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THE USE OF ABSORBING SMOKES FOR THE ATTENUATION OF INFRA-RED RADIATION

[R]

by

W.L. Dennis

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Chemical Defence Establishment,
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C.D.E. TECHNICAL PAPER NO. 97
DATE: MARCH 1972

THE USE OF ABSORBING SMOKES FOR THE ATTENUATION
OF INFRA-RED RADIATION

by

W. L. DENNIS

SUMMARY

A number of particulate clouds composed of carbon particles have been investigated in the laboratory to compare their efficiencies as absorbers of infra-red radiation. It was found that the most efficient were those produced from pulverized charcoals, one cloud giving almost uniform attenuation over the wavelength range 1 - 13 μm . A dispersion of this material was compared in the field with smokes produced from white phosphorus and from hexachloroethane smoke mixture (PN 800). Under the conditions of the trials it was found that for the same aerosol concentrations, the charcoal was about five times more efficient than the chemical smokes against radiation having a wavelength of about 5 μm .

WLD/PT

(Sgd.) R. G. DORMAN
Superintendent
Physics Division

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INTRODUCTION

In recent years great advances have been made in the detection of infra-red radiation and the techniques developed have been applied in many fields both military and civilian. For example, infra-red detectors are used in missile guidance systems, proximity fuses and in industry, spectroscopic methods of gas detection, while image converters or thermal imaging devices are used for reconnaissance, surveillance, night driving and camouflage detection. It is now possible to detect or "see" enemy vehicles at a considerable distance in the dark. The smoke screens in current use offer little protection for they are transparent to infra-red radiation.

The ease with which an object can be detected by infra-red depends upon its radiant flux, which may either be emitted by the body by virtue of its temperature or reflected from another source; that is the system may be either passive or active. A passive system depends entirely upon the radiation emitted by a hot part of the target, such as the exhaust of an engine, and has the advantage of not being detectable by the enemy.

The earlier detectors were of the lead sulphide type and were sensitive only to the shorter wavelengths up to about $3\mu\text{m}$ but with modern detectors the range has been extended to about $40\mu\text{m}$ for photo-conductive cells and to even longer wavelengths with thermistor bolometers. A modern infra-red camera, operating in the

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range 1.2 to 2.8 μm allows observation of scenes illuminated by near infra-red radiation, or of objects with a temperature exceeding 150°C by reason of their own radiation. Under favourable conditions a thermal television unit using a cooled mercury-doped germanium detector and working in the range 8 to 13 μm can resolve a temperature difference as small as 0.3°C . For aerial reconnaissance, equipment is available which, operating at wavelengths of 8 to 14 μm , can be used for photographic recording by day or night without artificial illumination.

A study of the attenuation of infra-red radiation by screening smokes was made at CDE some years ago (1) (2). Recently the Navy (3) has shown renewed interest in the use of particulate clouds since ships are vulnerable to attack by missiles having infra-red guidance systems. Ships present a large source of power discharged as heat, the hull and superstructure having a different temperature to the surroundings, while there are local hot spots such as the funnel casing. They also leave thermal scars and wakes. Similar considerations apply to military vehicles. Although the more intense sources of infra-red radiation can be suppressed by shielding and cooling, little can be done to control the temperature of the larger surfaces. Reduction in the temperature of the target results in a reduction in the relative intensity of the radiation, especially at the shorter wavelengths. For this reason infra-red detection systems are now operating at the longer wavelengths which give greater sensitivity to small temperature differences.

SCREENING SMOKES

The term smoke is used in this report to denote any particulate cloud which may be used for screening purposes, irrespective of the particle size.

Smoke attenuates radiation by scattering or absorption, or a combination of both. The extent of the scattering depends upon the refractive index of the material, the particle size and the

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wavelength of the radiation. It can be shown that for a given concentration of smoke the maximum attenuation at a given wavelength is obtained when the particle size is numerically equal to that wavelength. When this equality is fulfilled the amount of material required to produce a given attenuation increases rapidly with wavelength, partly due to the larger particle size and partly to the scattering properties of the material. The larger particle sizes may result in an unstable smoke due to sedimentation.

Fog oil smoke produced by vaporization and condensation of a high boiling point oil is a good example of a scattering smoke. As normally produced this gives an aerosol having a number median diameter of about 0.5 to 1 μm . The transmission through such a cloud of fog oil smoke, which is opaque to visible radiation, increases rapidly with wavelength until it is almost transparent at about 10 μm . Chemical smokes behave similarly but, in addition, show absorption bands.

Although the attenuation can be increased by increasing the particle size to match the wavelength of the radiation, in practice the chemical smokes produced in the field all have approximately the same particle size range. There appears to be no way of altering the size range to any great extent, although attempts have been made to make plastic "micro-balloons" having a greater size and lower density.

From the previous work (1,2,3) it was concluded that the best screening over the whole wavelength range, 2-14 μm , would probably be obtained by a cloud of absorbing particles. Experiments using several forms of carbon indicated that the most efficient material was pulverized charcoal which gave an attenuation almost independent of wavelength.

The material used for smoke must be cheap, readily available, non-toxic and easily disseminated. In this present study the previous laboratory work was extended using other forms of carbon,

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such as lamp black, to find the most efficient attenuator; in addition a large number of field experiments was carried out to confirm these results and compare the attenuations with those of other screening smokes.

LABORATORY MEASUREMENTS

Apparatus

The apparatus used for the laboratory measurements was similar to that used in the previous study (4) of the effects of dust on the transmission of infra-red radiation through the atmosphere.

The carbon in powder form was dispersed by means of a Wright dust feed mechanism (5). In this device the powder was compressed in a small cylinder and the surface pared off at a fixed rate by means of a rotating cutter which advanced into the cylinder. The powder was removed and dispersed by an air stream through the device. The carbon aerosol passed successively through two 10 litre glass aspirator bottles which served to remove any large aggregates and to homogenize the aerosol.

It then passed to a chamber shown diagrammatically in Fig 1 which was a modification of one used previously. The infra-red radiation from a Nernst filament was collimated into an approximately parallel beam and passed through a sodium chloride window at one end of the chamber on to a long focal length mirror at the opposite end. From there it was reflected back on to a plain mirror before passing out of the chamber through a window in the side opposite to the Nernst filament. In this way the beam traversed a distance of 275 cm, nearly three times the length of the chamber. Deposition of aerosol on the mirrors was minimized by fitting shields around them and having a flow of clean air over their surfaces. Similar precautions were taken with the windows.

The inlet for the aerosol was at the centre of the chamber, close to a small fan to ensure the uniform distribution of the

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smoke. The outlet was under very slight suction.

The spectrometer has been described previously (1). It was a double monochromator employing a diffraction grating and a sodium chloride prism and incorporating a Golay infra-red detector. The spectrometer covered a wavelength range of approximately 1.5 to 10 μm . The recording system for the spectrograms and the method of printing the results on tape have also been previously described (4). In this way the results were presented as a series of numbers which were proportional to the integrated transmissions in 0.5 μm intervals throughout the wavelength range.

EXPERIMENTAL PROCEDURE

Transmission measurements were made using aerosols of several forms of lamp black and of pulverized charcoal.

A blank run was first made and then the aerosol was passed into the chamber at a fixed rate of air flow, the concentration being adjusted to give a suitable transmission. Previous work had shown that a period of about twenty five minutes was required for the concentration to attain an approximately constant value. After this period another run was made on the spectrometer to measure the transmission throughout the required wavelength range. When considered necessary, another blank run was made to check that there was negligible deposition on the windows and mirrors etc. At least five experiments were carried out with each material and the mean transmissions over each 0.5 μm wavelength interval for a path length (L) of 1 metre and a concentration (c) of 1 g/m³ ($cL = 1 \text{ g/m}^2$) were calculated.

In each experiment the particle size distribution was determined by means of a thermal precipitator and the mean concentration by taking a Millipore filter sample throughout the run.

The materials examined and the number median diameters (NMD) of the aerosol particles are given in Table 1.

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TABLE I

Material		Number median diameter (NMD) (μm)
Neospectra	Furnace carbon blacks.	1.0
Furnex		0.7
Ukarb 327		0.84
Philblack A		0.82
Philblack G		0.55
Philblack I		0.69
Carbonized nutshell		0.80
Charcoal		0.69
Boiler coke		0.58
Anthracite charcoal		0.77
Coal base charcoal (207B)		1.03
Coconut shell charcoal (207C)		0.85

RESULTS

The results obtained are shown in Figs. 2 and 3. For the sake of clarity the experimental points have been omitted from the graphs. It will be seen that for all charcoals (Fig. 2) the percentage transmission increases with increasing wavelength but to a much greater extent for some than for others. From Table I it appears that there might be a correlation between the percentage transmission at the longer wavelengths and the particle sizes since the aerosols with the smaller sizes tend to have the higher transmissions. However, it is believed that this is coincidental since, according to theory, this particle size range would have little effect on the transmission at the wavelengths employed. It is much more likely to be due to the physical properties of the materials. Electron micrographs of samples of some of the particles are shown in Fig. 4.

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A similar set of results is shown in Fig. 3 for a number of furnace blacks. The variation between these transmission curves is much smaller than for the charcoals. They are similar to those having the higher transmissions. At shorter wavelengths, in the near infra-red region, they give a greater attenuation than the charcoals. Particle photographs are shown in Fig. 5.

FIELD EXPERIMENTS

Apparatus

As the concentration of a plume of smoke in the field varies rapidly with time and position, accurate sampling would involve a large number of measurements along the optical path. In the present experiments it was decided that the most suitable procedure would be to monitor the area concentration by means of the attenuation of a collimated beam of visible radiation as close as possible to the infra-red beam. The arrangement in the field was to have two sources, one for the visible radiation and the other having its peak energy in the infra-red region. The sources were housed in two adjacent huts, the distance between them being about 1.5 metres. The sources were directed at another large hut 60 metres away and housing the two receivers situated approximately the same distance apart. Each beam passed through an aperture in the wall of the building. Originally the beams were parallel to one another but experience showed that, under the meteorological conditions most suitable for the formation of a usable cloud of smoke, there was a significant interval between the times of passage of a given part of the cloud across the two beams. It was therefore decided to interchange the positions of the two receivers so that the beams intersected at a point midway between them and the sources.

