THE DIFFUSE REFLECTING POWER OF VARIOUS SUBSTANCES [1]

By W. W. Coblentz

CONTENTS

I. INTRODUCTION

In all radiometric work involving the measurement of radiant energy in absolute value it is necessary to use an instrument that intercepts or absorbs all the incident radiations; or if that is impracticable, it is necessary to know the amount that is not absorbed. The instruments used for intercepting and absorbing radiant energy are usually constructed in the form of conical-shaped cavities which are blackened with lampblack, the expectation being that, after successive reflections within the cavity, the amount of energy lost by passing out through the opening is reduced to a negligible value.

---

[1] This title is used in order to distinguish the reflection of matte surfaces from the (regular) reflection of polished surfaces. The paper gives also data on the specular reflection of polished silver for different angles of incidence, but it seemed unnecessary to include it in the title.

A simpler and older form of radiometer is a plane surface covered with an absorbing substance. In this case it is necessary to determine the amount of energy lost by reflection from the surface of the receiver. If the blackened receiving surface is small, it may be placed at the center of curvature of a hemispherical mirror, the the radiant energy being admitted through a hole in the center of the mirror. The receiver being at the center of curvature of the mirror, any radiations which are diffusively reflected from the receiver will impinge upon the mirror and will return to the receiver. The amount of energy lost by returning upon its path through the opening in the mirror can be determined experimentally.

The most useful substances for absorbing radiant energy are lampblack and platinum black. The present research was undertaken in order to establish methods for the production of standard absorbing surfaces from standard materials, and to determine the completeness of the absorption (i. e., the amount lost by diffuse reflection) of these substances in different regions of the spectrum.

The reverse problem was also presented, of finding a "white" surface, which absorbs the least radiation (high reflection) in the visible and in the adjoining infra-red part of the spectrum, and which has a low reflection in the region of 8 to 9 μ. Such a surface would absorb but little sunlight, and it would not become heated by the part that is absorbed, owing to reradiation, which is facilitated by the high emissivity in the region of 8 to 9 μ, where occurs the maximum radiation of substances having a temperature of 20° to 50° C.

Expressed in a more popular way, the interest in the present research was in finding substances having the extremes in diffuse reflection; i. e., the whitest "white" and the blackest "black," the former to be used as a paint (which will absorb but little of the sun's rays) to cover a building (e. g., an observatory dome) which is to contain instruments that are sensitive to changes in temperature, the latter to be used as the absorbing surface of a radiometer which is located within this building.

While it is beyond the scope of the present investigation to discuss the theoretical aspects of this subject, it is of interest to notice the extraordinary and apparently inconsistent ways in which these

extremes in diffuse reflection are produced. In optically transparent media (insulators), such as glass, the absorption coefficient and the refractive index are low and the amount reflected regularly ("vitreous reflection") is of the order of 4 to 5 per cent. On the other hand, in the metals (electrical conductors), such as platinum, the absorption coefficient and the refractive index are high and the amount reflected regularly ("specular reflection") is of the order of 80 to 100 per cent, depending upon the wave length. On first consideration it therefore seems somewhat contrary to the natural order of things to produce a high (90 per cent) reflecting (diffuse reflection) surface from the former and an extremely low (1.5 per cent) reflecting surface from the latter by merely changing the size of the grains which form the reflecting layer.

The high reflecting power of fine particles of transparent substances (insulators) is easily explained as the result of successive internal reflections and refractions of the light which penetrates their surfaces. If the particles are small, the chances are that total reflection will occur before the rays have penetrated to a great depth, and (there being practically no absorption) the rays are reflected with almost the same intensity as obtained in the incident radiations.

When the reflecting particles have a high absorptivity but have a low refractive index, which is true of lampblack, the same optical conditions obtain as in the more transparent particles, the only difference being that at each internal reflection the rays are further absorbed so that the intensity of the reflected rays is quickly reduced to a small value in comparison with the incident rays. The blackest deposits of soot are made by holding a metal plate in an acetylene flame, which forms an extremely fine-grained surface. Such a deposit, viewed at grazing emergence, has the appearance of a highly polished mirror of fairly high reflecting power.

The effect of grain size upon the amount of energy (diffusively) reflected from the surface is well illustrated in the present paper, which gives the reflecting power of a cleavage surface and of a coarsely ground surface of white marble. The cleavage piece (about 1 cm thick) was well illuminated throughout the interior, to the rear surface, owing to the large size of the individual crystals, some of which had cleavage faces 0.2 to 0.3 mm diameter.

The low reflecting power obtained by reducing the size of metallic particles (e. g., platinum black) to the dimensions of light waves is not so easily explained. If the black mass is a coagulation of colloidal metal, its optical properties (refractive index, etc.) are the same as that of the metal.[2]

Evidently it is not a question of roughness of surface, for a deposit of platinum black (upon a strip of platinum) when heated to a low red heat sinters into a white mass. By eliminating the high reflecting power platinum could become black by assuming a structure of fine particles, which consists of cavities with small openings. Such a condition would be realized if the material had the structure of a bundle of polished needles,[3] turned with their points toward the light. By multiple reflection the rays will travel down into the interstices between the needles (particles forming the spongy mass) and practically none will escape by reflection back upon their path. It is conceivable that by electrolysis the platinum black might be deposited in isolated points with relatively large spaces intervening, and that, as the electrolysis continues these points increase in height and diameter, thus forming a porous needle-shaped structure. This would increase the absorption of electrolytically deposited platinum black (as observed), but it does not fully explain the physical condition of the chemically precipitated material, unless we assume that the latter, which is colloidal, was built up in a similar manner by coagulation.

A more plausible explanation, alluded to by Kurlbaum,[3] is based upon the depth of penetration of the rays into the metal and the thickness of the reflecting layer. In order to obtain reflection a definite thickness of metal is required, which thickness is a function of the wave length of the incident light. Hagen and Rubens [4] determined the reflecting power of gold with thickness on the assumption that the layer is homogenous, i. e., not formed of discrete particles with intervening spaces of glass. They found that for a layer 0.01 μ in thickness the amount of light reflected was about 10 per cent of the total reflecting power for that wave length. The maximum thickness required for complete reflection of all

---

[2] Spence: Phys. Rev., 23, p. 233; 1909.

[3] Kurlbaum: Ann. der Phys. (3), 67, p. 855; 1899. Wood: Physical Optics, new ed., p. 449, Absorption by Porous Surfaces.

[4] Hagen and Rubens: Ann. der Phys. (4), 8, p. 432; 1902.

wave lengths was about 0.08 μ. The smallest particle of colloidal material, e. g., gold, observable in a microscope is of the order of 0.01 μ.[5] It is conceivable that there are colloidal particles which are still smaller, and that platinum black is made up of aggregations of these invisible particles. In this case it is conceivable that, if the thickness of the particle is less than the minimum thickness required in the transition layer to obtain reflection, then the rays will pass through the particle, diminished in intensity by the amount absorbed in the particle. This is the somewhat elaborated view taken by Kurlbaum (loc. cit.), who based his line of argument upon Stark's[6] investigations of the physical properties of soot. In a deposit of soot Stark considered the air a turbid medium containing the particles of soot.

Owing to the high absorption coefficient of metals the rays should therefore be completely absorbed in a thinner layer than is required in lampblack. Kurlbaum found that about 3.5 times as much (by weight) platinum black was required to produce the same absorption as in soot. Evidently not all of the individual particles of platinum black are of the minimum thickness required to avoid reflection or the material has some property as yet unknown. This is inferred on the assumption that the density and the thickness of the layer of these two materials is the same in the experiment, which was not the case. Evidently further investigations are necessary to decide these questions.

In the foregoing paragraphs we have noticed the most probable causes which are instrumental in producing these two extremes in diffuse reflection. In view of the fact that many of the insulators (optically transparent media, for the visible spectrum) have two types of absorption (reflection) bands in the infra-red, which sometimes fall within the spectral regions examined in the present investigation, it is important to notice the distinction between these two types of bands. For example, a plate of quartz is transparent to the visible spectrum, has absorption bands in the region of 4 μ, and a band of metallic reflection (of about 90 per cent) in the region of 9 μ. The apparently anomalous condition of a high (diffuse) reflection of the powder in the visible and at 8.8 μ and a low reflec-

[5] Burton: Phil. Mag., 2, p. 425; 1906. Spence: Phys. Rev., 23, p. 233; 1909.
[6] Stark: Ann. der Phys. (3), 62, p. 353; 1897.

tion at 4.4 μ is therefore easily explained; for in the region of 4.4 μ the surface permits the formation of "body color," as is true of pigments.[7]   In the region of 8.8 μ the high reflection in powdered quartz is owing to the coarseness of the grains.   If the grains were as fine as those of platinum black, one would expect the reflecting power in this spectral region to be as low as obtains in platinum black.   Similar conditions are to be observed in some of the pigments, e. g., litharge, yttrium oxide, and chromium oxide.

II. SUMMARY OF PREVIOUS INVESTIGATIONS

Three methods have heretofore been used in determining the amount of energy lost by diffuse reflection from rough surfaces. The first method is based upon the assumption that the diffusion follows the cosine law.   The amount of incident energy is measured; also the amount of energy reflected at a given angle from the normal.   By integration the total amount is obtained that is lost by diffuse reflection.   This method was used by Ångström.[8]   He used a surface bolometer at an angle of 40°, and found that for a thickly sooted platinum black surface the reflecting power varied from 0.82 per cent to 1.25 per cent, being apparently larger for the short wave lengths.   Practically the same method was used by Hutchins.[9]   With a radiomicrometer he investigated the cosine law of diffuse reflection of various substances.   He found that the diffusion from rough surfaces of such substances as magnesium oxide and plaster departed an appreciable amount from the cosine law, for large angles, while for paper this departure was very marked for angles between 20° and 60°.   By integration he found the total amount of energy lost by diffusion.

For a white surface, "plaster," using sunlight as a source of energy, the integrated value for the reflecting power (the albedo) was 92.7, for paper it was 82.6, and for a green leaf it was 30.2, which values are in fair agreement with the results of the present research.

Another method for obtaining the diffuse reflecting (the absorbing) power is to compare the emission of a heated surface with the

---

[7] See Wood's Physical Optics, new ed., pp. 441 and 439, Body Color and Surface Color.

[8] Ångström: Öfversight Af. K. Vetensk. Akad. Förhandlinger, Stockholm, **55** (No. 5), p. 283; 1898. Wied: Ann. der Phys. (3), **26**, p. 253; 1885.

