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6 THE EFFECT OF DUSTS ON THE
TRANSMISSION OF INFRARED RADIATION
THROUGH THE ATMOSPHERE [u] - 8

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BY

W. L. DENNIS.

MAY 2 1955

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PORTON TECHNICAL PAPER NO. 925
DATE: 1st March, 1965.
COPY NO: 70

THE EFFECT OF DUSTS ON THE TRANSMISSION
OF INFRA-RED RADIATION THROUGH THE
ATMOSPHERE

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SUMMARY

The attenuation of a collimated beam of infra-red radiation by
dusts and aerosols of solid substances has been investigated experi-
mentally. It is concluded that atmospheric dusts are not likely to
exhibit any significant absorption bands in the wavelength range
1.5 μ to 6.0 μ which includes the region of interest in operating C.W.
alarms.

Typical dusts having a number median diameter at 1 μ were found
to attenuate a beam of radiation by about 50% at 2.0 μ and 52% at 2.2 μ
in a path containing 1g/m² (concentration x wavelength). These
figures suggest that the operation of a sensitive C.W. alarm based
on the differential absorption of infra-red radiation at two adjacent
wavelengths in the 2 μ region would be affected by the presence of
dust raised by the wind or by the passage of vehicles if the value
of the concentration-pathlength product were in excess of 100 mg/m².

(Sgd.) W. R. Lane,
Superintendent,
Physics Research Division.

(Sgd.) A. S. G. Hill,
Deputy Director.

WLD/AH

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THE EFFECT OF DUSTS ON THE TRANSMISSION
OF INFRA-RED RADIATION THROUGH THE
ATMOSPHERE

by

W. L. Dennis

INTRODUCTION

Studies are being made of an early warning C.W. detection system based on the absorption of infra-red radiation by the vapour of an agent. If the radiation travels over a long path, say 400 m. and the transmission at a wavelength at which the vapour is known to absorb is compared with that at an adjacent wavelength showing no absorption, the presence of the vapour can be monitored. If several wavelengths are used it might be possible to identify one of a few known agents.

Thomas (1) has concluded that the best region of the spectrum to use is that between 1 and 2.5μ since, although the absorption is lower in this band than in the region around 10μ , the difficulties encountered by U.S. workers from atmospheric shimmer could be eliminated by the use of higher chopping frequencies attainable with photoconductive detectors, whose maximum sensitivity is in the near infra-red. Thomas has also drawn attention to the greater source energy available in this region. He has established (2) that GB, GD and VX have absorption bands of usable intensity at 2.25μ , i.e. in an atmospheric window where there is believed to be no significant absorption by the water vapour or carbon dioxide in the atmosphere.

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He estimated that if a difference of one part on 10^6 between the intensities of the two beams of infra-red radiation of different wavelengths could be detected, then a local alarm could be constructed which would respond to a concentration of 0.1 mg/m^3 in a path length of 10 metres. If however for a long path detector the distance were increased to 400 m and it is required to detect a concentration of 1 mg/m^3 , then the required discrimination would be 4 parts in 10^4 .

If such an alarm is to be developed it is essential to know to what extent atmospheric pollutants might interfere to give false alarms. The major air contaminants normally encountered are fogs, pollen, natural dust, smoke, industrial dust, sulphur oxides and vapours in varying proportions. The concentration of suspended particulate matter varies from about 0.01 mg/m^3 to as high as 1 or 2 mg/m^3 in cities. In industrial areas it is about 0.5 mg/m^3 (3). If the particle size is assumed to be 0.5μ , the amount of material required to obscure an object from an observer in daylight is about 500 mg/m^2 (concentration x path length) (4). A visual range of 3 miles would therefore correspond to a concentration of 0.1 mg/m^3 of pollutant in the atmosphere and there would be about 1600 particles per cm^3 , assuming unit density.

The high absorption of infra-red radiation by the water vapour and carbon dioxide of the atmosphere, except in the relatively narrow "windows", makes direct experimental measurement of the effect of solid pollutants difficult. Dennis (5) attempted to surmount this difficulty by collecting the pollutant on millipore filters and then, after transferring the deposits to sodium chloride discs, determining their transmissions. The samples were taken over periods of about six hours and, assuming single scattering only, the attenuation by a deposit was equivalent to that of the pollutants dispersed over a path length of about 10 miles. The results were expressed in such a way that, knowing the visual range, one could obtain an estimate of the concentration of pollutant present and hence calculate the amount in the required path. From a series of graphs one could then determine the transmissions at a number of wavelengths.

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Some of the most reliable experimental data on atmospheric transmission in the infra-red are those published by Gebbie and others (6). They assumed that the scattering was due to salt nuclei and explained their results on the basis of the change in size and refractive index of the droplets with humidity.

For purposes of computing transmissions through the atmosphere, workers in the U.S.A. have adopted a Standard Atmosphere (7) and Elterman (8) has augmented this by an aerosol component which yields a visual range of about 25 km. He has tabulated the aerosol number density against altitude and the aerosol attenuation coefficient against wavelength. At zero altitude the number density is 215 cm^{-3} and the attenuation coefficient 0.085 km^{-1} at a wavelength of 2.17μ . The tabulations may be used to calculate the horizontal, vertical or slant path transmissions from sea level or the transmission between two altitudes in the infra-red windows.

Curcio, Knestrick and Cosden (9) computed the accumulative attenuation for the particle diameter range 0.02 to 40μ for three wavelengths 0.535μ , 1μ and 5μ and refractive indices of 1.33 and 1.5 , covering an aerosol of diverse composition. They repeated this for several different particle size distributions, assuming pure scattering in all cases.

Previous experiments (10) have shown that aerosols of substances of low vapour pressure, such as stearic acid, paraffin wax and fog oil behave as almost pure scatterers and the attenuation produced by them is a function of their physical rather than their chemical properties. If the cloud is monodispersed the attenuation at a certain wavelength is a function of the concentration, particle size and refractive index. The effective scattering area per unit mass of material shows a maximum when the particle diameter is approximately equal to the wavelength. This maximum value decreases and becomes less pronounced for larger particle sizes (10).

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The investigations referred to above apply to what one might call general atmospheric pollution, that is pollution occurring over comparatively large areas, and from data given it is possible to obtain an estimate of the probable attenuation in the infra-red region over a given path length under given meteorological conditions. In considering the feasibility of a C.W. alarm based upon the principle of the variation in the transmission of infra-red radiation one must consider the possibility of more intense local pollution occurring in the optical path of the instrument. This might for instance occur as a dust cloud raised by moving vehicles. The present work was undertaken with a view to obtaining an estimate of the attenuation likely to be produced under such conditions and to obtain, at the same time, additional basic information on scattering and absorption of infra-red radiation by aerosols.

APPARATUS

The apparatus employed was basically similar to that used in a previous study (11). It consisted of four essential parts, the aerosol generator, the chamber having the long optical path, the spectrometer and the recording system.

The aerosol cloud was dispersed either by an atomiser spray, if a liquid or solution, or by the Wright dust feed mechanism (12) if a powder. In the latter device the powder was compressed in a metal cylinder and a rotating cutter, which advanced slowly into the cylinder, ~~and~~ pared off the surface at a fixed rate. This powder was removed and dispersed by a stream of air through the apparatus, any aggregates being broken up by impingement on a surface near the outlet. From the dispenser the aerosol passed through a 10 litre aspirator jar to ensure good mixing before entering the chamber having the long optical path. The dust feed mechanism was in all experiments operated at 4 lb/in² pressure, which produced an air flow rate of approximately 14 l/min. The powders were silicone-coated to make them more readily dispersible.

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It was established by independent experiments that this treatment did not significantly affect the optical properties of the particles. As a complete experiment took about $1\frac{1}{2}$ hours, a continuous flow of aerosol of constant concentration was essential to avoid errors due to sedimentation.