1. Visible source

This is shown diagrammatically in Fig. 6 and in the photograph Fig. 8. The light from a small car headlamp bulb (4 volt, 2 amp.) was concentrated by means of a Cassegrainian system into a parallel beam, the aperture of the larger mirror being 14 cm. The beam was modulated at a frequency of 200 Hz,

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by a chopper disc situated adjacent to the lamp. The chopper also intercepted the light falling on to a small cadmium sulphide photocell giving a reference signal synchronized with the main beam for transmission to the phase sensitive detector used in the detector system.

2. Infra-red source

The infra-red source consisted of a small coil of 28 swg Chromaloy wire mounted in a twin bore silica tube, Fig. 7 and held horizontally at right angles to the optical axis and at the focus of a 25 cm surface silvered concave mirror. The radiation was modulated at a frequency of 150 Hz by means of a cylindrical chopper which rotated about the axis of the source. This system enabled the maximum radiation from the source to be used. The voltage applied to the heated coil was 6 volts and the current 8 amps. The reference phasing device used with this source consisted of a small disc chopper, attached to the same spindle as the main cylindrical one, which intercepted the light falling on another photocell from a small pea-lamp (Fig. 6).

Each source was mounted on a rigid tripod having horizontal and vertical adjustments.

3. Visible receiver

The visible receiver consisted of a 25 cm mirror to focus the light on to a lead sulphide detector (Fig. 6). This type of detector is normally used for infra-red radiation but the sensitivity in the visible was ample for the present application. An infra-red absorbing glass filter was placed in front of the detector to prevent pick-up of the radiation from the infra-red source as this caused overloading of the amplifier.

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4. Infra-red receiver

A Cassegrainian system with a 25 cm diameter surface silvered mirror was used for the detection unit as this enabled a number of narrow band filters to be placed in the optical path before the triglycine sulphate infra-red detector (Figs. 6 and 9). The mechanism used for changing the optical filters, shown in Fig. 7b, operates on the principle of the Geneva cam. The wheel A rotates approximately once in three seconds so that the filter wheel rotates one sixth of a revolution each second and successively locates a filter in front of the detector. In the earlier experiments the filters were for wavelengths above 8 μm and all required a "cut-on" filter to eliminate radiation of shorter wavelengths, so that it was sufficient to locate this filter permanently in front of the detector. In the later experiments three of the filters were for wavebands in the near infra-red and the cut-on filter was only required for the other three, so that a cam consisting of a narrow strip of brass, C, of the shape shown in Fig. 7 was attached to the wheel, B, and served to remove the filter, D, from the optical path when not required.

The triglycine sulphate detector used is a recent development with a spectral response range of 2 - 25 μm and a fast response time of about 1 μs . It has the advantage of being a robust detector and does not require cooling.

Both the visible and the infra-red receivers were mounted on tripods and were protected by aluminium covers.

Recording system

The signal from each detector was passed to an A.C. amplifier and then to a phase sensitive detector, the output from which was fed to an ultra-violet recorder incorporating plug-in pencil type galvanometers. This electronic system has the advantage of being able to recover a signal buried in a relatively large amount of noise. The output from the infra-red detector corresponding to

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each filter varied considerably, as it depended upon the bandwidth and the relative energy of the source at that part of the spectrum. In order to obtain the same galvanometer reading for each filter, corresponding to 100% transmission over the optical path, it was necessary to attenuate the output from the detector by a different amount for each filter, a larger attenuation being required at the shorter wavelengths. To do this a switching device was incorporated which consisted of six reed switches mounted radially round a stationary disc concentric with wheel, B, (Fig. 7). Attached to the latter was a small permanent magnet so that as the wheel rotated, the magnet operated the reed switch corresponding to the filter in position in front of the detector. Consequently these switches successively inserted appropriate attenuating resistances in the recorder circuit as each filter was located in the optical path.

CALIBRATION EXPERIMENTS

As stated above, in the field the area concentration was monitored by measuring the transmission of a beam of visible radiation and it was therefore necessary to carry out a preliminary series of calibration experiments. These were done in a large plastic walled chamber, 5m by 10.9m by 4.3m high (volume = 234 m^3), built inside a windowless building having sliding doors at one end.

The optical arrangement is shown in Fig. 10. The visible source and the detector were situated outside one end of the chamber and a large mirror was placed inside at the opposite end, so that the beam of visible radiation from the source was reflected back to the receiver, the beam passing through two perspex windows in the walls of the chamber. The path length within the chamber was 20 metres. The smoke cloud was stirred continuously by three fans and was sampled by four Millipore filters at the positions indicated on the diagram, the sampling rate being 10 l/min, for 10 or 20 minutes depending upon the concentration of the smoke. The filters were always weighed immediately at the end of an experiment so that they remained in air at the same relative humidity.

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The experimental procedure was first to check the functioning of the receiver and source, then disperse the smoke cloud in the chamber and observe when it attained a steady state as indicated by a constant transmission. Sampling was carried out for the required time and the percentage transmission at the beginning and end of this interval noted. The concentration was expressed as the area concentration (g/m^2) of the aerosol between the source and the receiver. The experiments were repeated for a number of clouds of differing concentrations and the results plotted as a graph of mean percentage transmission against aerosol concentration (Fig. 11). Similar calibration curves were obtained for a number of smoke materials.

PROCEDURE FOR FIELD EXPERIMENTS

The experimental set-up in the field (Fig. 12) has been briefly described above. Trials were carried out using HCE (hexachloroethane), phosphorus and carbon smokes.

The visible and infra-red detectors were housed in a small building equipped with an electricity supply from a mobile generator. A close up photograph of the detector systems is shown in Fig. 13. Adjacent to the detectors was the ancillary equipment comprising low noise amplifiers, phase sensitive detectors and an ultra-violet recorder etc. Co-axial cables carried the reference signal from the sources to the detectors.

After preliminary adjustment, including alignment of the optics, recording of the visible and infra-red commenced, both being recorded on the same instrument. The record obtained gave a continuous trace for the visible and at the same time a discontinuous trace showing successive transmissions over one second intervals of time at six different wavelengths.

The smoke was generated at a suitable position relative to the optical path, depending upon the wind direction and velocity, so as to give as uniform a cloud as possible and a concentration

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which did not give less than about 10% transmission of the visible radiation. A smaller value would have made determination of the concentration inaccurate.

The phosphorus and HCE smokes were generated by burning the materials and the charcoal powder was dispersed by a simple venturi device operating on compressed air. A large number of experiments was carried out with each material.

RESULTS AND DISCUSSION

For each smoke trial a chart was obtained from the ultra-violet recorder, which showed a continuous trace of the transmission of the visible radiation and, simultaneously, a trace recording in successive cycles the transmissions of the infra-red radiation at six different wavelengths, each being for a one second interval.

The records were analysed by first determining the mean zero readings before and after the completion of the run.

The visible record showed the rapid fluctuations in the transmission and hence in the concentration of the cloud, which increased to a maximum value and then decayed. At the same time the I R traces showed a similar trend but to a smaller extent. From the records of each trial run, a number of values were obtained for the transmission at each wavelength and the corresponding visible transmission during the same time intervals. From the latter one could deduce the corresponding concentrations of the smoke.

A typical plot of the experimental results of the percentage attenuation against aerosol concentration is shown in Fig. 14. It will be observed that there is considerable scatter of the points. This is probably mainly due to the rapid fluctuations of the amount of smoke in the optical path. The best straight line for each set of results was obtained by the method of least squares.

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The final results for the three smokes have been plotted in Figs. 15 and 16. The experimental points are not shown but they are the mean values taken from graphs similar to Fig. 14. Smooth curves have been drawn through the points but it must be realized that there are probably absorption bands which have not been detected, as they lay between the fixed wavelengths of the filters.

DISCUSSION

A number of particulate clouds composed of carbon particles have been investigated to compare their efficiencies as absorbers of infra-red radiation. It has been found that generally the percentage transmission increases with wavelength of the radiation, especially for the furnace carbon blacks. Pulverized charcoals do not show this variation to the same extent; coal based activated charcoal giving almost uniform attenuation throughout the wavelength range covered in these experiments. The difference in the behaviour of these materials cannot be accounted for by their relative particle size distributions. It is more likely due to the physical structure of the materials. The charcoal particles were of angular shape whereas the furnace blacks consisted of aggregates of much smaller spherical particles. The most efficient material was found to be the coal based activated charcoal, except at the shorter wavelengths (1 to 2 μm).

In the field a dispersion of this material was compared with smoke produced from white phosphorus and from hexachloroethane smoke mixture (PN 800) and the results are given in Figs. 15 and 16. It will be seen that under the conditions of these experiments, at a wavelength of 5 μm the charcoal is about five times more efficient than the other smokes. The efficiencies of the chemical smokes however increase rapidly at the shorter wavelengths and, although not shown on this graph, are considerably superior to the carbon in the visible region.

It must be emphasized that all concentrations quoted in this report refer to the smoke particles or droplets; that is the

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concentration of the dispersed phase as determined by the Millipore samples which were taken and weighed under identical conditions of temperature and humidity.

Since the chemical smokes consist of deliquescent droplets the ratio of the quantity of aerosol produced to that of the original material depends upon the humidity of the air. In the phosphorus smoke experiments the mean temperature was 14.5°C and the relative humidity 73%, the corresponding values for HCE smokes were 11°C and 85%.

In considering the relative efficiencies of these smokes one should also take into account the efficiencies of the generators. For example, phosphorus can produce up to about seven times its own weight of smoke. A complete comparison of all these smokes cannot be made until a suitable method of dispersing the charcoal smoke has been developed and further field trials carried out.

Since the completion of this work the apparatus has been rebuilt and the smoke concentration range over which measurements can be made has been extended. This has been achieved by using the transmission at a wavelength in the near infra-red, instead of the visible, to monitor the concentration. The alterations overcome the difficulties experienced in determining particle concentrations too high for accurate measurement of transmission in the visible region.

ACKNOWLEDGEMENTS

The experimental work described in this report and most of the construction of the apparatus were carried out by R. Poynting and R.A. Cox. J. M. Creasey was responsible for the electron microscopy.