[9] Hutchins: Amer. J. Sci., **6**, p. 373; 1898.

emission of a black body which is at the same temperature. This method was used by Crova and Compan.[10] They found that the loss by reflection from the soot of a candle flame varied from 0.68 to 1.25 per cent, and for a layer of the same washed with alcohol the loss was 3.17 per cent. Kurlbaum [11] used this method to find the absorption (emission) of different thicknesses of electrolytically deposited platinum black and of soot. For soot the maximum emission of 94.5 per cent was attained in a deposit containing about 30 mg per dm ^{2}; but using a thicker deposit of about 100 mg per dm ^{2}, the emission was only about 88 per cent of that of a black body. For platinum black the emission was only about 30 per cent for a deposit weighing 30 mg per dm ^{2}. The maximum emission of 96.8 per cent was attained in deposits weighing about 200 mg per dm ^{2}, which value remained constant for deposits weighing 300 mg per dm ^{2}.

He recommended that for measuring radiations of wave lengths up to 8 μ it is sufficient to deposit the platinum black for three minutes, using the current density and concentration of solution, etc., described on a subsequent page. According to the present method of investigation, in which the platinum black was produced by the same formula as used by Kurlbaum, the deposition of platinum black should be continued for five to six minutes.

The main objection to this method is that it gives values for the complete spectrum.

A third method is to place the reflecting substance and a radiometer at the conjugate foci of a hemispherical mirror. The incident radiation is introduced upon the reflecting substance by passing through a hole in the center of the mirror. This method is the easiest to employ, but it requires the determination of several correction factors, which, however, are constant quantities in the investigation. These corrections are (1) the amount of radiation which escapes through the opening in the mirror, and (2) the amount of diffuse radiation, which, in its course from the reflecting substance to the radiometer, is absorbed by the silver mirror.

Using this method Royds [12] carried out a series of measurements under the direction of Paschen. In view of the fact that the

[10] Crova and Compan: Compt. Rend., **126**, p. 707; 1898.
[11] Kurlbaum: Ann. der Phys. (3), **67**, p. 846; 1899.
[12] Royds: Phil. Mag., **21**, p. 167; 1911. Phys. Zs., **11**, p. 316; 1910.

present research was well under way when the results of Royds were published, and that the methods differ only in minor yet important points (the results being at considerable variance), it is of interest to notice this work in some detail.

Royds used a hemispherical mirror of German silver 5 cm in diameter. The Rubens thermopile and the blackened strip were placed side by side in the focus of the mirror and the incident energy (the image of an illuminated slit) was projected on either the strip or the thermopile by means of an external concave mirror. The thermopile did not present a completely opaque surface to the incident radiations and hence a great amount of the available energy could not be utilized. Moreover, the slit image after reflection from the diffusing surface may not be very sharp and it may not be uniformly illuminated. This is very marked in the transparent, "white," substances, in which much of the light is reflected at considerable distance below the surface so that the observat ons must be made upon the assumption that the distribution of the radiation (the "illumination") is the same in the slit image before and after reflection from the diffusing surface. This uniformity of illumination is probably of minor importance for black surfaces, but it is of considerable importance with white surfaces which may reflect as high as 90 per cent of the incident energy. Royds makes no mention of having tested his outfit with a white diffusing surface, e. g., magnesium carbonate, which gives a surprising amount of information in regard to the adjustments, the distortion and illumination in the slit image, etc.

Since the thermopile and the reflecting surface were stationary and the image of the illuminated slit was projected upon either one by means of an external concave mirror the arrangement of the apparatus did not permit the use of a cone of rays which filled the opening in the hemispherical mirror. This resulted in a further reduction of the available incident energy, so that in order to be able to measure the small amount of energy which is reflected from lampblack, a very sensitive ($i = 0.7 \times 10^{-10}$ amp.) galvanometer had to be employed. As a result he had to apply corrections for diffuse radiation from the incident image, and for energy radiated from the black surfaces as a result of warming from exposure to the incident radiation. No corrections were made for absorption

by the mirror nor for the opening in the mirror, which correction he says could not be estimated. The various corrections to his observations were such that his "apparent" values are two to three times his "true" values. His "apparent" values are usually in fair agreement with results obtained in the present paper. He examined the spectral regions of 0.95, 8.8, 25, and 52 μ, but owing to the great impurity of the radiations in the last two spectral regions the observations can not be given much weight.

III. APPARATUS AND METHODS

In designing the present apparatus the attempt was made to utilize the maximum amount of the available energy. This permitted the employment of a galvanometer of low sensitivity, which eliminated such corrections as necessarily result when using a very sensitive radiometer. For example, the correction used by Royds for the diffuse energy falling upon the thermopile caused by the reflection from air particles when the incident radiation is directed upon the lampblack was nil in the present investigation. The utilization of a large amount of the available incident energy resulted from (1) the employment of a large hemispherical mirror which permitted the use of a large incident slit image and a large reflecting surface without distortion; (2) the use of a radiometer which intercepted the whole slit image; (3) the use of a beam of radiations which filled the opening in the hemispherical mirror, which was made possible by shifting the thermopile and the diffusing surface instead of shifting the slit image, as was done by Royds. The main objection to moving the thermopile from its position at the conjugate focus of the reflecting surface, p, Fig. 1, A, to the position, c, occupied by the reflecting surface, which is necessary in order to determine the intensity of the incident radiation, is the shift of the galvanometer reading owing to differences in emissivity and in temperature in the two positions. This is not marked, however, at the low galvanometer sensitivities used in the work.

The apparatus resulting from the foregoing considerations proved far more sensitive than was expected, so that for all spectral regions investigated (excepting at 24 μ) the galvanometer,[13] of 5.09 ohms resistance, was used on a complete period of two to three

---

[13] This Bulletin, **9**, p. 7; 1912.

seconds and a sensitivity of about 1×10^{-9} ampere. For the spectral region of $24\ \mu$ the complete period of the galvanometer was from four to five seconds, the corresponding sensitivity being about 4×10^{-10} ampere.

The ability to use a short-period galvanometer afforded a great saving in time. In fact, the time was consumed mainly in waiting for the optical system to come to temperature equilibrium after mounting a specimen in the hemispherical mirror. This, however, was not a serious matter, owing to the low radiation sensitivity required in the work.

1. **The Thermopile.**—The thermopile consisted of 22 junctions of bismuth and silver [13] mounted in a space 10.5 mm long, as shown at p, Fig. 1, A, and Fig. 1, E. Its width was 5 mm and its resistance was 10.8 ohms. The individual junctions were made of bismuth wire 0.1 mm in diameter and silver wire 0.0513 mm diameter, mounted upon an ivory support, i, as shown in Fig. 1, E. The wires leading to the galvanometer are attached to the binding posts $b\ b$, Fig. 1. The thermopile was blackened with a mixture of lampblack and platinum black, then smoked with soot from a sperm candle. It was covered with a sheet of glass 0.095 mm in thickness, for observations in the spectral region to 0.95 μ; and with a plate of clear rock salt 0.8 mm in thickness for the longer wave lengths. The use of a receiver that intercepted the whole slit image eliminated the question of distortion and uniformity of illumination. In the incident slit image the rays are received in practically a normal direction upon the thermopile. In the slit image, formed from the rays reflected from the diffusing surface, the rays fall upon the thermopile at all angles of incidence. The only assumption which is made is that the difference in the loss by reflection from the thermopile and the window is negligible in these two measurements.

2. **The Hemispherical Mirror.**—The diameter of the hemispherical mirror, which was made of glass, was 10 cm, and the opening for admitting radiation upon the thermopile was 10 by 20 mm.

The arrangement of the mirror in the mounting is shown in Fig. 1, B. The support for the thermopile and the substance to

be investigated was mounted upon a movable stage, *d*, *S*, which in turn was mounted upon a brass plate, which was provided
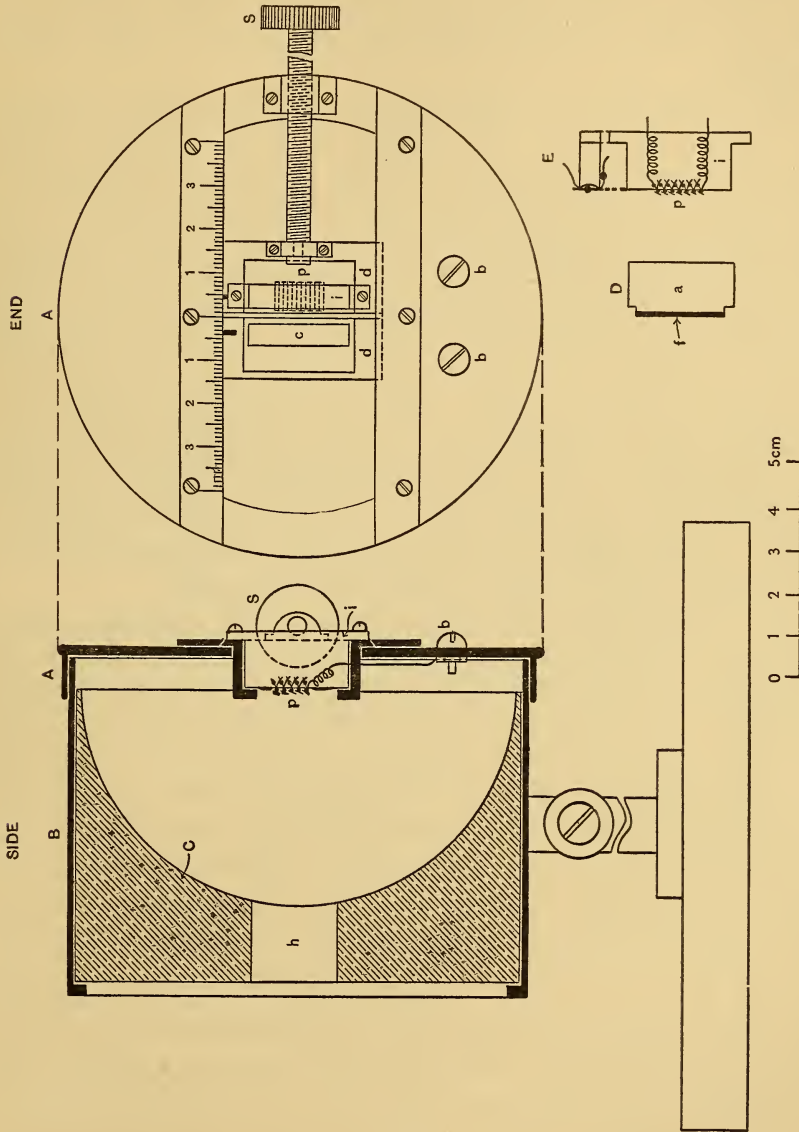

Fig. 1

with a wide flange, Fig. 1, *A*. By slightly tilting this brass plate, *A*, upon the support, *B*, it was possible to focus the slit image of

the radiations reflected from the diffusing surface, f, Fig. 1, D, upon the thermopile, p. This adjustment of focus was necessary for specimens which did not fit nicely in the place occupied by the brass block, a, upon which the substances, f, were usually mounted.

