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MOVEMENT OF SMOKE ON ESCAPE ROUTES

PART 1. INSTRUMENTATION AND EFFECT OF SMOKE ON VISIBILITY.

by

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

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Introduction

In order to study the movement of smoke in buildings it was necessary to examine the basic parameters and devise a technique which would be as realistic as possible and which would be reproducible. Smoke is one of those phenomena which is not easy to define and certainly under conditions of actual fires is as variable as the fires themselves. It was essential for experimental work that the smoke produced should be as consistent as possible and its presence easily detected and measured. A search was made of the literature on the subject to examine the techniques used by other investigators and to see if suitable measuring devices were commercially available.

It was visualized at the outset that it would be preferable on grounds of convenience, economics and speed to produce smoke by means other than actual fires. It was also considered desirable that it should be measured remotely and its effect related to a single physical phenomenon such as reduction of visibility.

This note is divided into sections dealing with the following aspects:

1. Smoke generation for experimental purposes
2. Quantitative measurement of smoke
3. Effect of smoke on visibility.

Smoke generation

A survey of the literature and discussions with various workers in the field showed that in the earlier experiments two methods of smoke production had been employed. Firstly, smoke candles or bombs had been used, consisting essentially of coal tar products and which in fact operated in a similar manner to a 'firework'. The smoke could be in a variety of colours, of which grey or black were most common and was usually of a pungent type. They were designed to last a period of 3 to 5 minutes, depending upon their shape and size, and produced copious quantities at nearly ambient temperatures. One could also include in this category, owing to similarity of some of the properties, smoke produced by the vaporization of fuel oil.

The second method, used by a number of laboratories in other countries[1,2] when conducting tests in full size buildings, consisted of the combustion of typical building contents such as tables, chairs, bedding etc. In one instance damp hay was used for this purpose. With the exception of the latter, smoke was produced at high temperatures and its behaviour was similar to that experienced in fires.

It was considered that both methods suffered from certain drawbacks. With the first method, using smoke candles, the duration of smoke generation was too short for experimental purposes and the smoke produced was of a 'cold' type having quite different flow and stratification properties from hot smoke. The average particle size and the colour of the smoke were also likely to be different. The second method, though producing smoke in a realistic manner, would involve long cooling periods between tests thus delaying experiments and would prove to be an expensive technique where a large number of tests were envisaged taking into account the quantities of fuels required and the essential repairs and making good between tests. In addition, of course, it was difficult to use it as a laboratory instrument owing to the problem of exercising rigid control over a number of factors to ensure reproducibility.

These considerations led to the development of a special smoke generator to produce controlled quantities of smoke of the type experienced in fires and at reasonably elevated temperatures. It was required to give consistent performance and to be portable so that some of the experimental findings could be checked and supplemented by tests in actual buildings outside the laboratory.

Type '2MB' Smoke Generator

The smoke generator finally developed as a result of experimentation is shown in Figure 1 and Plate 1. It consists essentially of an enclosed metal cylinder holding a fuel basket with a standardized arrangement and quantity of fuel and containing a controlled hot air supply. The inner expanded metal basket contains a 15 kg load of wood shavings, timber pieces and soft cellulosic boards arranged in layers to give a progressive decomposition of the contents.

The sheet metal outer cylinder has a low level air inlet of 10 cm diameter and a smoke outlet of the same size near the top. The top of the cylinder is closed by a metal lid after the basket has been loaded with fuel.

Generation of smoke is initiated by insertion of the nozzle of a hot air electric fire lighter through the inlet pipe. The fire lighter is of 620 watt rating and consists of a small fan passing air over a heated electric element so that approximately 9 dm^3 of air per minute is emitted at the nozzle at a temperature of between 250-275°C. An asbestos disc around the nozzle permits a controlled amount of secondary air to be introduced. After a period of 2 to 3 minutes consistent quantities of smoke are emitted from the upper nozzle and further control, within limits, is possible by adjusting the electricity supply to the fan. However, a generator of a given size is normally designed for a certain rate of smoke production, and generators of different sizes can be made to cover a wider range.

The '2MB' smoke generator produces smoke at a fairly constant rate for a minimum period of 30 minutes at a temperature between 250-300°C at the exhaust with a velocity of 45 to 60 m/min. The quantity of smoke produced is sufficient to fill a room measuring 3.5 x 3.0 x 2.5 m in about 5 minutes. In some experiments in an actual building two generators when used together on a floor measuring 30 x 60 m made conditions intolerable for the occupants in less than ½ hour.

The type of smoke produced by the generator was regarded by some fire fighting experts to be similar to that experienced in actual fires in its lachrymatric and irritant effects and its influence on visibility. It is a buoyant smoke with definite tendency to stratify. Smoke produced in actual fires is, however, likely to have higher temperatures with greater buoyancy than obtained with the smoke generator.

Measurement of smoke

To obtain a quantitative assessment of smoke encountered in the experiments and to judge the effectiveness of measures to clear smoke from escape routes a reliable method of measurement was necessary. In some of the full scale tests conducted abroad human 'guinea pigs' had been used but this was considered undesirable on a number of grounds. It was felt that human observers are highly unlikely to provide an objective and a consistent assessment as smoke produces different reactions in different people and the effects are a combination of physiological and psychological factors. Whilst at some stage it would be necessary to relate the behaviour of human beings under conditions of smoke, for the purpose of this investigation instrumented measurements with facilities for remote indication and recording were desirable.

The two methods commonly used for measurement of smoke consist basically of either noting the obscuration of a light beam passing through a smoke path or collecting smoke particles on a suitable medium and by gravimetric or optical methods determining its density. The latter method is generally used to give an integrated value of smoke density over a period of time, although sampling techniques are available for spot measurements. The first method appeared to offer certain advantages as it can provide a continuous indication of smoke density and does not require too complicated an arrangement for dealing with up to six measuring points simultaneously.

The commercially available optical equipment for measurement of smoke appeared to have been designed generally for measuring smoke emission from chimneys. It was usually bulky and primarily designed to have maximum sensitivity in the range of smoke density corresponding to the 'Ringleman number' specifying the upper acceptable level for smoke density. For the purpose of the present experiments the instrument was required to be sensitive to smoke in the lower range of densities varying from zero to that likely to reduce the visibility to a level at which escape routes would be no longer usable.

Type '2MB' Smoke Meter

Type '2MB' smoke meter, shown in Figure 2 and Plate 2, consists essentially of two cylinders, with light sensitive cells and a light source capable of sliding along an aluminium tube to permit adjustment of the distance between the two from a few centimetres to a maximum of 1.5 metres. The whole assembly can be suspended by light chains from a stand or from the ceiling of a room.

