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The Measurement of Absorptivity and Reflectivity

by

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The Measurement of Absorptivity and Reflectivity

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SUMMARY

To deduce the absorptivity from a measurement of reflectivity it is necessary to measure the reflectivity in such a manner that both diffuse and specular reflection are correctly included. A method of doing this is described which makes use of a modified integrating sphere. Results have been obtained for a variety of materials from wavelengths ~ 0.33μ to 2.3μ.

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1 Introduction

Requirements exist for the measurement of emissivity or absorptivity of various materials. Emissivity may be measured directly by comparing the radiation emitted with that from a black body at the same temperature. Absorptivity may be measured directly by irradiating the specimen and observing the rate of rise of temperature. However, this method is difficult when the result is required at specific wavelengths, because the radiation has first to pass through a monochromator which seriously limits the radiant flux available and secondly one has to compare the specimen with a black body of identical thermal capacity and conductivity. In view of these difficulties it is more convenient to develop a general purpose apparatus which measures reflectivity and to deduce the absorptivity or emissivity from the measurement of reflectivity.

2 The Reflection, Absorption and Emission of Radiation

When radiation of wavelength λ falls on a surface a fraction A_λ is absorbed, a fraction R_λ is reflected and a fraction T_λ is transmitted. Evidently,

$$R_\lambda + A_\lambda + T_\lambda = 1 \qquad (1)$$

The reflection may occur at the surface or by scattering in the body of a translucent inhomogenious medium, similarly the transmission may occur with or without scattering; but this is immaterial provided R_λ and T_λ are the total fractions reflected or transmitted at all possible angles. All the specimens examined to date have been opaque hence $T_\lambda = 0$.

In addition to the energy reflected and transmitted there will be thermal radiation from the surface, which will be a function of surface temperature and the emissive power or emissivity* E_λ.

Kirchoff's law, which may be proved by considering the equilibrium of a body in an enclosure states that

$$E_\lambda = A_\lambda \qquad (2)$$

If we measure A_λ by measuring $R_\lambda + T_\lambda$ and using (1), R_λ and T_λ must be measured for all possible angles i.e. for the whole hemisphere in the case of plane specimens.

It is not necessary for the incident radiation to come from all angles, although the value obtained for A_λ may be different for different directions of incident radiation. When stating the value of A_λ it is necessary to specify the direction of the incident radiation, although it would not vary appreciably with the angle of incidence except for rather unusual materials.

It follows from a generalisation of Kirchoff's law that when E_λ is deduced from A_λ, the value applies only for measurement of the radiation in geometrically similar conditions to the irradiation used in the

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* See definition. Appendix.

determination of R_λ and T_λ from which A_λ was deduced, i.e. if we irradiate a specimen normally and measure R_λ and T_λ for all possible directions, we obtain a value of A_λ which is the absorptivity for normal radiation, and this is equal to the emissivity E_λ measured normal to the surface. If both the irradiation and measurement had been omnidirectional, we would have obtained the absorptivity for omnidirectional radiation and the emissivity integrated over all possible directions.

It should be noted that if we irradiate within some restricted range of angles and measure the reflected radiation within a limited solid angle, nothing can be deduced concerning the absorption except for certain surfaces whose characteristics are well known. It is therefore necessary to use some optical system which can handle the radiation over a whole hemisphere, for which purpose an integrating sphere suggests itself.

3 Use of Integrating Sphere

The usual method of using an integrating sphere to measure reflectivity is to send a beam of monochromatic radiation into the sphere so as to irradiate a specimen set in an aperture in the wall, the reflected radiation strikes the inside of the sphere and suffers multiple reflections, a portion reaching a photocell set in an aperture in the sphere wall (Fig 1). The measurement is made by deflecting the beam so as to strike a reference specimen such as magnesium oxide and taking the ratio of the photocell output in the two cases (Fig 2). If an absolute measurement is desired, the apparatus is modified by placing a shield between specimen and photocell, so that radiation reflected from the specimen cannot reach the photocell directly but only by reflection from the sphere lining. The radiation is then reflected from the specimen to the sphere lining a certain fraction entering the photocell after single and multiple reflections from the lining. The reference beam is arranged to strike the sphere lining directly in such a position that the reflected radiation is not obstructed by the shield, a certain fraction enters the photocell as in the previous case. Thus in one case the radiation reaches the sphere lining directly and in the other case it reaches the sphere lining after reflection from the specimen, and the ratio of the meter readings gives the reflectivity of specimen. This method is open to the following objections when one tries to cover a wide range of wavelengths:

(1) Since the system relies on multiple reflections within the sphere, its lining must be highly reflecting and almost perfectly diffusing. If this condition is not satisfied this method will give different results for surfaces with different types of reflection, and these differences may be different at different wavelengths.

(2) The total path length (when examining the surface) from source to detector is appreciably different from that when making the comparison with the direct reading off the wall. This does not affect results in the visible region but would be an appreciable source of error in the 1.4μ, 1.8μ and any longer wavelength atmospheric absorption bands.

(3) The photocell cannot be made to accept radiation from a solid angle of 2π (a whole hemisphere).

If the source and detector were interchanged, the lamp would have to be placed so as to give uniform irradiation of the whole sphere.

To overcome these difficulties it was proposed to arrange lamps and specimens near the centre of the sphere, with the lamps in a ring around the specimen. This is slightly in front of the plane of the lamps so that it is not illuminated directly by the lamps. (Fig 3). This arrangement has the advantages that the lamps irradiate the sphere reasonably uniformly even without multiple reflections, and that the sphere lining irradiates the specimen uniformly from all directions even if this lining is only a poor diffuser, since even if the lining was a specular reflector the radiation from the lamp would be approximately focused onto the specimen after a single reflection from the sphere lining.

The radiance (steradiancy, brightness) of the specimens is compared with that of the sphere lining, the reference line of sight passing to the sphere lining through the space previously occupied by the specimen. The total optical path length is the same when observing the specimen as when observing the sphere lining. Since each part of the sphere lining is always illuminated directly by radiation which has traversed one radius and secondly by multiple reflections and the initial irradiation is the same at all points, each point receives the same contribution by multiple reflections as any other point. Then in one case this radiation has to cross a diameter to emerge from sphere and in the other case, it has to traverse one radius to reach the specimen, regardless of where it has come from, and one radius from specimen to hole in the sphere wall.

In this apparatus the specimen is irradiated uniformly from all directions and the radiation reflected in one particular direction is measured. This is equivalent to a system in which the specimen is irradiated from that particular direction and the total energy reflected in all possible directions is integrated. This principle by which the special distributions of incident and reflected flux may be completely interchanged without altering the measured value of the reflectivity is known as the Helmholtz reciprocal relationship. It is equivalent to a statement that if we interchange source and detector and thus reverse the direction of all rays, the same fraction of the radiation from the source will enter the detector. The interchange of source and detector implies that the interchange is complete, i.e. the detector has to assume the geometrical form of the source and vice versa.

It should be noted that the reflectivity of the sphere lining does not influence the result except in so far as it influences the uniformity of the irradiation onto itself by determining the portion of this irradiation which is due to multiple reflections. We observe either the irradiation of the specimen by observing the radiation which is reflected from a portion of the sphere lining towards the specimen, or the radiation reflected from the specimen; the ratio of these two giving the reflectivity of the specimen. A source of error arises if the portion of the sphere lining which we observe is not reflecting the same quantity of radiation as the remainder of the sphere.

In the case of diffuse reflecting specimens if the part of the sphere lining which is observed when making the reference measurement is brighter than the suitably weighted average of the remainder we obtain a value lower than true for the reflectivity. In the case of specular reflecting specimens we obtain a value lower than true for the reflectivity if the reference portion is brighter than the corresponding portion of the other half of the sphere whose image is seen reflected by the specimen. There is, however, no reason why this portion of the sphere lining should differ appreciably either in irradiation or reflectivity from the reference portion.

4 Experimental Details

The sphere was made of aluminium, one meter in diameter. It was coated internally with the following, in the order listed:-

Titanium Dioxide White Undercoat, DTD.314A,
Titanium Dioxide and Gelatin in Water,
Magnesium Carbonate and Gelatin in Water.

The reflectivity of this sphere lining is unfortunately not perfectly constant with wavelength, and the fall in reflectivity at wavelengths greater than 2.2 microns sets the long wave limit to the range over which accurate measurements can be made. At the short wavelength end of the range, the reflectivity of the lining, energy emitted from the lamps, transmittance of spectrometer and sensitivity of the detector, all fall off. Since the observed output is proportional to the product of all these factors, it falls off exceedingly rapidly. The limit is approximately 0.4 microns with a PbS cell and 0.32 microns with an ultra violet sensitivity photo multiplier, even using the most powerful source practical. This consisted of a ring of 8 x 240 watt, 26 volt aircraft landing lamps. These lamps have thick filaments and can be run at high temperature, (3,000°K) which is essential when making measurements in the violet and near ultra violet regions of the spectrum, but when working at longer wavelengths the voltage on the lamps was reduced to lengthen lamp life and reduce the heating of the sphere.

The radiation emerging from the sphere was focused onto the entrance slit of a Leiss Double Monochromator fitted with quartz prisms, which is described elsewhere(1). A chopper was placed in front of the entrance slit to interrupt the radiation at 800 c/s as the detector was used with an amplifier tuned to this frequency. The detector was situated in a light-tight box behind the exit slit of the monochromator.

The measurements were carried out by setting the spectrometer to pass a particular wavelength and moving the specimen to compare the radiance of the specimen with that of the sphere lining. A subsidiary experiment showed that the radiance of the sphere lining was not altered by moving the specimen.

