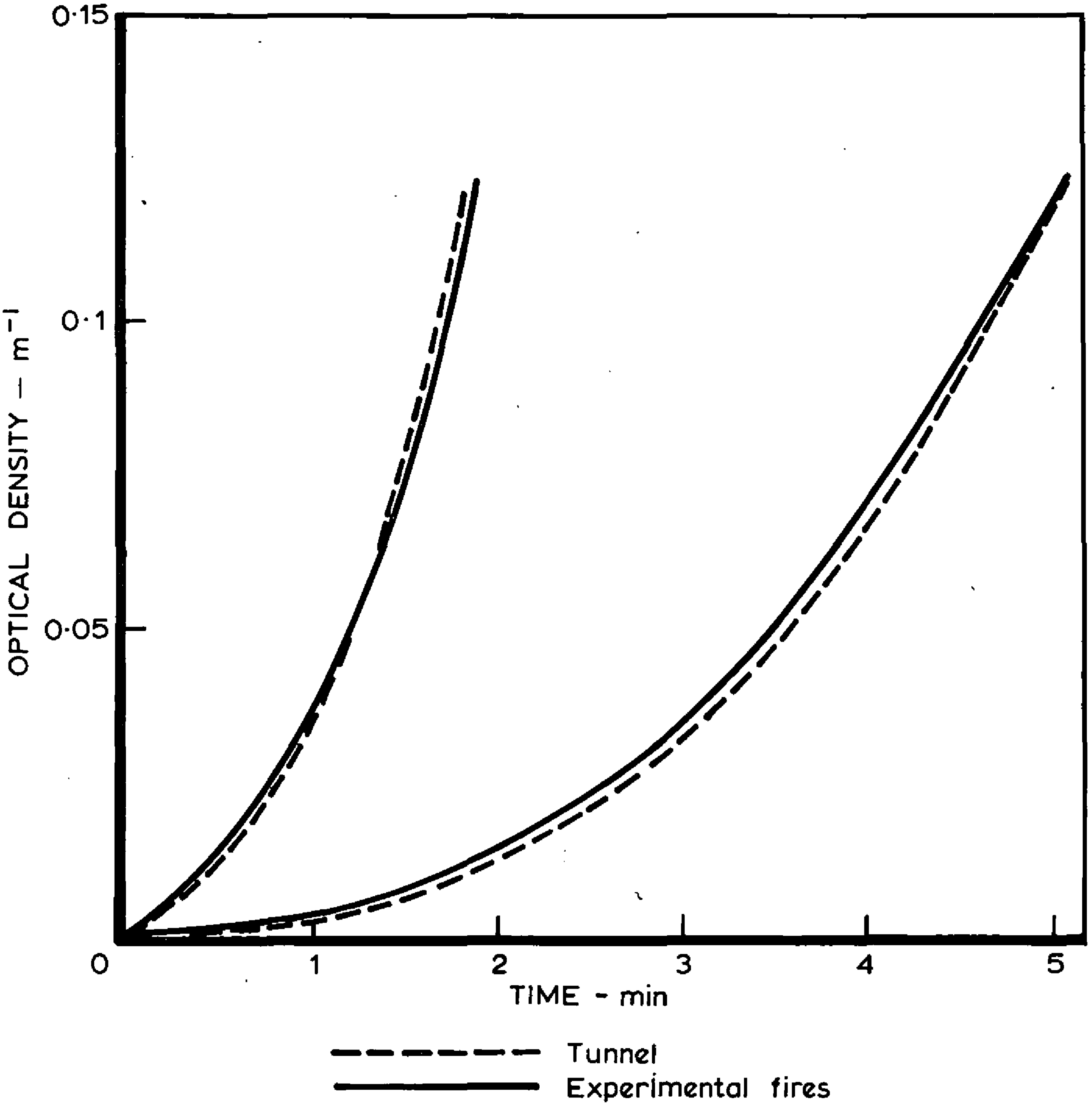


FIG. 2 OPTICAL DENSITY OF SMOKE IN THE SMOKE TUNNEL AND FROM EXPERIMENTAL FIRES

Drg No. 12072A FR 822

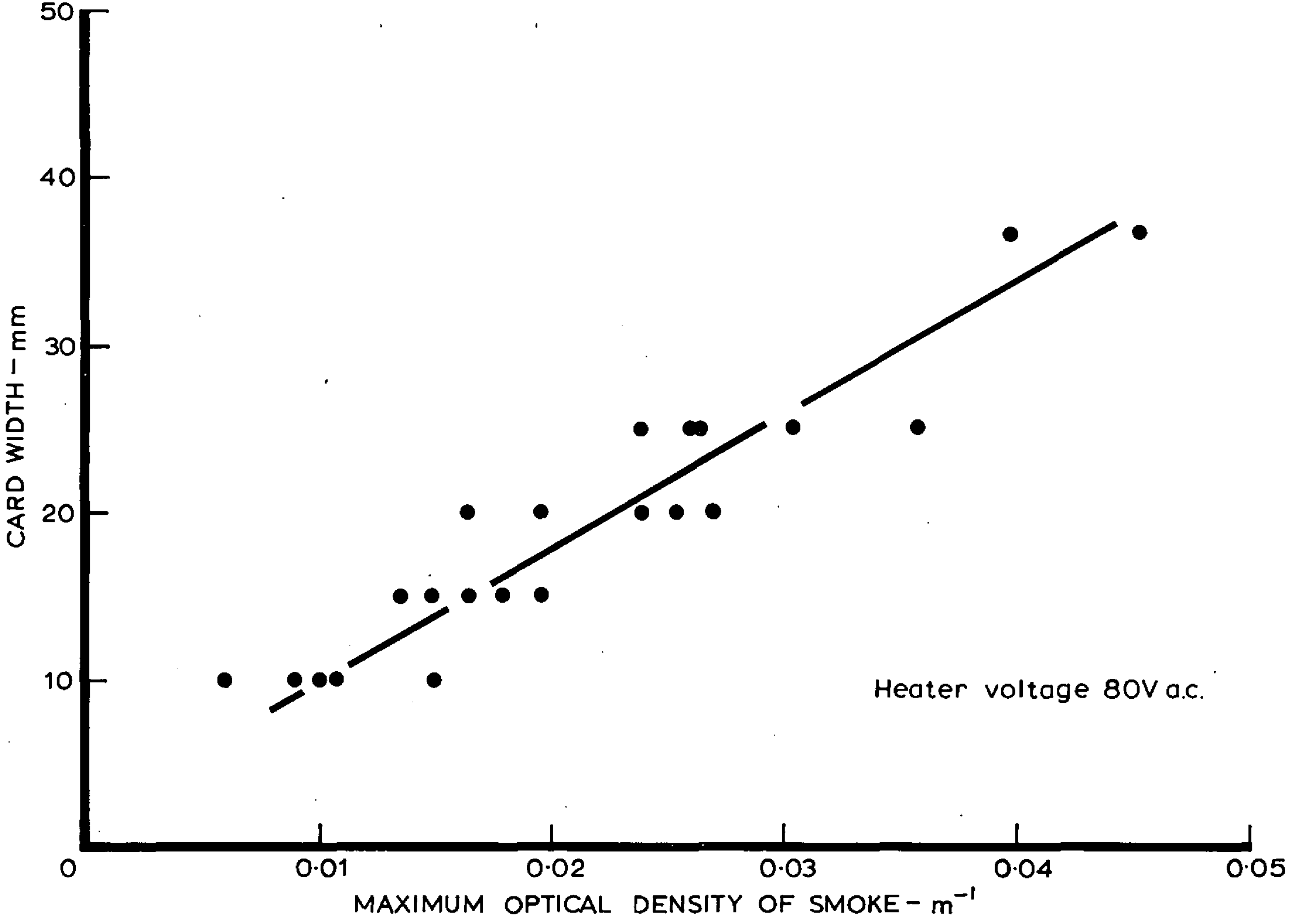


FIG. 3 VARIATION OF (MAXIMUM) SMOKE CONCENTRATION