Assembly A (Plate 3) contains the light source consisting of a 12 V 30 Watt projector lamp, a convex lens to provide a parallel beam of approximately 5 cm diameter, and a compensating photo-electric cell. Assembly B contains a similar photo-electric cell mounted at the back. The cells used are of the selenium barrier layer type having a spectral response shown in Figure 3, the maximum sensitivity of the type of cell used is at a wavelength of 0.57 , similar to that stated for the average human eye.

Assembly A with the light source was ventilated to dissipate heat generated by the electric bulb. The monitoring cell was located at a sufficient distance away to be reasonably unaffected by radiation from the light source. At the front of each housing a clear glass window was provided to prevent entry of smoke; in the preliminary investigations no serious deposition of smoke particles was observed on the glass windows and therefore no special provisions such as heating the windows were made. The windows were cleaned at the start of each test. The length of Assembly B was such that the cell was virtually unaffected by stray light other than that transmitted from the light source. The inside and outside of the cylinders were given a matt black finish to eliminate light reflection.

The circuitry used for the smoke meters is shown in Figure 4. The light source was supplied from a 12 V constant voltage transformer via a ballast box to maintain a constant current through the supply circuit irrespective of the number of lightmeters in use. The circuit is designed to obtain a linear response for light obscuration up to approximately 70 per cent. The output from the lightmeter is fed to a potentiometric millivolt recorder of 10 mV range, which with 100 per cent light obscuration gives a 90 per cent movement on the scale.

In use the smoke meter measures the obscuration of light between the glass windows of the two assemblies, representing the length of the smoke path. If the smoke particles are not properly diffused and the smoke is entering the area of measurement through small gaps, e.g. the edges of a door, the path length of the measuring device should be such that it gives an accurate measure of the average density. In the majority of tests a path length of 0.91 m has been used as this enables the meters to be used near normal hinged doors and provides a measure of the average density. The shape of the meter is such that it offers little resistance to flow and diffusion of smoke.

Before use, the bi-convex lens in front of the light source is adjusted to give a light output of 25 ft candles at the glass window in front of the receiver photocell. With switch in position I, the variable resistance is adjusted to give a reading of 9.5 mV on the recorder. The window of the receiver is then blanked off, the switch moved to position II and the position of the compensating cell adjusted to obtain a reading of 0.5 mV on the recorder. With the switch back in position I, the receiver is exposed to full light and the full scale reading on the recorder is checked and adjustment made, if necessary. The process is repeated until the maximum and the minimum deflections are separated by exactly 9.0 mV. With the switch in position III, the cells are put in opposition and the meter is ready for use in a test.

The smoke meters are calibrated by using neutral density optical filters of known obscuration values and the output curves obtained. A typical curve showing the relationship between the percentage light obscuration and the output of a meter is shown in Figure 5. It is seen from the graph that for up to 60 per cent light obscuration virtually a linear relationship exists. The sensitivity of the meter readily drops off as the smoke density increases above this value.

Light transmittance and its measurement

Attenuation of light when passing through the atmosphers is termed obscuration[3]. If I_o is the intensity of incident light and I_x is the amount received after passing through a path length x, then the obscuration S_x expressed as a percentage is

$$S_x = 100\left(1 - \frac{I_x}{I_o}\right)$$

e.g. 80 per cent obscuration means that after its passage through the path only 20 per cent of the transmitted light is received.

It has been shown that when a parallel beam of monochromatic light passes through a smoky atmosphere its absorption follows a Logrithmic law

$$I_x = I_o\ e^{-kx}$$

where k is a coefficient depending upon the properties of smoke.
Beer extended this law to include smoke concentration and the Beer-Lambert law is expressed as

$$I_x = I_o\ e^{-kcx}$$

where c is the smoke concentration

$$\text{or } \log_{10} \frac{I_o}{I_x} = \frac{kcx}{2.303}$$

The expression $\log_{10} \frac{I_o}{I_x}$ is called the optical density D_x. An optical density of 1.0 means that 90 per cent of the emitted light has been obscured.

For a given type and concentration of smoke factors k and c are constant, therefore the optical density is directly proportional to the length of the path through which the light is passing. Optical density per unit length is a convenient method of expressing the light absorption properties of smoke and it permits the data to be applied to path lengths other than those tested and enables a comparison to be made on a common basis between different investigations.

In Figure 6 optical density and light obscuration are plotted in relation to each other and in Figure 7 the output curve for a smoke meter is plotted in terms of optical density/metre.

The voltage produced across a selenium barrier layer photocell under suitable conditions of illumination, is usually expressed as follows:

$E_o = k \log_{10} I_o$ where k is a constant for the cell and I_o is the intensity of light falling on the cell.

If a parallel beam of light of initial intensity I_o passing through a smoke obeying the Beer-Lambert law is reduced to I_x through a path length x, then

$$E_o - E = k \log_{10} \frac{I_o}{I_x}$$

i.e. the difference in the output of the photocell is directly proportional to the optical density of the smoke.

Smoke and visibility

Smoke produces a variety of effects on human beings which may be physical, such as reduction in vision; physiological such as lachrymation, irritation of throat and lungs and toxicity, as well as psychological effects demonstrated as fear or panic. Physiological and psychological effects are beyond the scope of the Fire Research Station, and this report is concerned solely with the effect on visibility. It might be thought, however, than any provision which can be made to improve visibility will have a beneficial effect on them as well. Toxic effects are being studied elsewhere at the Fire Research Station and will in due course be reported on separately.

Visibility is taken as the distance at which an object can be just clearly seen in a given atmosphere under prevailing conditions of illumination. It depends amongst other factors upon the contrast that exists between the object and the background and whether the light source is behind or ahead of the observer. For the purpose of these experiments, a simplified approach was made to study the effect of smoke in the atmosphere on the visibility of objects. A standard object consisting of letter C in black on a white background was selected as an observation target and the point at which it just disappeared from vision under conditions of gradually increasing smoke density was taken as the threshold of visibility.

Tests were conducted in a disused air raid shelter, nearly 12 metres long, in which six standard objects were suspended, as shown in Figure 8, from the ceiling at eye level at distances of 1.5, 3.0, 4.5, 6.0, 7.5 and 9.1 metres from an observation point behind a glazed screen. Tungsten lights were arranged in the ceiling to illuminate each object which received an incident light of 97 lumens/m^2 with the type of light source employed. A smoke meter was placed close to each object to measure continuously the mean density of smoke in the area. The air raid shelter was gradually filled with smoke by using the smoke generator connected to a long perforated hose lying on the floor for the length of the shelter.

The experiment was repeated with three separate operators and the results are plotted in Figure 9. It should be noted that only one reading was obtained for the maximum distance of 9.1 metres due to the difficulty of observing precisely the time at which the standard object disappeared at this distance. There is some scatter of results, presumably due to the subjective nature of the observations made; the curve drawn in Figure 9 indicates the relationship between visibility and optical density of smoke produced by the smoke generator.

