# OPTICAL PROPERTIES OF CARBON FILMS.[1]

BY HERBERT A. CLARK.

PURE carbon has been generally supposed to be a black body. Rosicky[2] in 1878, and later Stark,[3] investigated smoke films. The latter considered a smoke film as a turbid medium of air and carbon, and concluded that its dispersion is between that of air and of pure carbon. Ångström,[4] working in the infra red, obtained a rapidly increasing absorption in the case of lampblack from a wave length of 9,000 $\mu\mu$ down to 690 $\mu\mu$. Wood,[5] in 1901, using prismatic methods on smoke films, found the red rays retarded more than the blue, from 663 $\mu\mu$ to 414 $\mu\mu$; and, using interference methods, that films deposited on plate glass inside an electric lamp globe seem to show the same. For the latter films, he obtained a refractive index of 2.2 for the *D* line.

About the same time, E. L. Nichols[6] and Blaker[7] found that carbon rods and incandescent lamp filaments, both "treated" and "untreated," show, as their temperature increases, a more rapid increase in the radiation of the spectrum in the yellow than in the red or blue. Dr. Brace suggested[8] that the electro-magnetic theory shows that this increase in the radiation and the anomaly as found by Wood, both point to an absorption band in the yellow. Nichols[8] had found a maximum of absorption in the visible spectrum at the wave length 520 $\mu\mu$, in the case of lampblack. B. E. Moore and Ling[9] found the same in deposits on incandescent lamp globes at

[1] Read in part before the Am. Phys. Soc. at Chicago, April, 1905; and in part before the meeting at New York, December, 1905.

[2] Rosicky, Wiener Berichte, 78, II., p. 407, 1878.

[3] Stark, Wied. Ann., Vol. 62, p. 353, 1897.

[4] Ångström, Wied. Ann., Vol. 36, p. 715, 1889.

[5] Wood, Phil. Mag., VI., Vol. 1, p. 407, 1901.

[6] Nichols, PHYS. REV., Vol. 13, p. 129, 1901.

[7] Blaker, PHYS. REV., Vol. 13, p. 345, 1901.

[8] Nichols and Blaker, PHYS. REV., Vol. 13, p. 378, 1901.

[9] Nichols, Am. Jour. Sc., Vol. 34, p. 277.

the wave length 635 $\mu\mu$, from "treated" filaments, but not from "untreated" filaments. Neither Rosicky [1] nor Stark [2] noticed this maximum in the absorption.

Nichols,[3] working also with a prism of asphalt, which he considers a solution of carbon, determined the refractive index at four points in the red and yellow; and found an anomaly at a wave-length of 568.2 $\mu\mu$, with a refractive index of 1.6339. In the infra red, he found the absorption of asphalt to be very similar to Ångström's [4] values for lampblack, only that the change is much more abrupt.

None of these investigators, however, so far as I know, have determined by direct methods, the reflection, the refraction, and the absorption, all from the same specimen of pure carbon in a dense form. At Dr. Brace's suggestion, I have attempted to do this. This problem presupposes the use of transparent films of carbon. As yet, films of two kinds only have been considered; namely, those produced by Wright's [5] cathode method of deposit, and those obtained from the inside of incandescent lamp globes.

## Making the Films.

Longden [6] has shown that the character and the rate of deposit from a cathode upon a glass plate in a vacuum, depend upon the vacuum, the electromotive force, the current density over the cathode surface, and the distance from the cathode to the glass plate, as well as upon the material of the cathode. A vacuum tube (shown in cross section in Fig. 1) was so constructed that these conditions might be varied at will to produce the best results. It was made of two ordinary low form glass bell jars; the flanges of which were ground on a plane surface, so that they fit closely together, flange to flange. $C$ is a carbon cathode, surrounded by mica. A hole in the upper mica sheet at $D$ allows the cathode discharge to deposit carbon on the lower face of the glass plate, $A$. This plate is supported by the anode, $B$, a sheet of brass. The anode, in turn,