An experiment was carried out to determine the uniformity of irradiation of the sphere lining, by mounting a lead sulphide cell in the aperture in the wall and observing the variations of the irradiation of the cell as the ring of lamps was rotated. The brightest part was a few per cent brighter than the dimmest part, but the part of the sphere lining in the reference line of sight had a radiance which was very nearly equal to the average for the whole sphere, (within 1%) This measurement applied to the whole of the lead sulphide band, and it is possible that at wavelengths where the sphere lining is not a good reflector more serious variations may occur.

5 Results and Conclusions

The observed values of reflectivity of various materials are tabulated and graphs plotted of reflectivity versus wavelength. Figs 4 to 12 are absolute reflectivity. A specimen of smoked magnesium oxide was measured as a check on the apparatus when used to measure absolute reflectivity. It will be seen that the result for magnesium oxide is in good agreement with published data. When, later, the measurements were extended into the ultra violet a spurious absorption of some 10% was found in the observed reflectivity of MgO at 0.33 microns, all other substances examined showed absorption at this wavelength, and to eliminate that fraction of the absorption which was believed to be spurious the curves of Figs 13 to 19 have been plotted relative to magnesium oxide as 100%. The results for polished silver are in reasonable agreement with published data, but the results for Brytal appear to differ from results obtained by N.P.L. The reason for this error is not known, but it is perhaps due to the dielectric interference layer on the surface of this material. Some small irregularities in the results between 0.5 and 0.6 microns may be due to the fact that the detector was changed at this point, and slightly different results were obtained with PbS cell and photo multiplier respectively. The curves have in this case been drawn between the observed points. When irregularities occur at longer wavelengths the curves have been drawn through the points because it is to be expected that relatively sharp absorption bands may occur in this region.

The principal source of error is the lack of perfect uniformity of radiance of the sphere lining at wavelengths at which it has low reflectivity. An experiment to measure the variation in irradiation of the lining has been referred to above and the variation does not appear to be serious, neither does it effect the observed reflectivity of either magnesium oxide or polished silver. Almost any surface can be regarded as intermediate between these two cases of diffuse and specular reflectors, so we conclude that the apparatus gives reasonably accurate results for any surface.

APPENDIX

Definitions

Reflectivity

This is the fraction of the incident radiation which is reflected from the specimen.

Absorptivity

This is the fraction of the incident radiation which is absorbed by the specimen.

Transmissivity

This is the fraction of the incident radiation which is transmitted through the specimen.

Since these are the properties of a particular object, rather than a particular medium, it may have been more logical to use the terms reflectance, absorptance and transmittance, reserving the term transmissivity for unit thickness (c.f. use of the terms resistivity and resistance etc.). This has not been done because the terms absorptance and transmittance are not generally accepted, while reflectivity, absorptivity and emissivity are widely used.

Emissive Power

A surface at temperature T emits an amount of energy per unit area equal to $E_\lambda \, d\lambda$ ergs per second, between the wavelengths λ and $\lambda + d\lambda$. E_λ is called the Emissive Power for the wavelength λ. E_λ is thus the quantity of energy emitted in ergs per second per unit range of wavelength. This excludes phenomena such as luminescence and limits consideration to temperature radiation.

Emissivity

The Emissivity of a surface is the ratio of the radiation emitted by that surface to that emitted by the same area of a Black Body at the same temperature.

Emissivity at a wavelength λ

This we define as $$\frac{E_\lambda \text{ for the specimen}}{E_\lambda \text{ for a Black Body}}$$

Table of Results

Percentage Reflectivity at various wavelengths

λ (μ)	Silver	Smoked MgO	X74 MgO	X84 TiO_2	Y13	X53 $BaWO_4$	Y11 $PbWO_4$	X64 Al_2O_3	X76 ZnS	X63 ZnO	X81 $PbCO_3$	Brytal	Y15
0.39	69												
0.4	79.2	91.5	83	57.7	91.3	82	84.8	78	74.6	76.1	89.3	87.5	67.6
0.42		96	82.7	85.3	87.5	88.4	87	84.6	83	82.5	89.6	85.5	61
0.45	84.2	96.6	86.8	89.7	91.2	90.1	90.7	86.3	87.9	88.3	91.4	88	60
0.47												87	60.4
0.5	90	98.5	91.4	92	93.5	92.7	92.7	88.9	91.6	89.6	94	86.5	59.5
0.52												86.2	60.2
0.55	90	98	94.5	92.9	93.7	93.6 95.2	93.6 95.2	90.8	93.7	90.9	95	85.5	58.6
0.55	91.75	98.5	93	92	93.3	92.8	94.1	90.4	93.4	91.4	95.3	88.5	58.2
0.6	92.7	98.8	93.7	92.6	94	94.9	94.9	93.0	94.6	91.1	96	85	57
0.65	94	99.0	93.7	93.4	94.1	94.8	95.8	92.3	95.5	91.6	97.1	84	55.2
0.7	95.5	98.8	94.5	94	94.4	94.3	95.3	91.8	96.2	91.2	97.2	83	53.8
0.75	96.2	98.25	93.5	94.4	94.5	94.8	94.8	92.7	97	91.3	97.3	80	52.3
0.8	96.7	98.5	93.75	94.2	95	94.3	98.5	92	96.9	91.0	97.1	83.7	52
0.85	97	98.0	93.4	94.4	94.4	94.6	95.5	92	97.5	91.3	98.2	85.5	55.6
0.9	98	98.8	94.2	94.4	94.6	94.4	95.3	91.4	96.5	90.6	97.8	89.2	58.1
0.95	98.5	98.7	94	95	95	95.0	96.0	93.7	96.6	90.0	97.9	91) 90.6)	59.6) 59.5)
1.0	97	99	94.5	94.3	94.3	93.8	95.3	92.5	97.5	91.1	98.9	93	61.2
1.1	99	99.2	94.2	94.4	94.4	94.9	96.0	91.7	97.4	89.9	99.0	94	61.5
1.2	99	99	93.2	93.6	93.6	93.7	95.2	90.6	96.8	89.2	99.1	94.5	62
1.3	99	98.3	88	89.7	90.9	89.4	93.1	82	92	87.2	95.2	95	61.4
1.4	99.5	97.2	89	86	86	86.9	89.8	77.1	87.5	82.4	95.1	96.2	61.5
1.6	100	99	89.5	85.9	85.2	87.6	90.7	76.1	89.4	82.5	96.9	97.8	62.75
1.8	98	97.5	84.5	82.7	81.9	78.5	86.4	69.5	82.4	79.8	93.4	96	60.75
2	98	95.5	73.5	68.9	67	70.8	79.0	63.9	74.0	65.3	85.25	94	61
2.1	100	97.8	71	63	62.5	70.3	79.7	58.5	76.1	60.5	85.7		62.5
2.2		99	65					54.4	77.5	58	79		

λ (μ)	TiO_2 Rutile/gel $\frac{Y84}{MgO}$	TiO_2 Anatase/gel $\frac{Y13}{MgO}$	TiO_2 (Rutile in 827) $\frac{X21}{MgO}$	TiO_2 (Anatase in 827) $\frac{X31}{MgO}$	Lead Carbonate (gel) $\frac{X81}{MgO}$
0.328					87.4
0.338	52.9	60.1	57.7	59.9	88.6
0.348	27.4	43.4	34.0	36.9	87.7
0.362	15.9	26.8	17.9	25.9	89.4
0.373	12.2	39.3	13.0	38.0	90.5
0.385	12.7	54.0	14.5	52.8	91.6
0.393	17.6	72.1	21.0	66.8	92.9
0.402			36.7	75.3	92.7
0.413	65.0	91.5	68.1	83.9	92.0
0.470	95.9	95.9	93.8	91.5	96.5
0.470			90.5	89.5	92.3
0.540	92.4	92.2	93.4	90.0	96.0
0.595	93.3	94.5	94.8	91.4	97.2
0.645	94.4	94.9	96.4	93.7	98.4
0.700	92.0	93.4	95.8	94.3	97.0
0.761	93.4	95.0	97.1	94.8	99.4
0.890	93.4	94.7	96.8	92.4	98.2
1.000	94.2	94.2	96.4	91.2	99.4
1.096	94.3	94.3	95.2	89.9	100
1.315	93.5	92.5	93.3	87.0	100
1.55	85.4	84.0	85.4	79.7	96.4
1.69	86.0	83.0	75.9	67.2	97.2
1.89	82.3	78.8	76.4	70.5	94.2
2.068	69.6	65.5	67.3	61.2	88.8
2.293	59.7	55.2	39.4	32.5	80.1