A distance of 4.5 metres[4] is sometimes regarded as the maximum distance which a person should be expected to pass through smoke. In so far as this may be valid the results show that for visibility not to be reduced below this level the optical density/metre of smoke should not be in excess of 0.21

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(2) On some tests about the Spread of Smoke through a building. Brandveiligheidsinstituut T.N.O. (Private communication).

(3) Smoke density indicators and recorders. B.S. 2811 : 1957. B.S.I. London.

(4) Precautions against fires Part 1. Fire precautions in flats and maisonnettes over 80 ft in height. C.P. 3 : Chapter IX (1962) B.S.I. London.

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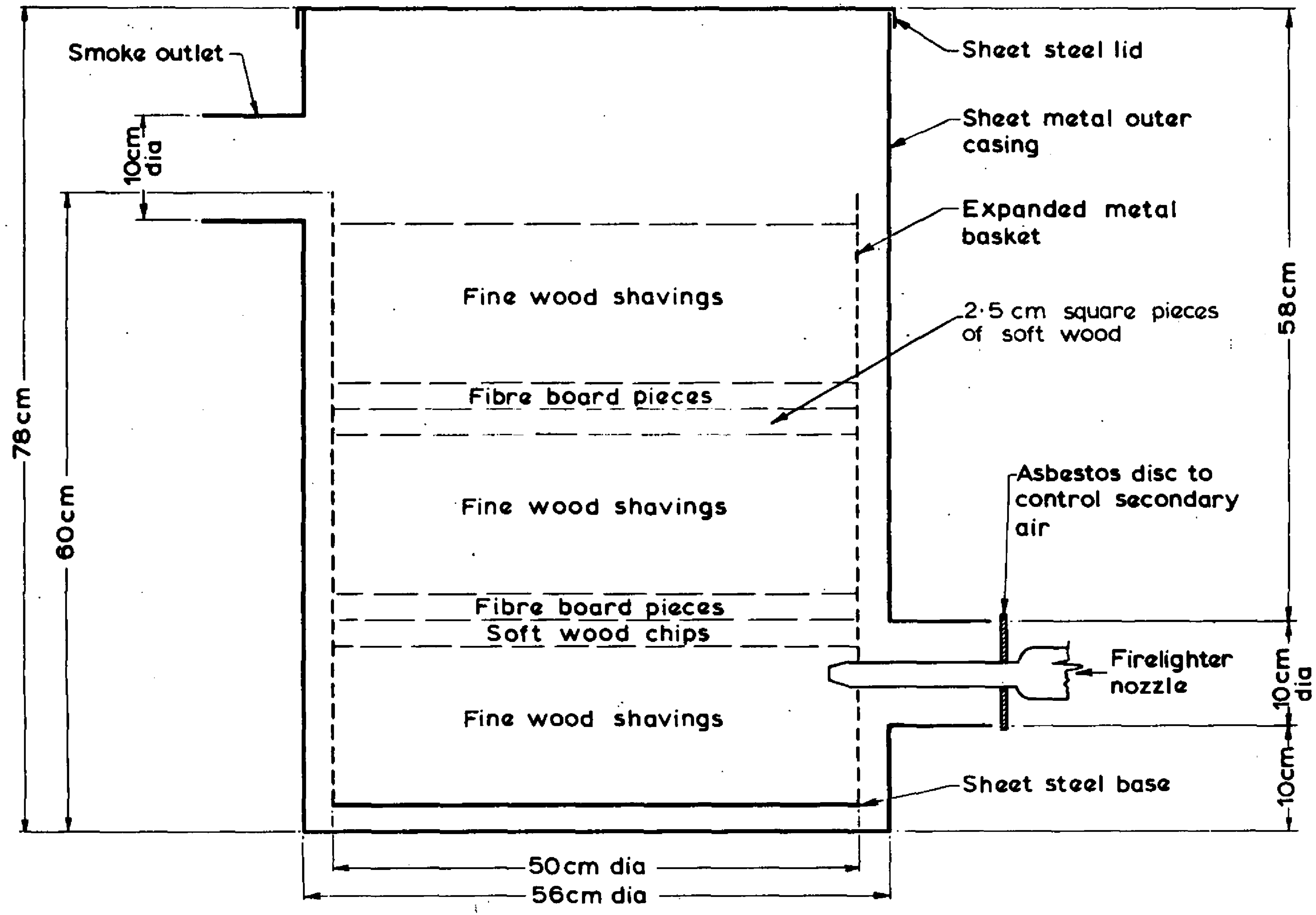