The chamber is shown diagrammatically in Fig. 1. It consisted of a wooden box 154 x 40 x 24 cm, blackened on the inside and having a hinged top giving easy access for adjustment and cleaning. The infra-red radiation from a Nernst filament was focussed through one of the sodium chloride end windows on to the long focal length mirror at the opposite end of the chamber. It was then reflected back again through the length of the chamber and passed through the other window to the spectrometer, this arrangement providing a path length of 270 cm. By means of partitions at either end, clean air was made to flow over the windows and mirror to prevent deposition of particles on to them. A small fan ensured good mixing in the chamber. The inlet and outlet for the aerosol were at opposite ends of the chamber. The optical density of the cloud could be monitored by a simple nephelometer arrangement in the chamber, consisting of a lamp housing at one end producing a parallel beam of light falling on to a photocell at the other end, the photocell current being indicated by a microammeter.

The spectrometer used has already been described in a previous report (11). It was a double monochromator employing a sodium chloride prism and a diffraction grating. A Golay pneumatic infra-red detector was incorporated, the output from which was proportional to the intensity of the radiation. The spectrometer covered the wavelength range of approximately 1.5μ to 10μ . In the present study the cams were driven by a synchronous motor through a gear box to provide four different times to scan the wavelength range. In most experiments in this investigation this time was about 25 minutes.

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The output from the Golay detector amplifier was connected to a recording milliammeter which produced a spectrogram of radiation intensity against wavelength on a 6 inch chart. To determine the transmission of an aerosol it was necessary to make two runs, one being a blank and the other with the cloud in the chamber. The transmission at a given wavelength was determined from the ratio of corresponding ordinates on the two charts. In previous investigations, on account of the complexity of the water vapour and carbon dioxide absorption bands, the spectrograms had been divided into 0.5μ intervals and the transmission at the mean wavelengths determined by measuring the areas under the two curves with a planimeter. This was a long and tedious process which in the present work was eliminated. A 10 ohm resistance was inserted in one of the leads to a 3000 ohm recording milliammeter and the voltage drop across it was applied to the input of a D.C. amplifier, the output being used to drive a D.C. low inertia integrating motor (Fig. 2). The speed of this motor was then proportional to the current through the milliammeter and hence also to the intensity of the radiation passing through the spectrometer. Since the diffraction grating was rotated at a uniform rate, thus producing a linear wavelength scale on the spectrogram, the number of revolutions made by the integrating motor in a given time was proportional to the area under the spectrogram during the same time. The number of revolutions made by the motor was counted and printed on tape at intervals by a printing impulse counter (Sodaco. Type IT pb 3). A contact on one of the rotating shafts of the spectrometer gearbox, operated a relay to send a pulse to the printing circuit at equal time intervals, corresponding to 0.25μ or 0.5μ wavelength intervals on the spectrogram. Another relay connected to the same contact, simultaneously operated a marker on the chart to show the points at which the number counts had been printed out on the tape.

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Thus, during any run with the spectrometer the recording millimeter traced a spectrogram in which the deflection was proportional to the intensity of the radiation passing through the instrument, and the printing impulse counter at the same time printed on tape a series of numbers proportional to the integrated transmission at 0.5μ intervals throughout the wavelength range. If two runs were made, one being a blank and the other with the aerosol in the chamber, the mean percentage transmissions for each wavelength interval could be easily calculated.

As a check on the recording system, experiments were carried out in which the percentage transmission was calculated from the planimetered areas on the spectrogram and then compared with those calculated from the corresponding numbers recorded by the impulse counter. A typical set of results is given in Table I for an aerosol whose concentration was low and which therefore produced only a small attenuation of the radiation. The agreement was considered satisfactory. It is probable that the results obtained from the impulse counter were the more accurate.

EXPERIMENTAL PROCEDURE

The first experiments were carried out using simple inorganic substances which were readily available as powders of suitable particle size range and could be easily dispersed as particulate clouds. They were in most cases substances which might occur naturally, or were included because of some similarity in chemical composition (e.g. oxides, carbonates, magnesium compounds). In later experiments the dusts used were obtained by pulverising samples of soil and rocks in a ball mill until of sufficiently small particle size and then, as mentioned above, treating them with a small amount of silicone fluid MS.1107.

Preliminary calculations, and experimental observations of the optical density when an aerosol was passed through the chamber at the fixed flow rate used in most experiments, showed that a period of about 25 minutes was required for the concentration to attain 98% of its maximum value. This concentration was controlled mainly by the speed of the Wright dust feed mechanism.

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The blank run completed, the aerosol was passed into the chamber for 25 minutes and then another run was made to determine the transmission through the cloud. In some cases, where considered necessary, another blank run was made at the end of the experiment to ensure that it was unchanged. This was a check on the constancy of the amplification of the Golay detector and also that no deposition had taken place on the windows or mirrors. The optical density of the cloud in the chamber was monitored with the nephelometer. Five experiments were carried out with each material and the mean value of the transmissions calculated, these being corrected to a path length of 1 metre and a concentration of 1g/m^3 . [The transmission would of course be the same for any path length for which path length (metres) x concentration (g/m^3) = 1 g/m^2].

RESULTS AND DISCUSSION

The results are shown in figs. 3 to 9. It will be observed that the transmissions of all the materials used are of the same order in the wavelength range 1.5μ to 6μ , varying by not more than a factor of about two. In this region no absorption bands were found in a number of substances likely to occur as common dusts, although at longer wavelengths most of the substances show marked absorption bands either at about 7μ or at 9 to 10μ . The bands at about 7μ are due to the presence of carbonates; Calopake for example is a precipitated calcitic calcium carbonate. The bands found at 9 to 10μ are characteristic of silicon compounds such as sand, shale and sandstone. Clay showed both absorption bands.

All the dusts used had a number median diameter between 0.6μ and 1.4μ (Table II) and the slopes of all the size distribution curves were similar. It has been emphasised previously (10) that the attenuation by an aerosol depends critically upon the particle size distribution. This is illustrated here in the case of the two samples of Calopake. The sample F has the larger particle size and shows a higher attenuation in the 1 to 4μ region of the spectrum. At longer wavelengths the difference is not so marked except at the absorption band.

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The spectrograms from the Salisbury and Porton dusts are generally similar; any difference between them is probably due partly to slightly different particle size distributions and only partly due to a variation in the chemical composition. The Porton soil was more chalky but apparently not sufficiently so to show the carbonate absorption band.

For comparison purposes, spectra of a few of the substances were also determined by the Chemical Research Division by the conventional alkali halide disc technique. Three of these are shown in figs. 10, 11 and 12. If one compares for example figs. 6 and 10 for sand, although they both indicate minimum transmission at the same wavelength, the curve of fig. 6 shows a much narrower band. From figs. 4 and 11 it will be noticed that the alkali halide disc method shows the finer structure of the absorption band of magnesium carbonate which is probably missed by the aerosol method or the lower resolution of the instrument used. These differences are to be expected since the disc method yields a measure of the absorption by the substance in a compressed state while the present method determines the attenuation brought about by particles of the aerosol and this is due mainly to scattering and only partly to true absorption.

It is interesting to note that calcium carbonate and quartz both show the phenomenon of "reststrahlen" (13) i.e., they show high reflection at wavelengths of 6.7μ and 9μ respectively and these are the wavelengths at which apparent absorption occurred with the calopake and sand. The present study does not distinguish between true absorption and scattering but measures the overall transmission. It is possible that the method proposed by Wootten (14) to measure the true absorption by an aerosol might help to clarify this anomaly.