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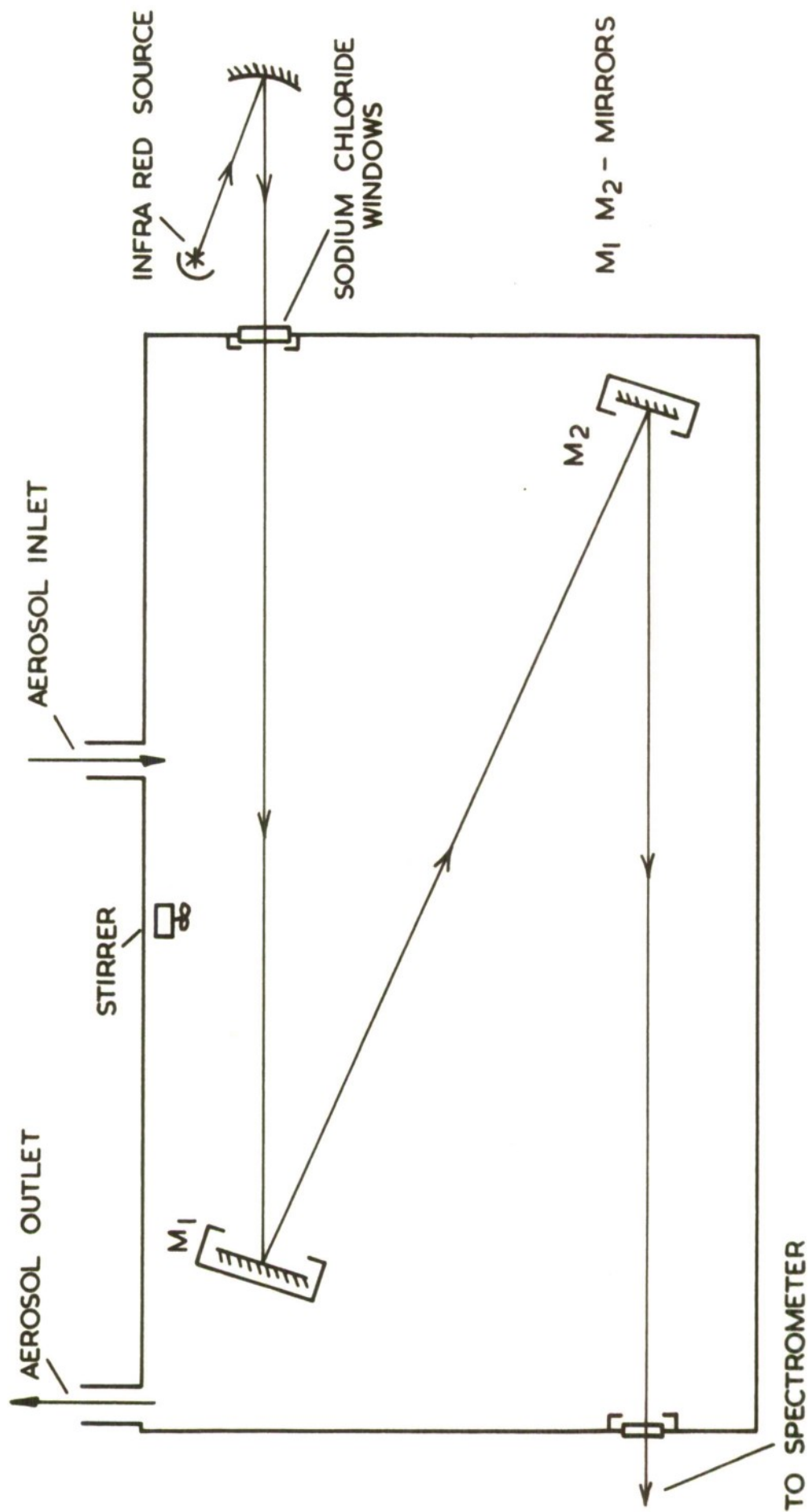
AEROSOL CHAMBER

FIG. I.

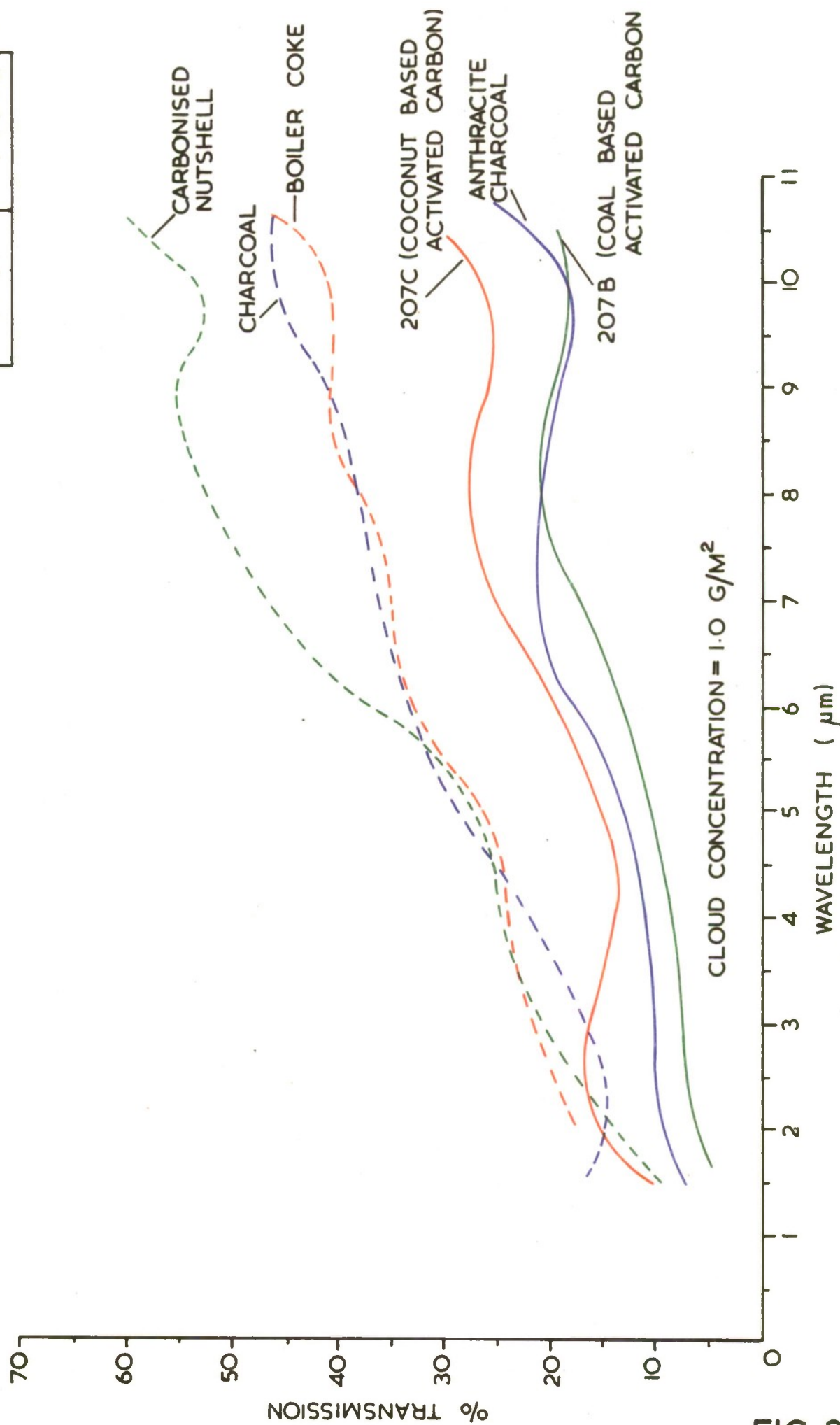
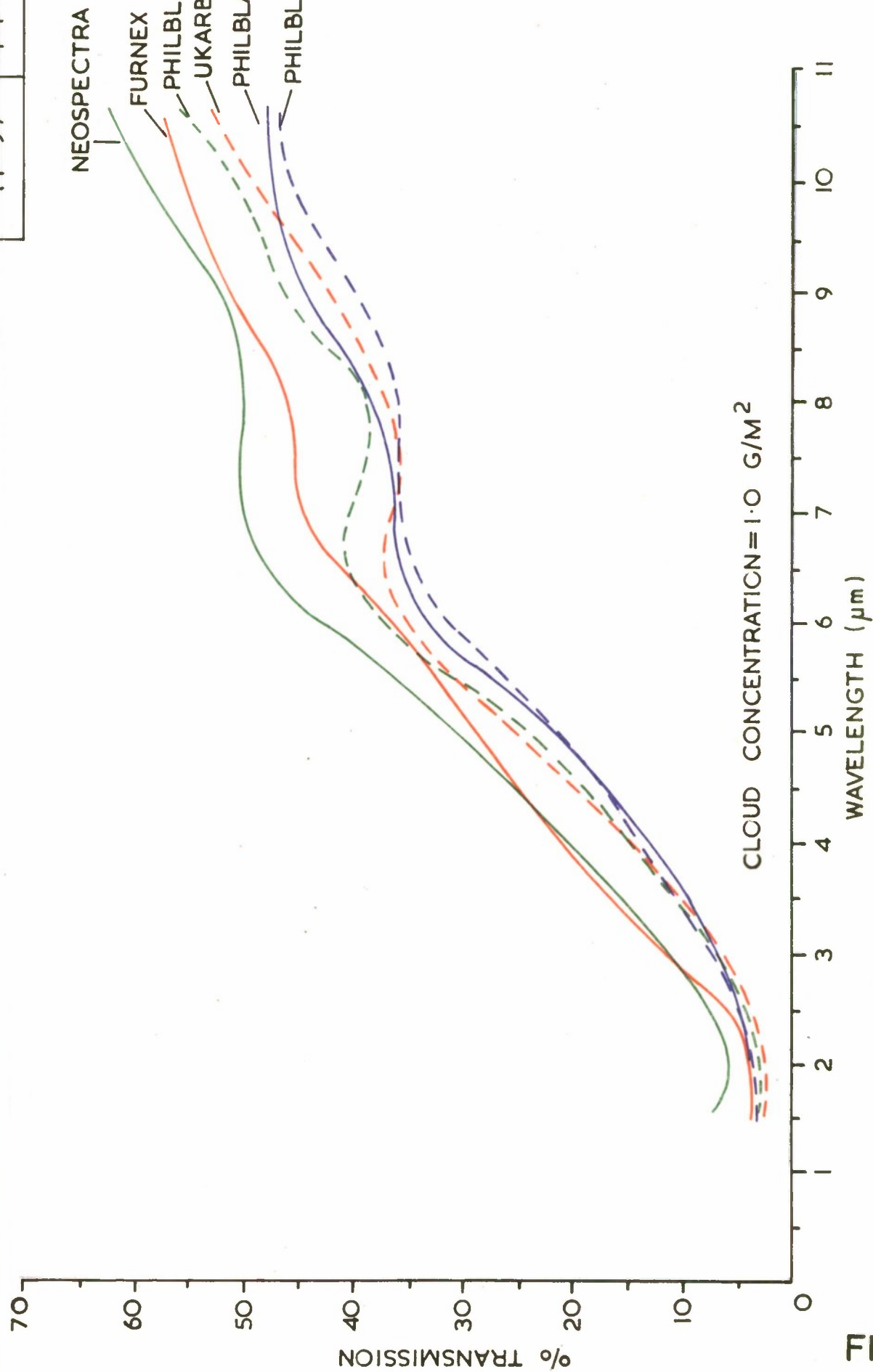


FIG.2.