FIG. 1. '2MB' SMOKE GENERATOR

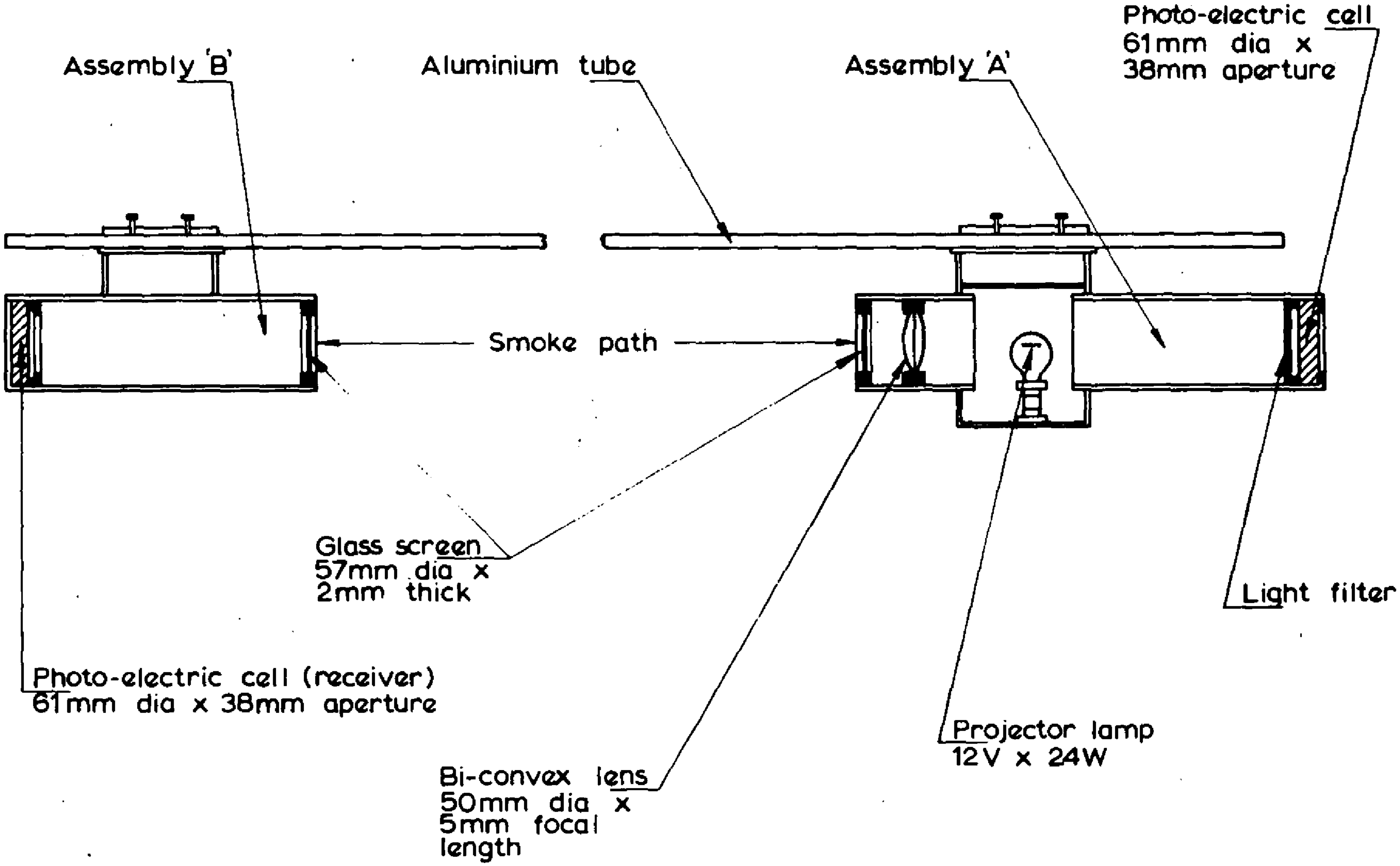

FIG. 2. '2MB' SMOKE METER

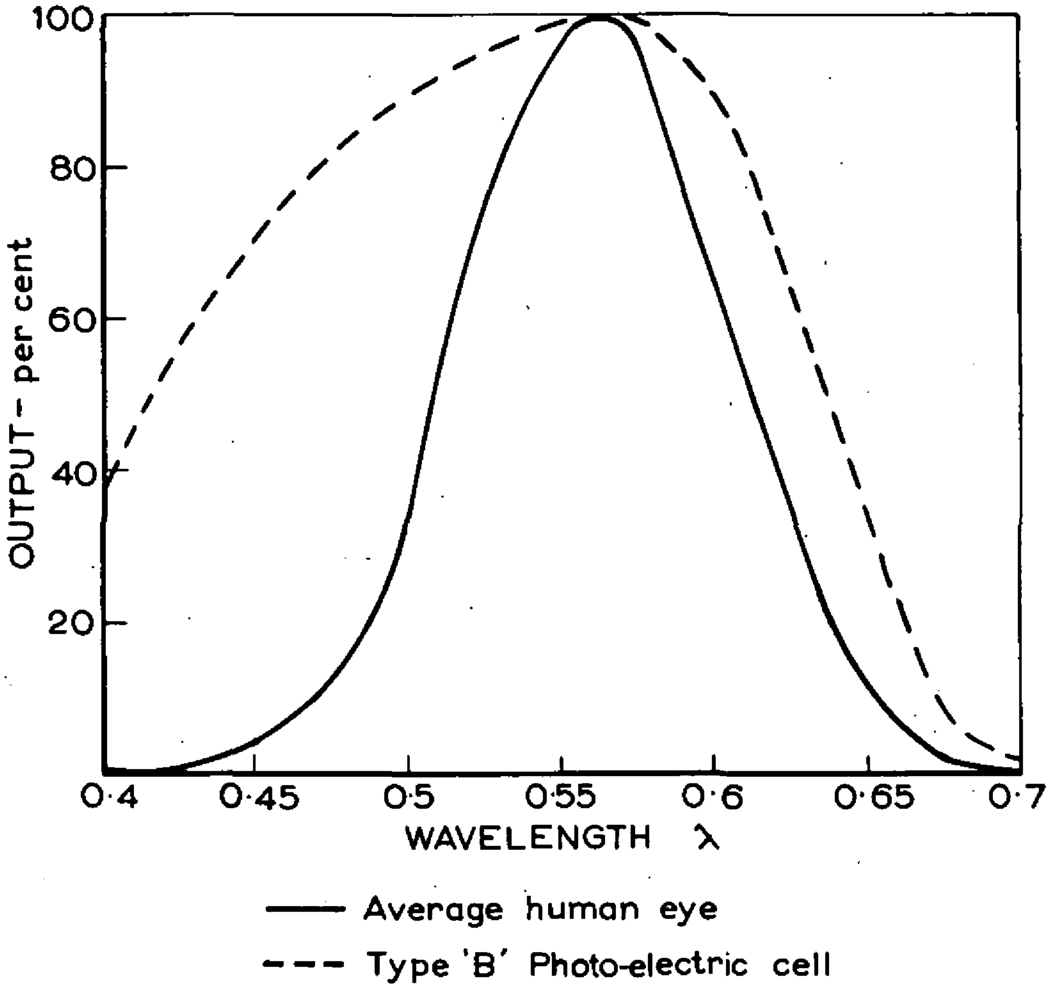

FIG. 3. SPECTRAL RESPONSE OF PHOTO-ELECTRIC CELL