λ (μ)	Aluminium in 827 $\frac{A1827}{MgO}$	Lead Carbonate in 827 $\frac{Y33}{MgO}$	P1 $\frac{P1}{MgO}$	P2 $\frac{P2}{MgO}$	P3 $\frac{P3}{MgO}$	P4 $\frac{P4}{MgO}$	Y42 $\frac{Y42}{MgO}$	Y47 $\frac{Y47}{MgO}$
0.328	53.7	76.0	25.3	70.4	32.2	40.0	64.3	32.5
0.338	50.8	58.7	19.7	46.9	31.4	38.2	48.0	31.3
0.348	47.9	47.9	15.2	29.3	31.4	36.9	33.5	29.9
0.362	48.6	43.4	14.3	19.5	32.0	39.5	26.5	23.7
0.373	49.9	47.7	10.8	15.6	35.4	43.5	37.5	25.1
0.385	50.1	51.0	8.43	15.4	37.9	47.0	50.6	29.2
0.393	52.2	57.4	8.83	21.1	41.3	49.9	66.5	35.0
0.402	52.0	64	10.1	37.8	42.8	52.4	76.6	41.7
0.413	54.5	70.6	15.3	69.8	44.8	55.6	83.9	49.8
0.470	55.1	83.2	31.2	93.7	49.5	61.6	89.3	66.7
0.470	51.1	79.2	28.2	87.7	50.7	62.8	84.9	62.7
0.540	50.6	84.3	42.1	90.4	56.4	67.2	88.7	65.8
0.595	50.8	88.6	48.4	92.0	60.7	71.3	91.4	70.4
0.645	50.6	91.7	51.0	94.2	61.7	71.4	91.9	72.4
0.700	(47.4)	90.3	49.3	93.1	62.0	71.1	92.76	72.6
0.761	47.3	92.0	45.6	94.2	63.5	72.0	94.0	72.7
0.890	45.2	90.5	34.8	90.8	62.5	69.2	91.4	69.7
1.000	50.6	90.5	29.9	90.3	63.2	67.9	89.2	71.8
1.096	53.5	89.7	29.4	87.9	62.7	84.0	88.3	72.7
1.315	56.3	90.4	33.8	87.5	62.7	68.5	85.3	73.5
1.55	56.2	81.9	31.6	82.6	57.4	65.0	77.1	60.1
1.69	55.8	74.6	12.2	67.7	51.1	59.6	64.5	43.7
1.89	55.8	74.8	18.7	71.8	52.6	62.9	67.0	46.1
2.068	56.2	65.1	16.1	64.7	40.3	60.2	57.8	39.6
2.293	54.1	40.8	6.2	38.2	20.6	34.3	31.7	17.5

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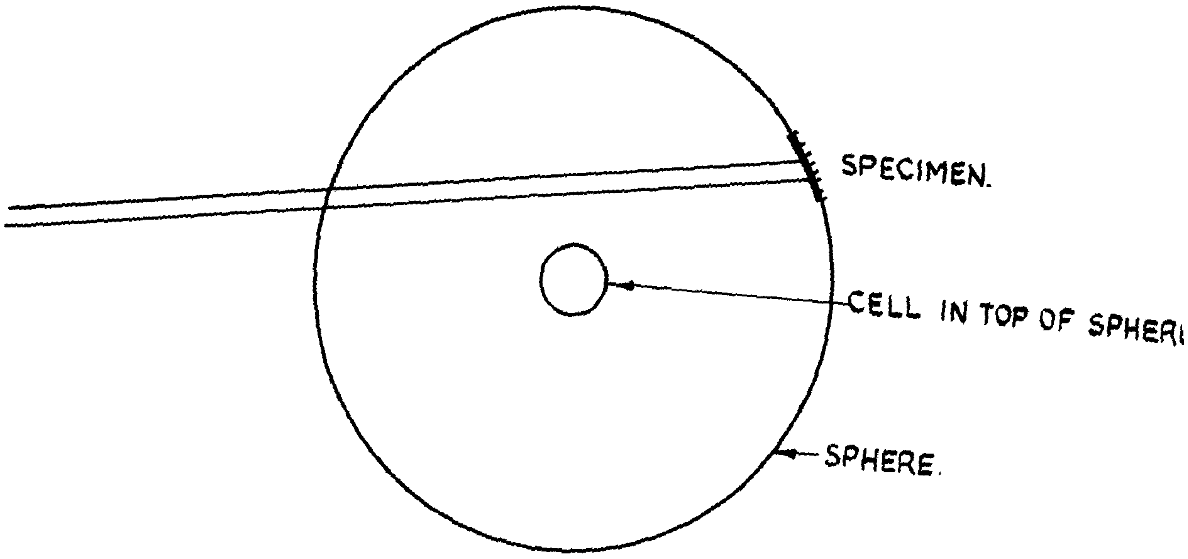


FIG. 1.

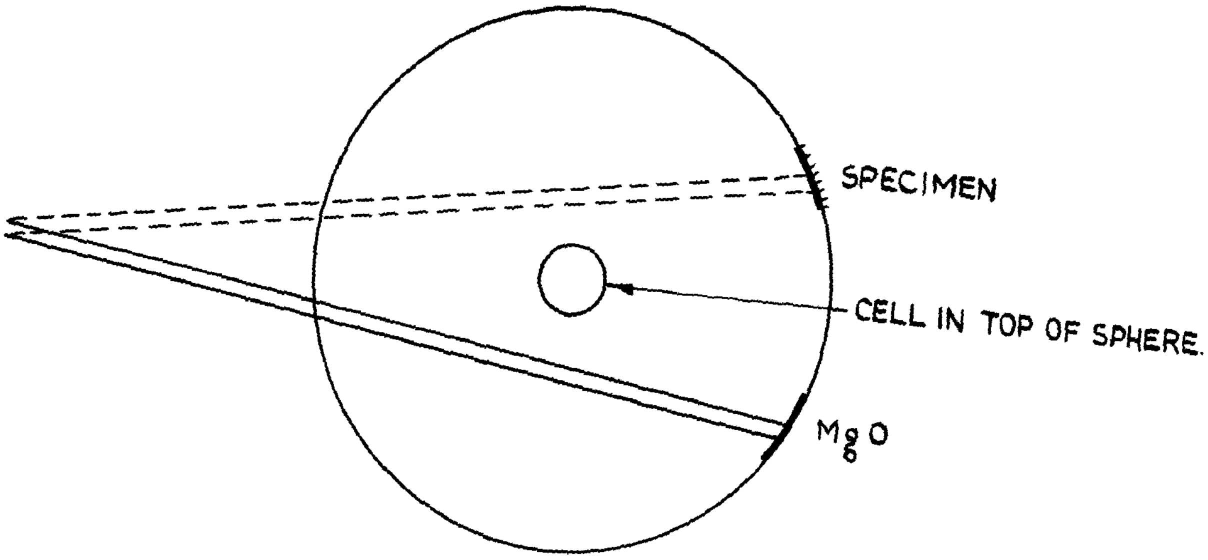


FIG. 2.

INTEGRATING SPHERE FOR MEASUREMENT OF REFLECTIVITY.

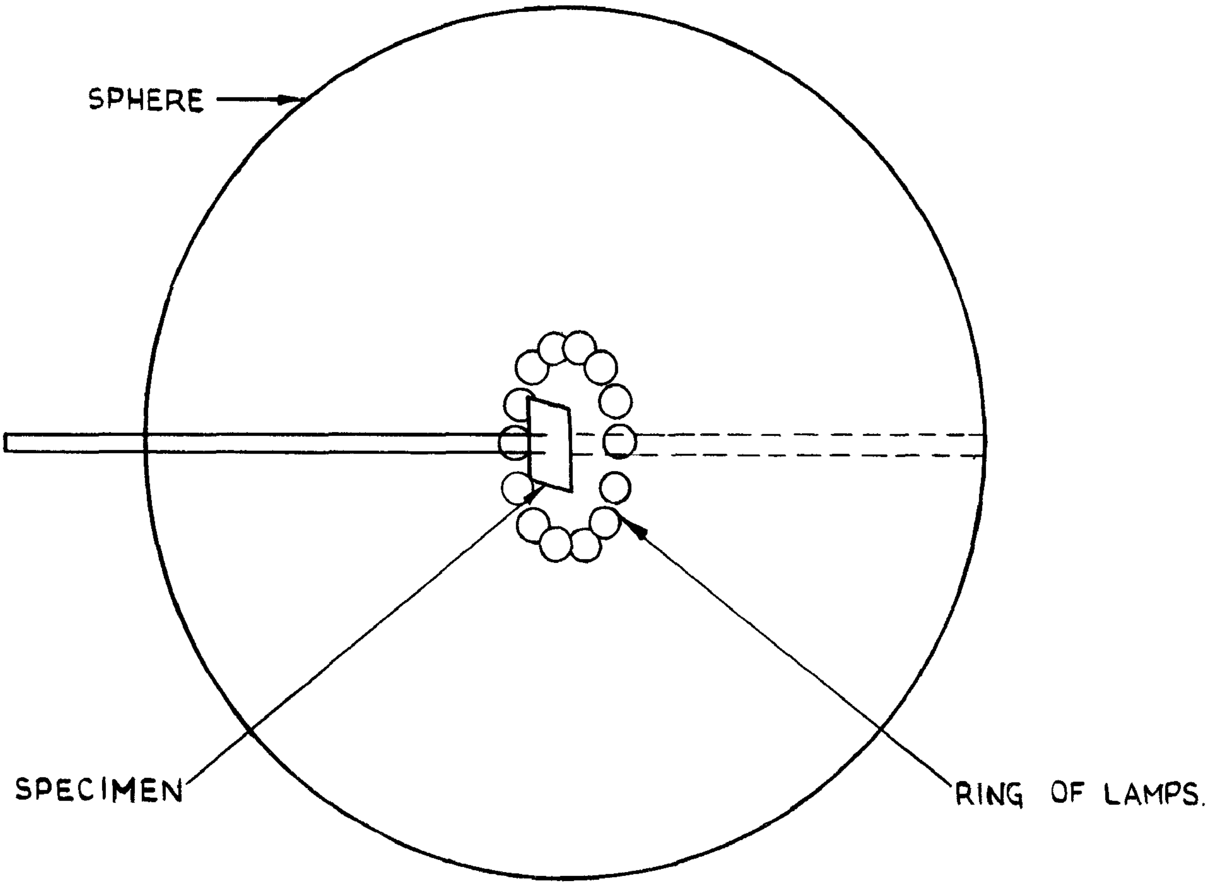


FIG. 3.