[1] Rosicky, l. c.
[2] Stark, l. c.
[3] Nichols, Phys. Rev., Vol. 14, p. 204, 1902.
[4] Ångström, l. c.
[5] Wright, Am. Jour. Sc., III., Vol. 13, p. 49, 1877.
[6] Longden, Phys. Rev., Vol. 11, p. 40, 1900.

is carried by a metallic stem, *M*, the lower end of which is of square cross section; the upper end is threaded. By turning the ground joint, *H*, the glass plate may be moved into the cathode stream, or out of it; by turning *K*, the distance between cathode and plate can be varied. The electric circuit in the tube is from the anode terminal, *F*, through a wire to a threaded nut in *K*; through the stem, *M*, to the anode, *B*; through the gas to the cathode, *C*; through a wire protected by a glass tube to a mercury cup, *E*; thence to the cathode terminal, *G*. Ordinary stop cock grease served to make the joints, all of which are ground glass, perfectly air tight. The cathode was made by combustion of granulated sugar, which is considered by chemists to yield the purest form of carbon, excepting the diamond.

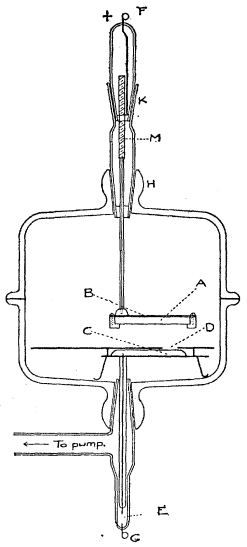

Fig. 1.

The films were deposited in atmospheric air which had been dried carefully, at low pressure, in contact with phosphorus pentoxide. A high potential storage battery served as a source of current, which was unidirectional. The best conditions for depositing carbon in air were found by trial to be as follows: a voltage of about 1,100; a current density of about .05 milliampere per square millimeter of cathode surface; a distance from cathode to glass plate of about fifteen millimeters; and such a gas pressure that the Crookes' dark space extended 5 or 6 millimeters from the cathode. The gas pressure was not measured definitely, but was less than one millimeter of mercury. Since slight changes in gas pressure change the resistance of the tube very appreciably, a galvanometer in series with the tube was used to determine the constancy of the gas pressure.

The films, under carefully adjusted conditions of deposit, were slightly prismatic, were reddish brown or black in color by transmitted light, appeared perfectly homogeneous and highly polished to the naked eye, varied in thickness from 0 to 10 $\mu$ and in transparency from 0 to 100 per cent., according to the thickness.

Viewed by reflected white light, they show beautiful interference bands, up to five or ten orders. They are almost as easily injured by rough usage as is a half-silvered coat on an interferometer plate, but seem to be independent of time changes except for a cracking and scaling off of the thicker portions. Those used were about one year old when measurements were made.

The second kind of films was unusually heavy deposits found on the inside walls of an ordinary incandescent lamp, which had been run at an abnormal voltage. The exact composition of the carbon filament in this case is not known.

## Test for Anomalous Dispersion.

The supposed pressure of an anomaly in the refractive index curve of carbon led to making a test for this, by a method devised by Dr. Brace.[1] If light reflected from the two surfaces of a thin film is resolved by a prism or a grating, the spectrum will be crossed by dark lines, or "spectral bands," at those wave-lengths for which destructive interference occurs. If this film has an anomaly in its dispersion, the "spectral bands" will be variable in width; but they will coincide in width with similar bands from an air film at a maximum or a minimum point in the dispersion curve, if the order of interference is the same for the two films at this wave-length. Between the maximum and the minimum points, the "air bands" will be narrower than those of the medium; elsewhere the "air bands" will be the broader. Or, if the anomaly is very slight, the maximum and minimum may coincide, giving a point of inflection; in this case, the "air bands" will be broader on both sides of this point.