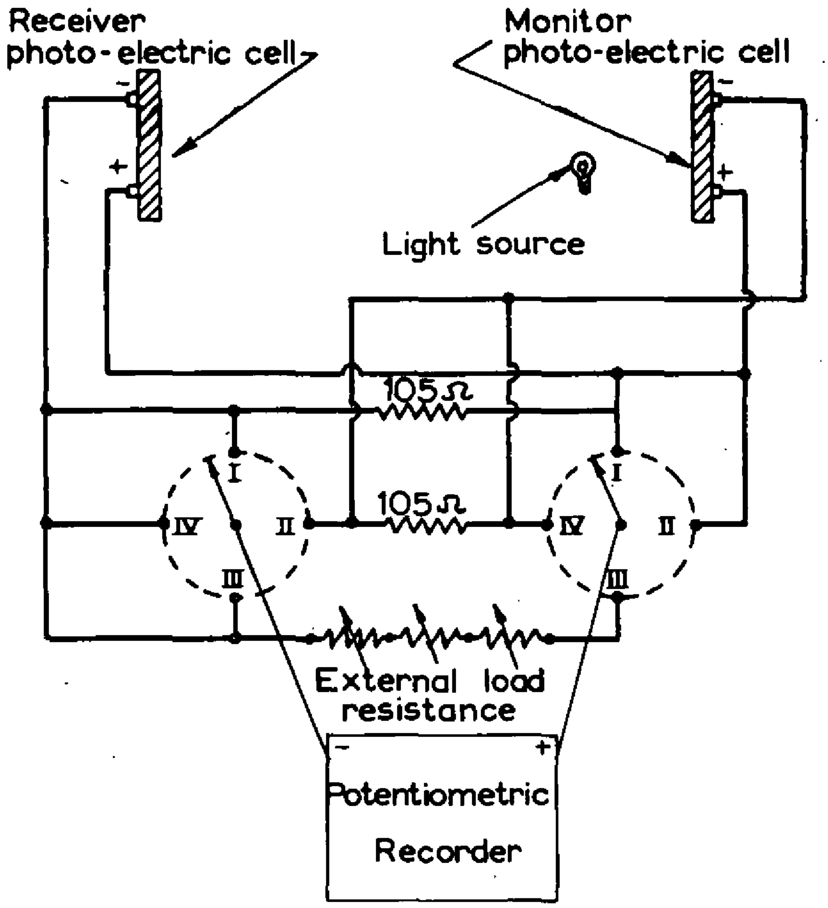

FIG. 4. ELECTRIC CIRCUIT FOR SMOKE DENSITY METERS

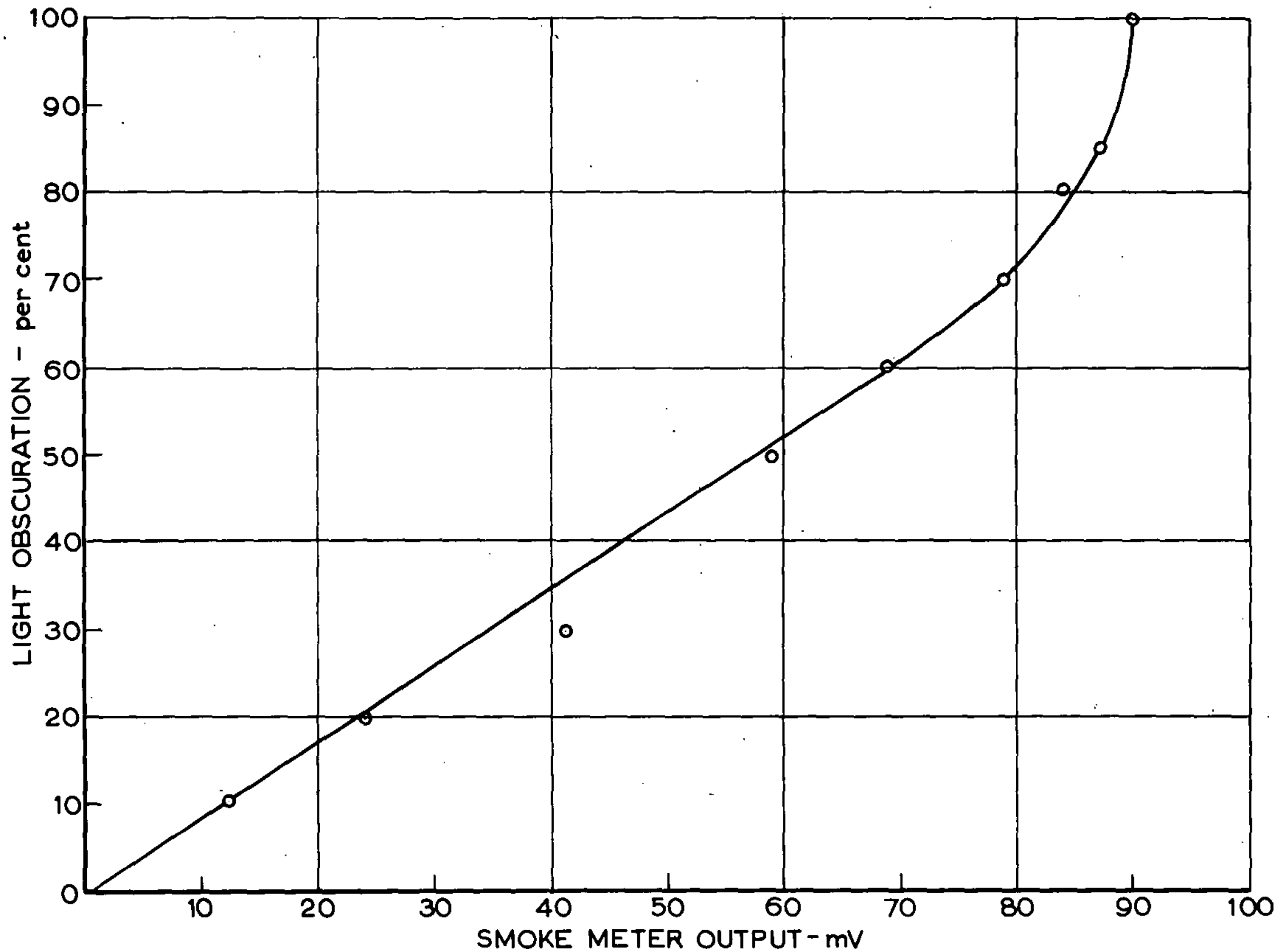

FIG. 5. A TYPICAL OUTPUT CURVE FROM A SMOKE METER

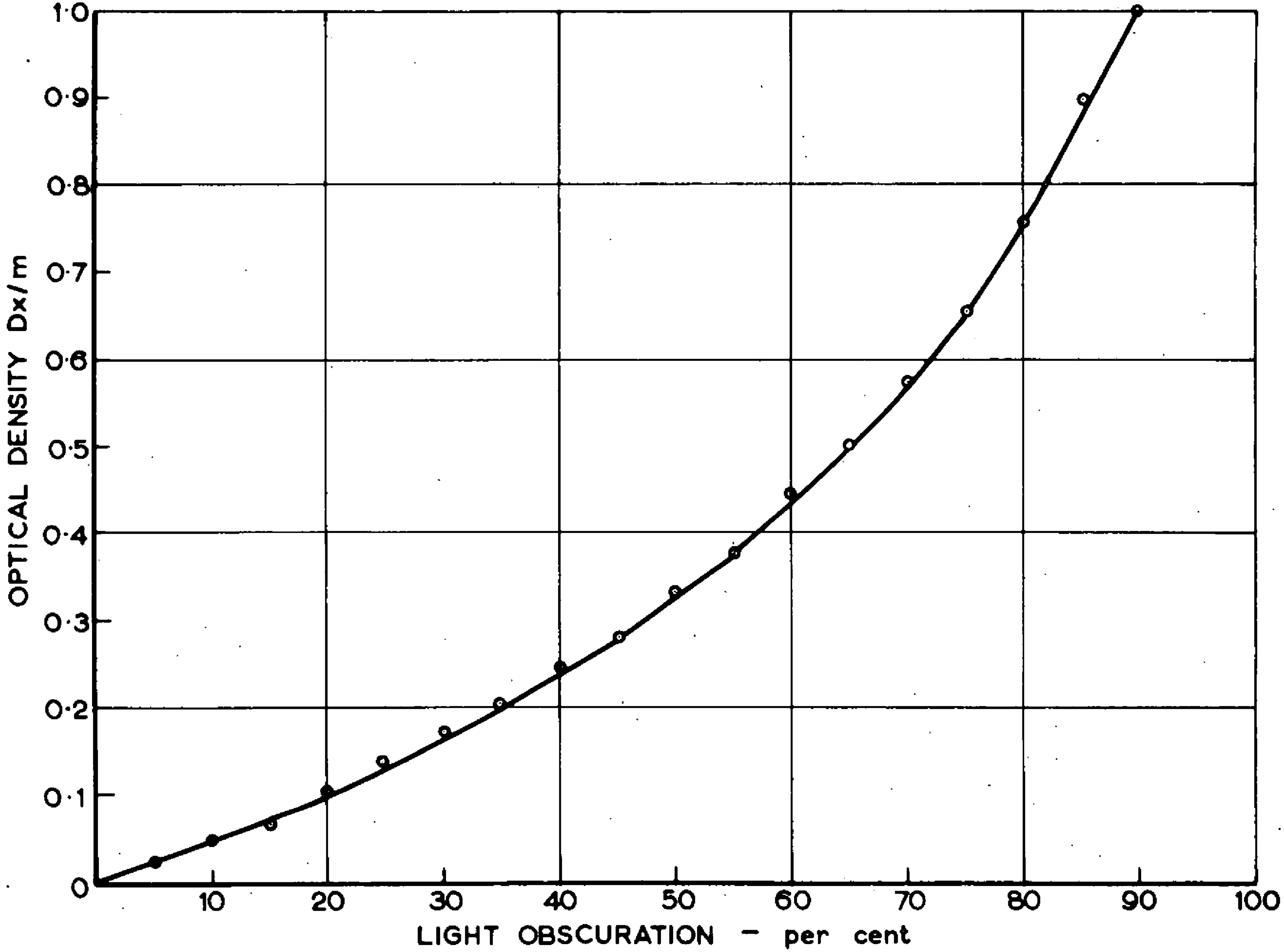