The main practical objective of the present work was to provide experimental data upon which to base an assessment of the probability of interference by airborne dust with reliable operation of an automatic C.W. alarm based on infra-red absorption. One important and reassuring feature of the results is the absence of any marked absorption bands in the region 1.5μ to 6μ in any of the dusts examined, so it seems rather unlikely that serious difficulties due to such bands would arise in practice.

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The variation in the attenuation with wavelength seen in the case of all the dusts tested, however, raises the question of the effect of airborne dust on the transmission at the two adjacent wavelengths (agent and reference) employed in a detection system based on differential infra-red absorption.

It will be seen from the graphs in Figs. 6 and 7 that for a CL (concentration x path length) value of 1 g/m^2 the transmission through a dust at 2μ is approximately 50% whilst at 2.2μ it is 52%. Using these figures a simple calculation shows that the transmission through an atmosphere containing 0.08 mg/m^3 dust (corresponding to a visual range of 6 miles) over a path length of 400 metres (CL = 32 mg/m^2) would be about 97.8% at 2.0μ , but there would be a difference of approximately $1.2 \text{ in } 10^4$ in the transmissions at 2.0 and 2.2μ respectively. This figure of $1.2 \text{ in } 10^4$ should be compared with the discrimination of $4 \text{ in } 10^4$ quoted above for a detection system having this path length.

CONCLUSION

It is concluded that an alarm based on the differential absorption at two adjacent wavelengths in the 2μ region which operated over a path length of 400 metres with a wavelength discrimination of 1 in 2,500 would be affected by a dust cloud if the concentration path length product exceeded about 100 mg/m^2 . This product could be readily attained if the dust were raised by the wind or the passage of vehicles.

ACKNOWLEDGEMENTS

Mr. R. Poynting assisted with the experimental work and carried out most of the computations.

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Physics Research Division.

(Sgd.) A. S. G. Hill,
Deputy Director.

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Table I

Wavelength (μ)	Percentage Transmission	
	Planimeter	Integrator
1.31	73.5	71.5
1.79	73.5	72.5
2.28	79.5	76.5
2.78	82.0	81.5
3.27	85.5	87.0
3.76	88.0	86.0
4.25	85.0	87.5
4.74	90.0	91.0
5.24	94.0	95.5
5.73	94.0	95.0
6.22	95.5	96.5
6.70	83.0	82.0
7.19	84.0	83.0
7.69	90.0	90.5
8.18	94.0	94.5
8.67	95.5	95.0
9.16	96.0	95.5
9.65	97.0	96.0
10.15	96.5	98.0

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Table II

Material	Distribution by number		
	10%	50%	90%
		(μ)	
Calopake H	0.55	0.79	1.35
Calopake F	0.63	1.15	2.80
Sodium chloride	0.51	0.69	1.02
Magnesium sulphate	0.56	0.95	1.95
Magnesium carbonate	0.62	1.00	2.10
Magnesium oxide	0.60	0.92	1.75
Talc ($3\text{MgO} \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$)	0.91	1.61	2.99
Manganese dioxide	0.63	0.97	2.50
Sand	0.59	0.89	1.63
Clay	0.58	1.00	2.02
Shale	0.75	1.30	3.72
Sandstone	0.86	1.36	2.45
Granite	0.60	0.95	2.03
Porton dust	0.56	0.85	1.46
Salisbury dust	0.58	0.87	1.65

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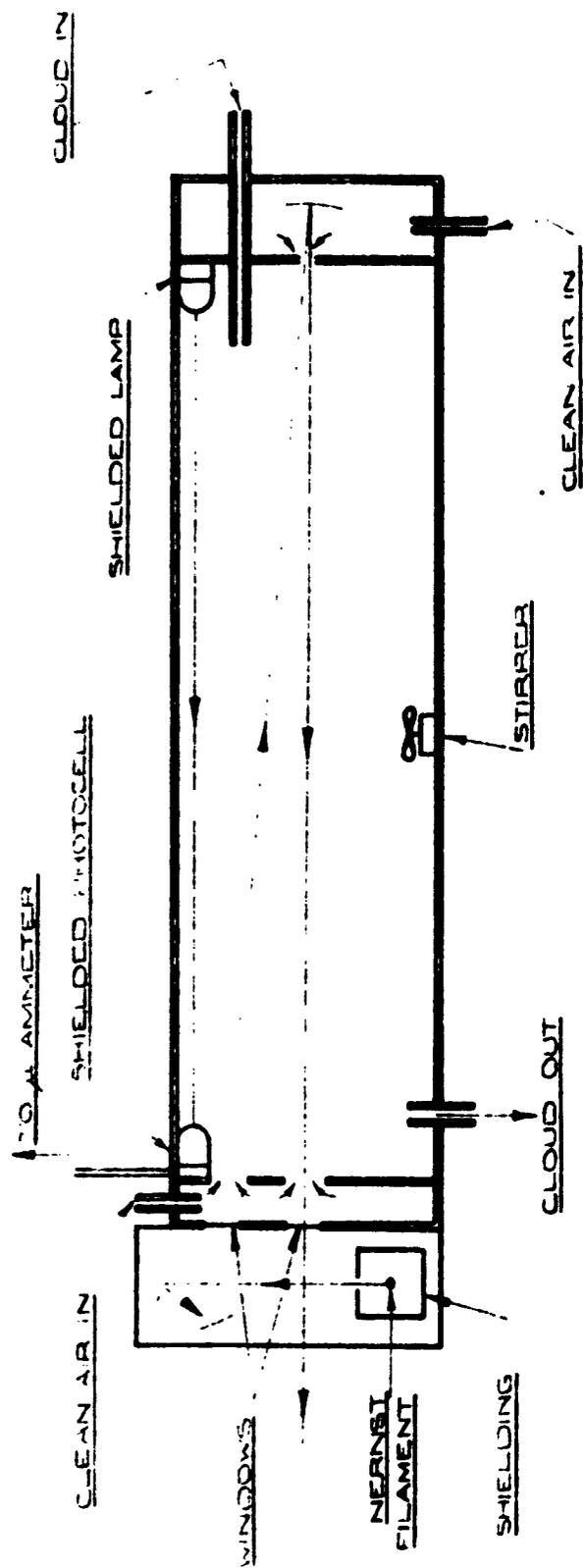


FIG. 1.