The distance (6 to 7 mm) between the centers of the incident slit image (falling upon the surface, c) and its reflected image upon the thermopile, p, Fig. 1, A, was made as small as possible in comparison with the size of the hemispherical mirror. Previous tests with a Nernst glower 10 mm long showed no distortion of the image of the glower for a displacement of 1.2 cm from the axis of the mirror. However, in the slit image of the light reflected from the diffusing surface the illumination did not appear so uniform, and there appeared to be more abberation at the ends of the slit image. This was especially marked in a cleaveage piece of marble, from which the reflected slit image was surrounded with a hazy illumination. A piece of white cardboard with an opening 5 by 10 mm was placed over the thermopile. This facilitated in focusing and in determining that all the diffusely reflected light fell upon the thermopile.

These adjustments were made with a white diffusing surface (of Al_2O_3 of $PbCO_3$) of the same thickness as the lampblack surfaces, which, owing to its high reflecting power, produced a bright slit image. In this manner the effect of change in focus upon the amount of radiation falling upon the thermopile was investigated.

3. The Optical System.—The arrangement of the optical parts of the auxiliary apparatus is shown in Fig. 2, which shows the hemispherical mirror, A, containing the reflecting substance, f, and the thermopile, p. The cylindrical acetylene flame was at a and the Bunsen flame, or Welsbach mantle, was at b. The shutters, d and e, were made of thin sheet aluminum (10 by 15 cm), with an intervening layer of asbestos about 3 mm in thickness. They were bright on the front side and painted black on the side toward the thermopile. A large water-cooled diaphragm, with an opening 5 cm in diameter, was placed at C, and all of the apparatus to the right of C, Fig. 2, was inclosed to exclude stray light. A flame placed back of a large plate of sheet iron with a slit, s,

represented the source of energy. An image of this slit was pro-
jected into the hemispherical mirror by means of a large concave
mirror, B (17 cm diameter, 100 cm focal length), or by means of a
triple achromatic lens, L, having a diameter of 6 cm and a focal
length of 18 cm. In the latter arrangement, which was used in
the first observations at 0.6, μ the slit, s, and flame, a, were of
course placed on the axis of the lens, L.

The arrangement of the two flames, a and b, the concave mirror,
B, and the plane, silver on glass, mirror, M (with or without an
absorption cell, c), as shown in Fig. 2, permitted the measurement
of the radiations at 0.60, 0.95, and 4.4 μ in succession before
changing a specimen. For isolating the radiations at 8.8 μ two
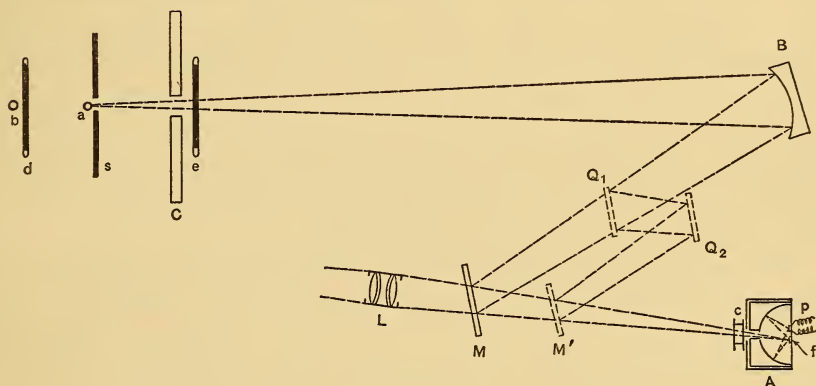
Fig. 2

quartz plates, 5 mm in thickness (ground and blackened on the
rear side) and the silver mirror, M', were placed as shown at Q_1
and Q_2. Two fluorite plates were placed at Q_1 and Q_2, respec-
tively, for isolating the radiations at 24 μ. The proper positions
of these mirrors were obtained by focusing with silver on glass
mirrors at Q_1 and Q_2, respectively.

The beam of light did not entirely fill the opening, h, in the
hemispherical mirror, so that by slightly turning the mirror, B,
about a vertical axis it was possible to change the angle of inci-
dence of the radiations and project them upon different parts of
the reflecting surface, f, which usually was about 6 mm wide and
from 12 to 20 mm in length.

The material to be examined was usually mounted upon a brass block, *a*, Fig. 1, *D*, which was 25 by 6 by 10 mm, which was inserted in the opening, *c*, in the stage, *d*, Fig. 1.

The arrangement of the shutter, *d*, and the gas mantle, *b*, at a distance of about 15 cm from the slit, *s*, Fig. 2, prevented the latter from becoming warm and radiating upon the thermopile which would happen when the water cell, *c*, was not in place. When the gas mantle or the Bunsen flame were used (for radiations at and beyond 4.4 μ) the acetylene flame was of course extinguished, the shutter, *e*, was kept raised, and the absorption cell, *c*, was removed.

When using the triple achromatic lens for projecting the slit image, the size of the opening in the sheet of metal, *s*, which formed this slit was 1.5 by 7.5 mm and the image was practically the same size. Owing to the large angle of incidence there was some astigmatism in the image produced by the concave mirror. The slit was therefore reduced to 7 by 2 mm and finally to 7 by 1.5 mm. In all cases the image of the slit at *f* was about 8 by 2 mm, hence there was no danger of the radiations falling outside of the thermopile, especially after reflection at *f* and refocusing at *p*, Fig. 2, when the slit image was not very sharp.

The method of determining the reflecting power consisted in observing the galvanometer deflection when the radiations were projected upon the specimen at *f*, and after reflection therefrom were focused upon the thermopile at *p*; then, moving the stage, *s*, Fig. 1, until the thermopile occupies the position of *f*, observing the galvanometer deflection for the direct slit image. The ratio of the reflected radiations to the direct radiations (in galvanometer deflections) gives the reflecting power. The observations were duplicated for most of the substances. This is especially true for the radiations at 0.65 μ where the triple achromatic lens and also the concave-mirror arrangement were used for projecting an image of the slit upon the substance; also for the radiations at 0.95 and 4.4 μ, using the concave mirror for projecting the slit image. In the final work many of the original observations were repeated at 0.95 μ and 4.4 μ (using the two flames and shutters as already described) before removing the specimen, and the results were found in excellent agreement. Throughout the work the various specimens were kept covered to prevent the deposition of dust.

The source of radiation usually remained constant to 1 part in 200 for several hours.

4. Regions of the Spectrum Examined.—The reflecting power of various substances was found for the following regions of the spectrum:

1. That part of the radiation of an acetylene (cylindrical) flame which is transmitted through a 1 per cent solution of cupric chloride [14] 2.5 cm in thickness. Such a solution is opaque to all radiations lying beyond 0.7 μ. The energy curve of this transmitted radiation does not differ markedly from the solar energy curve. The maximum of the transmitted energy lies at 0.6 μ.

2. That part of the radiation from an acetylene flame which is transmitted by a 1 per cent solution of cupric chloride 2.5 cm in thickness and a plate of green glass 2.5 mm in thickness. The transmitted radiation is fairly monochromatic, the maximum being at 0.54 μ.

3. The radiation of an acetylene flame which is transmitted through a 2 cm layer of water. The water cell transmits uniformly all the visible and part of the infra-red to 1.4 μ. The maximum of the energy curve of the transmitted radiation lies at 0.95 μ. By using a plate of red glass 2 mm in thickness, as indicated in the tabulated data, the radiations are more homogeneous, extending from 0.67 μ to 1.4 μ.

4. The radiation from a Bunsen flame which consists of a small emission band at 2.7 μ and a very strong band at 4.4 μ. About 90 per cent of the energy emitted by a Bunsen flame lies at 4.4 μ.

The purity of the maximum emission was tested with a thick plate of glass which is opaque to radiation lying beyond 3.5 μ. A sheet of plate glass 8 mm in thickness transmitted 5.8 per cent and a sheet 15 mm in thickness transmitted 3.7 per cent of the radiation from the flame. From this it appears that the homogeneity of the Bunsen flame radiation at 4.4 μ is not seriously affected by the weak radiations at 1.9, 2.7, and 5.3 μ.

5. The residual rays from quartz. The source of energy was the radiation from a Welsbach mantle which was reflected from two surfaces of quartz, which has two intense bands of selective reflection at 8.50 and 9.05 μ, respectively. The mean of the energy

---

[14] This Bulletin, **7**, p. 619, 1911, and **9**, p. 110, 1912.

curve is at 8.8 μ.   The maximum of this radiation was very homogeneous, only 0.43 per cent of the total radiation being transmitted by a glass plate 1.5 mm in thickness.   The glass plate transmitted radiations to 4.5 μ, beyond which point, up to 8 μ, the reflecting power of quartz is extremely low, and throughout this region of the spectrum the radiation from the gas mantle is very weak.

6. The residual rays from fluorite.   The source of energy was an incandescent gas mantle, the radiation from which was reflected from two plates of fluorite.   The maximum of the energy curve was fairly homogeneous, 1.5 per cent being transmitted by glass (opaque beyond 4.5 μ) and 7.8 per cent being transmitted by a plate of fluorite 1.5 mm in thickness, which is opaque beyond 10 μ.   The homogeneity could have been increased by adding another reflecting surface of fluorite, but it would have been at a sacrifice of the total energy available.   Most of the black reflecting surfaces examined increase in reflecting power with wave length.   Hence it is to be inferred that the observed values would be a trifle higher than here observed if the radiation had been more homogeneous.   This is of minor importance, owing to the variation in reflecting power of the different samples of the same substances.   The thermopile was covered with a plate of rock salt 0.8 mm in thickness, which is opaque to radiations beyond 30 μ; hence the maximum of the residual rays is shifted from its true position to about 24 μ.

5. **Corrections to Observations.**—A part of the energy reflected from the substance under examination escapes through the opening which admits the radiations into the mirror.   The amount of energy thus lost was determined experimentally by covering temporarily a part of the silvered surface adjoining the opening by means of a thin sheet of aluminum blackened in an acetylene flame.   The aluminum sheet was bent to fit the curvature of the mirror, and the area of the blackened surface was 10 by 20 mm.   When not in use, this blackened surface was withdrawn through the opening in the hemisphere.   The experiment consisted in noting the amount of energy (in galvanometer deflections) reflected from a layer of lead carbonate *with* and *without* the blackened surface in place within the hemisphere.   The ratio of the galva-

nometer deflections in four complete series of observations varied from 97.1 to 97.5 per cent with a mean value of 97.3 per cent. On the assumption that, in the region occupied by the black surface, the illumination differs by a negligible amount from the value for the center of the mirror, the amount of energy lost by escaping through the opening is about 2.7 per cent of the total energy diffusely reflected within the hemisphere.