FIG. 6. RELATIONSHIP BETWEEN LIGHT OBSCURATION AND OPTICAL DENSITY

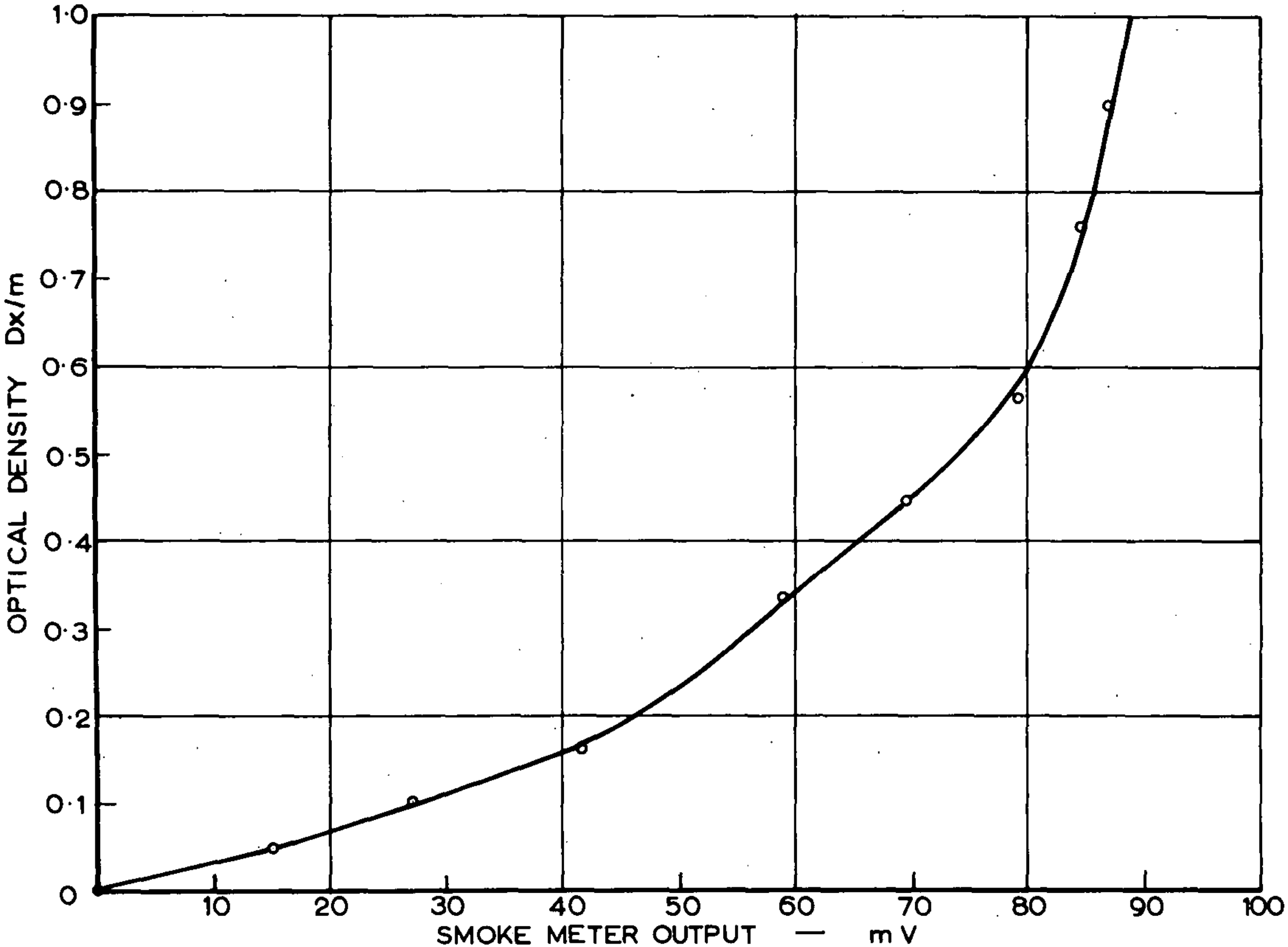

FIG. 7. TYPICAL OUTPUT CURVE FROM A SMOKE METER

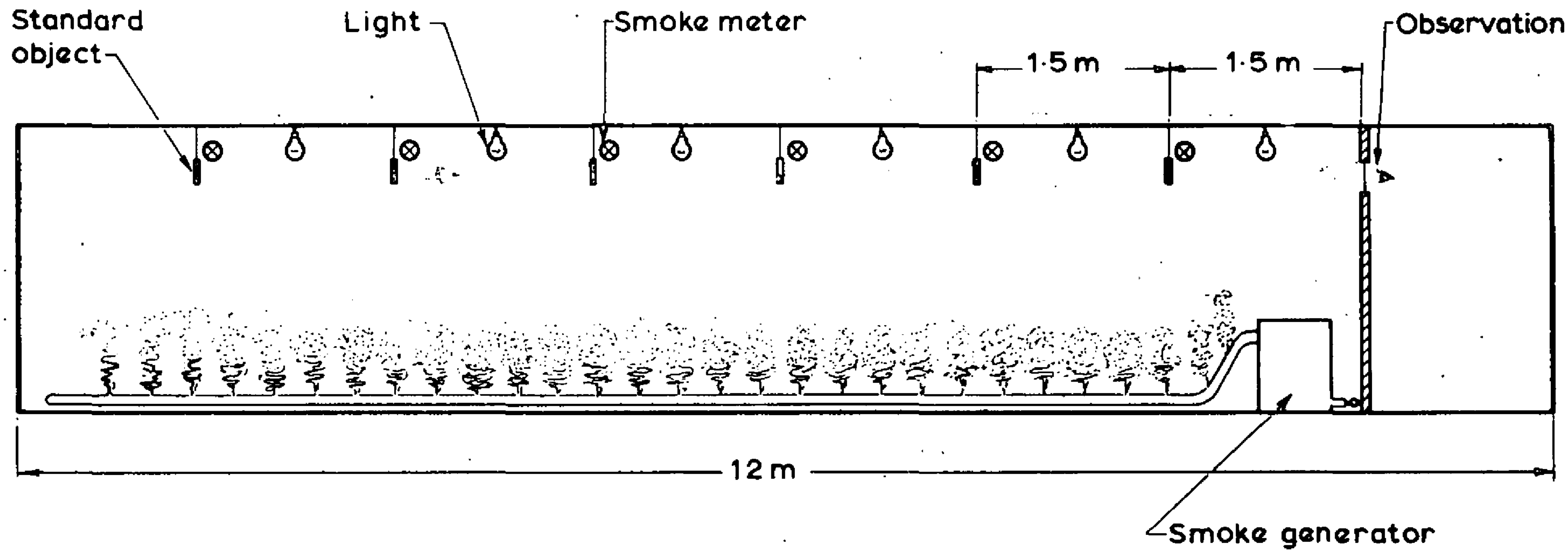