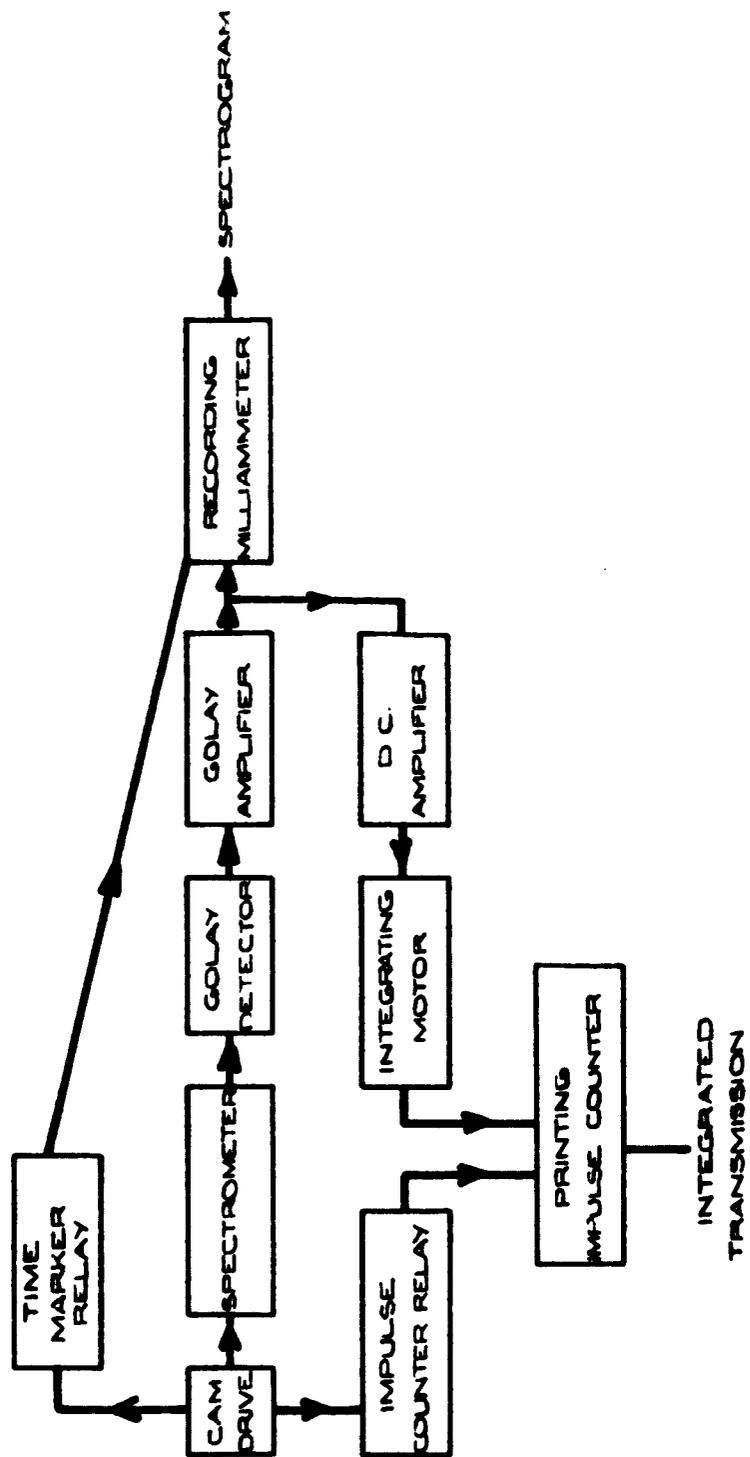


FIG. 2

- CALOPAKE 'H'
- × CALOPAKE 'F'
- SODIUM CHLORIDE

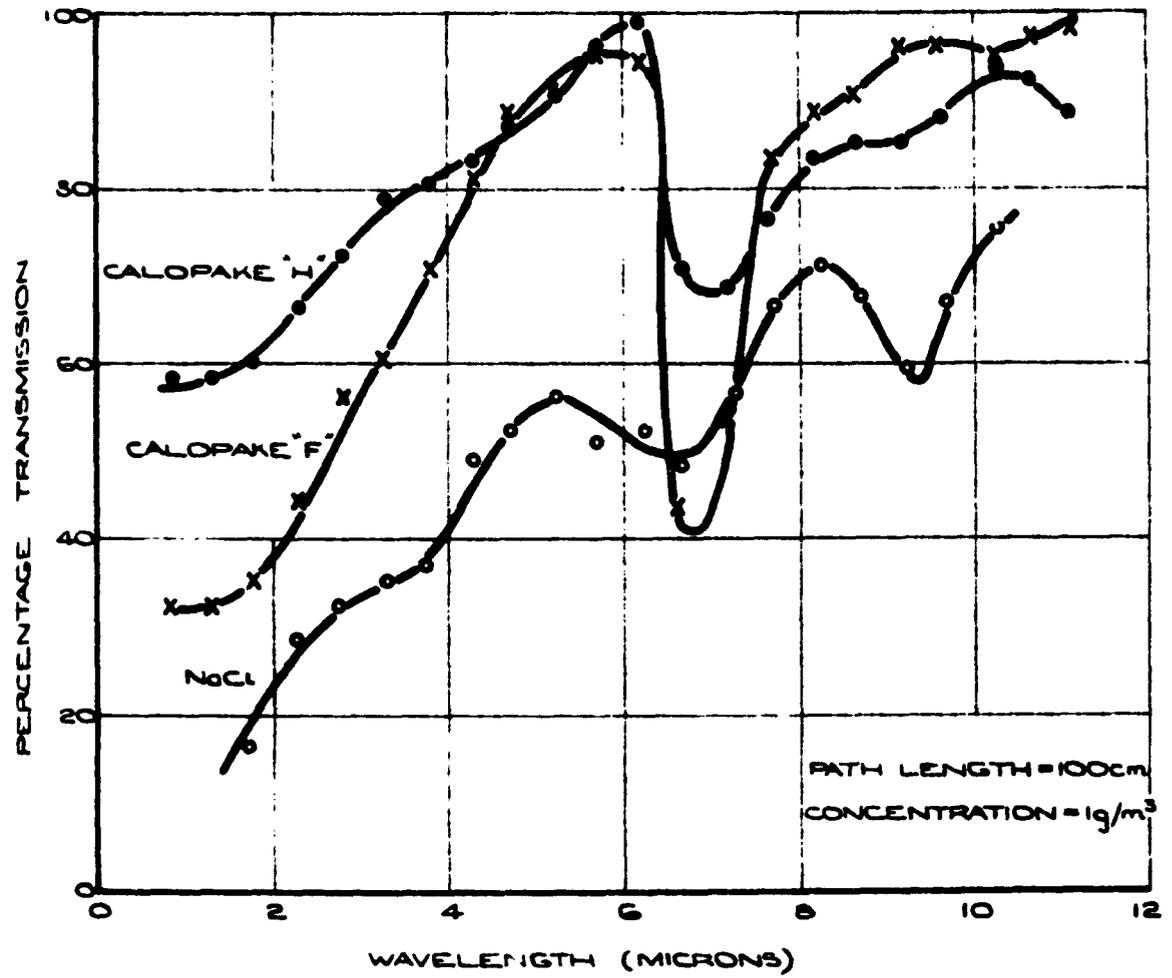


FIG. 3

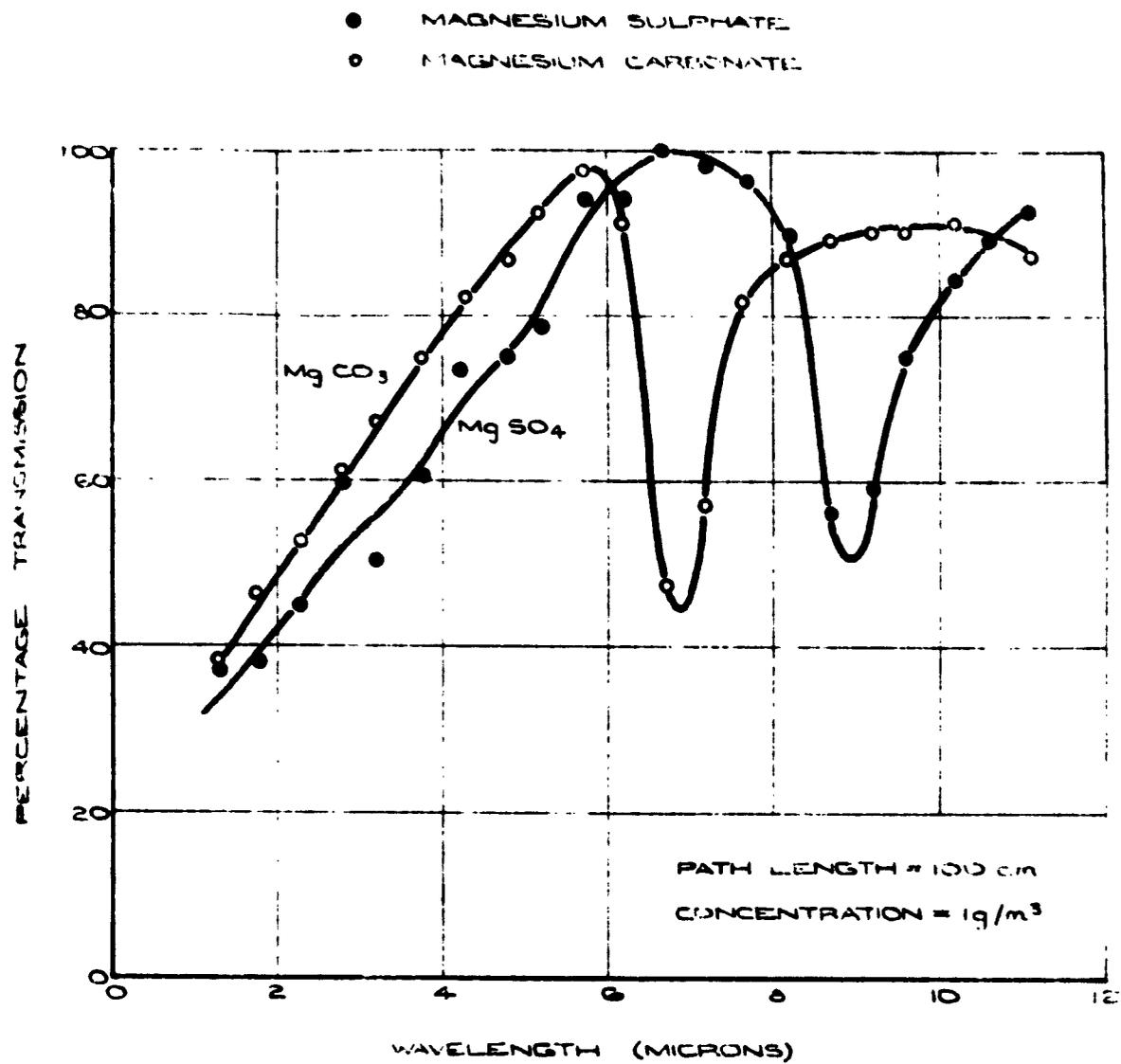


FIG. 4

- MAGNESIUM OXIDE
- X TALC $3\text{MgO}, 4\text{SiO}_2, \text{H}_2\text{O}$
- MANGANESE DIOXIDE