IN TUNNEL WITH SIZE OF CARD ON HEATER

Drg. No. 12074A FR. 822

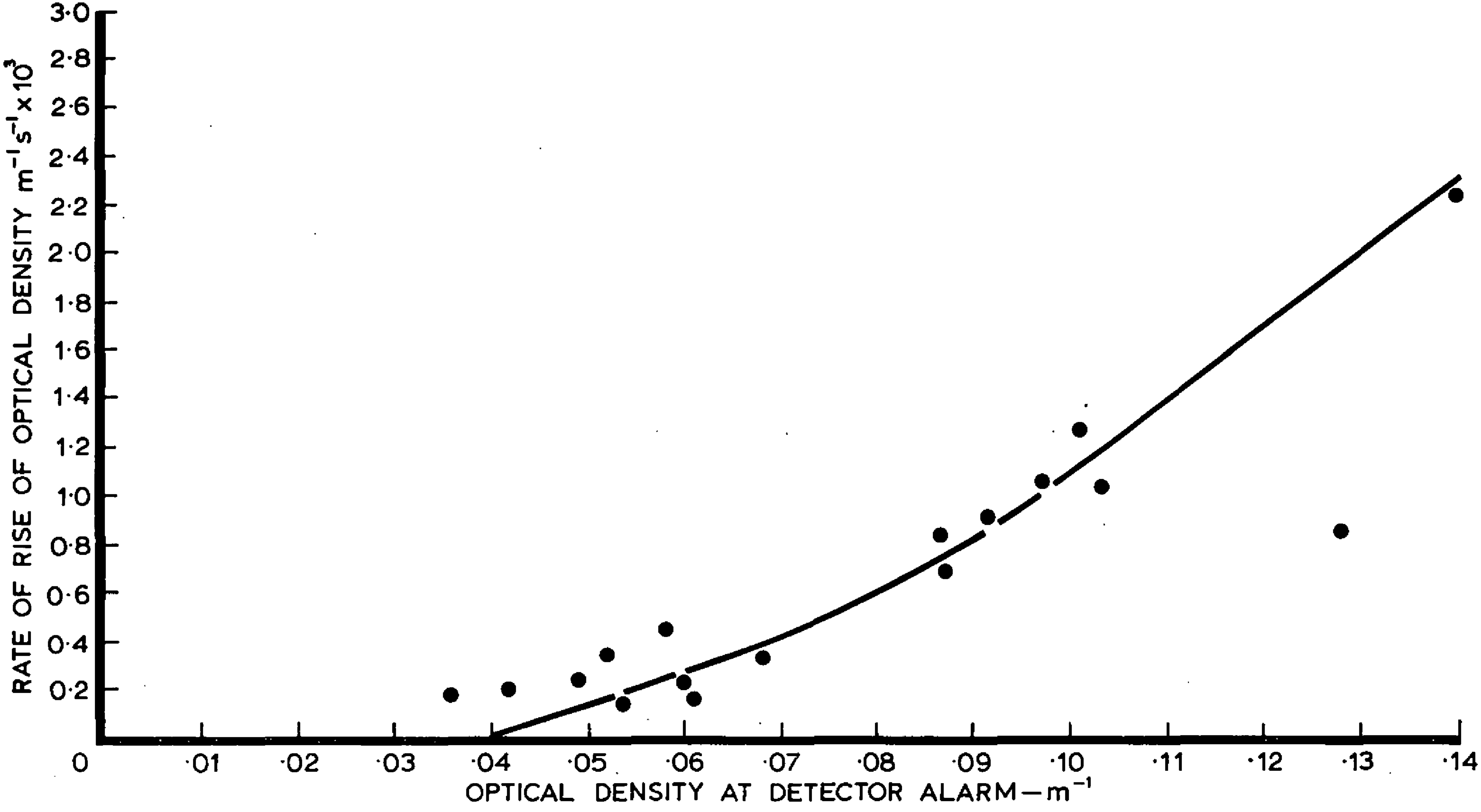


FIG. 4 DEPENDENCE OF OPTICAL DENSITY AT DETECTOR ALARM ON RATE OF RISE OF OPTICAL DENSITY (OPTICAL SCATTERING TYPE DETECTOR)