A further correction is necessary for the absorption of the diffuse radiations by the silvered surface of the hemispherical mirror. This correction, which depends upon the spectral region observed, was determined by placing a newly silvered plane mirror in the place occupied by the diffusing surface, *f*, Fig. 2, and at *c*, Fig. 1, *A*. This plane mirror was placed at the proper angle to reflect all the incident energy upon the interior of the hemispherical mirror and from thence upon the thermopile. The ratio of the galvanometer deflection for the energy reflected from the silvered surface to the deflection for the energy falling directly upon the thermopile gave the reflecting power of the two silver surfaces and the square root gave the value sought for a single reflecting surface. These values of the reflecting power, determined by this method, are in excellent agreement with the values obtained by the methods previously employed by other observers. The values of the reflecting power of silver, for the spectral regions employed, are given in Table I. In this same table are given the complete correction factors with which the observed (the "apparent") reflecting power of the various substances was multiplied in order to obtain the "true" (the absolute) values recorded in these tables. These factors are the reciprocals of the products obtained by multiplying the reflecting power of silver by the per cent of diffuse energy (97.3) which is intercepted by the hemispherical mirror. The silvered surface being well protected does not tarnish, so that these correction factors are constant for the investigation.

The corrections used by Royds, viz, (1) the correction for extra radiation falling upon the thermopile, as the result of scattering by air and dust particles when the incident radiation was projected upon the diffusing surface, and (2) the correction for reradiation upon the thermopile, as a result of warming of the diffus-

ing surface by the incident radiation projected upon it, were nil in all cases except when very thick (0.3 to 0.4 mm) layers of lampblack were examined. The thick lampblack surfaces seemed to become heated when they appeared to radiate upon the thermopile. To the eye they were just as black as thin deposits of (acetylene) soot. Nevertheless, they apparently reflected from 2.5 to 2.8 per cent at 0.95 μ and 4.4 μ, and 8 to 12 per cent at 8.8 μ. A thin deposit of soot which appeared equally black and examined at the same time would reflect less than 1 per cent. The lampblack paints also reflected about 3 per cent, and they appeared very much lighter (reflected more of the incident radiation upon the thermopile, as could be observed visually) than the soot deposits. To prevent radiations of the heated thick films of soot from falling upon the thermopile, a thin (0.09 mm) sheet of glass was placed over, and about 1 mm from the surface of, the deposit of soot. The reflecting power of the thick layer at 0.95 μ was then reduced from 2.7 per cent to 1.08 per cent, which is about as low a value as was observed on a thinner film in which the conductivity to the brass block was effective. It was evident that the high values found for the reflection were caused by reradiation, and no attempt was made to examine very thick films, such as used by Royds. The thickness of the deposits of soot were of the order of 0.1 mm, which was found by experiment sufficient to absorb the maximum amount of radiation. The presence of stray radiations was also tested. For this purpose the reflecting surface (brass block) was removed from the carrier, *d*, Fig. 1, and the radiations coming through the opening, *h*, in the hemispherical mirror were permitted to pass out through *c* to the rear of the apparatus and fall upon a piece of black velvet. This test was applied at various times in the different spectral regions used and at various galvanometer sensitivities, but no deflection (as large as 0.1 mm) could be observed which was caused by radiations scattered by air and dust particles. The galvanometer could be read to 0.1 mm. The smallest deflections observed by reflection from the blackest surfaces were from 8 to 10 mm, and usually they were much larger. Hence, if there had been corrections such as observed by Royds, they could not have escaped notice. As mentioned elsewhere, the apparatus was designed so

as to require a low radiation sensitivity, which eliminated these corrections, and the accuracy which one could easily attain was 1 part in 200 to 400. Evidently from the nature of the material it would have been illusory to attempt a higher accuracy. As an illustration of the accuracy attainable on a low reflecting power substance, the values found for platinum black (No. 16, Table II) may be cited. Two determinations on different days gave, respectively, 2.71 and 2.75 per cent for the reflecting power.

IV. REFLECTING POWER OF LAMPBLACK

The experimental results obtained in this research may be briefly portrayed by means of tabulated data and by brief comments relating thereto. As found by others, all sorts of lampblack (soot) surfaces can be prepared, differing in reflecting power, for the same flame and for different flames. The most permanent coatings are of course layers of paint made by mixing lampblack with turpentine, or, if the latter dries too slowly, with turpentine and alcohol. A weak alcoholic solution of shellac gives a much more grayish appearance to lampblack, as shown by the highest values obtained in Table I. But the reflecting power of the paint is so high that it is a question whether it might not be better practice to resmoke radiometers when the soot comes off.

Owing to the fact that many of the soot deposits became soiled before they could be examined in another spectral region, and also to the fact that in any given spectral region various deposits of soot were examined when they were removed from the brass blocks to be replaced by others, but few of the same deposits were examined in more than two or three parts of the spectrum. Hence (for clearness) Table I differs from the other tables in that the observations of reflecting power upon the same film in different spectral regions are joined by dotted lines. The additional observations in any spectral region, e. g., sperm candle, at 8.8 μ, are recorded without any special reference to the other observations.

Various experiments were performed on lampblack paints prepared from commercial lampblack. The best (purest) material gave reflecting powers varying from 2.9 to 3.1 per cent at 0.60 μ. This is in agreement with results obtained by depositing soot from burning camphor in a "watch crystal" and working it into a

smooth paint with turpentine.   As shown in Table I the reflecting power of lampblack paint is fairly uniform in the region of 4 to 8 μ, and a fair correction factor for (diffuse) reflection from a radiometer is from 3.3 to 3.5 per cent.

Finely ground boneblack, although having a very brownish color, becomes quite black (R about 1.5 per cent) when the turpentine has not thoroughly dried.   From this it would appear that if the proper vehicle could be found it might be a much darker paint than ordinary matte lampblack paint.

The deposits of soot from the different flames were "hot" when the brass block was drawn through the flame or "cold" when the flame was cooled by a sheet-iron funnel with an opening 1 by 10 mm at the top through which the smoke issued and over which the brass block was held.   The cold deposits usually had a higher reflecting power than the hot deposits.   As already mentioned, layers 0.05 to 0.1 mm in thickness usually produced a maximum absorption.   Thicker films gave higher "apparent" reflecting powers; but this was owing to heating of the surface, as the result of lack of conduction to the brass block, which then radiated upon the thermopile.

Some of the samples of soot appeared to have a slightly higher reflecting power in the visible than in the infra-red, as was shown by repeated measurements upon the same film.   In the case of the deposit of soot (from a sperm candle) upon the layer of platinum black, No. 19, Table II, the reflecting power is considerably higher at 0.95 μ than at 4.4 μ.   Whether this is due to the structure of the material, depth of penetration (which is a function of the wave length), and consequent variation in conductivity, is unknown. It does not appear unreasonable to suppose that for visible radiations which do not penetrate deeply the surface might become hotter (hence reradiation to the thermopile) than it would for the same amount of energy of wave lengths at 4.4 μ, which penetrates more deeply into the layer of soot, hence is absorbed nearer the brass surface, where conditions are more favorable for heat conductivity.   It so happened that for the spectral regions of 0.95 μ, 4.4 μ, and 8.8 μ the incident radiation was of practically the same intensity.

In all cases the blackest obtainable deposits of any given source were investigated. The paraffin candle was discarded because of the difference in the boiling points of its constituents. The deposits were usually whitish. The rosin was burned in a sperm candle and it, as well as camphor (which burns without the presence of other ingredients), tends to give granular brownish deposits having a reflecting power of about 1.3 per cent in the visible spectrum. The cold deposits from a standard candle are fairly uniform, reflecting about 1.25 per cent. The "hot" deposits are much blacker and reflect about 1 per cent. Viewed at grazing emergence the surfaces appear as smooth as polished mirrors.

The blackest obtainable "hot" deposits were made in the acetylene flame, the lowest observed reflecting power being 0.42 per cent and the average deposit reflecting power being about 0.6 per cent at 0.6 μ. The "cold" deposits, obtained by holding a piece of sheet iron against the flame and allowing the resultant smoke to deposit upon the brass block, give somewhat higher reflecting powers, which are of the order of 0.8 per cent. None of these deposits have the brownish appearance to be observed in all deposits of soot from burning camphor. All these deposits were obtained by using standard burners. To test the effect of combustion without air being mixed with the gas before ignition, a glass tube was drawn down to a point which then formed the "burner." The flame emits, of course, a dense cloud of smoke. The deposit upon the brass block was smooth and brownish in color, similar to camphor soot. The reflecting power (see Table I, Acetylene, "no air") was 1.33 per cent, which is the average value of camphor soot.

In a previous paper [15] which gives data on the absorptivity of an acetylene flame attention was called to the peculiar selective absorption band in the visible spectrum which was similar to bands found in metals—e. g., nickel and platinum—which are in a colloidal state. Moreover, in the beginning of this paper attention was called to the seemingly colloidal properties of platinum black. Platinum black and acetylene soot are the blackest substances yet recorded, and of these the acetylene soot has the

---

[15] This Bulletin, 7, p. 243; 1911.

greater absorption. It is not unreasonable to consider the carbon particles (and the platinum in the electrolyte) to be in the colloidal condition at the instant of disruption of the gas molecule. In the hottest part of the flame one obtains the finest particles— i. e., the blackest surfaces. These surfaces viewed at grazing emergence appear as perfect mirrors having a high reflecting power.

Acetylene soot has a very low heat conductivity, which permitted warming of the superficial layers of a thick deposit of soot. The temperature rise was sufficient to cause reradiation upon the thermopile, and, as explained elsewhere in this paper, the apparent reflecting powers at 4.4 to 24 μ were of the order of 2.6 to 3 per cent, when an equally black, thin film reflected less than 1 per cent. By placing a thin sheet of glass in front of the thick film (this was possible for the region of 0.95 μ without disturbing the adjustments), which absorbed all the radiations of long wave lengths, the reflecting power was reduced from 2.6 per cent to 1.08 per cent, showing that the high value was erroneous. In practice a radiation instrument should therefore be covered with a film of acetylene soot which is less than 0.15 mm thick.