% TRANSMISSION VERSUS WAVELENGTH FOR VARIOUS MATERIALS.

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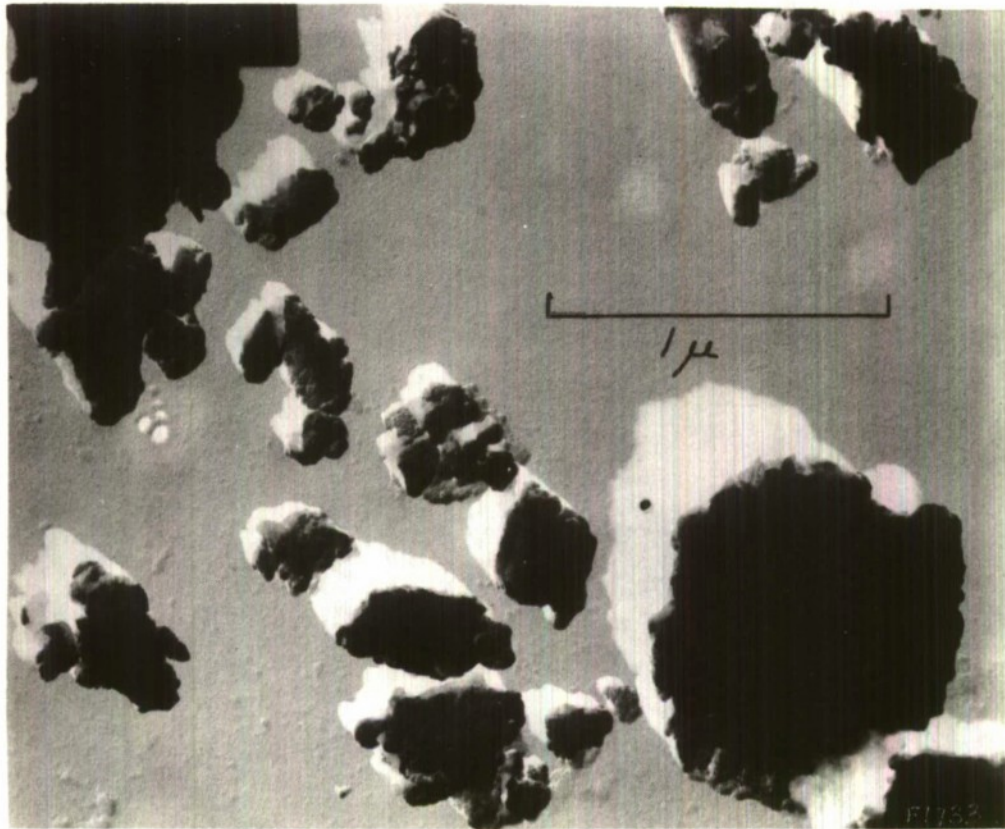
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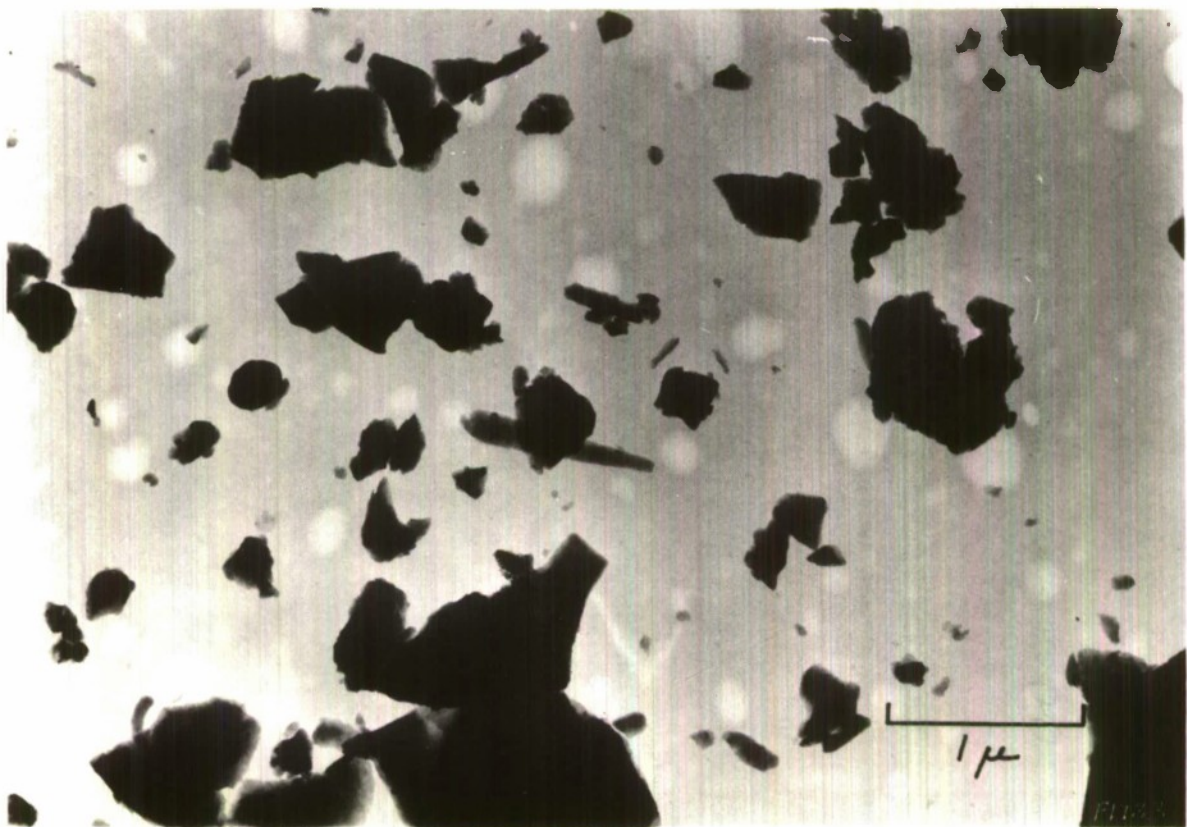
% TRANSMISSION VERSUS WAVELENGTH FOR VARIOUS MATERIALS

FIG.3.