Drg No. 12075A Fa 822

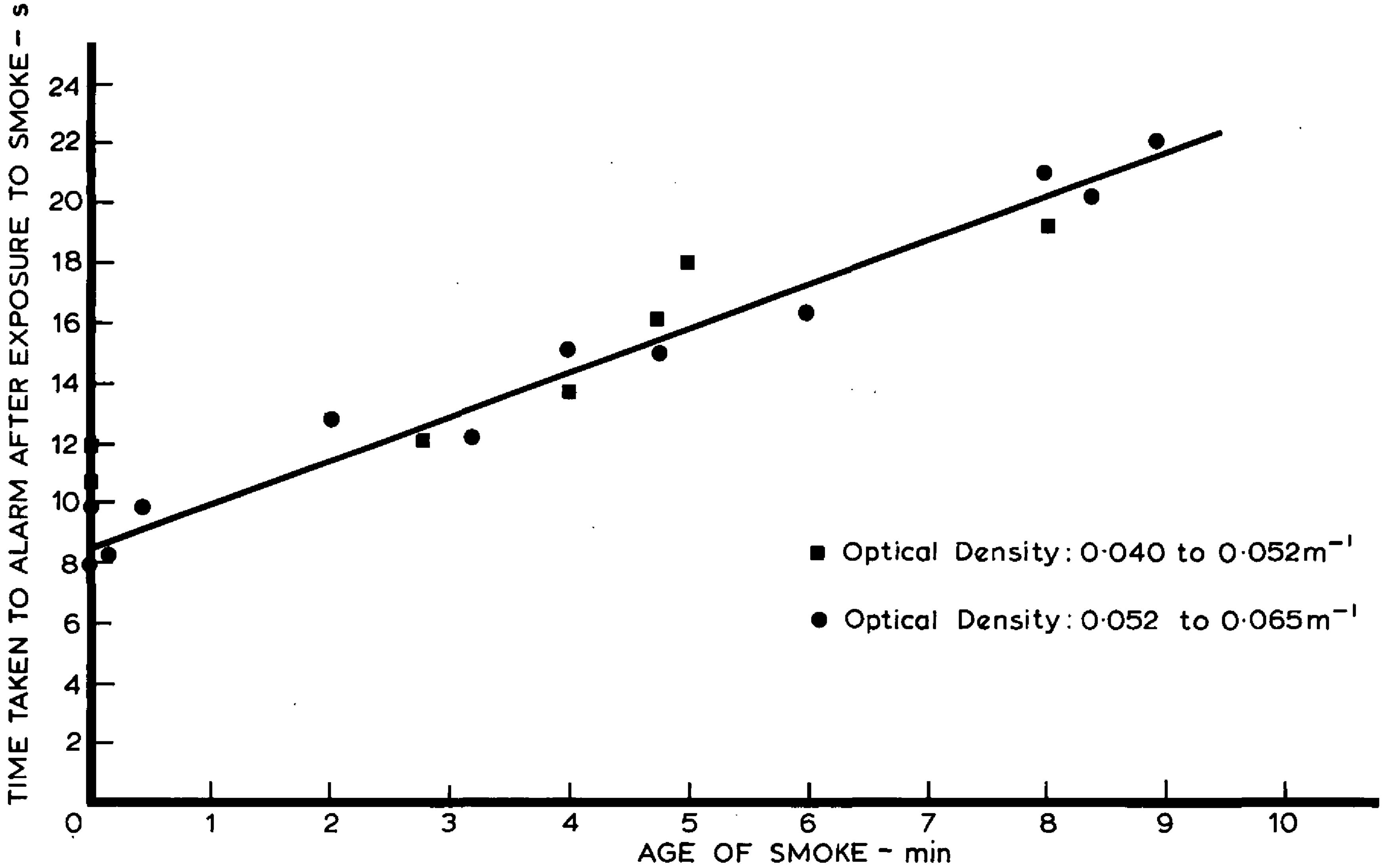


FIG. 5 VARIATION OF ALARM TIME WITH AGE OF SMOKE IONISATION - CHAMBER TYPE DETECTORS