FIG. 8. CROSS-SECTION OF AIR RAID SHELTER

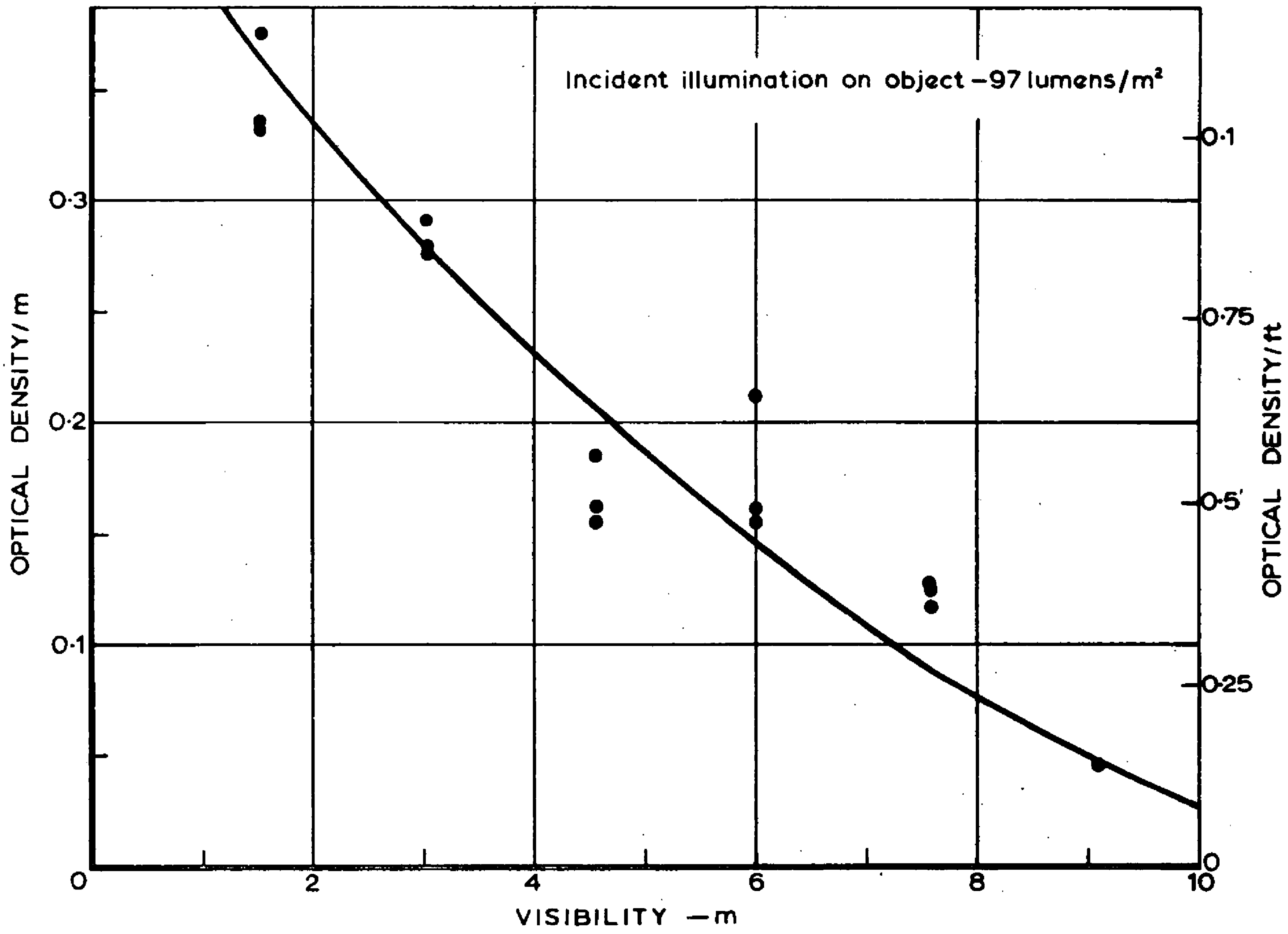

FIG. 9. RELATIONSHIP BETWEEN OPTICAL DENSITY AND VISIBILITY

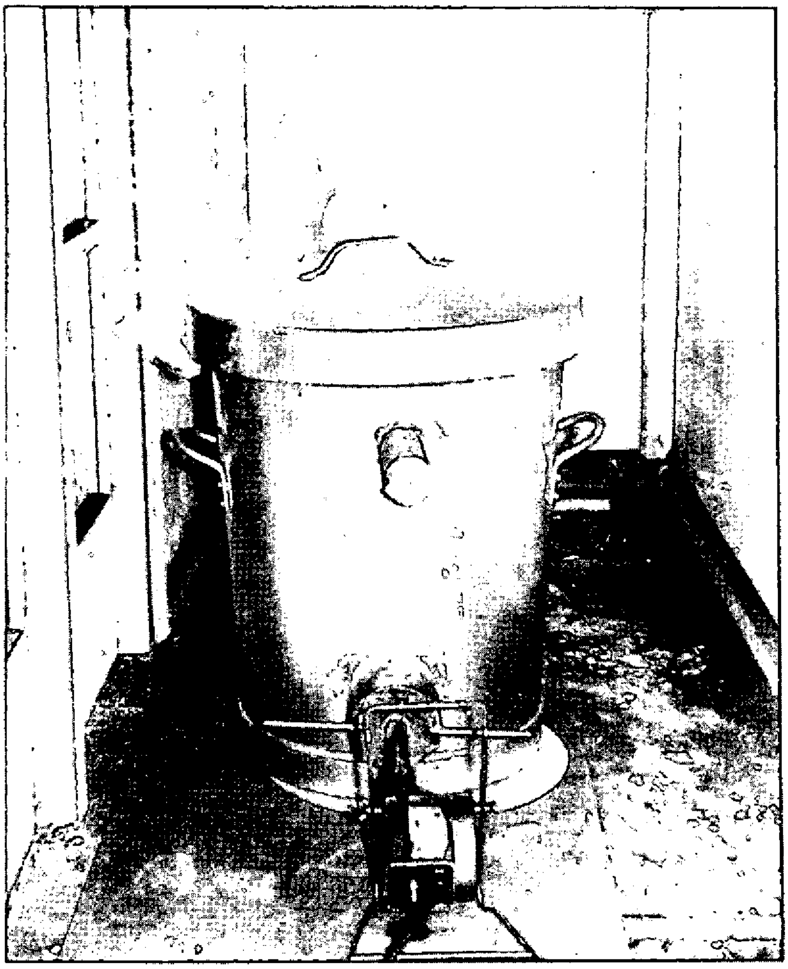