The blackest deposits of soot are obtained by holding the metal plate in the flame. But this will be rarely possible with radiation instruments. Furthermore, unless one constructs a special burner it is not possible to blacken large surfaces in the flame without having them streaked with grayish colored material. One must therefore use cold deposits and standard material. The standard sperm candle is the most promising source, the reflecting power of the blackest surfaces being about 1 per cent in the visible spectrum, which is the order of accuracy of radiation work at the present day. It is difficult to remove fine dust from these surfaces; hence it appears advisable to use a hemispherical mirror to intercept the diffusely reflected rays.

For the absorbing surface of a secondary radiometer which has been calibrated against a primary standard it seems desirable to use the best quality of lampblack paint, the vehicle being a volatile turpentine. If the turpentine has polymerized and dries slowly, then a mixture of turpentine and alcohol should be employed. The turpentine is of course used simply to render the

lampblack adhesive, and it is used instead of the dilute alcoholic solution of shellac because, as already mentioned, the latter tends to produce a grayish surface. All these surfaces are of course perfectly matte. The lampblack paint is easily freed from dust, hence is to be preferred to soot when the instrument must be operated in the open air.

V. REFLECTING POWER OF PLATINUM BLACK

The electrolytic deposits of platinum black were deposited upon sheet platinum 0.02 mm in thickness and having an area of about 0.5 by 5 cm. These platinum sheets were then mounted upon the brass blocks already described by means of Khotinsky cement. The first surfaces were made from a solution of platinum chloride, which usually gave grayish deposits. After many attempts which included Nos. 4 and 5, Table II, a new solution of chloroplatinic acid was prepared by dissolving a known weight of platinum (4 g of sheet platinum) in aqua regia. This material was evaporated to as near dryness as was possible over a water bath. This evaporation process was repeated after adding hydrochloric acid. The resulting material, which is a thick reddish sirup, contained 8.3 g (theoretical value) of H_2PtCl_6. From this a solution of the proper concentration recommended by Kurlbaum [16] was made up, viz, 5 g of $H_2Pt Cl_6$, 150 g of water, and 0.04 g of lead acetate. The deposits of platinum black were made by passing a current of 0.03 ampere per cm² of exposed surface, the time being varied from one to seven minutes. By occasionally jarring the electrodes the escape of gas bubbles was prevented. This procedure seemed to assist in forming black deposits. The cathode (strip to be blackened) was, of course, placed between two strips of platinum, which formed the anode. The distance between the anode and cathode was about 2 cm. The platinum strips were made sufficiently long and every other precaution was taken so as not to contaminate the solution by contact with the copper leads.

The manner in which the reflecting power decreases with increase in thickness of the deposit is well illustrated in the samples, Nos. 14 to 20, given in Table II. The reflecting power

---

[16] Kurlbaum: Ann. der Phys. (3), **67**, p. 846; 1899.

is a function of the wave length, a much thinner deposit being required to produce a maximum absorption for the spectral region of 4.4 μ than for the region of 8.8 μ. At normal incidence the thin deposits appear darker and more velvety than the thick ones, but a slight deviation from the normal increases the reflecting power, as illustrated in No. 4 at 8.8 μ. Moreover, some of the very dark velvety thick deposits tend to give high values beyond 4.4 μ, although they show an abnormally low reflection in the visible spectrum. This was definitely determined by repeated tests on No. 16, which was similar in appearance to No. 17. To the eye No. 16 appeared slightly darker than No. 12. The deposits Nos. 18 and 19 were on the opposite sides of a strip of platinum, deposited at the same time. The reflecting powers (1.78 and 2.13 per cent, respectively) are considerably different at 8.8 μ. Of course this is quite a severe test of reproducibility. Deposits that were continued for more than seven minutes became rough and nodular. From Table II it may be noticed that the deposition of platinum black should be continued for at least five minutes to obtain a maximum absorption at 4.4 μ; and the best practice is to continue the process six to seven minutes, when the maximum absorption is attained at 8.8 to 24 μ. The reflecting power then rises gradually from about 1 per cent in the visible to 3 per cent at 24 μ.

The deposits are quite adhesive, so that if kept free from dust the reflecting power changes but little with age. This is illustrated in the two series of measurements on Nos. 18 and 20 at 4.4 μ, which were reexamined after an interval of about a month, when the apparatus was entirely readjusted and different-sized slit images were used. The ever-present particles of lint were first removed by blowing gently with the breath. In the second set of measurements on Nos. 18, 19, and 20 the observations at 0.95 μ and 4.4 μ were made in succession before removing the specimen. It is, of course, to be understood that owing to the labor involved in making the adjustments of the quartz and fluorite plates the regions of 8.8 μ and 24 μ were examined separately. Hence, the specimens were all examined in succession at 8.8 μ before turning to the region of 24 μ.

The deposit No. 19 was smoked with soot from a sperm candle, which raised the reflecting power in the visible spectrum without materially affecting the region of 4.4 μ.

Chemically precipitated platinum black was also examined. It is quite brownish in appearance. One of the three samples was a layer of the material pressed upon the brass block, as already described. The others were painted on the brass plates by means of a solution of alcohol and turpentine, which dries quicker than turpentine. In both cases the reflecting power is high (2 per cent) in the visible, increasing to 12 per cent at 24 μ. This is owing to the property of the material and not to the thickness of the layer. The thickness of the layer in the various samples examined varied from 0.1 to 0.3 mm. By mixing lampblack and platinum black, equal parts (by bulk), and applying it as paint the reflecting power is raised in the visible and reduced at 24 μ. This specimen was then covered with soot and the reflecting power was reduced to about 1.4 per cent. Although the reflecting power is now more uniform throughout the spectrum, it is not more so than the electrolytic deposit, which reflects only about one-third as much energy. Hence the precipitated material or mixtures of the same are less desirable than the best obtainable lampblack paints. (See Table I.)

With lampblack difficulty was experienced in making measurements owing to reradiation, which resulted from the low heat conductivity and consequent heating of the thick layers of soot. This was not experienced in platinum black owing to better thermal conductivity. The glass window over the thermopile absorbed this reradiated energy from the black surfaces. In the case of platinum black (which was more thoroughly studied than soot because it gives more permanent surfaces) the reflecting power at 0.95 μ was determined with a glass and with a rock salt window on the thermopile. The values are in perfect agreement, showing that there was no reradiation upon the thermopile when the rock salt window was used. The values are therefore to be considered reliable, and the slight variations in the reflecting power observed in the table are owing to differences in the structure of the deposits. Even with the new solution one of the

deposits came out quite grayish in appearance. This seemed to have been caused by excessive agitation of the electrolyte to keep the electrodes free from the stream of gas bubbles.

An examination of 6 surface bolometers (12 branches or 24 surfaces), purchased from instrument makers, showed that all the herein-described deposits of platinum in which the deposition of platinum black was continued for at least 4 minutes, were better than the surface of the best of these bolometers. The bolometer surfaces (even the thick deposits) showed bright spots where the metal was exposed. One bolometer had a thin deposit, similar to the 1 to 2 minute deposits shown in Nos. 13 and 14, Table II. From this the conclusion is to be drawn that the correction for diffuse reflection from a commercial surface bolometer is from 2.5 to 3 per cent or perhaps as high as 5 per cent. In fact, with the improved facilities now at hand, it is better to obtain new data on the total radiation of black bodies rather than attempt to correct the old data, which are now of historical interest.

With this end in view, now that the present research is completed, it is purposed to use the knowledge gained as well as the hemispherical mirror and thermopile in obtaining data on the constants which enter into the Stefan law of total radiation.

VI. REFLECTING POWER OF GREEN LEAVES

The first examination of diffuse reflecting power of growing leaves was undertaken in May, 1908, the apparatus employed being a bolometer, a mirror spectrometer, and a fluorite prism. The leaves were mounted upon a holder beside a silver comparison mirror, and the observations were carried out in the same manner as was employed in the determination of the reflecting power of plane mirrors.[17] The angle of incidence was 45°, and the distance of the reflecting surface to the spectrometer slit was about 6 cm. The source of light was a Nernst glower. The values thus obtained are of course only relative for the different wave lengths. The observations extended to 3μ (see Fig. 3), and in all cases there appeared to be a decrease in the amount of energy reflected with increase in wave length. This seems plausible, for the increase in opacity with wave length beyond

---

[17] This Bulletin, 2, p. 457, 1906, and 7, p. 197, 1911.

1.4 μ, which obtains in water, would decrease the amount of radiation that can return by internal reflection. The curve "Red Oak, II a," was obtained after the sample "Red Oak, II," had remained upon the spectrometer overnight, when considerable of the moisture had evaporated. It is therefore to be expected that the reflecting power would be less than when the cells contained moisture.

For magnesium carbonate the decrease in reflecting power with increase in wave length might result from a decrease in refractive
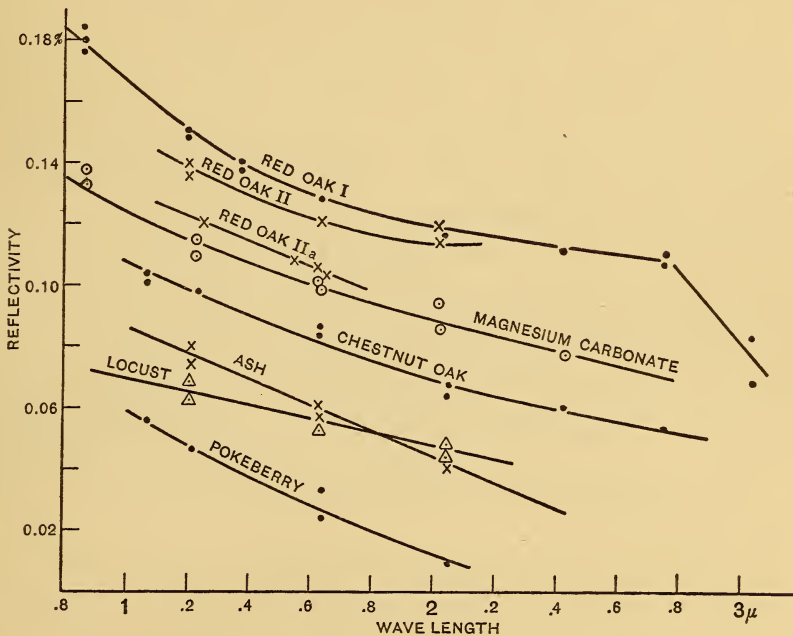
Fig. 3.—*Reflecting power of green leaves*

index, which obtains in all similar "transparent media." This decrease in reflecting power is more noticeable in the region of 4.4 μ.

In this year's work, unless otherwise noted, the green leaves were examined in the latter part of May. The oldest (darkest green) leaves were selected, which were entirely free from injury. The reflecting power is somewhat less for the fully matured leaves of the oak and the tulip tree, Table III, gathered in July. The clover, locust, laurel, and lilac leaves appeared well matured when examined.