INTEGRATING SPHERE FOR MEASUREMENT OF REFLECTIVITY.

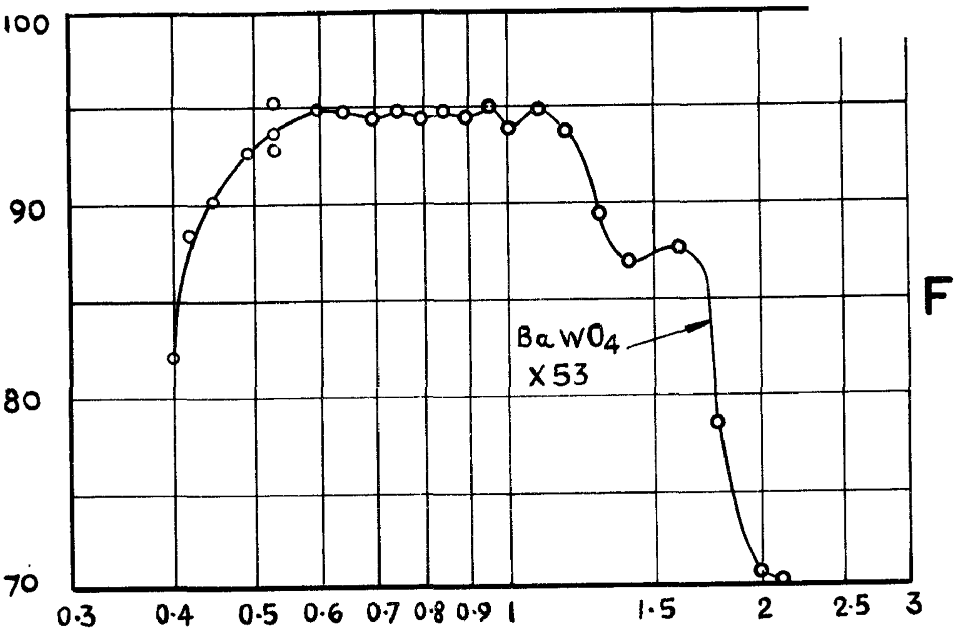
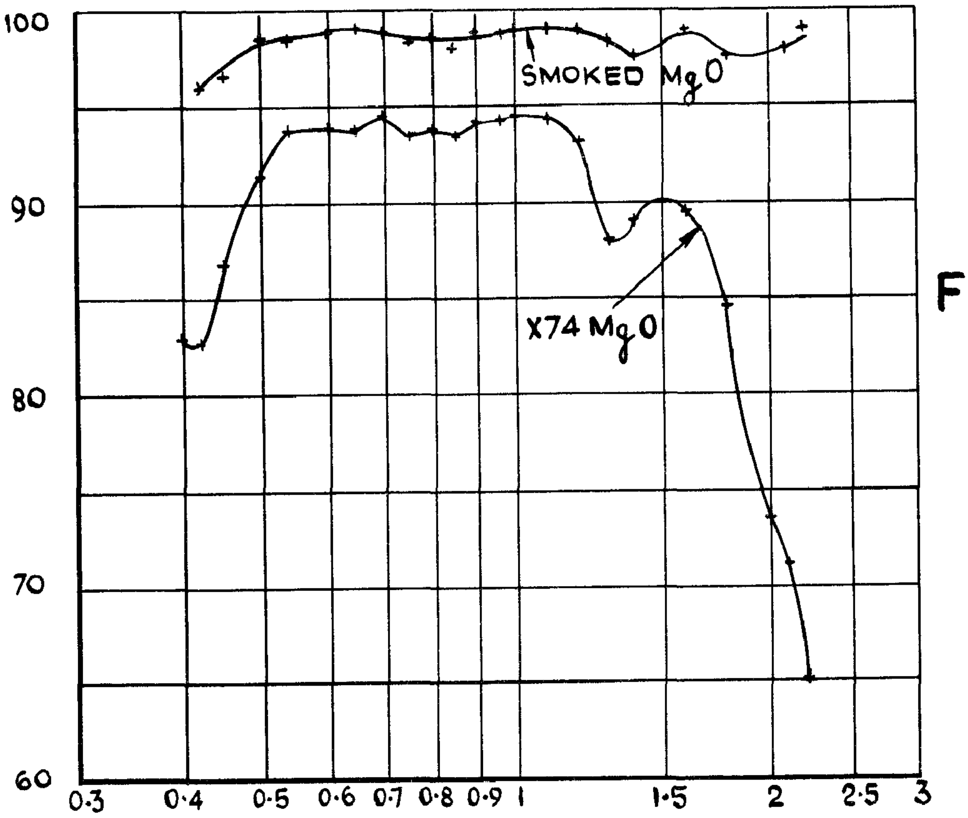


FIG. 4.



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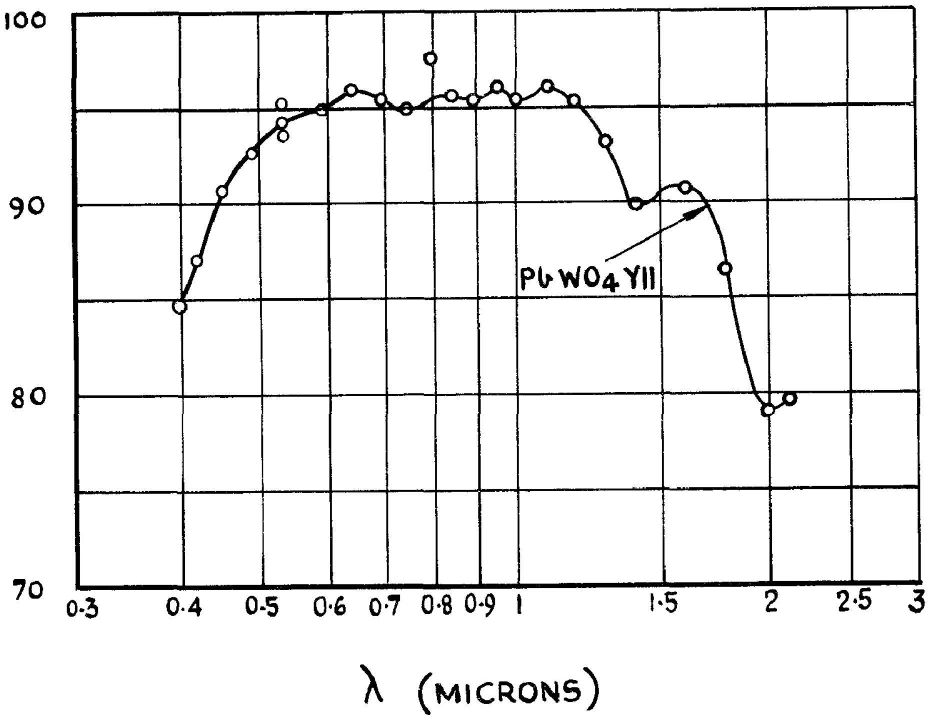