Two sets of "spectral bands" can be compared directly for this test, either with the eye or by photography, by means of a device shown in Fig. 2. A second collimator, *H*, is inserted into the side of the usual collimator, *C*, of an ordinary spectrometer. A mirror, *A*, set at an angle of 45° to either line of collimation, covers half the cross-section of *C*. The upper half of one collimator slit and the lower half of the other are covered with black paper. Then two spectra are seen in the eye-piece of the observing telescope;

[1] Brace, PHYS. REV., Vol. 21, p. 291, 1905.

one in the upper half of the field, the other in the lower. By carefully adjusting *A*, these two spectra may be made to coincide throughout, line for line, the dividing line between the two becoming almost a vanishing line. *B* is a glass plate holding a thin film of the substance under investigation. A very small mirror, *D*, shown in the enlarged diagram, Fig. 3, enables light to be reflected at nearly normal incidence, from the film into the collimator. The use of this small mirror is far more satisfactory than that of a small, totally reflecting prism inside the collimator, one 45° edge of the

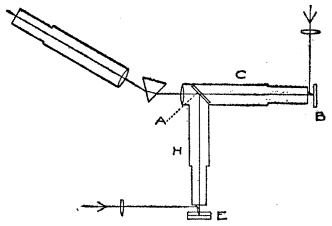


Fig. 2.

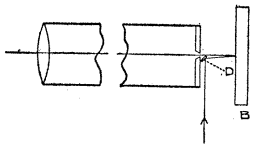


Fig. 3.

prism serving as one edge of the slit; as the prism produces too much diffuse radiation inside the collimator, when highly absorbing substances are examined. Reflection from the two surfaces of the film gives "spectral bands," which may be compared with similar bands obtained from the surfaces of the air space between two glass plates, *E*. If this space is prismatic, "air bands" of any desired order, to coincide with the order of those from the film, may be brought into the telescope by sliding along the plates, *E*, in front of the slit. A Nernst lamp was used effectively as a source of light. Ten "spectral bands" between wave-lengths of 687 $\mu\mu$ and 472 $\mu\mu$ were obtained; but no anomaly was detected, although the irregularity in the dispersion curve (*A*, Fig. 9) suggests a very slight anomaly in the region of the *C* line.

## THE INTERFEROMETER SYSTEM.

In determining the refractive index, interference methods were used entirely, in preference to prismatic. The interferometer employed was of the Jamin type, essentially the same as the one used by Cartmel.[1] Certain slight changes in arrangement and

[1] Cartmel, Phil. Mag., VI., Vol. 6, p. 214, 1903.

adjustment proved so advantageous, however, that a description is here given. In Fig. 4, *a* is the source of light, a Nernst glower; *b* is an adjustable slit in a screen; *c* is a nicol prism; *d* and *d'* are achromatic lenses of 25 cm. focal length; *e* and *e'* are the half silvered plates, and *f* and *f'*, the full silvered mirrors of the interferometer; *k* and *k'* are mica strips, the latter being a compensator;

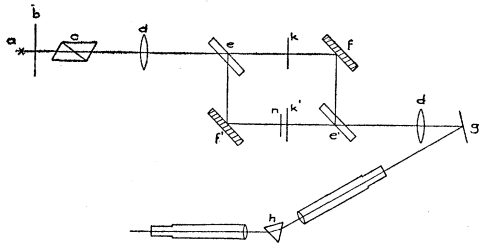


Fig. 4.

*n* is the film under investigation; *h* is a spectroscope; and *g* is a mirror, which allows the spectroscope to be placed in such a position that the operator can easily reach all parts of the system without changing his position.

The interferometer plates are first adjusted for parallelism by alignment on an object at a distance of at least two miles, instead of only two or three hundred meters. It was found by trial that the consequent higher degree of accuracy in the parallelism of the plates made the "spectral bands" much more distinct and clear. The two light paths, *efe'* and *ef'e'*, are next made exactly equal by examining a very near object through them with the naked eye, and then the colored fringes of white light come into view. These fringes are then made vertical. No "spectral bands" will appear in the spectroscope as yet, for they are due to a slight difference in the two light paths. This difference is obtained by moving one of the mirrors *f* or *f'*, parallel to the direction of the ray from *e* to *f*. No further adjustment of the interferometer is needed to give clear, sharp "spectral bands," white light being used.