Drg. No. 12076A FR 822

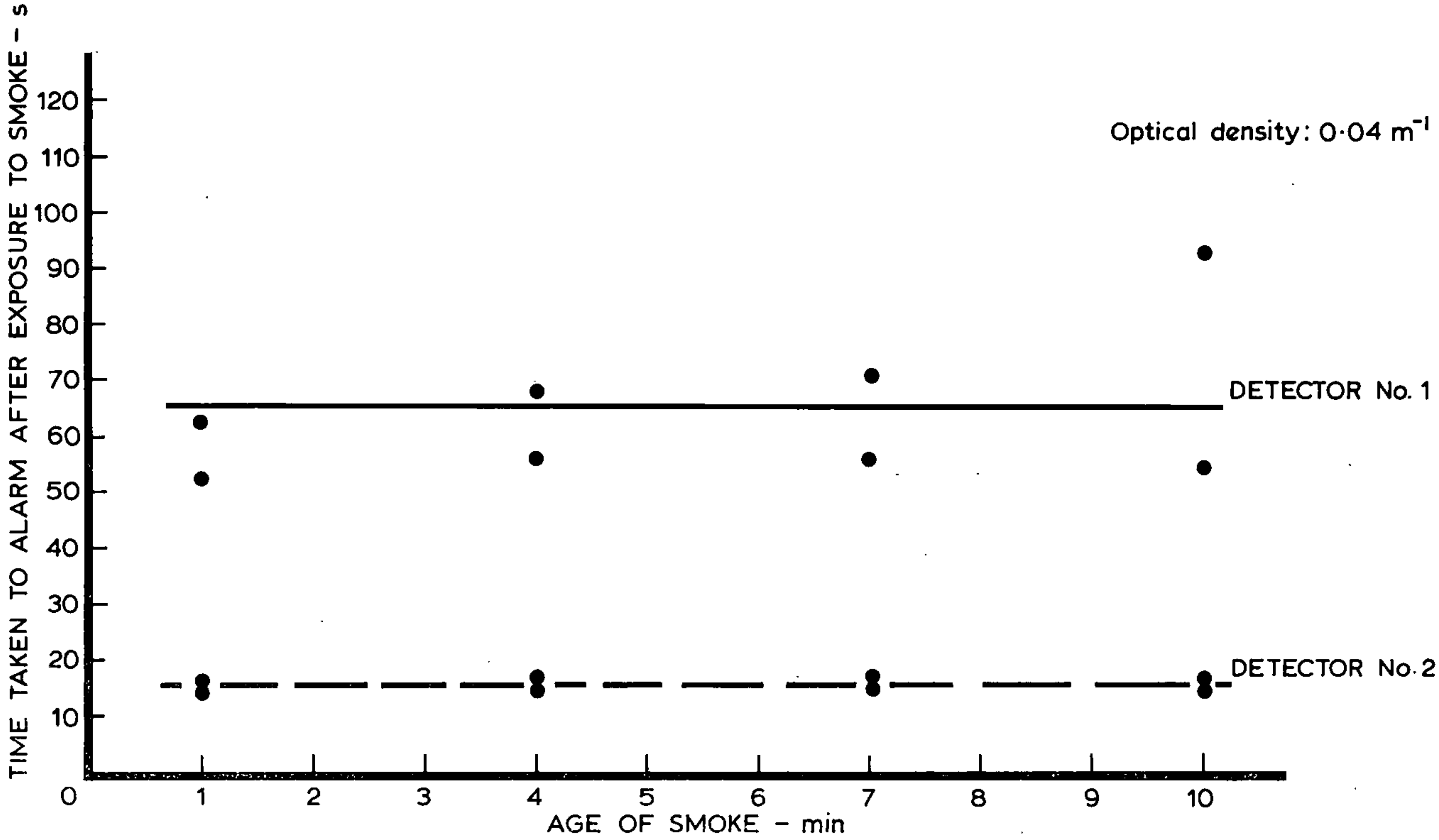


FIG. 6 VARIATION OF ALARM TIME WITH AGE OF SMOKE (OPTICAL SCATTERING TYPE DETECTORS)