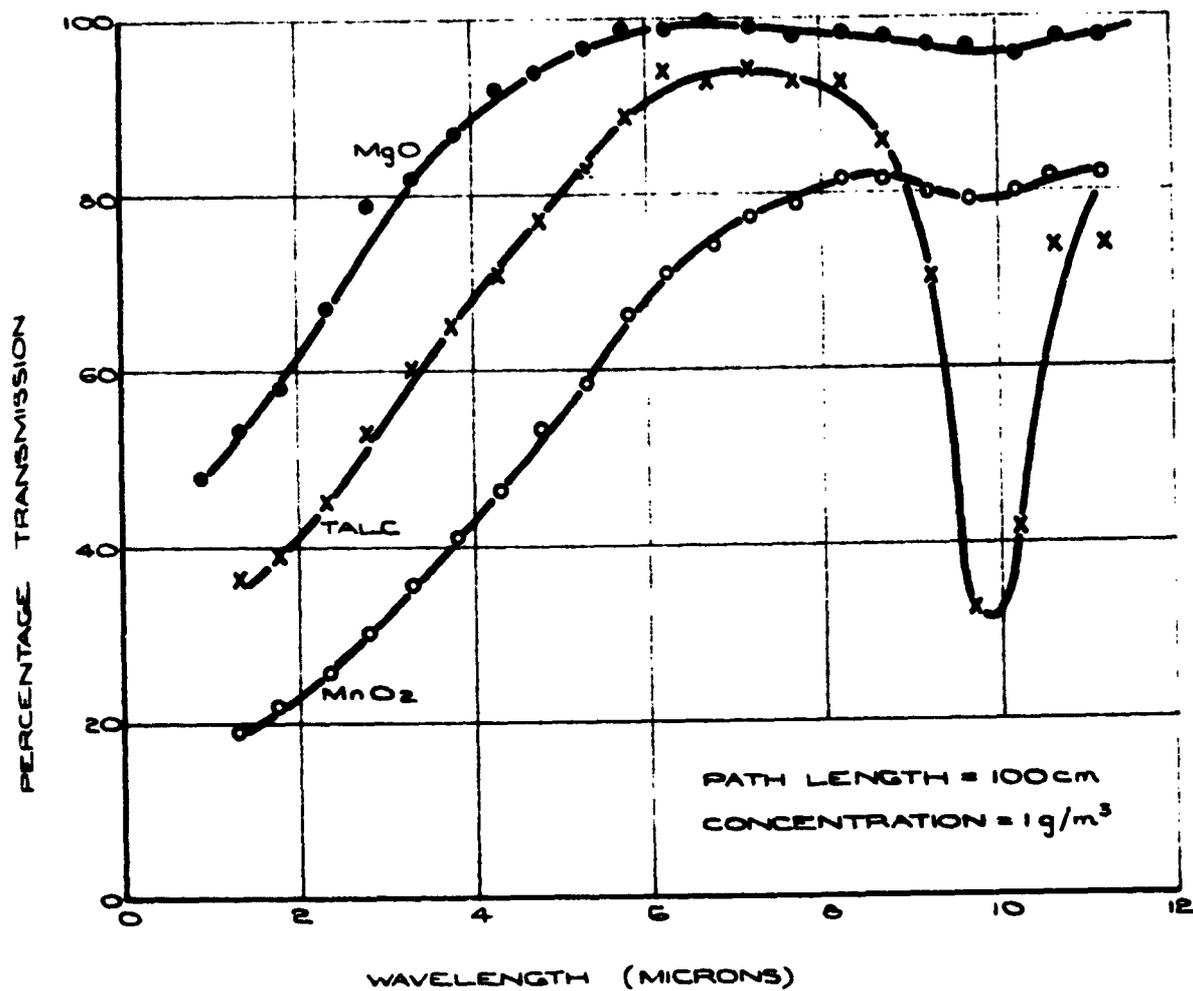


FIG. 5

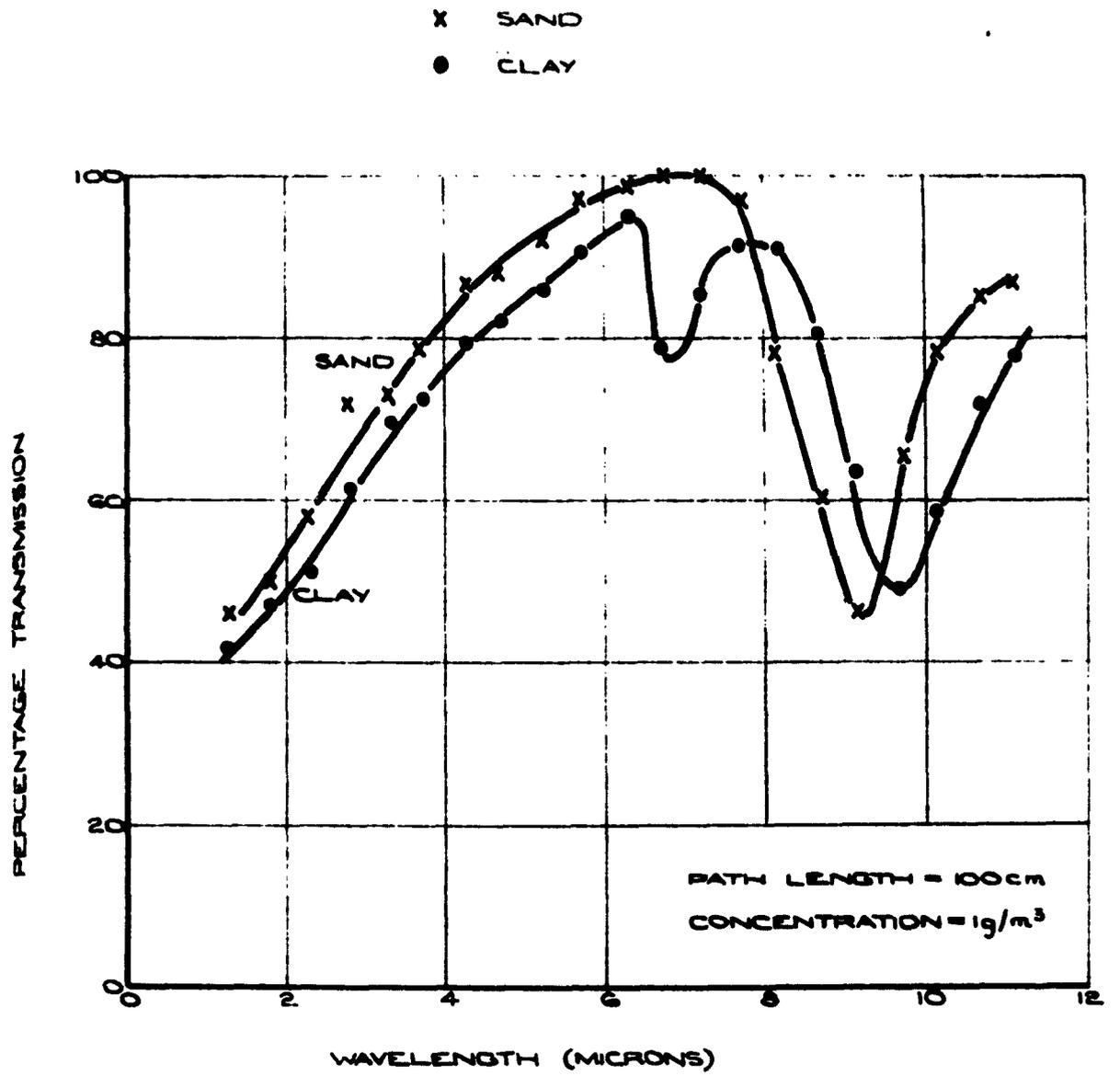