The nicol prism is turned so that its plane of polarization is vertical; consequently, nearly all of the light that is reflected from the half-silvered plates, comes from the rear (the half-silvered) surface. This makes the "spectral bands" more distinct, by eliminating all

but one set of interfering rays. In case the lens, $d$, forms an image of the slit, $b$, upon the film, $n$; and the lens, $d'$, casts an image of that in turn upon the slit of the spectroscope, no "spectral bands" are seen. But let the spectroscope now be moved a few centimeters toward $g$, then bands are seen very plainly. In practice, however, the lens, $d$, is placed to form an image of the slit, $b$, upon the interferometer plate $e'$; then the lens, $d'$, produces an image of the film, $n$, upon the slit of the spectroscope. This allows a concentration of light upon the highly absorbing film under investigation at $n$, without recombination of the interfering rays into white light by the lens, $d'$.

Positions in the spectrum were determined by means of a tangent screw attached to the telescope, the micrometer head being about 6 cm. in diameter. This enabled the readings to be taken much more easily and quickly than if the usual circular scale had been used; and also made the order of accuracy of the readings somewhat higher, about the same as that of the settings. This method is much preferable to the use of a micrometer eyepiece, because of the unavoidable parallax while examining "spectral bands." The compensator $k'$, is the same kind as was used by Cartmel.[1] In addition, however, another piece of mica, $k$, of exactly the same thickness and with its optic axis in the same direction, is put in the other interferometer path. Another plate of glass of exactly the same thickness and composition as that of the one upon which the film, $n$, is deposited, is placed next to $k$. The two light paths, $efe'$ and $ef'e'$, are thus identical except for the presence of the film itself and for the slight increase of length of one light path *in air* over that of the other. Any observed differential dispersion, then, is not affected by the presence of the compensator or of the glass.

## THE REFLECTION ATTACHMENT.

To measure the absolute reflection of any surface directly, it is essential that the path of the beam of light which is reflected and the path of another beam, which is used for comparison, shall be identical from the source to the eye, except that the first beam suffers reflection from the surface considered. It is also essential that

[1] Cartmel, l. c., p. 217.

the two beams shall be identical in intensity at the source; or else, that each can be compared directly with a third, the intensity of which varies exactly with that of the beam being examined. The first essential condition is realized by the use of a reflection attachment for the spectrophotometer, described below. In the second condition, two alternatives are offered. The first is difficult to attain. The second is readily realized by the use of the Brace spectrophotometer,[1] to one collimator of which the above attachment is fastened. The illumination of the two collimator slits comes from opposite sides of one point in an acetylene flame. Any gradual variations in the intensity of the source, then, can not affect the results, unless the intensity of the two sides of the flame at the same point should vary unequally; which is not likely. The adjustments of the spectrophotometer have been given by Tuckerman.[2]

The instrument readings taken, when the illumination for one collimator slit is reflected from the surface under consideration, are designated as the "reflection readings"; those taken when an identical beam does not suffer this reflection, the "direct readings." The absolute value of the reflection follows directly, then, as the ratio of the "reflection reading" to the "direct reading." The upper part of Fig. 5 shows a plan and the lower part, a side elevation, of the reflection attachment. $A$ is the slit end of one collimator; $B$ and $C$ are small, totally reflecting prisms. $B$ may be rotated by means of a crank, $D$, about an axis approximately parallel to the line of collimation, $HK$, through an angle of nearly 90°, fixed by adjustable stops (not shown in the figure). Prism $C$ is arranged to slide from the position shown in the figure to a position directly over prism $B$, by means of the long guard arm $E$. Projections at either end of $E$ are carefully fitted into slots in the bed plate, $F$. This allows the motion of $C$ to be made parallel to the line of collimation. This motion is also regulated by adjustable stops (not shown). The operation is as follows. Light from the source behind strikes prism $B$, is reflected down to the horizon-

[1] Brace, Phil. Mag., V., Vol. 48, p. 420, 1899; also Astrophys. Jour., Vol. 11, p. 6, 1900.