From Table III it appears that vegetation reflects about 25 per cent of the solar rays. The value may be a little higher than this, for the absorption cell used with the acetylene flame produces an energy distribution, which is somewhat richer in red and infra-red rays than obtains in average sunlight. This value can not greatly differ from the true one, however, for using monochromatic radiation corresponding closely with the color of leaves (green glass; $\lambda = 0.54 \mu$), the observed reflecting power of clover, lilac, and tulip tree leaves is not much higher than for the composite rays which have a maximum at 0.60μ. These tests were of course applied on the same leaf by simply placing a green glass before the absorption cell. The mullein leaf gave surprising results, the reflecting power differing but little from that of other leaves. Because of the densely wooly surface the expectation was to observe a high reflecting power. Evidently the tomentous covering contributes but little in raising the reflecting power. This is of interest in connection with desert plants having a wooly covering. The transmission was difficult to observe owing to the warming of, and the consequent reradiation from, the leaves upon the thermopile. The leaf to be examined was placed over the thermopile, the distance between the two being about 1 mm to avoid heat conductivity to the thermopile. The transmission of a leaf (after correction for reflection) is about 20 per cent, Table III. The two kinds of leaves, lilac and locust, differed considerably in thickness.

According to the measurements of Brown and Escombe [18] the absorption of leaves is 68 to 69 per cent of the total solar energy. Their values for the loss of solar radiation by transmission through the leaf are of the order of 30 per cent, depending, of course, upon the kind of leaf. These values are in fair agreement with present observations, considering the nature of the material and the apparatus used. Brown and Escombe (loc. cit.) have also published values for the total energy expended in internal work, viz, the energy used for photosynthesis (about 1.5 per cent) and the energy used in transpiration of water (10 to 60 per cent, depending upon the kind of leaf). They found that the maximum temperature excess above its surroundings to which a growing leaf can be raised in still air and exposed to the sun is about $0°.02$.

---

[18] Brown and Escombe: Proc. Roy. Soc., Lond., B, 76, p. 29; 1905.

All these data are very instructive when compared with the reflecting power of building material, e. g., brick, marble, granolith, and asphalt, given in Table V. In the latter the energy absorbed is not utilized in internal work, and the temperature may rise a very considerable amount, the rise depending upon exposure to wind, etc. Hence in marked contrast with vegetation, when the sun is obscured or has set, the building material continues to reradiate the energy absorbed during the daytime.

It is beyond the scope of this paper to discuss the economic importance which would result from the application of these data. Suffice it to say that until traffic demands the full width, a considerable portion of the total width of a street and sidewalk should be occupied by trees and grass instead of asphaltum and granolith. The same thing is true of observatories, which should be surrounded with thickly growing vegetation, such as Norway pine and dwarf evergreens. Evergreen trees which are not too tall to interfere with telescopic work should stand thick and close to an observatory, so as to shield it from the sun.

The reflecting power of a green leaf in different spectral regions is given in Table V. The reflecting power is much higher for an old leaf from which the chlorophyll has disappeared. A bright yellow undried leaf of the tulip tree reflects almost half of the incident light, Table III.

VII. REFLECTING POWER OF PIGMENTS

The powdered material was mounted upon the brass block, Fig. 1, *D*. In some cases the material was moistened with water containing a trace of gum arabic, but there was difficulty in causing the material to adhere to the block. This difficulty was overcome by putting a thin coat of shellac varnish upon the brass block. After the shellac had become quite dry a thick (0.3 mm) layer of the powder was pressed upon the block and flattened with a plate of glass. The effect of smoothness usually was not noticeable. However, in substances having high metallic reflection, e. g., silicates, carbonates, and sulphates, at 8 to 9 μ (see Table IV, quartz at 8.8 μ) the smoothness of the surface was of importance. For example, a rather coarse-grained sample of powdered feldspar reflected 10.3 per cent at 8.8 μ. On pressing the material into a more compact mass the reflecting power rose to 14.6 per cent.

Zirconium oxide mounted by the two methods gave concordant results. Owing to the high reflecting power of the material so much energy was thrown upon the thermopile that the glass window, which absorbs about 15 per cent of the radiations at 4.4 μ, became sufficiently warm to cause the galvanometer to drift. It was therefore impossible to obtain trustworthy values of the reflecting power of the white powders with the glass window in place. It was therefore replaced by a window of rock salt. When examining the black substances at 4.4 μ the opposite condition obtained. In comparison to the total amount reflected the temperature rise was such that reradiation from the lampblack became appreciable. The glass window was therefore used over the thermopile to absorb the radiations from the black substances.

As mentioned elsewhere, there is a distinction between the high reflecting power observed at 4.4 μ and at 8.8 μ. The high values (40 to 50 per cent) at 4.4 μ are to be ascribed to internal reflection. On the other hand, it is a common property of insulators to be very opaque beyond 5 μ and to have bands of selective reflection beyond 6 μ. For example, carbonates have bands of selective reflection in the region of 6.9 μ; sulphates and silicates have bands of strong selective reflection in the region of 9 μ. Hence the high reflecting powers observed in the case of carbonates and silicates, Table IV, at 8.8 u is owing to selective reflection from the surface of the particles.

The low reflecting power of the aluminum oxide at 8.8 μ is of interest, because the observations were made in the region of anomalous dispersion, where the reflecting power is abnormally low,[19] followed by bands of metallic reflection at 12 to 14 μ. Zinc oxide also has a low reflection at 8.8 μ. The reflecting power of a plane highly polished surface is low and uniform throughout this region.[20] By pressing the powdered material into a smooth, compact mass the reflecting power (3.2 per cent) was not materially increased. This shows that it is not a surface phenomenon, as found in silicates and carbonates. For example, in lead carbonate which was pressed into a smooth, hard mass comparable with that of the zinc-oxide sample just mentioned the diffuse

[19] See Investigations of Infra-red Spectra, Publication No. 97, p. 18, Carnegie Institution, 1908.
[20] Carnegie Publication, No. 97, p. 17.

reflecting power was raised from 8.3 to 13.2 per cent. These surfaces, including zirconium oxide, which has a low reflecting power, appeared dull at normal incidence, but when viewed at grazing incidence appeared like highly polished mirrors. The difference between "surface color" and "body color" is well illustrated in lead carbonate and in zinc oxide.

Lead oxide appears to have an extremely high reflecting power in the region of 8.8 μ, and by using a plane highly polished surface the reflection spectrum of this substance should be examined for residual rays in the region of 8 to 10 μ.

Many of the substances examined show a high reflecting power for the spectral region of 24 μ, from which it is to be inferred that they possess strong selective reflection in this region of the spectrum. It is of course already known that carbonates and silicates have bands of selective reflection in this region of the spectrum.

Mention was made in the beginning of this paper that the most efficient paint to protect a building from solar rays is one having a high reflecting power in the visible spectrum and a low reflecting power in the region of 8 to 9 μ. Of the various materials used in paints, zinc oxide would be the most efficient radiator in the region of 8 to 10 μ, but, as will be noticed presently, it does not appear to reflect so highly as lead carbonate in the visible and in the violet. The same condition is found in the dry pigments. However, the white lead does not appear so bluish white as the zinc oxide.

VIII. REFLECTING POWER OF MISCELLANEOUS SUBSTANCES

In Table V are given the data obtained on various substances not closely related to the groups already described. The ground and the cleavage surface of white marble illustrate the effect of grain size upon the reflecting power as mentioned in the beginning of the paper. The brown sand examined illustrates the average reflection from material obtainable along roadsides. Fine dust would probably have a higher reflection. The effect of fine dust upon asphaltum is also shown in this table. The sample examined was a piece of road material which was being removed after some years usage. The granolith was a piece of pavement which was

washed free from dust. Of the other building materials the slate used in roofing is of interest, for it reflects only about 6.7 per cent of the solar rays.

For convenience in tabulating, the data on "bluestone" (the dark-colored sandstone extensively used in buildings) are given in Table IV. This material cleaves into thin flat lamina. The reflecting power at 8.8 μ and 24 μ is very high, owing to the bands of selective reflection (silica) and the presence of fine crystal surfaces. The reflecting power of powdered feldspar and of quartz ("French flint") are also given in Table IV. These data are of interest in connection with the question whether the observed lunar radiation in the region of 8 to 10 μ is really, to a large extent, selectively reflected solar radiation.[21]

Black velvet has a very low reflecting power. The reflecting power of the sample of black felt recorded in Table V was examined several times on different days. The final test was made with a thin sheet of glass over the felt in addition to the glass window covering the thermopile, and in another test the thermopile was covered with a sheet of red glass 2 mm in thickness. The values for the reflecting power were always high, and it was concluded that this is owing to the manner in which the dye has affected the cellular structure of the fibers. Other samples of woolen cloth were examined, all of which had a high reflecting power. (See Table VI.) A similarly high reflecting power was also observed in all of the cotton cloths examined except the "sulphur black," which reflected only about 2.43 per cent. Using two thicknesses of this cloth the reflecting power was 2.37 per cent. This shows that the high reflection in the equally thick woolen samples was not caused by warming and reradiation. Similarly, the high reflecting power (33 per cent) of one and of two layers of "Diamine fast black," Table VI, showed that this was not owing to reflection from the brass block upon which the cloth was mounted. These samples of cloth were attached to the brass blocks already described by means of a thin coat of shellac varnish, which was allowed to become quite dry before applying the cloth. The samples of cloth recorded in Table VI were taken from the pattern sheets published in the Journal of the Society of Dyers and Colorists for 1912.

---

[21] Coblentz: Phys. Rev. **24**, p. 307; 1907.

At first it was thought that the high reflection might be caused by the superposition of an infra-red fluorescent radiation (of wave lengths between 1.5 μ and 3 μ) upon the diffusely reflected radiations of $\lambda = 0.6$ μ and 0.95 μ, respectively; but the tests applied did not give conclusive evidence of such a phenomenon. This is a question that requires further investigation.[22]

IX. SELECTIVE REFLECTION AND EMISSION OF WHITE PAINTS

The problem is to find a white paint that reflects a maximum amount of visible rays and a minimum amount of infra-red rays of wave lengths between 6 and 10 μ. In this manner a large portion of the solar rays will be reflected into space, and the rise in temperature resulting from the solar rays that are absorbed will be prevented by reradiation, which is facilitated by a high emissivity (low reflection) at 6 to 10 μ.