FIG. 6

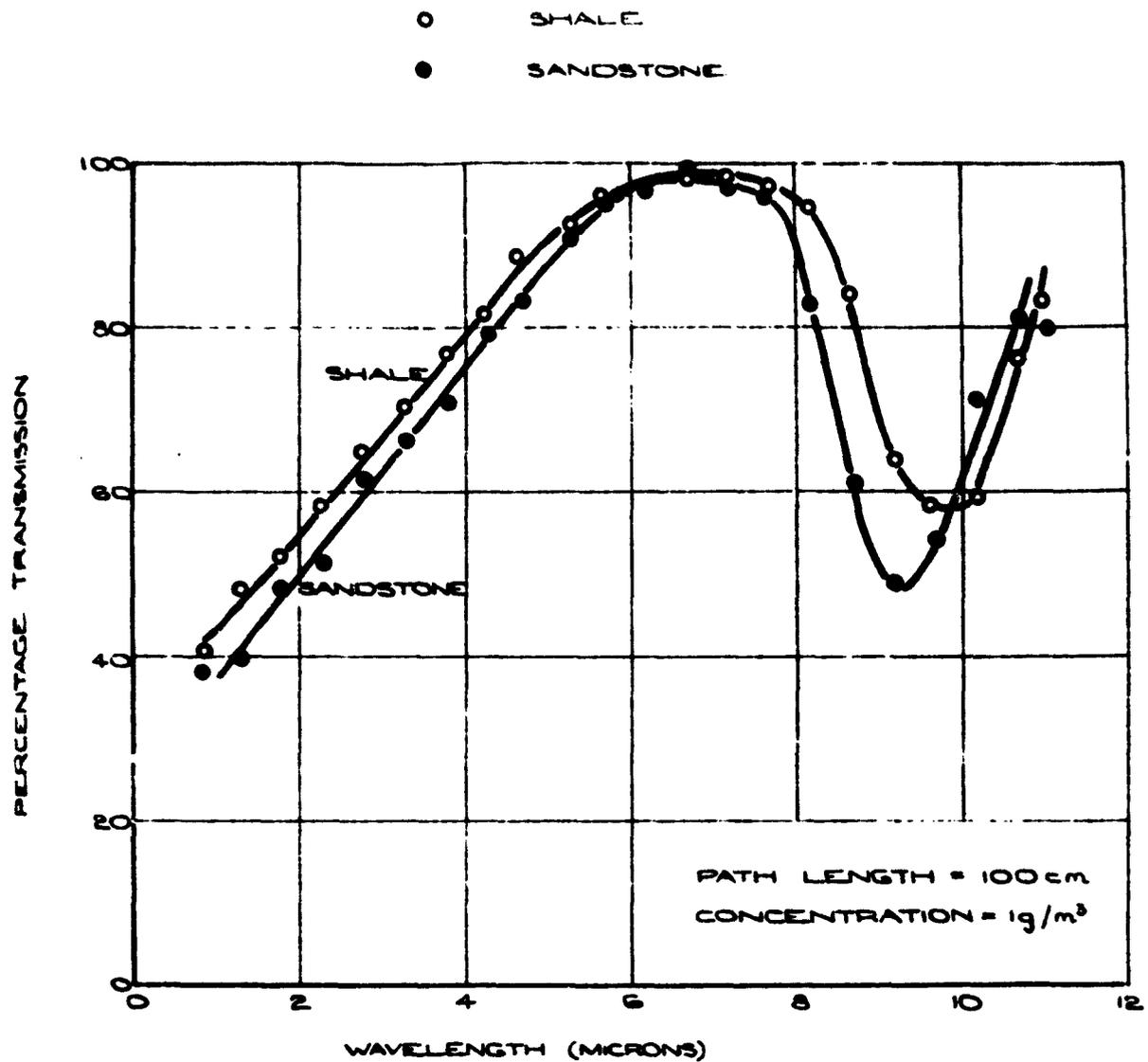


FIG. 7

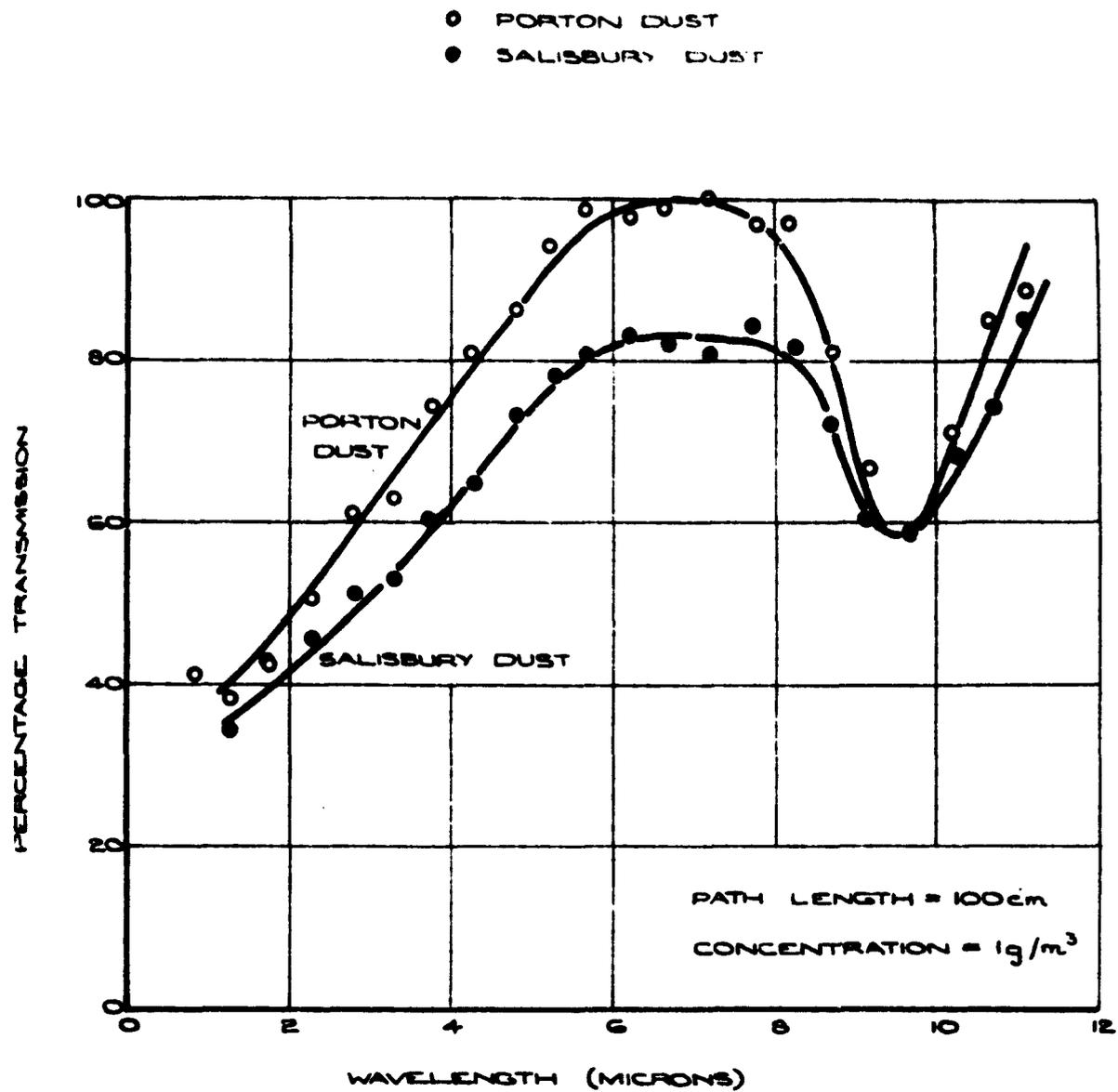