Drg No. 12077A FR. 822

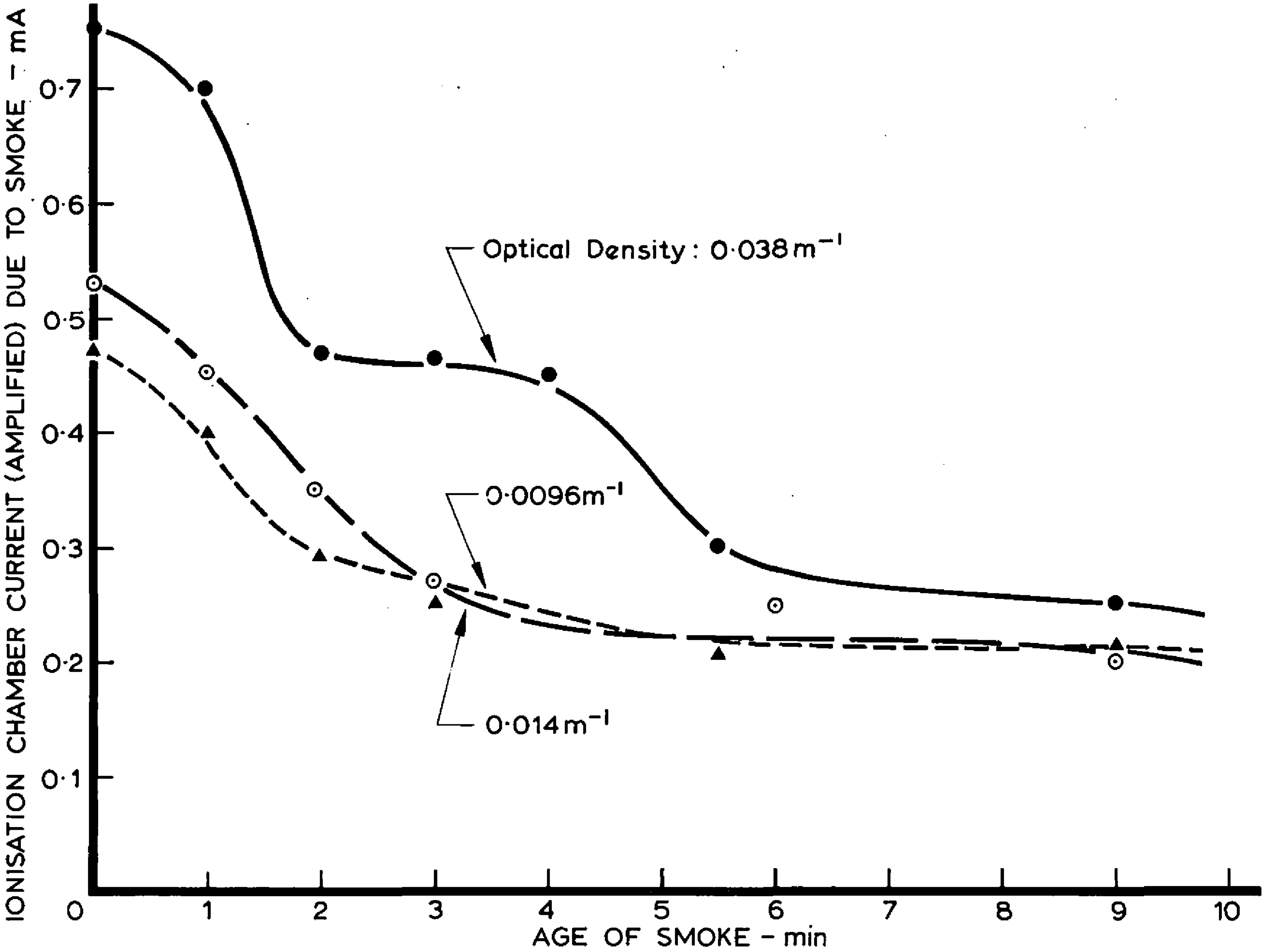


FIG 7 CHANGE IN IONISATION CURRENT (AMPLIFIED) - mA

Drg. No. 12078A- FR 822

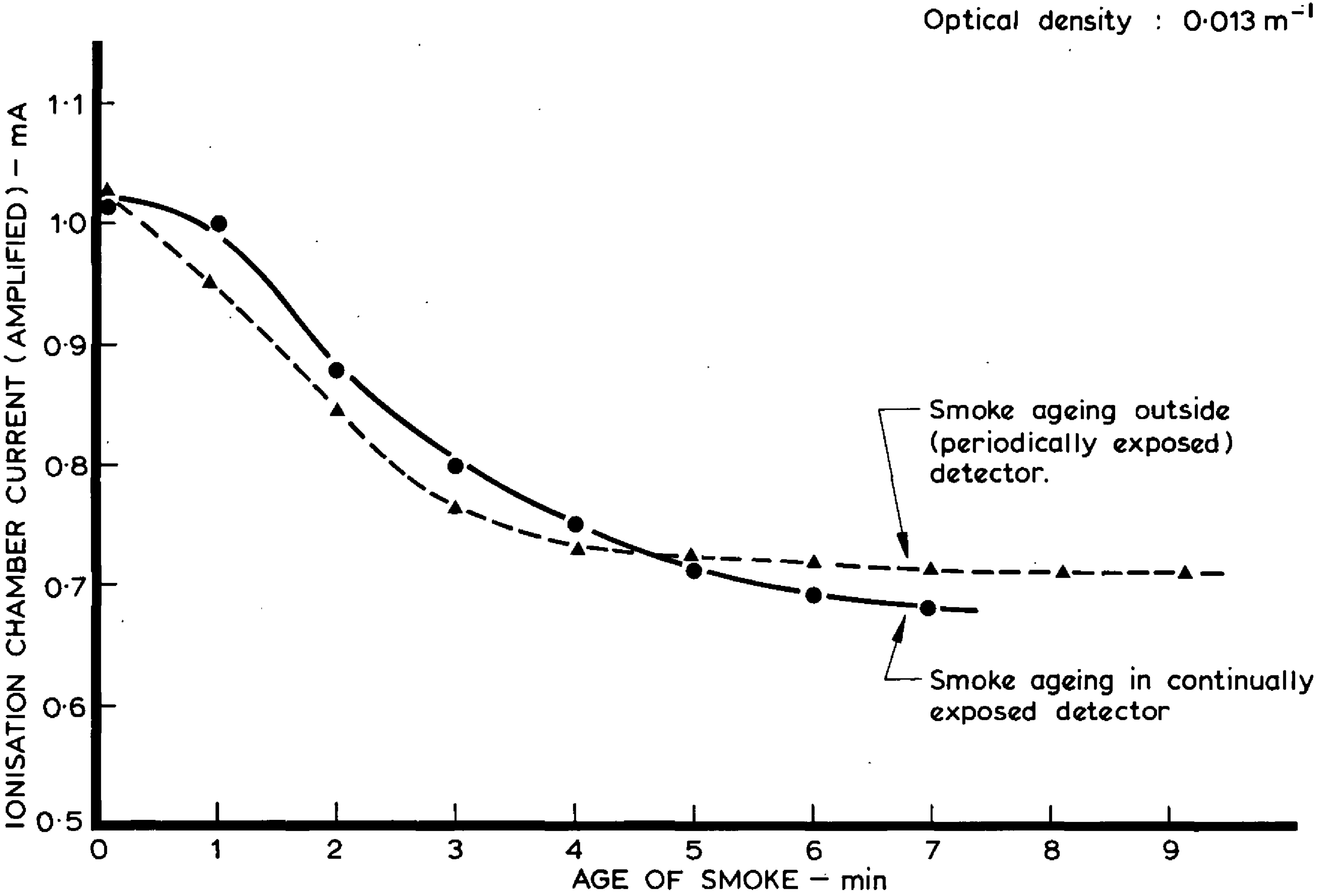


FIG. 8 VARIATION OF IONISATION CHAMBER CURRENT (AMPLIFIED) WITH AGE OF SMOKE : CONTINUALLY EXPOSED AND PERIODICALLY EXPOSED DETECTORS

Drg No. 12079A FR 822.