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(a) Boiler coke

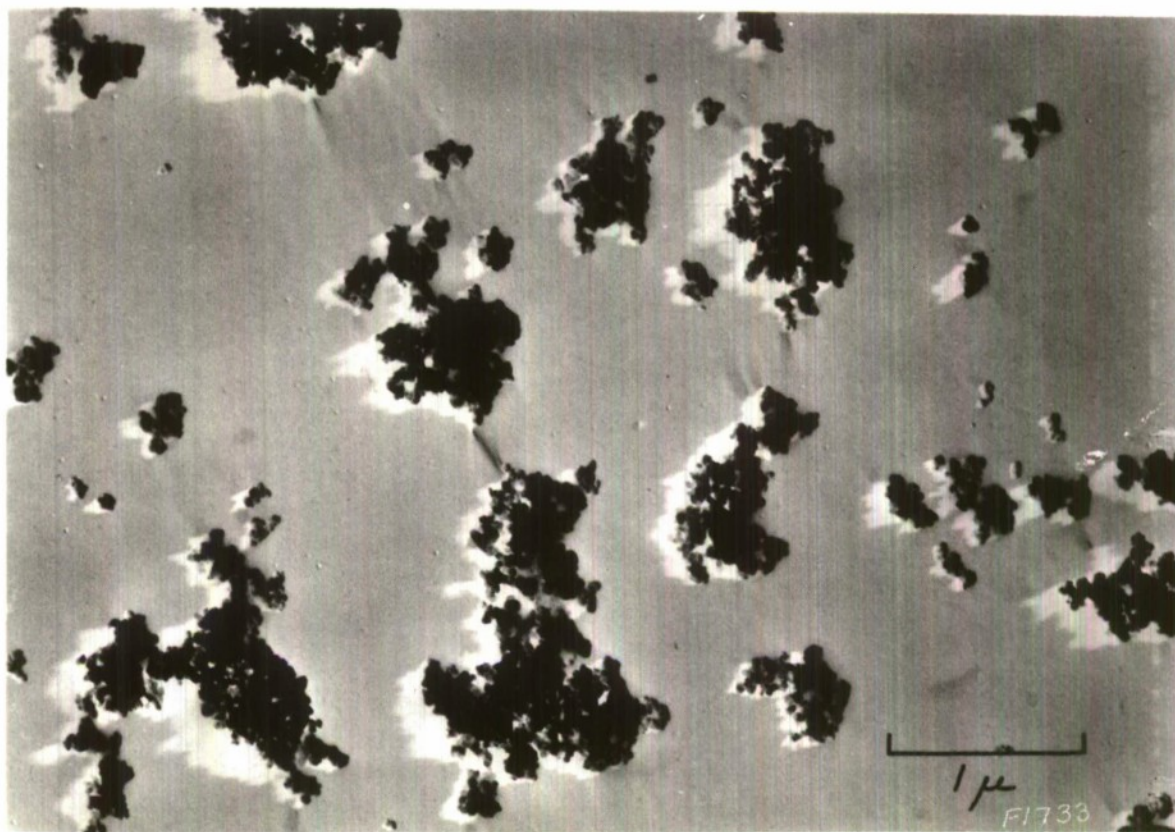


(b) Carbonized nutshell

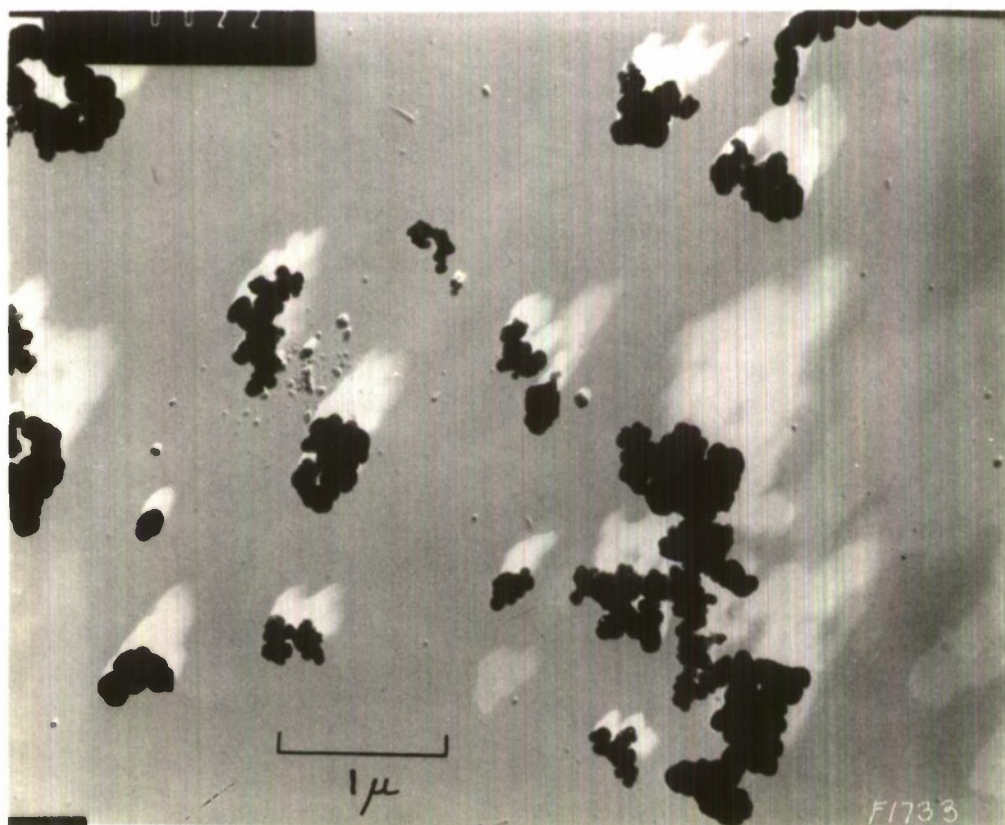
FIG 4

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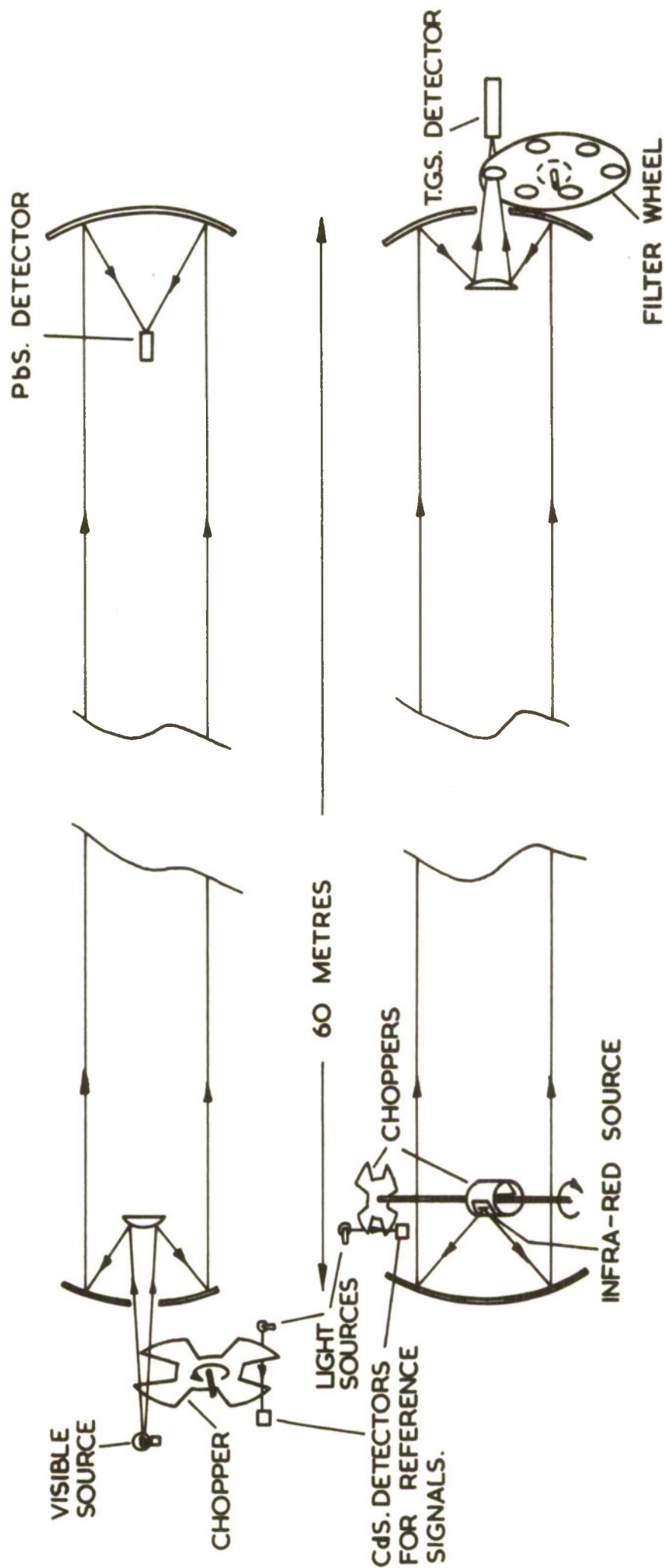
(a) Philblack I