FIG. 8

GRANITE

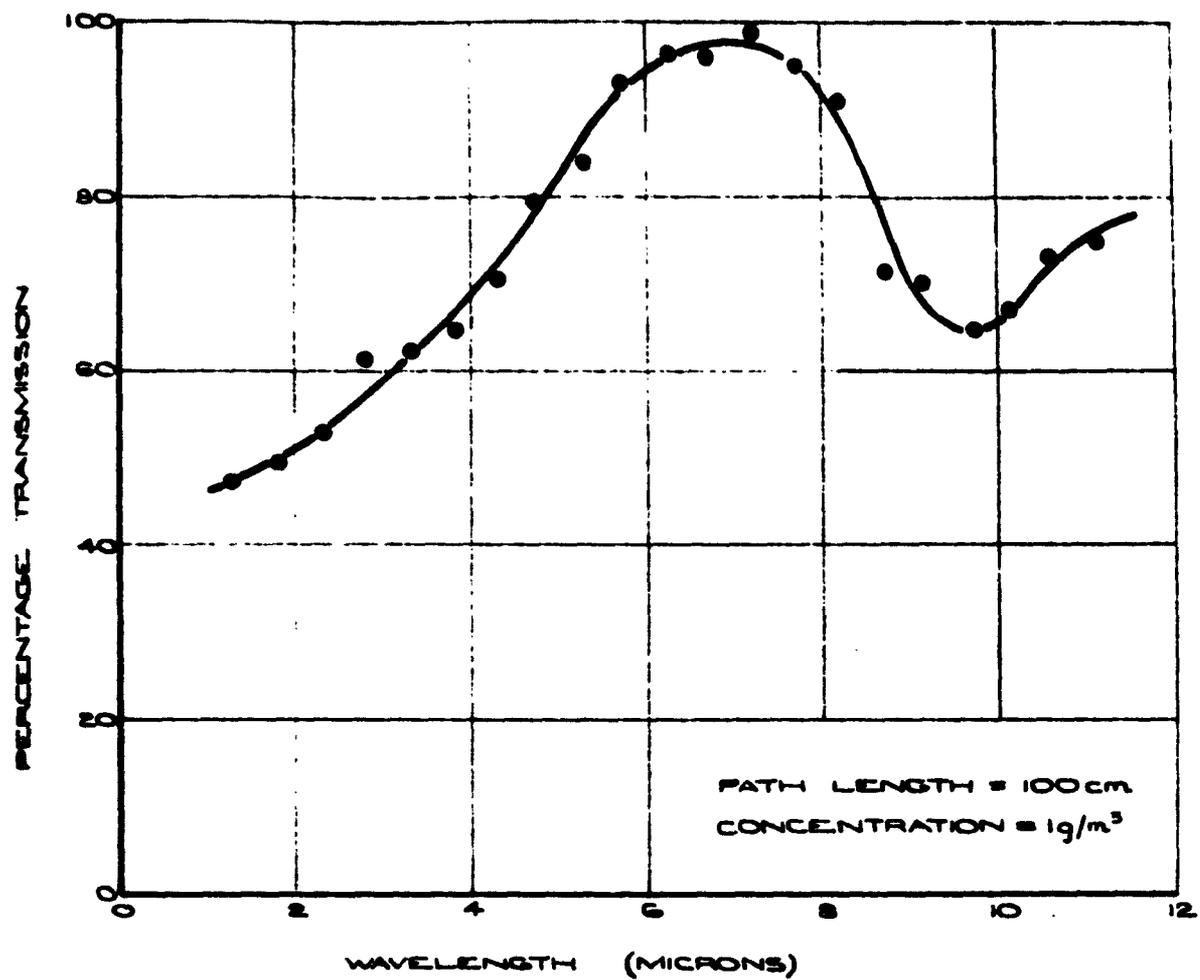


FIG. 9.