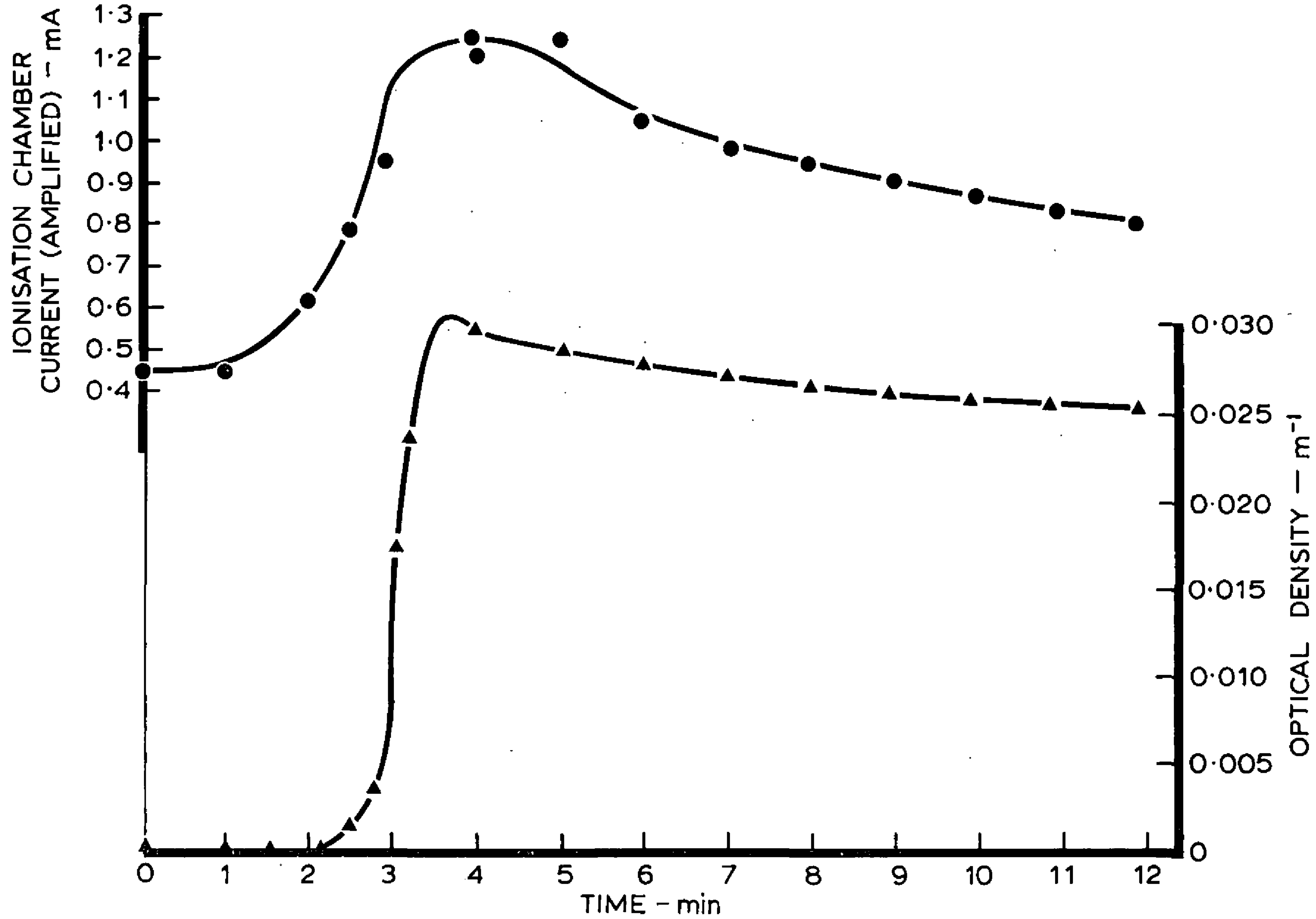


FIG. 9 VARIATION OF IONISATION CHAMBER CURRENT AND OF OPTICAL DENSITY DURING PRODUCTION AND AGEING OF SMOKE

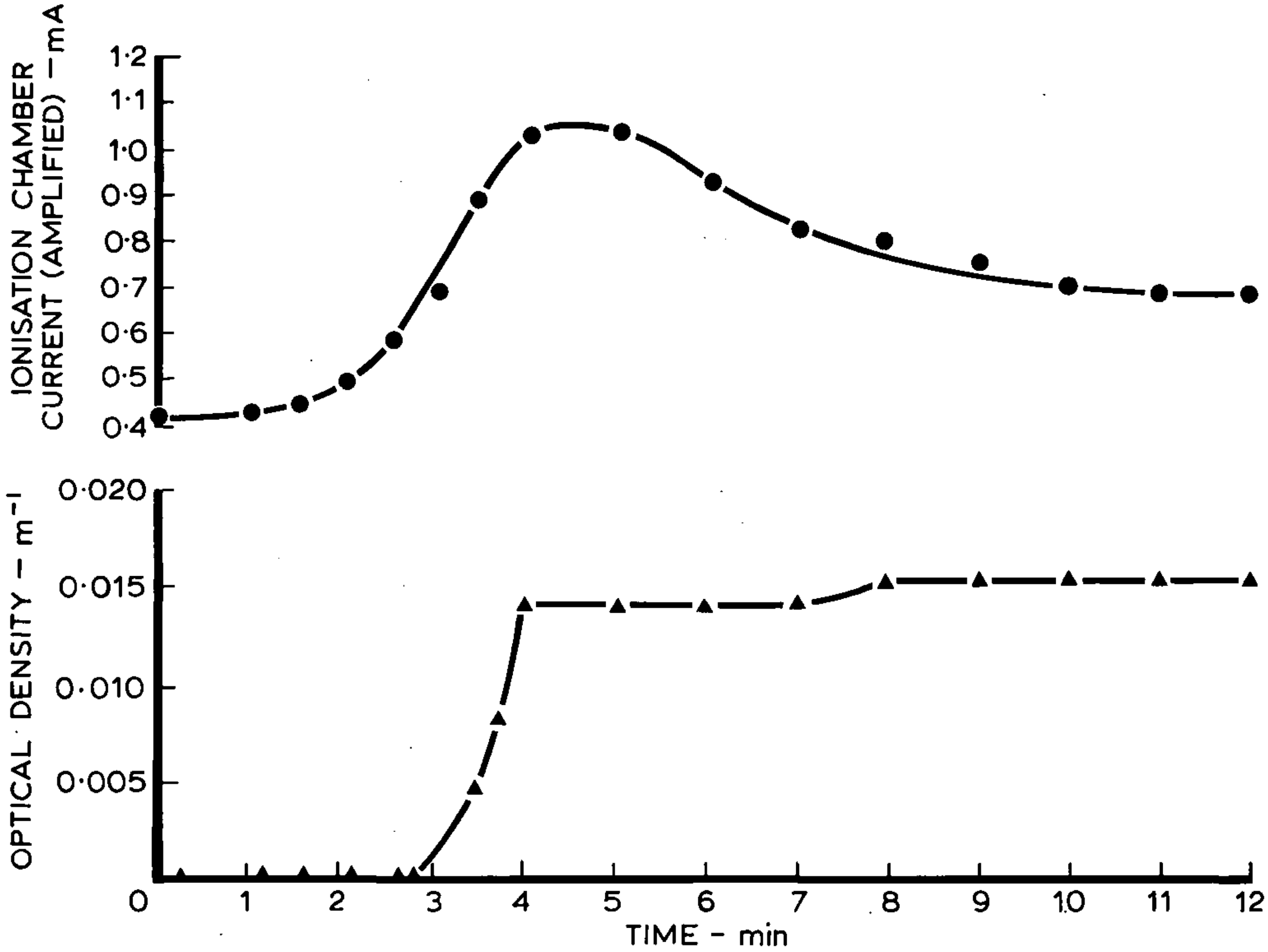


FIG. 10 VARIATION OF IONISATION CHAMBER CURRENT (AMPLIFIED) AND