(b) Ukarb 327

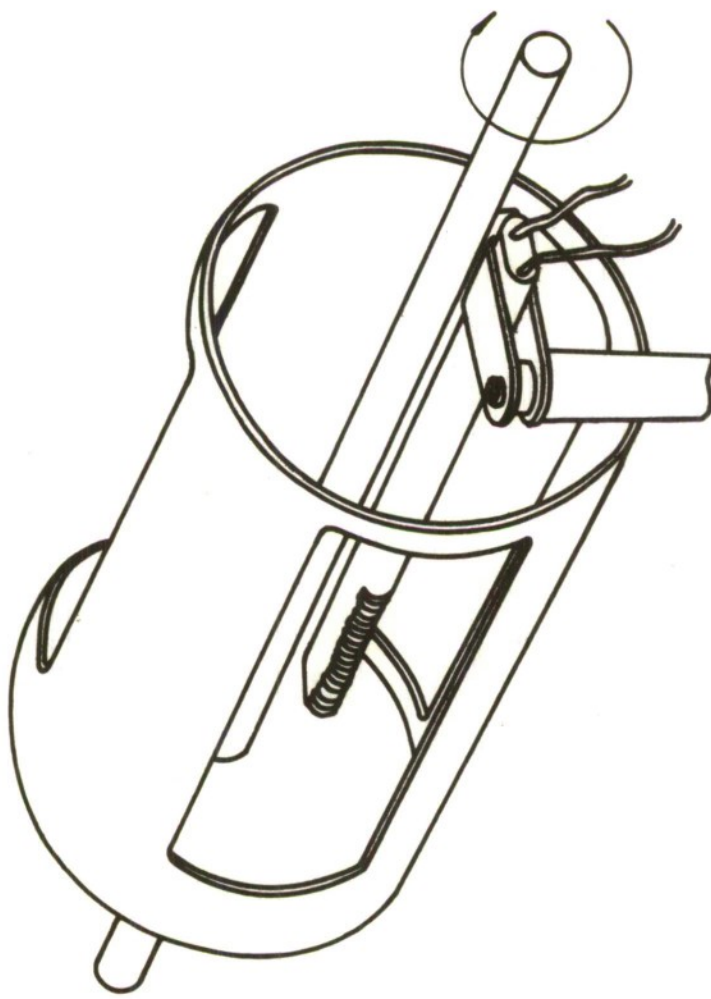
FIG 5

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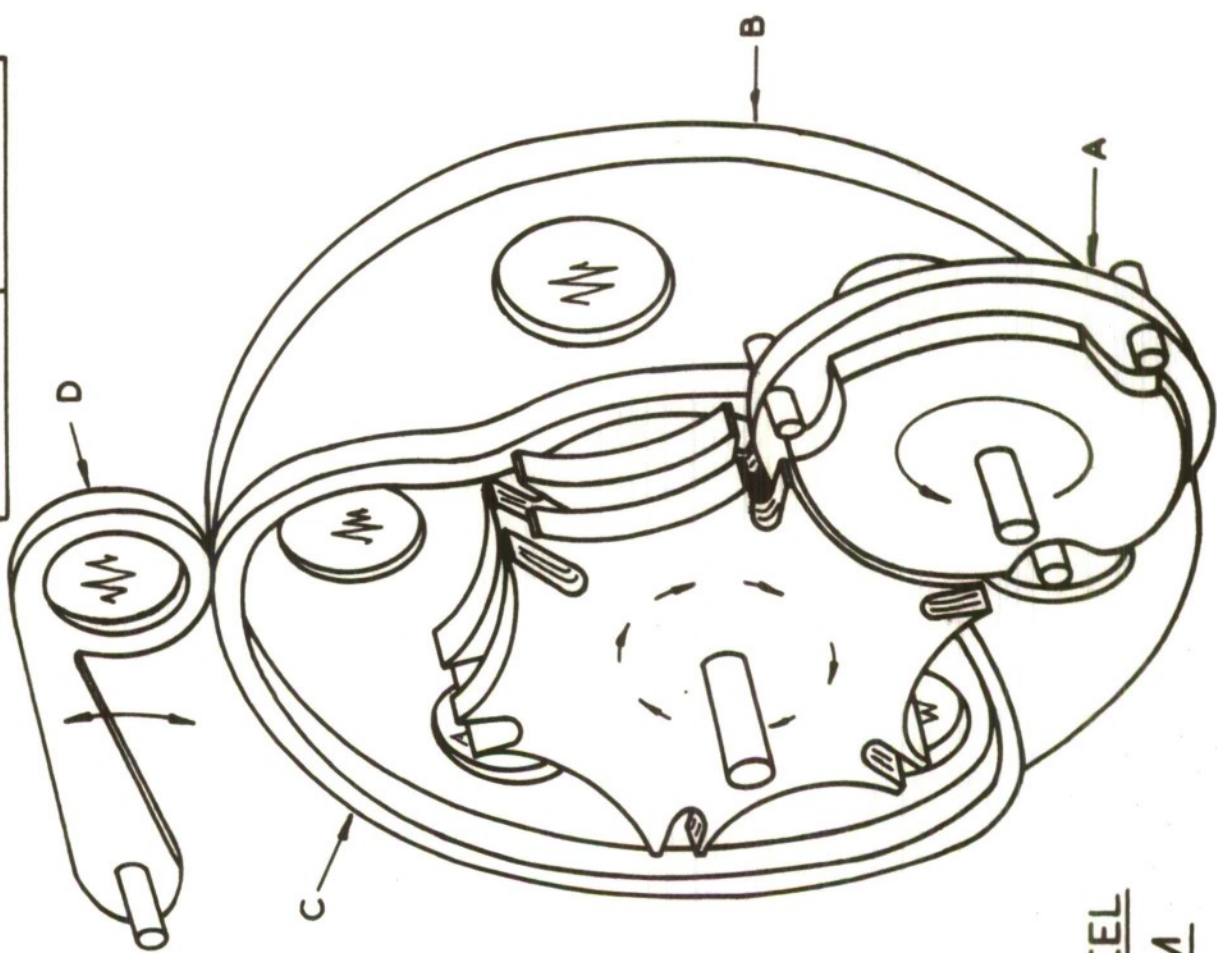


OPTICAL ARRANGEMENT OF VISIBLE
AND INFRA - RED BEAMS

FIG.6.



INFRA - RED SOURCE AND
CHOPPER
(a)



FILTER WHEEL
MECHANISM
(b)

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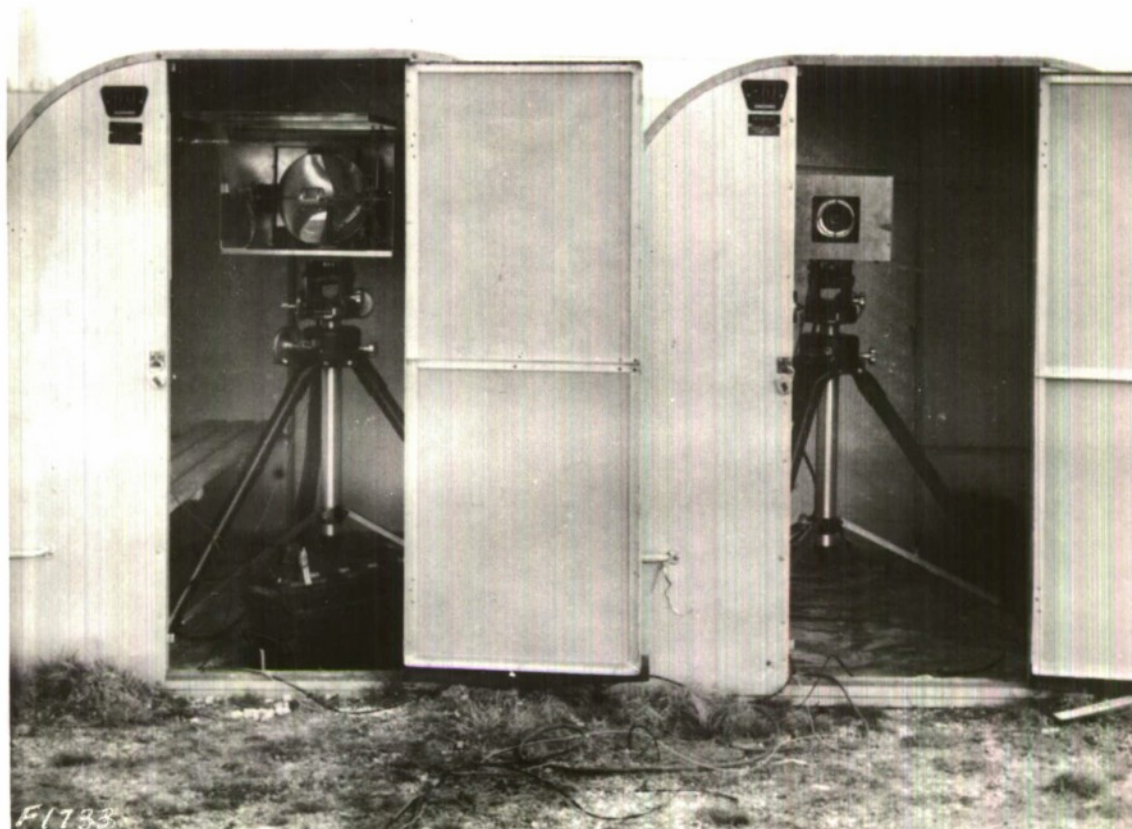