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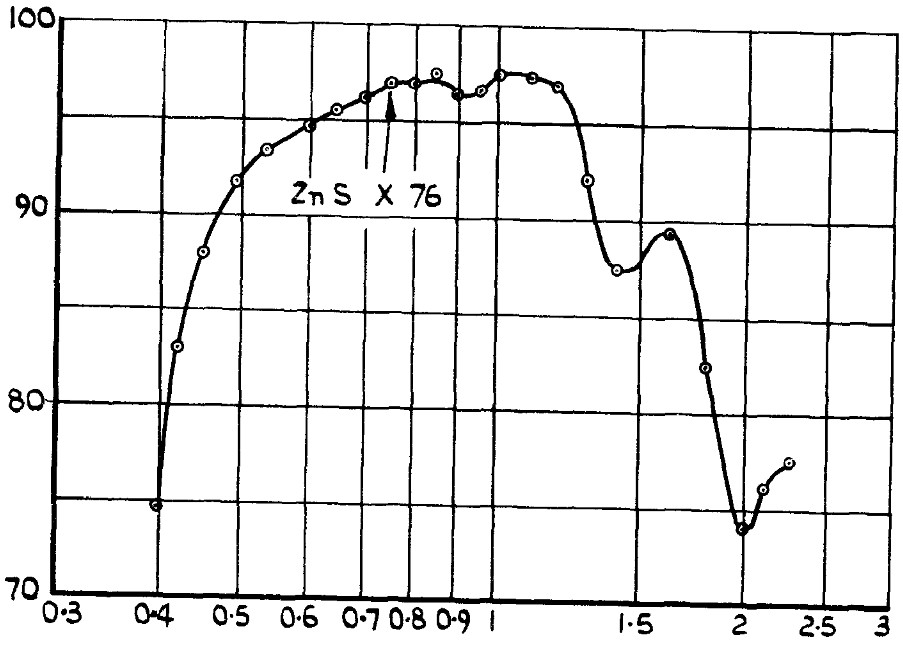
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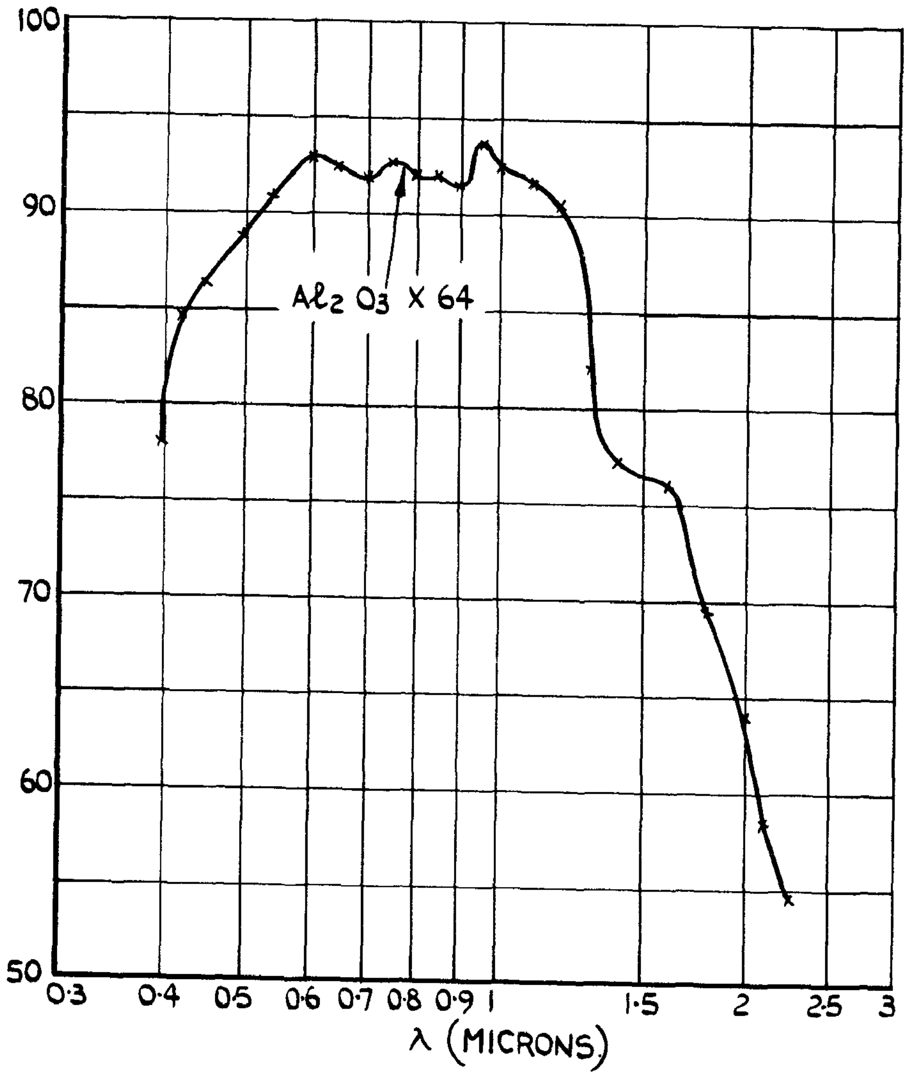
FIG. 7.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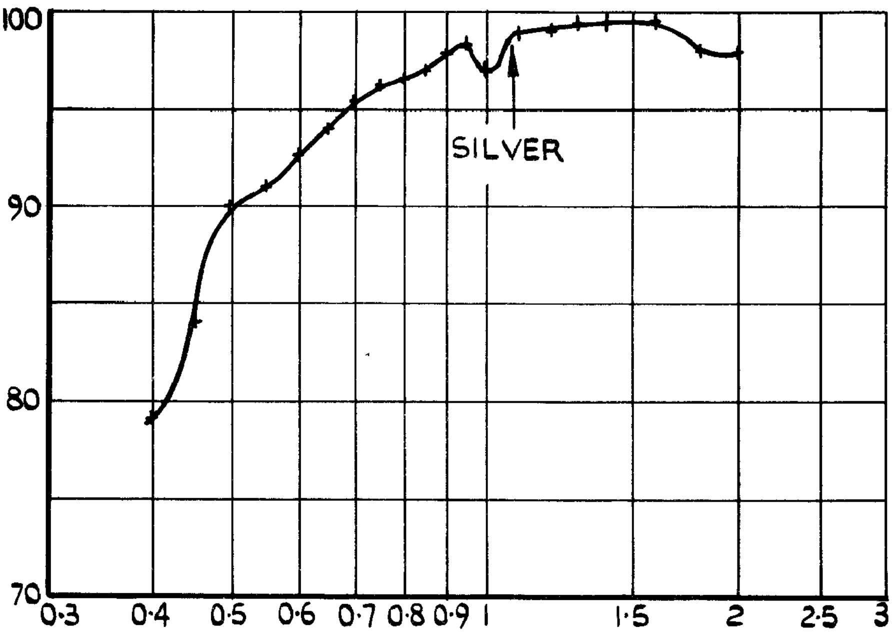
λ (MICRONS)

FIG. 8.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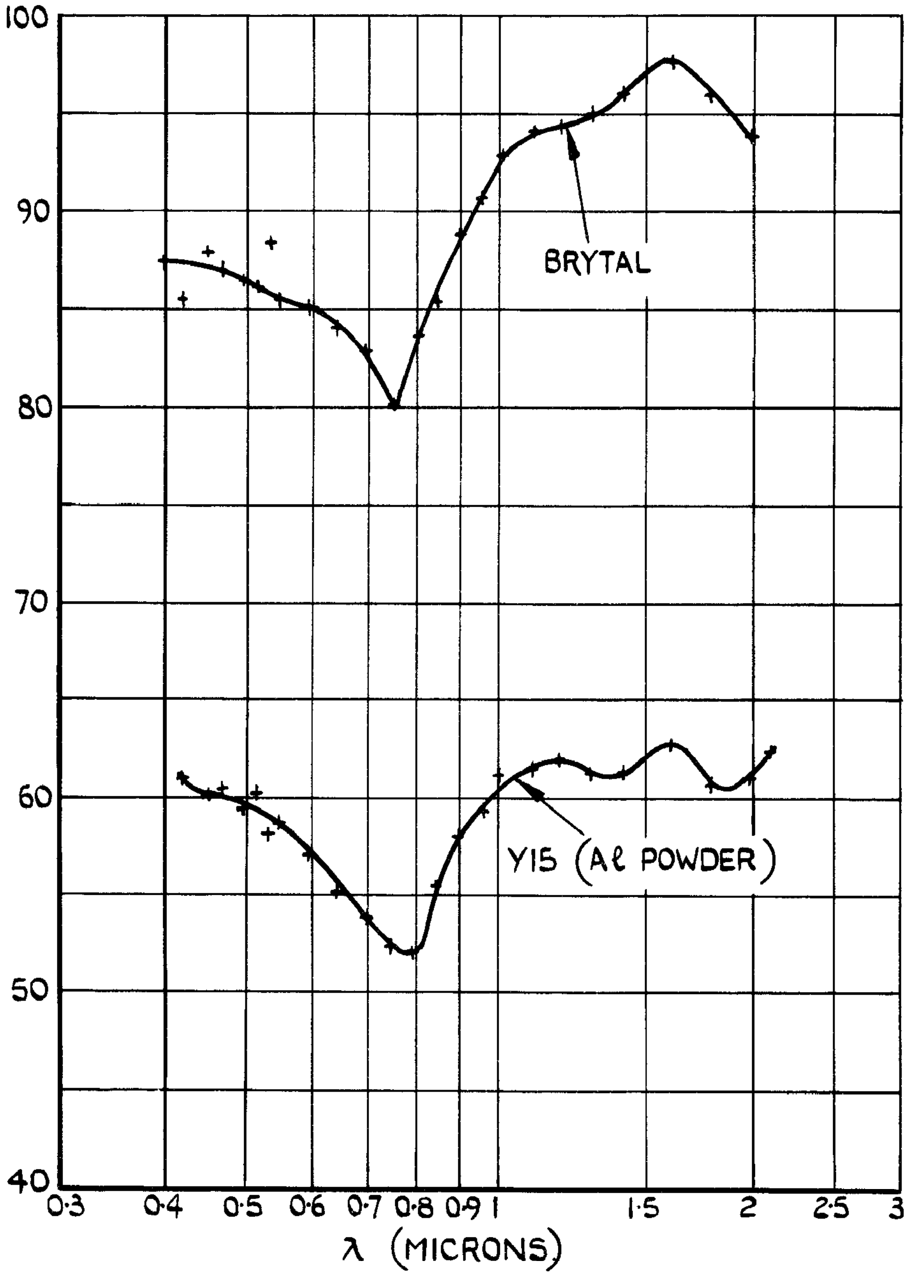
SILVER