Unfortunately, the paint (zinc oxide) that fulfills the latter condition has a lower reflecting power than white lead in the visible spectrum. It can not be used for exterior work. The next best primary paint for exterior work is white lead, but like all carbonates its infra-red emissivity is not as high as that of zinc oxide. Radiometrically it would therefore appear to be better to use a mixture composed of white lead and as high a proportion of zinc oxide as is permissible to form a good paint.

The carbonates, sulphates, and silicates have bands of strong metallic reflection in the region of 7 to 9 μ, which suppress the reradiation of the absorbed solar rays. In binary mixtures, sulphates and silicates are less desirable than carbonates, for their infra-red reflecting power is higher and the bands do not lie close to those of lead carbonate. This suppresses the emissivity over a wide range of the infra-red spectrum. Of course, a few (5 to 8) per cent of silica or china clay, which is said to improve

---

[22] As this paper goes to press some results on diffuse reflection have been published by Dr. Nutting. (Trans. Illum. Eng. **7**, p. 412; 1912.) The instrument used by him for measuring the diffuse reflection is built upon an entirely different principle. Nevertheless, our results are entirely in agreement. For example, he found the reflecting power of black velvet to be 1.8 per cent (really 1.75 for the mean of the two positions of his photometer), as compared with 1.75 per cent by the present method. For one sheet of ordinary white paper he found a reflecting power of 72.2 per cent and for several superposed sheets he found a value of 73.3 per cent. In the present research the reflecting power of a single sheet, of the same kind of paper as used by him, was found to be 71.7 per cent and for two superposed sheets it was 73.4 per cent.

white lead mechanically, can not seriously affect the radiating properties of the primary, viz, white lead. The combination of calcium sulphate and of barytes with white lead appeared much darker than a similar combination with calcium carbonate.

The white paints examined quantitatively for reflection were samples which had been ground in linseed oil under standard conditions.[23] They were painted (five or more coats) upon the aforementioned brass blocks and were thoroughly dry. There was no marked difference in the reflecting power of white lead made by different processes (American, Dutch, and French), the reflecting power of various samples varying from 74.3 to 76.0 per cent. (See Table VI.) Similarly, the samples of zinc oxide paints reflected from 68 to 69 per cent. This agrees with previous observations on the dry pigments, which show that lead carbonate has a higher reflecting power than zinc oxide. A mixture of equal parts of white lead and of zinc oxide reflected 71 per cent. In view of the fact that the reflecting power of aluminum, Table I, is high in the visible and in the ultra-violet, it was of interest to determine whether sheet aluminum would be more satisfactory than white paint for protecting a building against warming by solar rays. The difference in reflecting power of aluminum and white paint is not so marked in the visible spectrum as in the infra-red Both materials absorb considerable sunlight, but the aluminum has the lower emissivity for the radiations at 6 to 12 μ. Hence, it can not radiate the absorbed energy as rapidly as the white paint and its temperature rises above that of white paint. This conclusion is borne out by the following experiments, in which the temperature of two similar plates of aluminum was observed before and after one plate was painted with white lead ground in pure linseed oil. Two sizes of sheet aluminum were tested: A, 46 by 48 by 0.718 mm; B, 68 by 69 by 0.245 mm. Thermocouples of copper and constantan wires were inserted and riveted in holes drilled through the aluminum plates, and as a further attempt to obtain good contact the junctions were tightened with Wood's alloy. The constantan wire was 0.31 mm and the copper was 0.40 mm in diameter. The cold junctions were kept in ice. The aluminum sheets were mounted side by side

---

[23] Proc. Amer. Soc. for Testing Materials, **11**, p. 226; 1911.

upon a board of yellow poplar 20 by 19 by 1.8 cm and exposed to direct sunlight. The temperature of the pairs of sheets, A and B, and the difference in temperature was measured by means of a potentiometer. The thick unpainted plates (A), covered with window glass and exposed to sunlight, showed no difference (difference $= 0°05$) in temperature; but in the thin sheets B–I was about $1°1$ hotter than B–II, when at a temperature of about $37°$ C. The tests were made on a somewhat windy day, which prevented accurate measurements without glass covers over the aluminum plates. There is no reason, however, for thinking that the observations would have been different without the glass. Sheets No. II of both A and B were then given two coats of pure white-lead paint. Exposed to sunlight under glass the temperature of the painted surface of A (II) was about $0°8$ higher than A–I. Similarly, the temperature of B–II (the painted surface) was about $0°9$ higher than B–I, the actual temperature being from 46 to $47°$ C. The sky was perfectly clear (Oct. 7, 1912) with only a slight breeze blowing. Without the glass coverings, which is the test of most interest, the unpainted aluminum plate was the hotter. For A–I the temperature of the bare aluminum was $3°0$ to $3°1$ higher than the exactly similar sheet having two coats of white-lead paint. The actual temperature of A–I was about $44°7$. Similarly, for B–I the temperature excess of the bare aluminum sheet was $2°3$ to $2°4$, the actual temperature being about $43°7$. The intensity of the solar radiation, Q, was about 1.161 g cal. cm² min.

These tests were repeated, using three coats of paint. The weather was perfectly clear (Oct. 10, 1912), and no breeze blowing. The intensity of the solar radiation was 1.157 gr. cal. cm² min. The plates were exposed directly to the sun—i. e., no glass intervening. For A–I the temperature excess was $4°1$ to $4°3$, the actual temperature being about $45°$ C. Similarly, for B–I (unpainted aluminum) the temperature excess was $3°0$ to $3°2$, the actual temperature being about $42°7$. From these tests it is evident that a metal roof painted with several coats of white paint is far superior to one of bright metal. As already mentioned, this is owing to the fact that white paint has a higher emissivity than metals in the infra-red.

The unpainted sheets of aluminum (A–I, B–I) were then given three coats of zinc oxide paint. When thoroughly dry, the sheets containing the zinc oxide paint appeared to be at about the same ($+0°.1$) temperature as obtained in the white lead. Another coat of paint was then applied (making four coats in all) to each sheet. When exposed directly to solar radiation, the temperature excess of the zinc oxide paint for the thin sheets, B, was $\pm0°.1$ and for the thick sheets it was about $+0°.5$. From this it appears that, in comparison with white lead, what is gained in higher emissivity in the infra-red in the zinc oxide paint is lost by its higher absorption (lower reflecting power) in the visible spectrum, so that radiometrically it is no more efficient than white lead.

The white lead paint was removed from the sheets, A–II, B–II, which were then painted with a matte layer of the lampblack, used in the experiments already described. When exposed directly to the sun, the temperature of the lampblack sheet, A–II, was about $16°$ higher than the zinc oxide paint, A–I, the actual temperature of the lampblack being about $52°.2$ for solar radiation of intensity, $Q=1.16$. Similarly, the temperature of the lampblack sheet, B–II, was $17°.5$ higher than the zinc oxide plate, B–I, the actual temperature of the aluminum sheet covered with lampblack paint being about $53°.3$ C and the room temperature (i. e., in the shade) being about $23°.1$ C. The infra-red reflecting at 8.8μ differs but little for these two substances; hence there is no great difference in their emissivities for low temperatures. In the visible spectrum the absorptivity of the zinc oxide is only about 30 per cent, and for lampblack it is 97 per cent. Hence the lampblack must become the hotter, for it absorbs energy at three times the rate and it emits energy (low temperature radiation) at practically the same rate as does the zinc oxide paint.

X. SUMMARY.

1. This paper gives an account of an investigation of the reflecting power of matte surfaces of various substances (also of polished surfaces of silver and aluminum) for the spectral regions of 0.54, 0.60, 0.95, 4.4, 8.8, and 24μ.

2. The diffusely reflected radiations were collected by means of a hemispherical mirror and projected upon a surface thermopile

of bismuth and silver, which was used to measure the intensity of the incident and the reflected radiations.

3. The substances examined include lampblack, platinum black, pigments, white paints, green leaves, dyed cloth, and building material. The object of the investigation was to find the blackest and the whitest substances—the former to be used as absorbing surfaces of radiometers, the latter to be used as a covering for buildings exposed to intense sunlight.

4. Methods are given for preparing standard black surfaces, and quantitative data are given for the loss by reflection of the same.

WASHINGTON, *October 31, 1912.*

NOTE I.—VARIATION OF THE SPECULAR REFLECTING POWER OF SILVER WITH ANGLE OF INCIDENCE

The variation of the specular reflecting power of polished metals with the angle of incidence, using unpolarized light, has been investigated by various observers.[24] The measurements were made photometrically and also radiometrically, and the general conclusion is that the reflecting power passes through a minimum, for angles of incidence between 60° and 70°, for unpolarized light. For silver no conclusive quantitative data, which is needed in spectroradiometric work, was available, and the question was therefore investigated anew.

In spectroradiometric work it is customary to have the collimating arms fixed and to rotate the prism table, upon which is mounted a plane reflecting mirror in addition to the prism. This combination forms the Wadsworth method [25] for maintaining a minimum deviation for all the rays. The angle of incidence of the light upon the mirror varies as the prism is rotated, and the problem was to determine the resultant change in reflecting power of the silver mirror. This is a difficult problem, for the variation in reflecting power is small, and it is necessary to keep the source of energy and the radiometer sensitivity constant for a considerable time. This question was therefore investigated only for the angles of incidence (about 54° for $\lambda = 0.5896\mu$; the angle between the mirror and the adjacent prism face is about 80°) at which the rays

---

[24] Provostaye and Desains: (3), **30**, p. 276; 1850. Jamin: Ann. Chim. et Phys. (3), **19**, p. 296; 1846 Knoblauch: Ann. der Phys. (3), **1**, p. 1; 1887.

[25] Wadsworth: Phil. Mag. (5), **38**, p. 346; 1894.

must fall upon the mirror in order to pass through a fluorite prism at minimum deviation. As used at present in determining spectral energy curves of a black body, this involves an increase of about 4° in the angle of incidence in passing from $\lambda = 0.5896\mu$ to $\lambda = 6\mu$.

For determining the variation in reflecting power a freshly silvered plane mirror was mounted upon the prism table of a small, high-intensity spectrometer having triple achromatic lenses 6 cm in diameter and 18 cm in focal length. The collimating and the telescope arms were attached to the spectrometer table by means of an automatic slide-arm arrangement, such as is commonly used in maintaining a prism at minimum deviation. The energy reflected from the mirror was measured by means of a bismuth-silver thermopile [26] of 20 junctions, 1.4 mm wide, which was mounted in place of the eyepiece of the movable telescope. The collimating arm, with a slit 1.2 mm wide, was fixed, and before it was placed a Nernst glower. Beween the glower and the slit was placed a shutter and a cell, 2 cm in thickness, containing a 3.5 per cent solution of cupric chloride, which absorbs all the infra-red beyond 0.7μ.[27] This limited the radiations to be measured to the region of the visible spectrum, with the maximum at about 0.55μ.