FIG 8 Infra-red (left) and visible (right) sources

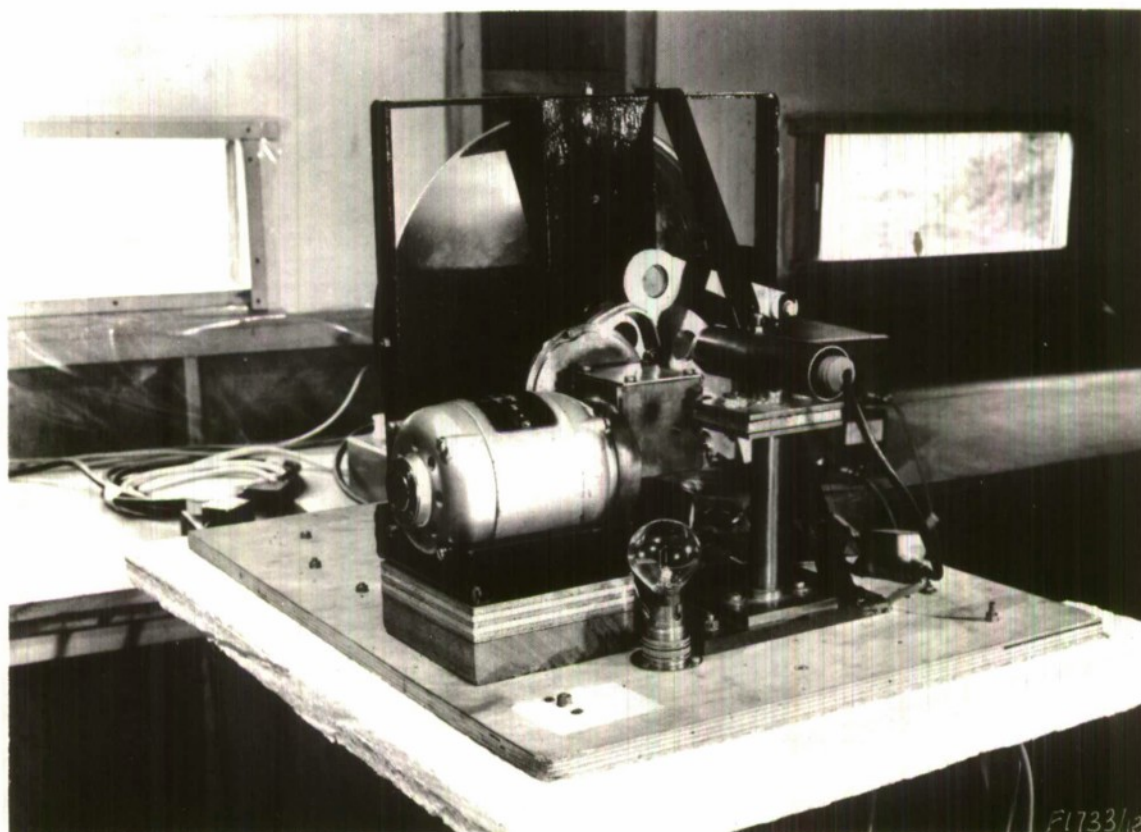


FIG 9 Infra-red detection system

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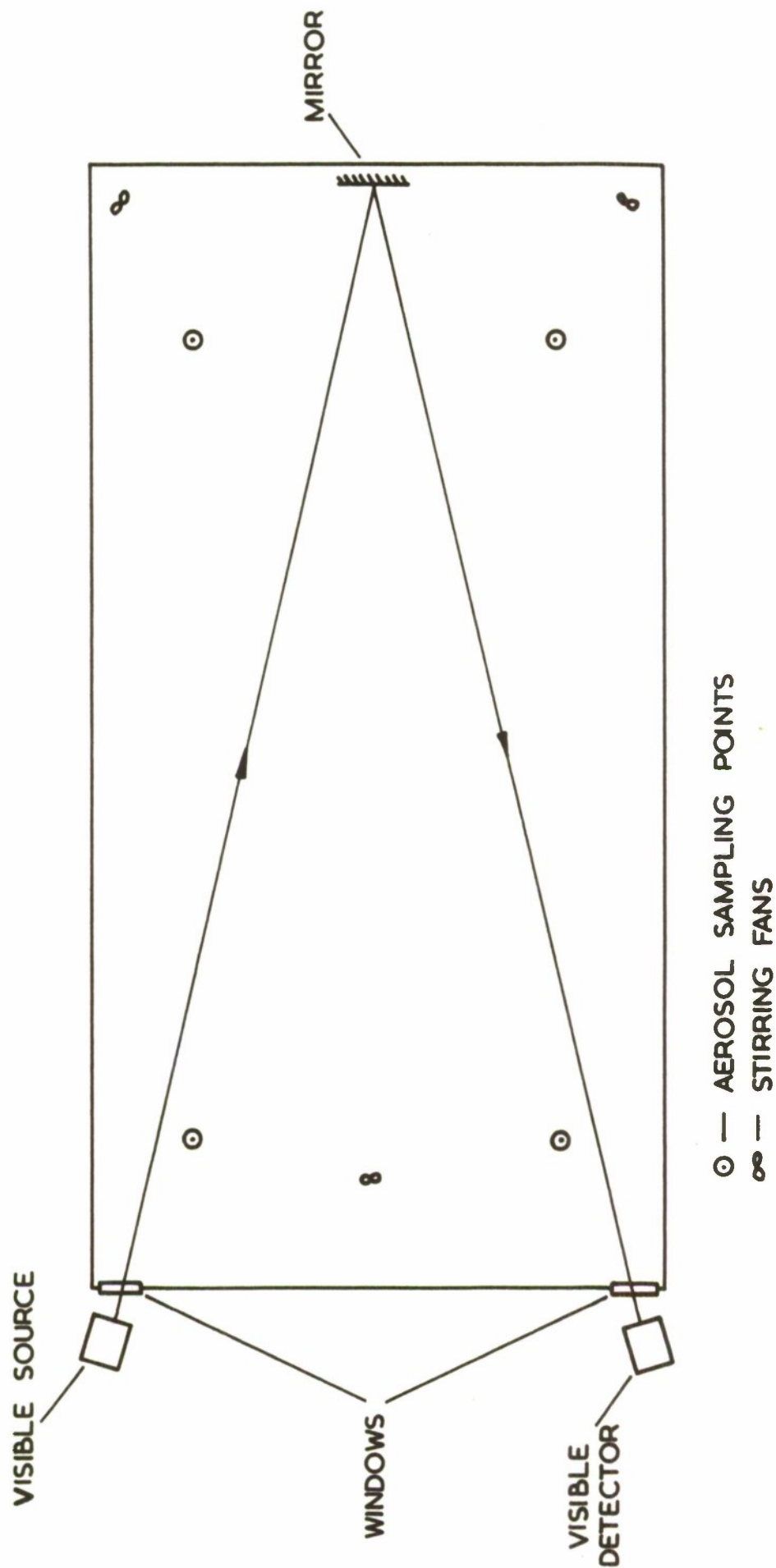
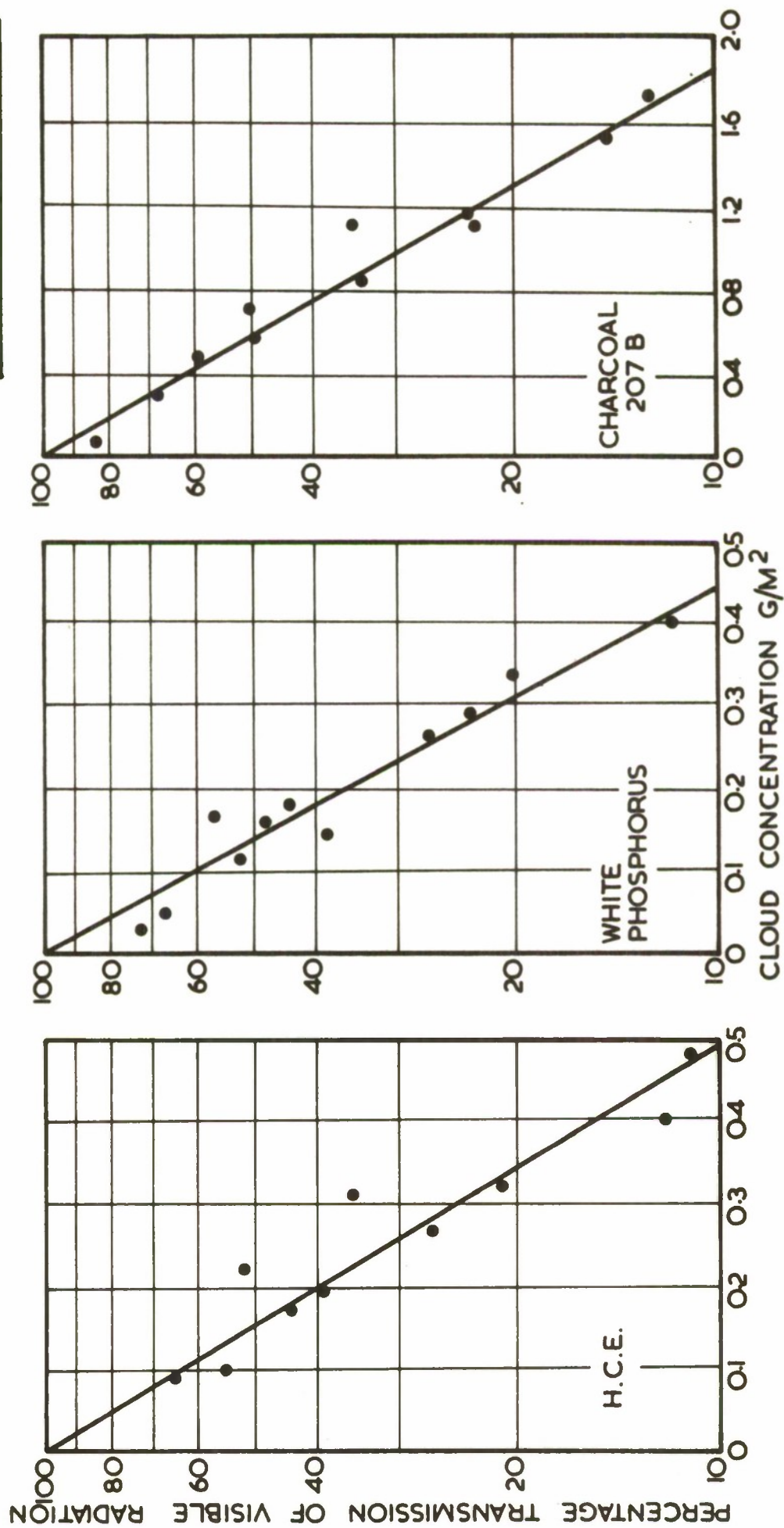


FIG.10.

DIAGRAM OF CHAMBER USED FOR MEASUREMENT OF VARIATION
OF VISIBLE TRANSMISSION WITH CLOUD CONCENTRATION



VARIATION OF TRANSMISSION OF VISIBLE RADIATION WITH CLOUD CONCENTRATION

FIG.II.

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FIG 12

Lay-out on the range

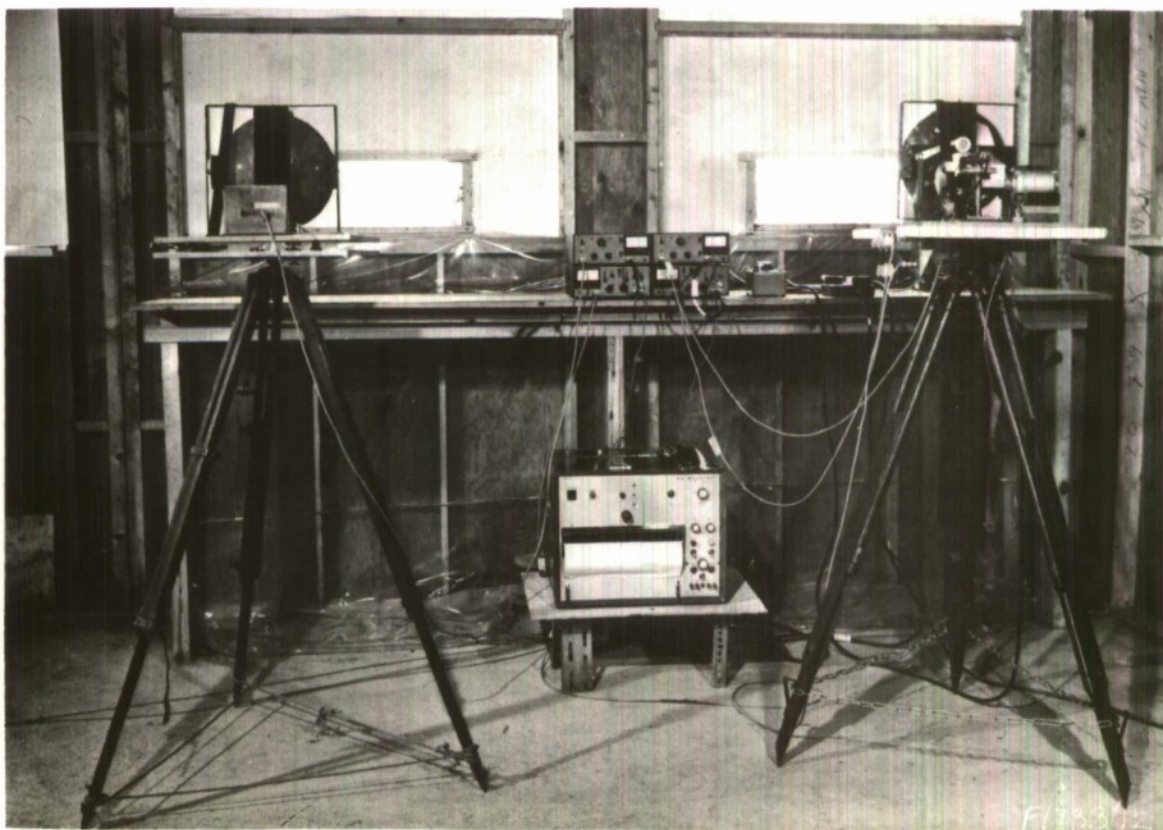
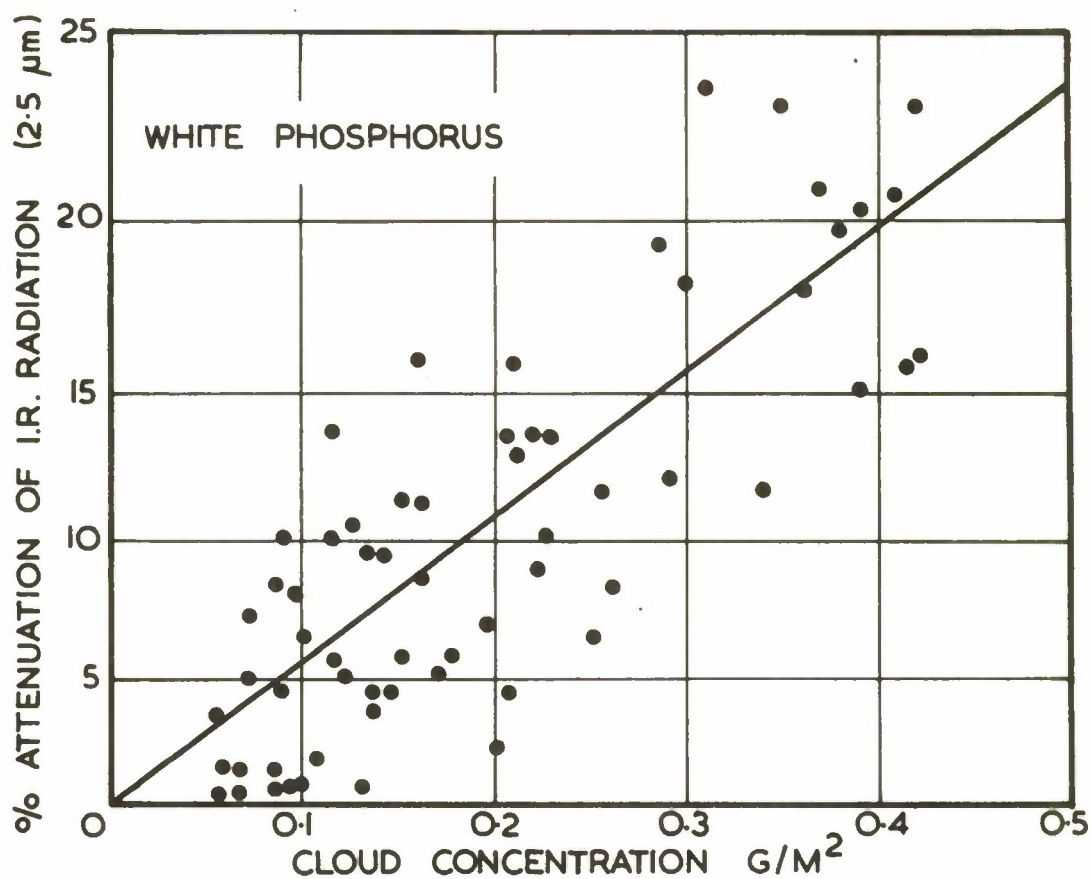