FIG. 9.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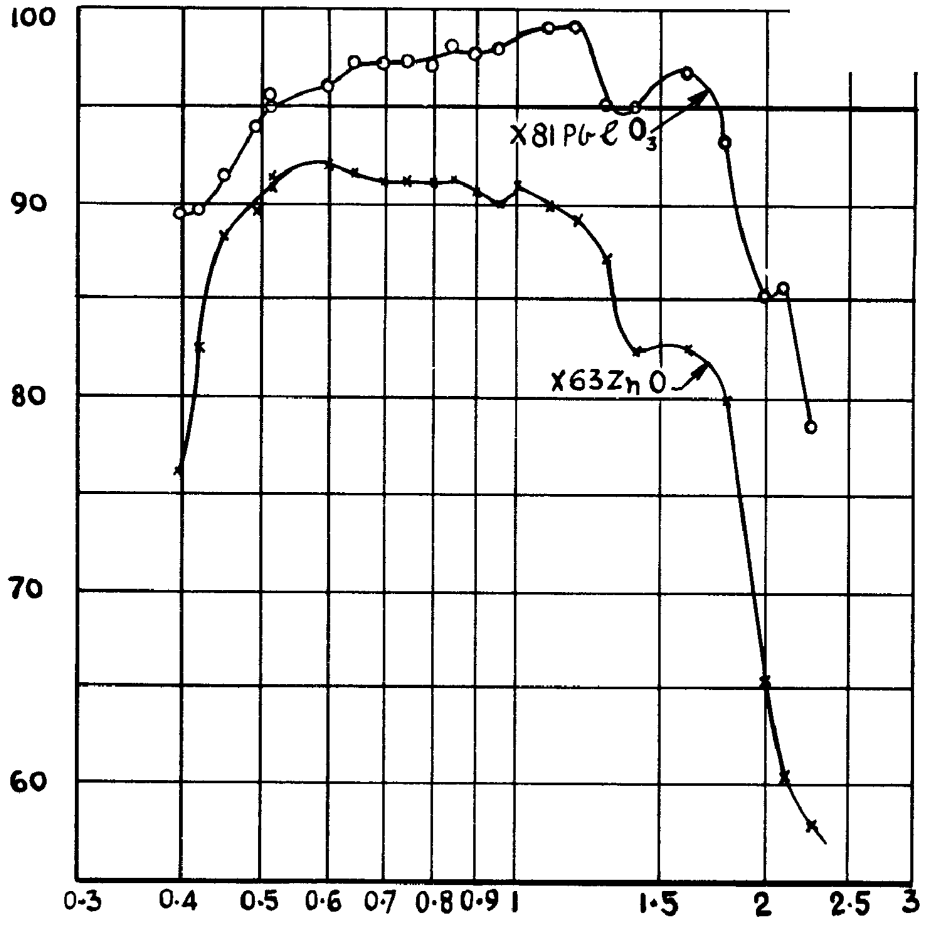
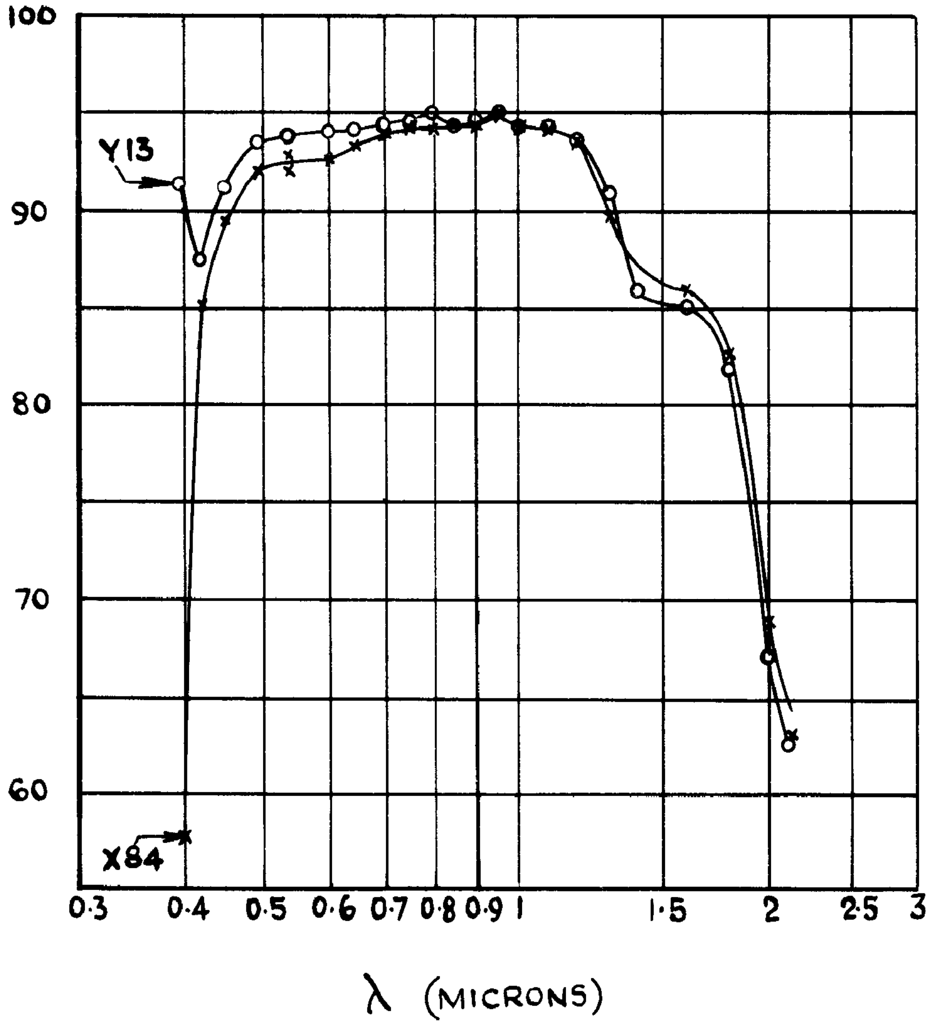
3
λ (MICRONS)
BRYTAL
Y15 (Aℓ POWDER)

FIG. 10.



100
90
80
70
60
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1
1·5
2
2·5
3
X81 PbCO3
X63 ZnO

FIG. 11.



100
90
80
70
60
Y13
X84
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1
1·5
2
2·5
3
λ (MICRONS)

FIG. 12.

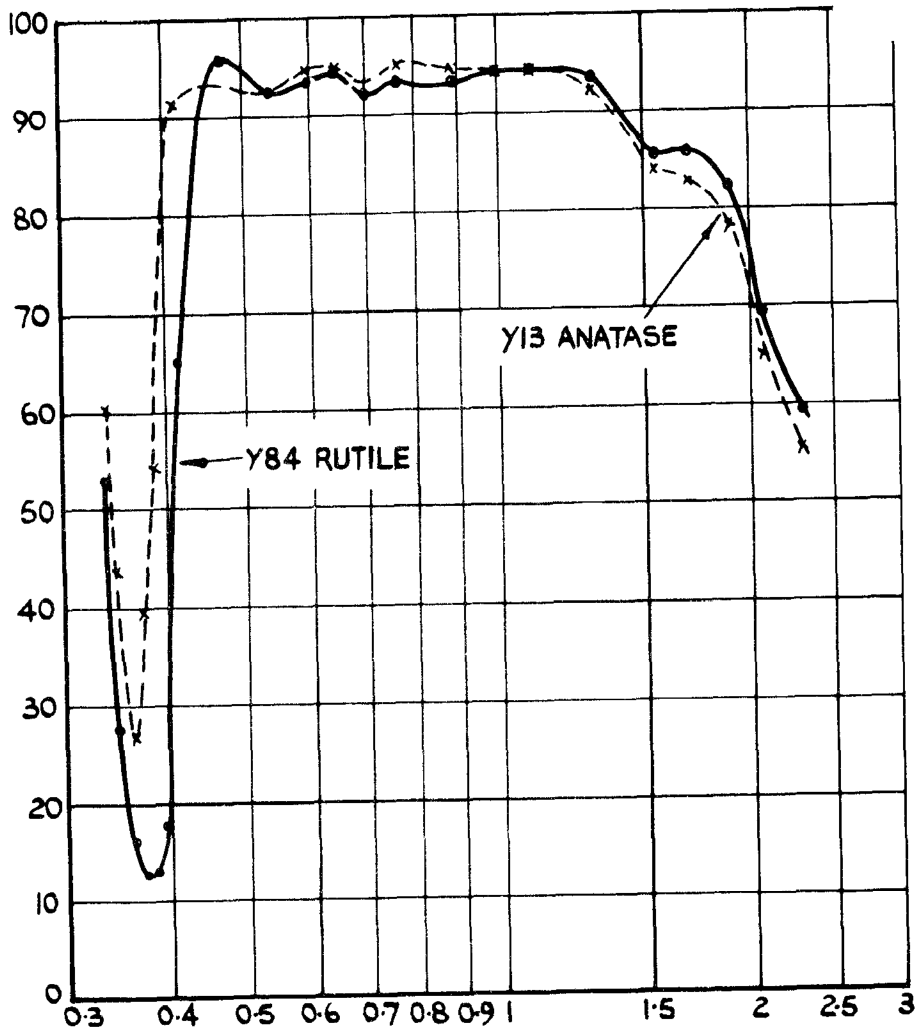

100
90
80
70
60
50
40
30
20
10
0
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1
1·5
2
2·5
3
Y84 RUTILE
Y13 ANATASE

FIG. 13.