PLATE 1 MODIFIED VERSION OF SMOKE GENERATOR

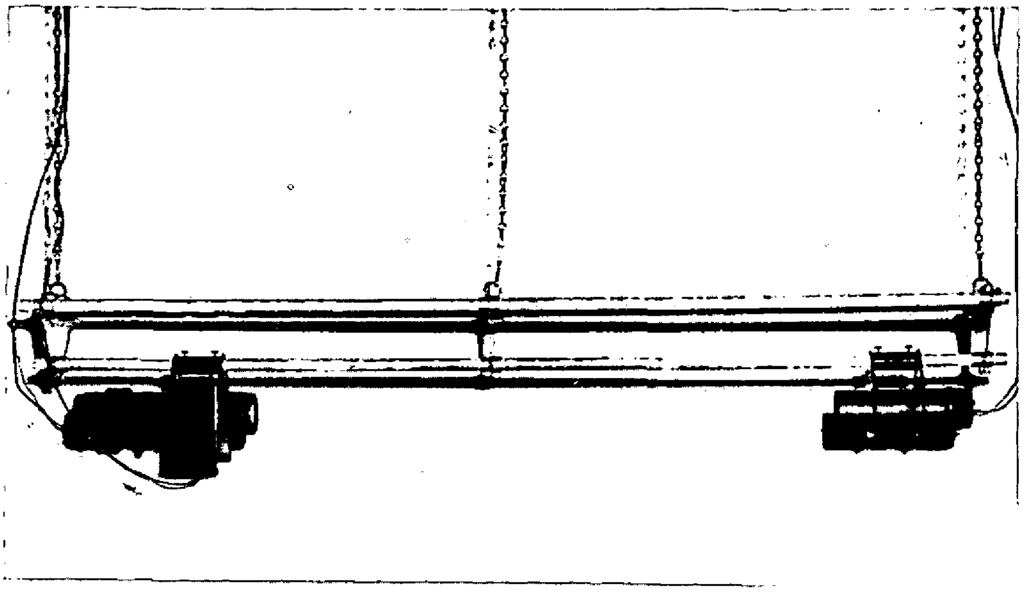

PLATE 2 '2MB' SMOKE METER

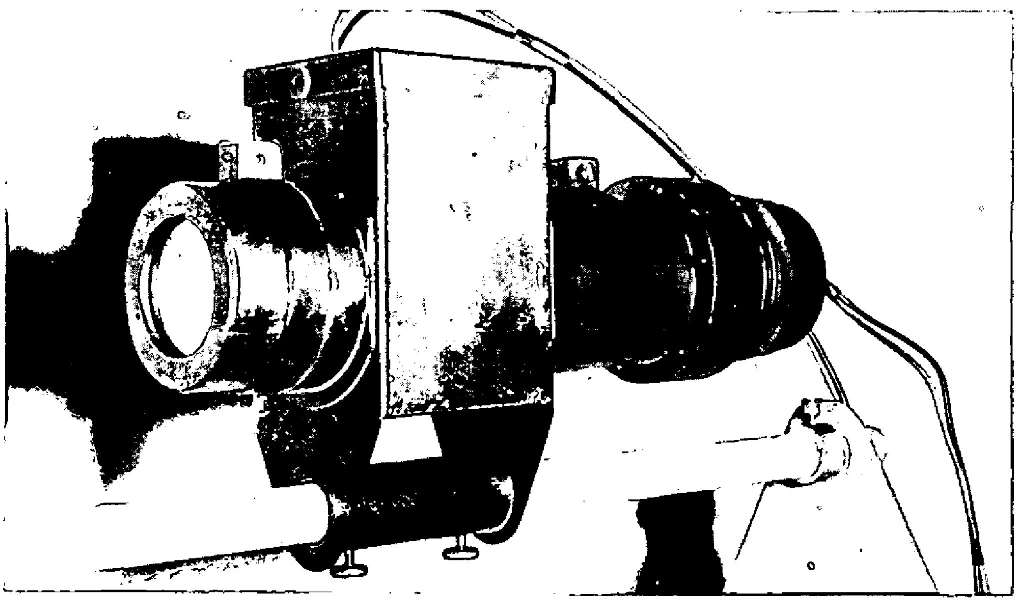

PLATE 3 CLOSE UP OF LIGHT UNIT AND MONITORING PHOTOCELL