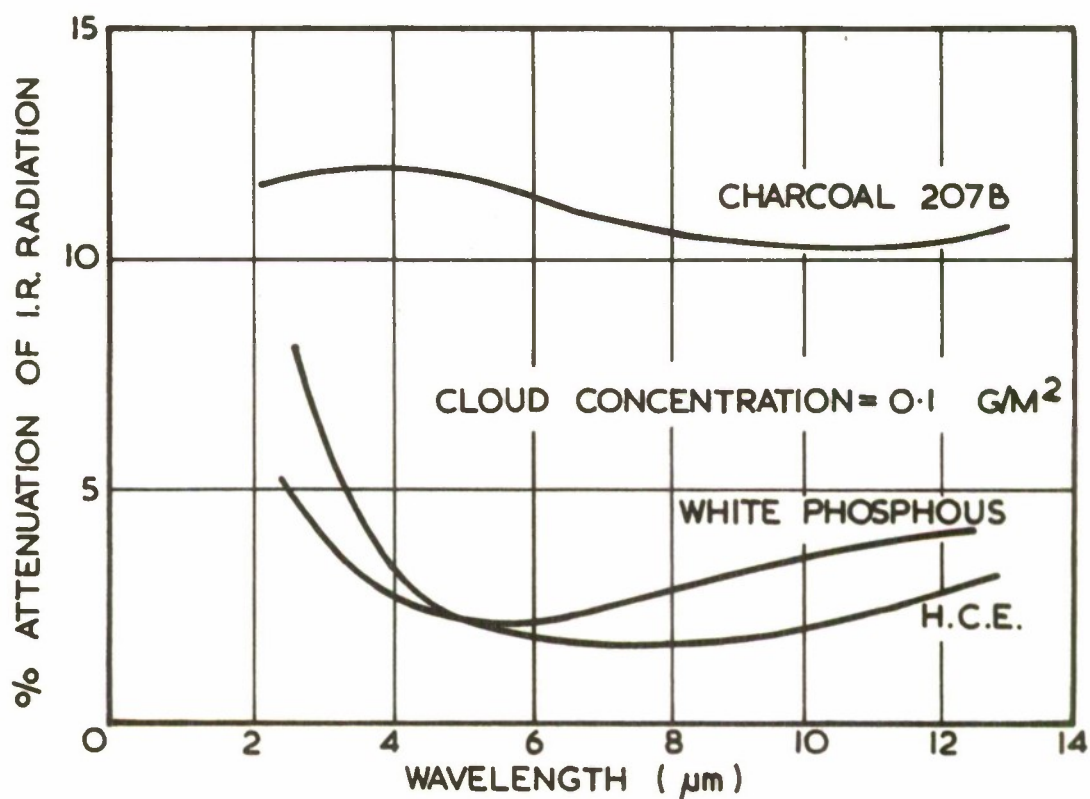
FIG 13 Visible and infra-red detectors (covers removed)

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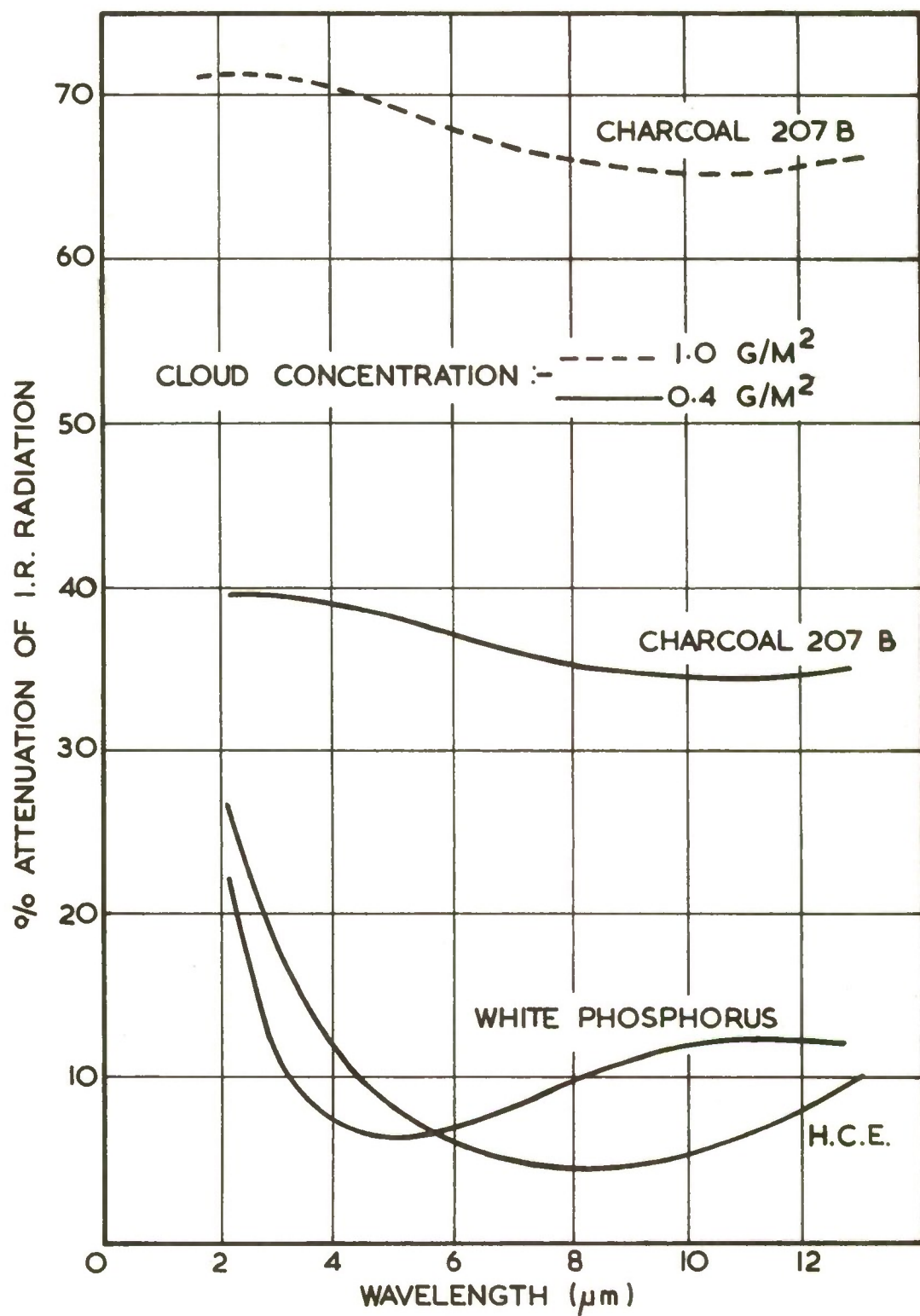
TYPICAL GRAPH OF EXPERIMENTAL RESULTS

FIG.14.



VARIATION OF ATTENUATION OF INFRA RED RADIATION WITH WAVELENGTH.

FIG.15.



VARIATION OF ATTENUATION OF INFRA-RED RADIATION
WITH WAVELENGTH

FIG. 16.

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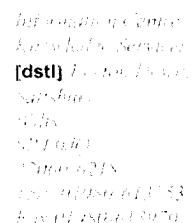
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Summary: WO 100/1014
Title: The use of absorbing smokes for the attenuation of infra-red radiation
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