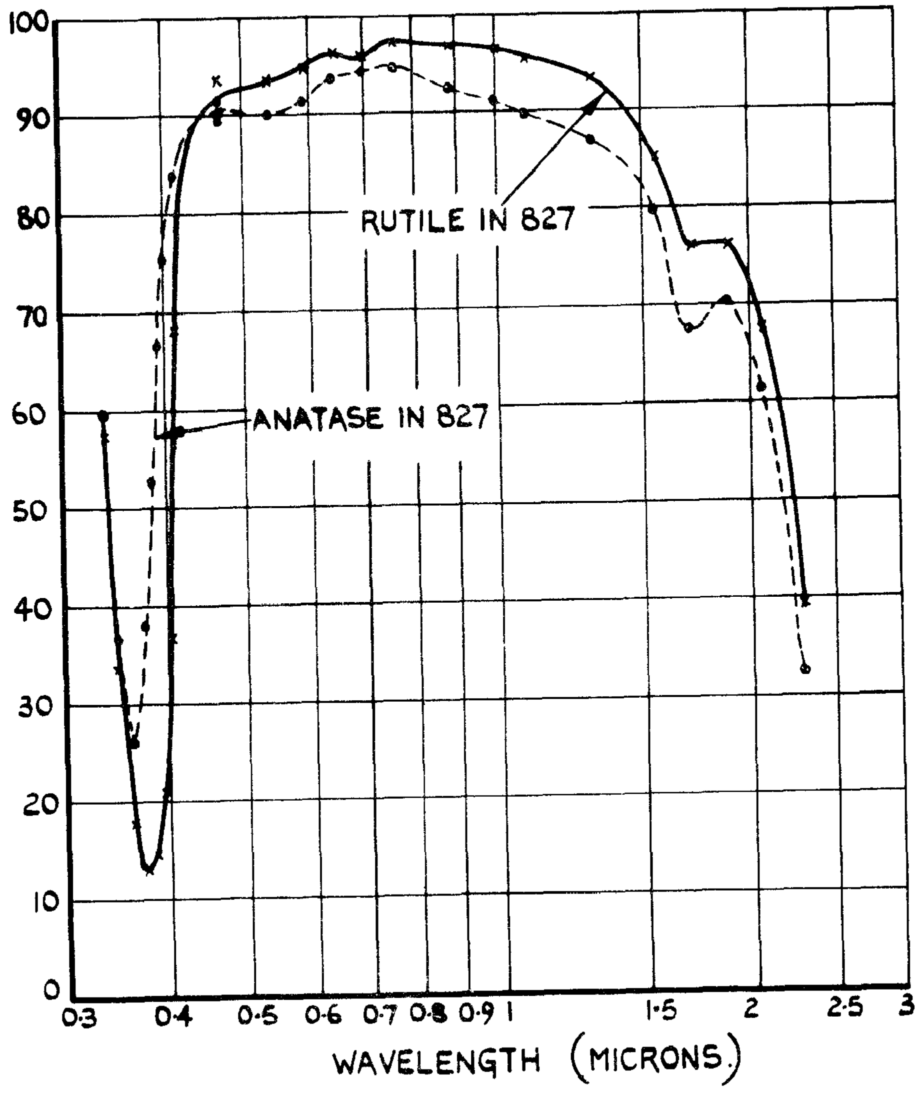
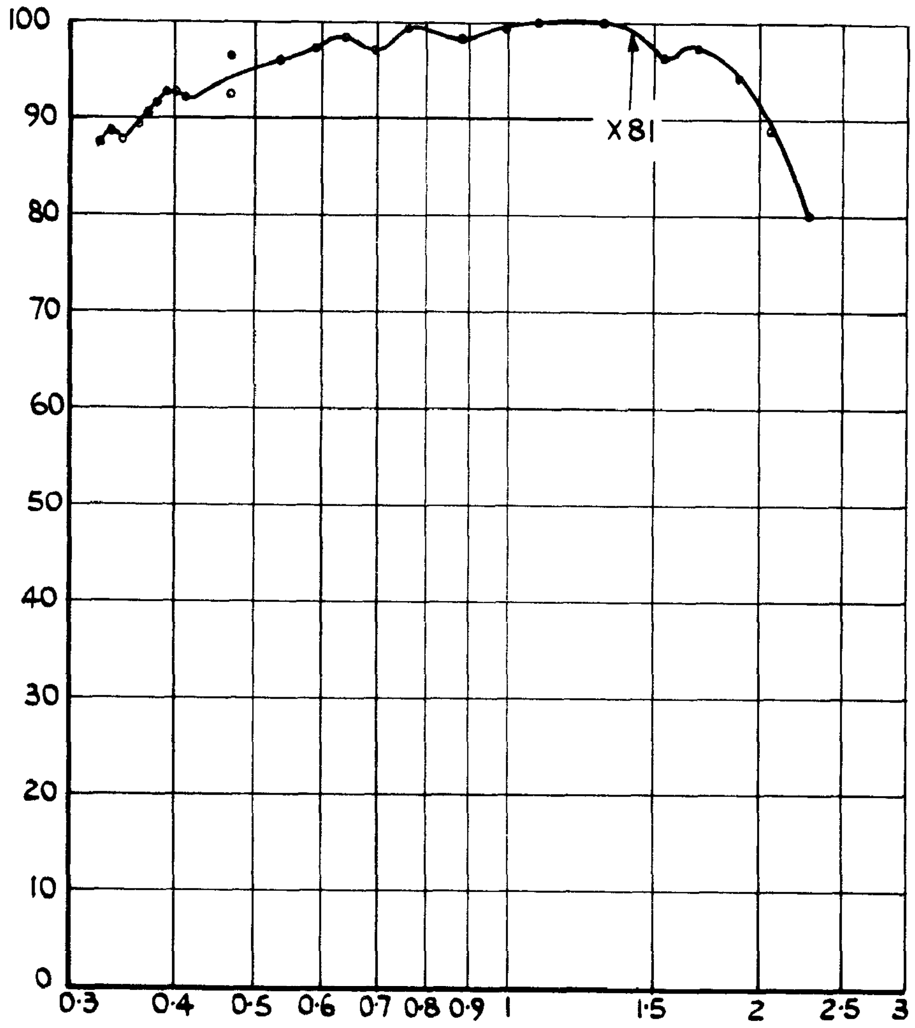
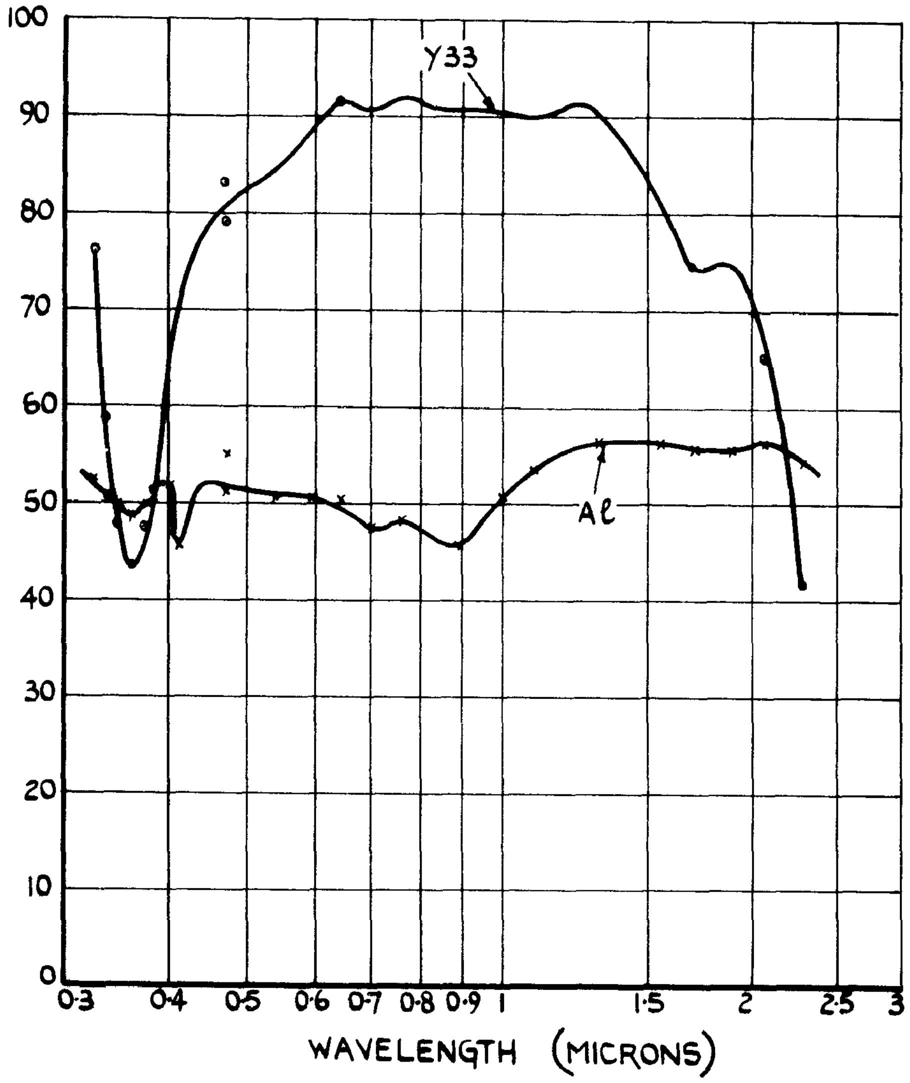

100
90
80
70
60
50
40
30
20
10
0
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1
1·5
2
2·5
3
RUTILE IN 827
ANATASE IN 827
WAVELENGTH (MICRONS)

FIG. 14.