OF OPTICAL DENSITY DURING PRODUCTION AND AGEING OF SMOKE

Drg. No. 12081A- F.R. 822.

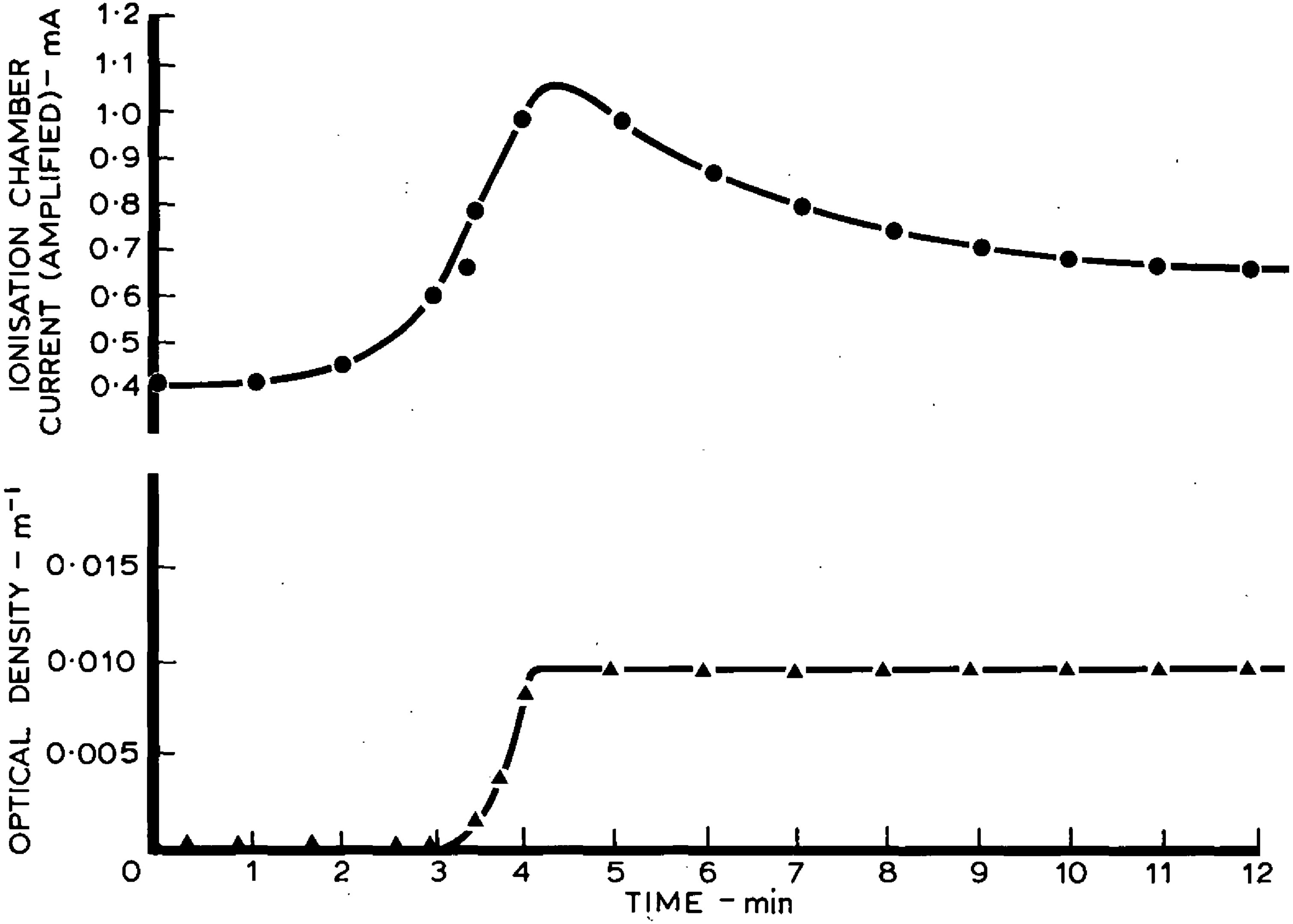


FIG. 11 VARIATION OF IONISATION CHAMBER CURRENT (AMPLIFIED) AND OF OPTICAL DENSITY DURING PRODUCTION AND AGEING OF SMOKE