Owing to the fact that the spectrometer was not adapted to a large rotation of one arm, with the automatic slide arm in place for maintaining minimum deviation (really for varying the angle of incidence upon the mirror in this investigation), the variation in reflecting power was determined for an angle of incidence of 54° and for 64°. This required a rotation of 20° of the telescope arm, and although the whole was completely inclosed to exclude stray light there was an appreciable shift in the zero reading of the galvanometer in passing from one to the other of these two positions. This of course does not interfere with the observations when thermal equilibrium has been established after moving the thermopile to the new position. The various sources of error were of course tested before making measurements. The most important error that might be introduced would result from the automatic slide-arm arrangement, which might not always cause

---

[26] This Bulletin, **9**, p. 7; 1912.
[27] This Bulletin, **7**, p. 619; 1911; and p. 110, 1912.

the slit image to fall exactly upon the thermopile when changing to a different angle of incidence. By experimentally determining the axis of rotation of the mirror and making all the rotations in the same direction to eliminate backlash this error was eliminated.

The variation in reflecting power was determined by noting the galvanometer deflections when the angle of incidence was varied 10° (also 8°), the source of radiation being kept constant. In all six distinct series of measurements were made. With an increase of 10° in the angle of incidence the galvanometer deflections were decreased by amounts varying from 1.0 to 1.6 per cent, the mean value being 1.2 per cent. This gives a decrease of 0.12 per cent per degree increase in the angle of incidence for angles of incidence varying from 54° to 64°. From this it is evident that the correction to spectral energy curves owing to the difference in reflecting power for different angles of incidence is negligibly small. It would of course be profitable to determine this variation over a wider range, but much more elaborate apparatus would be required.

TABLE I

Reflecting Power of Lampblack

Wave length λ max.	0.54μ	0.60μ	0.95μ	0.95μ (Red glass)	4.4μ	8.8μ	24.μ
Silver	93.2%	89.9%	93.4%	94.6%	98.0%	98.0%	98.5%
Aluminum		68.5			92.3		
Correction factor	1.102	1.143	1.100	1.086	1.049	1.049	1.043
Lampblack paint		2.94..............................3.24					
		3.02..............................3.29					
		3.58..............................3.60⎫					
		3.72..............................4.86⎭ Alcohol+shellac					
		3.10......3.38.......3.36.......3.34......3.75......4.4					
Paraffin candle		0.97%					
(Cold soot)	⎰..............1.07 ⎱..............1.43						
Rosin		1.26...................1.31					
		0.85.....1.07......2.8					

TABLE I—Continued

Reflecting Power of Lampblack—Continued

Wave length λ max.	0.54μ	0.60μ	0.95μ	0.95μ (Red glass)	4.4μ	8.8μ	24.μ
			0.91		0.67......1.44......3.9		
			1.02		0.93......1.27......4.1		
Sperm candle			1.25..................1.03				
			1.07		0.77	1.28	
			1.01		1.36	1.23	
					1.28	0.87	
Camphor			1.34		1.38......1.46		
			1.30		0.95......1.65......5.7		
			1.36..................1.15				
(Paint)..2.80..................3.24							
Acetylene			0.59				
			0.82		0.92......1.12......3.0		
			0.64		0.71......1.24		
			0.54..................0.81				
			0.42..................0.71				
(Cold deposit)......................................0.86							
(No air)..1.33							

TABLE II

Reflecting Power of Platinum Black

Wave length λ max.	0.60μ	0.95μ	0.95μ (Red glass)	4.4μ	8.8μ	24μ
Chemically precipitated paint.............	2.01%	2.92	....	6.00	....	....
	....	2.43	2.50	....	....	....
	....	....	2.53	5.76	8.67	12.1
Platinum black and lampblack paint	2.77	2.70	2.84	4.02 / 3.94	6.44	8.2
Ibid. and soot	1.46	1.38	....	....	....	....
Electrolytic No. —						
4..	....	1.22	....	8.8	13.2	....
5..	....	0.98	....	2.64	4.63	....
Ibid..	....	1.16	....	2.68	....	....
14; 1 min	....	....	....	....	25 to 30	....
13; 2 min	....	....	....	....	11.3	....
9; 3 min	....	....	....	....	5.9	....
10; 3 min	....	0.99	....	1.72	3.66	7.5
11; 4 min	....	....	....	1.54	2.40	4.4

TABLE II—Continued

Reflecting Power of Platinum Black—Continued

Wave length λ max.	0.60μ	0.95μ	0.95μ (Red glass)	4.4μ	8.8μ	24μ
Electrolytic No. —						
Ibid	....	1.16	....	1.59	....	....
12; 5 min	....	1.12	....	1.50	1.84	3.9
16; 5 min	....	0.85	....	1.48	2.71	....
15; 6 min	....	1.01	....	1.51	2.23	3.4
18; 6 min	....	....	....	1.33	1.78	....
Ibid	....	1.08	....	1.35	....	....
19; 6 min	....	....	....	....	2.13	....
19 and soot	....	....	....	0.93	1.27	4.1
Ibid	....	1.25	....	0.99	....	....
17; 7 min	....	0.98	....	1.44	1.82	3.3
20; 7 min	....	....	....	1.29	1.88	2.9
Ibid	....	0.97	....	1.31	....	....

TABLE III

Reflecting Power of Green Leaves

Wave length λ max	Remarks	0.54μ	0.60μ
Clover (*Trifolium pratense*)	....	23.9%	21.3%
Lilac (*Syringa vulgaris*)	May 3	26.0	25.3
	June 8	....	23.6
	Transmission	....	19.6
Locust (*Robina Pseudacacia*)	May 3	....	25.4
	June 8	....	23.9
	Transmission	....	20.7
Tulip tree (*Liriodendron tulipifera*)	May 3	28.1	27.2
(See also Table V)	July 29	....	22.0
	Oct. 31	47.0	48.8
Laurel (*Kalmia latifolia*)	....	....	23.2
	Rear side	....	27.7
Basswood (*Tilia Americana*)	....	....	26.9
Elm (*Ulnus Americana*)	....	....	25.7
Oak (*Quercus rubra*)	Young leaf	....	29.3
	Dark green	....	21.8
Mullein (*Verbascum thapsus*)	....	....	24.2

TABLE IV

Reflecting Power of Pigments

Wave length λ max.	0.54μ	0.60μ	0.95μ	0.95μ (Red glass)	4.4μ	8.8μ	24μ
Cobalt oxide, Co_2O_3	....	3.02%	3.92 4.04 2.49	....	13.9	14.6 11.8	5.9
Copper oxide, CuO	....	....	23.5	....	15.2	....	4.4
Chromium oxide, Cr_2O_3	24.1	27.0	44.6	....	32.9	5.0	8.2
Lead oxide, PbO	....	51.8	....	....	50.6	25.6	9.5
Red iron oxide, Fe_2O_3	....	26.3	41.0	53.6	29.9	3.7	9.1
Yttrium oxide, Y_2O_3	....	73.8	....	....	34.4	11.1	10.
Lead chromate, $PbCrO_4$	61.2	70.2	....	....	41.2	4.74	7.4
Aluminum oxide, Al_2O_3	....	84.1	87.7	....	20.8	2.34 1.64	6.5
Thorium oxide, ThO_2	....	86.0	....	....	46.9	7.11	10.0
Zinc oxide, ZnO	....	82.2	86.4	....	8.5	3.2 2.1	5.1
Magnesium oxide, MgO	....	86.3	....	....	16.0	2.5	9.1
Calcium oxide, CaO	....	85.4	....	....	22.3	3.6	6.2
Zirconium oxide, ZrO_2	82.2	85.8	84.1	83.2	23.2	5.1	5.4
Lead carbonate, $PbCO_3$	....	86.8 89.9	90.8 92.8 94.5	....	29.2	8.3 13.2	6.9
Magnesium carbonate, $MgCO_3$	....	85.2	89.4	....	10.8	4.1	8.8
White paper	....	71.7 73.4 for two thicknesses	74.7	....	18.2	5.0	....
White paper (Bond)	....	75.2	....	....	....	....	....
Feldspar, $KAlSi_3O_8$	....	....	86.7	....	38.2	10.3 14.6	9.7
Ibid (cleavage)	....	39.4	....				
Bluestone (sandstone) SiO_2	....	....	18.4	....	8.1	17.6	11.0
Quartz (powder, French flint), SiO_2	....	....	81.0	....	41.5	7.9 13.4	9.0

TABLE V

Reflecting Power of Miscellaneous Substances

Wave length λ max.	0.60μ	0.95μ	4.4μ	8.8μ
Brick:				
Light buff	48.4%			
Darker	40.0			
Red brick	30.1			12.4
Darker and glazed	23.4			
White marble; $CaCO_3$; ground; unpolished	53.5		6.4	5.1
Ib d.; cleavage	40.8			
Indiana limestone; $CaCO_3$	42.9		20.3	5.0
Granolith (pavement)	16.9			
Asphalt (pavement)	14.8			
Ibid.; free from dust	7.2			
Slate (dark clay)	6.7			20.0
Blue flannel	17.5			
Black velvet	1.75		3.66	2.7
Black felt	13.9	21.2		
	22.5	25.6		
Deep blue cloth (Navy Dept.)	17.0			
Lighter shade	18.2			
Green leaf (tulip tree)	21.9	38.0	5.6	

TABLE VI

Reflecting Power of Dyed Cloth and White Paints

Wave length λ max	0.60μ	0.95μ	Wave length λ max	0.60μ	0.95μ
Linen; starched, dull finish	81.2%		Cotton cloth—Continued.		
White lead No 103	76.2	79.3	Diamine Aldehyde Black		
White lead No. 102	74.3		B—		
Zinc lead white No. 107	69.6		Pattern sheet No. 193	29.5	
Zinc oxide No. 104	68.1	72.1	Sulphur Black A W L—		
White lead 50%⎫ No. 209	70.8		Pattern sheet No. 192	2.43	2.57
Zinc oxide 50%⎭			Ibid.; two layers	2.37	
Cotton cloth:			Woolen cloth:		
Diamine Fast Red, 8 B L—			Lanacyl Blue B N—		
Pattern sheet No. 187	43.8		Pattern sheet No. 189	25.1	
Diamine Fast Black C B—			Salacine Blue Black A E—		
Pattern sheet No. 186	33.1		Pattern sheet No. 193	14.6	17.8
Ibid.; two layers	33.5		Salacine Black P B—		
Columbia Fast Black R—			Pattern sheet No. 192	11.8	15.1
Pattern sheet No. 185	28.7		Ibid	13.2	