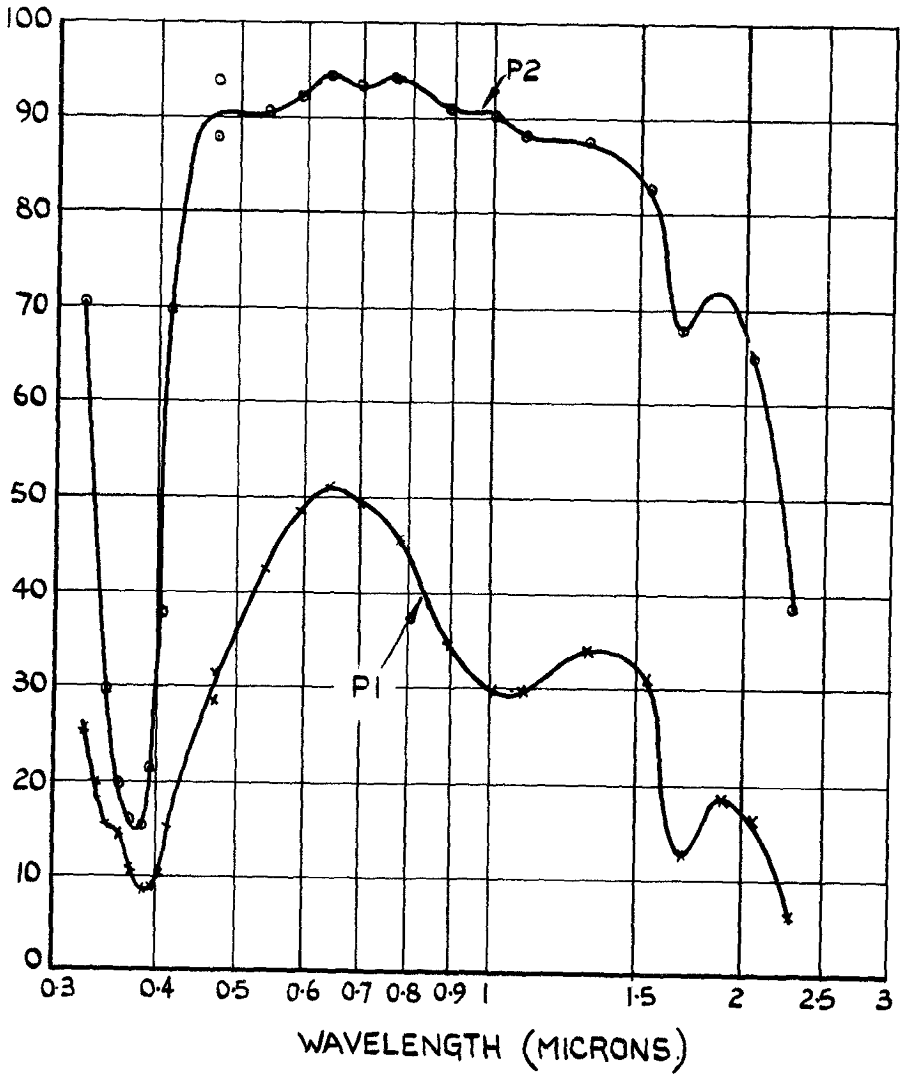
100
90
80
70
60
50
40
30
20
10
0
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1
1·5
2
2·5
3
X81

FIG. 15.



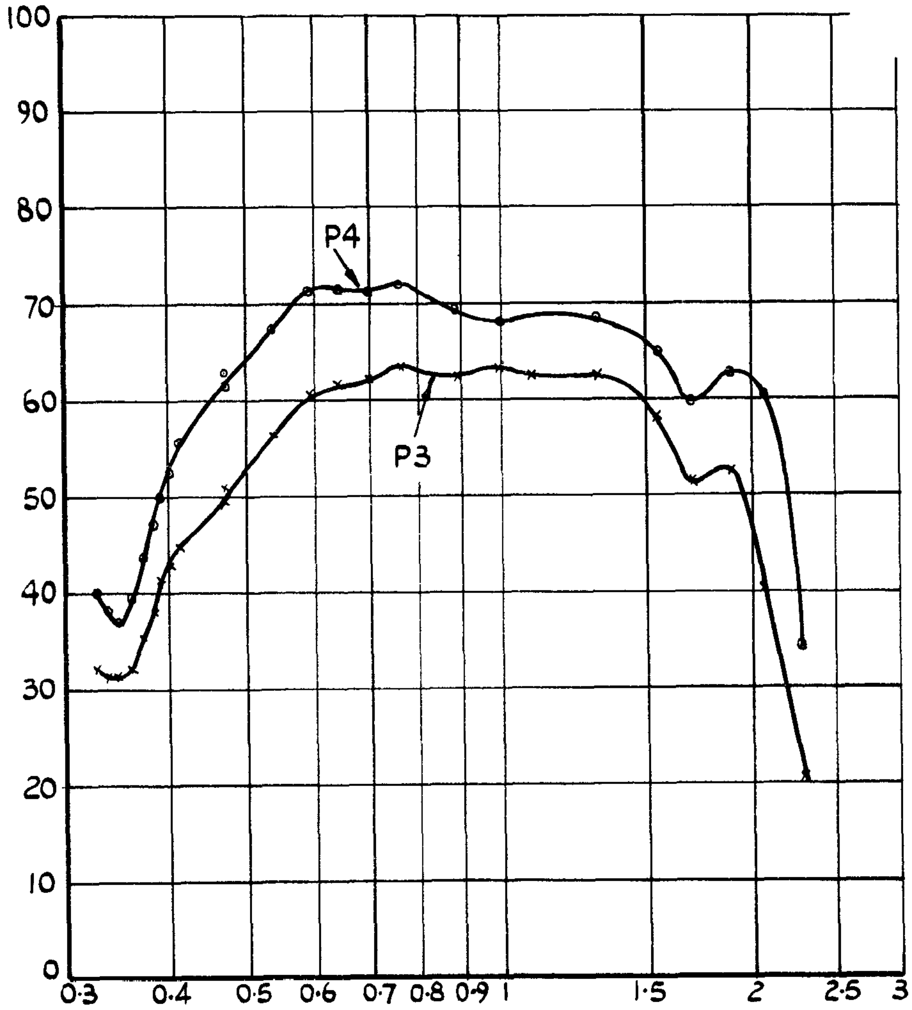
100
90
80
70
60
50
40
30
20
10
0
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1
1·5
2
2·5
3
Y33
Al
WAVELENGTH (MICRONS)

FIG. 16.



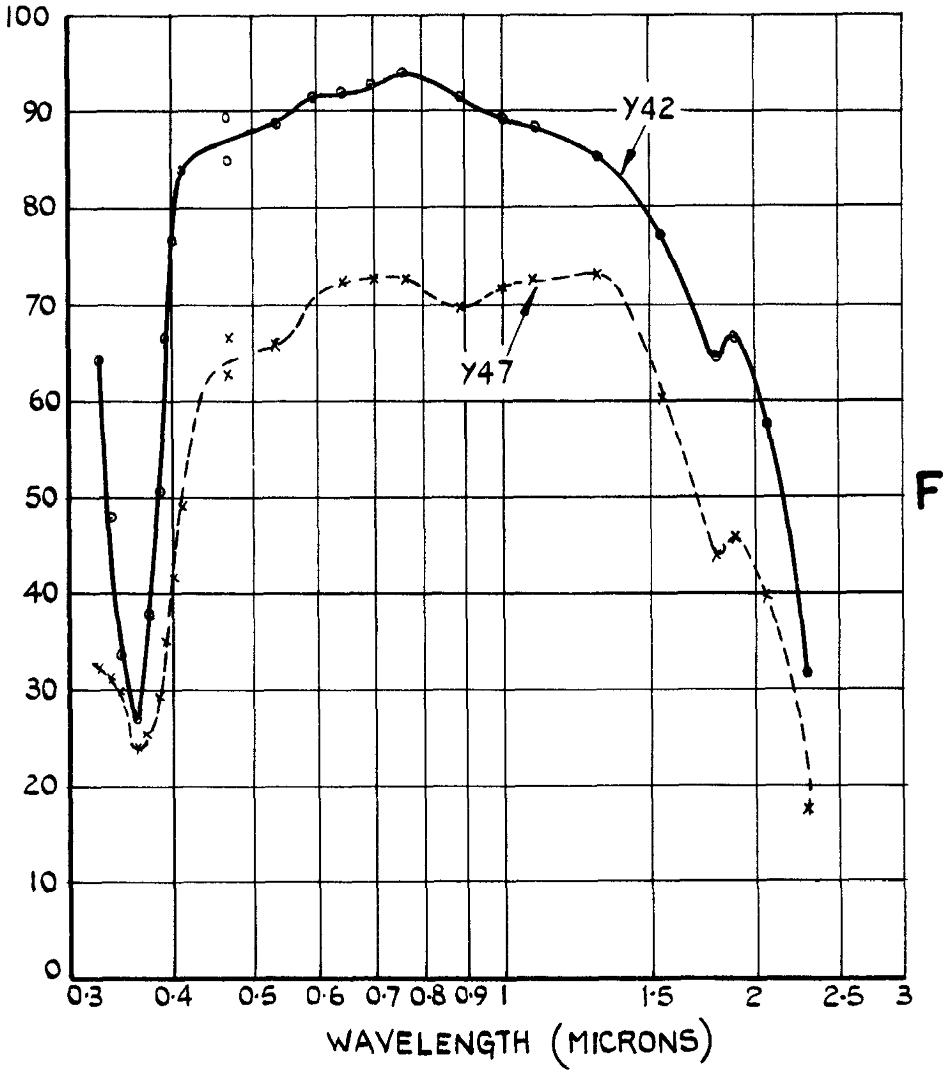
100
90
80
70
60
50
40
30
20
10
0
P2
P1
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1
1·5
2
2·5
3
WAVELENGTH (MICRONS)

FIG.17.



100
90
80
70
60
50
40
30
20
10
0
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1
1·5
2
2·5
3
P4
P3

FIG.18.



100
90
80
70
60
50
40
30
20
10
0
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1
1·5
2
2·5
3
Y42
Y47
WAVELENGTH (MICRONS)

FIG.19.

A.R.C. C.P. No. 601. October, 1956. 535.32/34:
535.84

de la Perrelle, E. T. and Herbert, H.

THE MEASUREMENT OF ABSORPTIVITY AND REFLECTIVITY

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