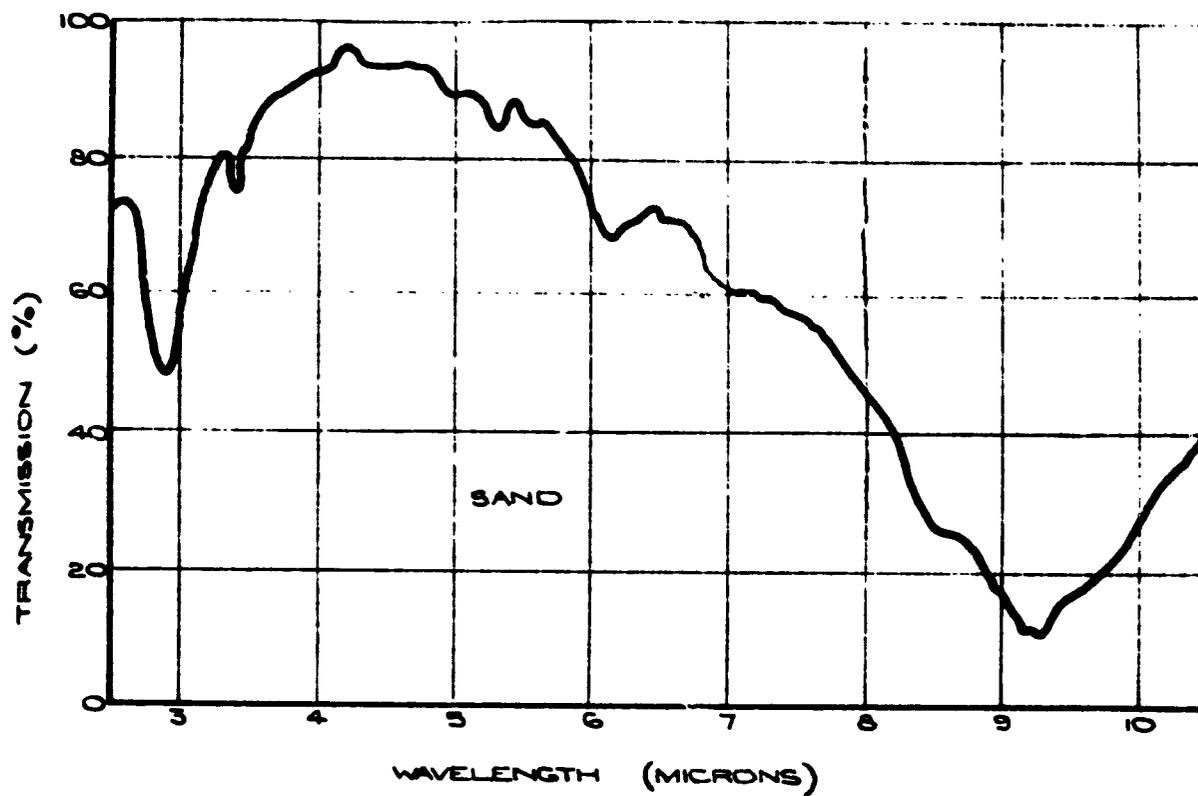


FIG. 10

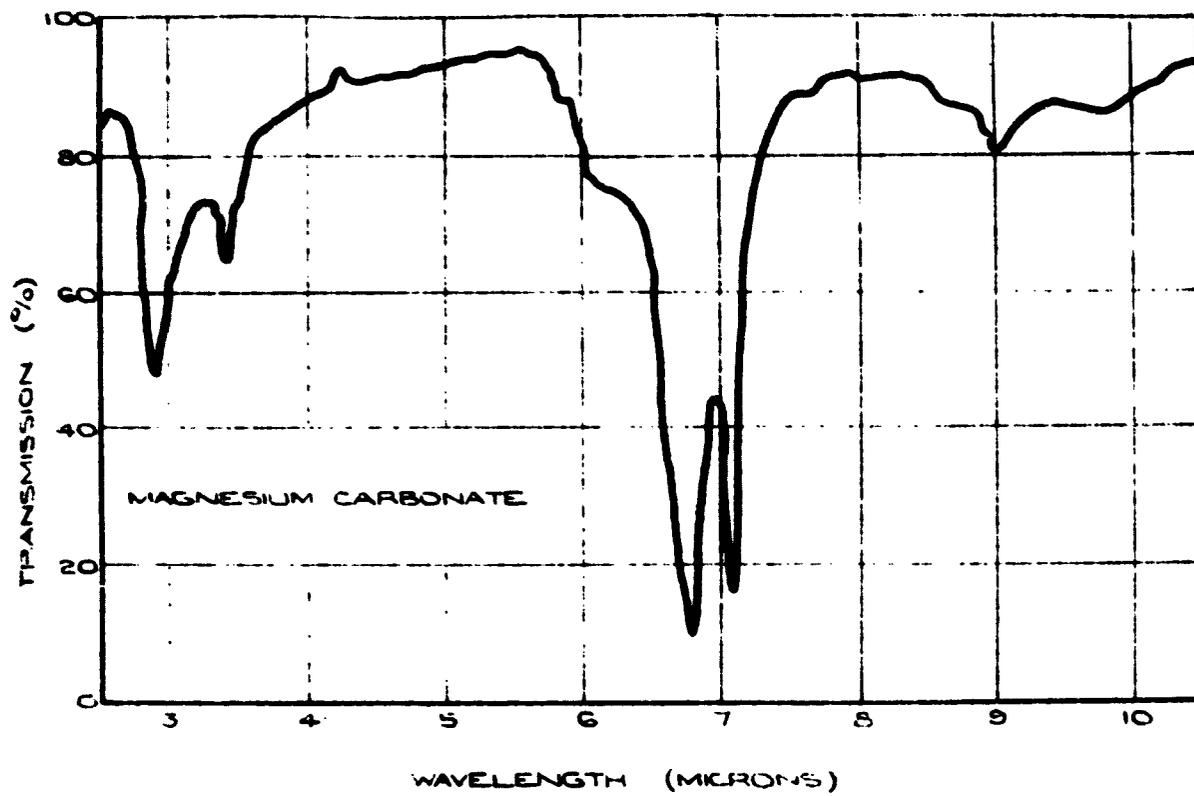


FIG. 11

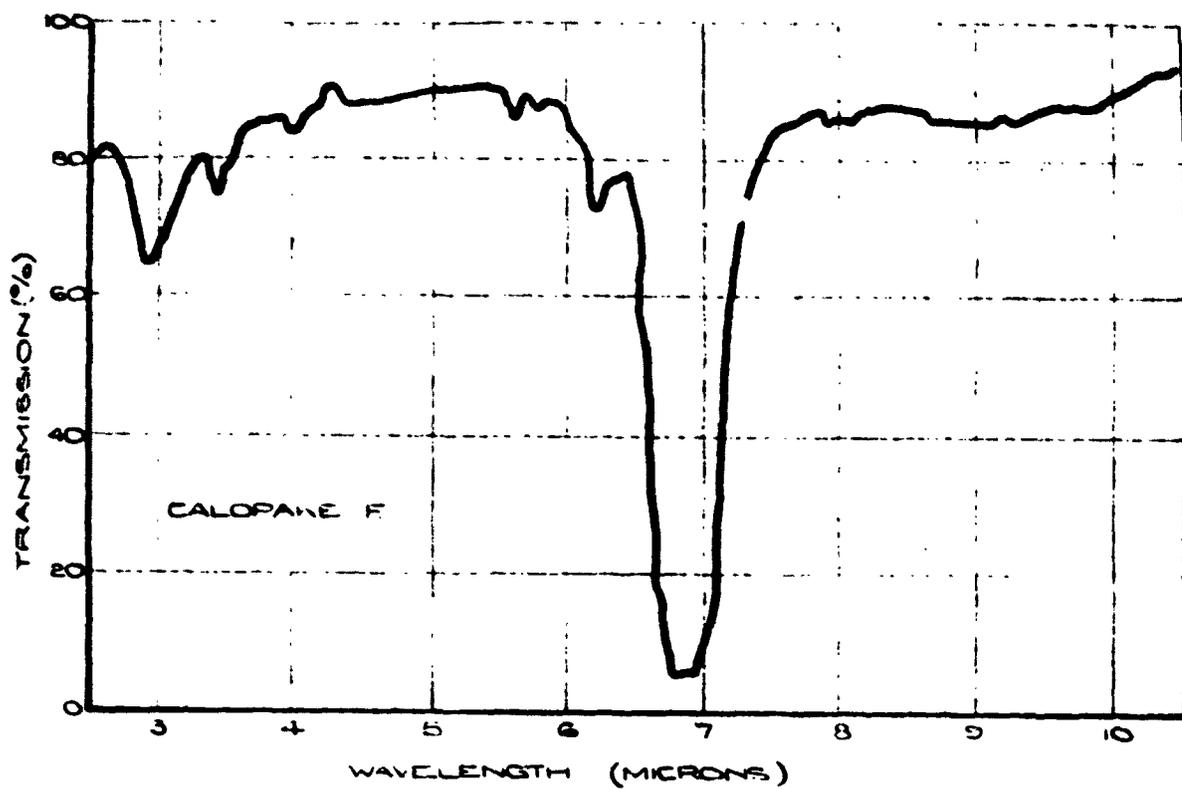


FIG. 12

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