[2] Tuckerman, Astrophys. Jour., Vol. 16, p. 145, 1902.

tal plate, *M*, whose reflection is to be measured, then up to prism *C*, then into the slit of the collimator, *A*; and a "reflection reading" is taken. Prism *B* is next rotated (nearly 90°) until it reflects the light up; prism *C* is moved over it, reflecting the ray again into the slit; and a "direct reading" is taken. To make the light paths in the two collimators symmetrical, two prisms corresponding to *B* and *C*, cemented together with Canada balsam, were placed in front of the other collimator slit.

The adjustment of the reflection attachment is as follows. An acetylene flame is put at the ocular slit of the spectrophotometer,

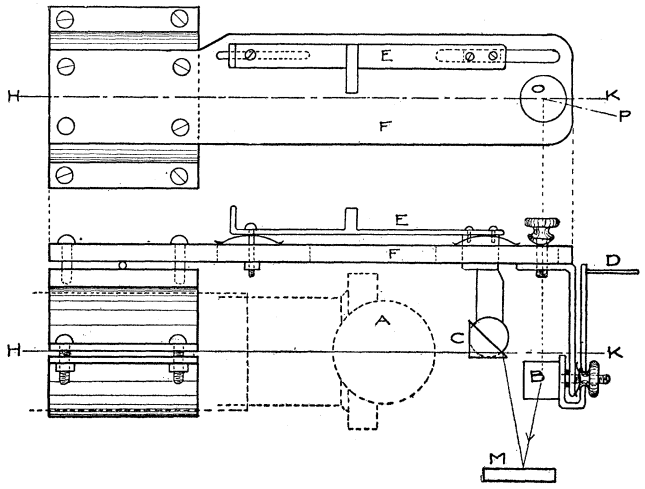


Fig. 5.

whence light passes through in a direction opposite to the usual one; hence the beams from the two collimators reach the plane in which is placed the source, ordinarily. Between each collimator slit and this plane is an achromatic condensing lens, forming an image of each slit upon the plane. By suitable adjustments, these images of the two slits are made to coincide, for both the "reflection" and the "direct reading" positions of the movable prisms. Further adjustments will make both the "reflection" and the "direct reading" beams pass through the same part of the condensing lens, as is determined by cross wires over the lens. If, now, prism *B* be tilted on its base through a definite angle, and its axis of rotation be

moved about a vertical axis through a definite angle to a position, *OP*, light will pass through it perpendicular to both faces, and along identical paths, in its two positions; except that for one, the beam enters *B* where in the other it emerges, and *vice versa*.[1] Further, the objective of the telescope, which has a focal length of 300 mm., is diaphragmed down to 5 mm. in diameter, making an angular aperture of about 1°. The light paths for the two positions of prisms *B* and *C* are now identical from source to ocular slit, except for that part between them, where reflection takes place in one case. That this distance is greater for the "reflection readings" than for the "direct readings" is immaterial, if the intensity of the source over the area considered is uniform at any one instant. This area is about 1 sq. mm. for an angle of incidence of 5.75° upon the plate *M*, whose reflection is to be measured. At this angle, determined by a distance of 2 cm. between *B* and *M*, all of the readings were taken. The advantages of this method are: (1) the absolute reflection is measured directly for the chosen angle of incidence, as is shown above; (2) since the reflecting surface is horizontal, the method may be used for liquids; and (3) the area considered is small, — not greater than 0.4 mm. square in this case, — thus giving the value at a point, instead of an average value over a surface. The surface as a whole, therefore, need have no definite curvature, — it is necessary only that it be plane over a very small area.

## Transmission.

Measurements of the transmission of the films were made in the visible spectrum with the Brace spectrophotometer. Tables II. and III. give two sets of readings for the transmission of film No. 9, a cathodic film, at a point where its actual thickness is 4.67 $\mu$; Table I., of film No. 15, an incandescent lamp film, the thickness being .236 $\mu$. The "transmission" is given as the ratio of the intensity of light through the film, to that of light through the clear glass upon which the film is deposited, the two intensities being determined at places not more than 4 mm. apart. These results are shown graphically in Fig. 6; curve *A* is an average from the two sets of readings on film No. 9; curve *B*, for film No. 15. If there is a

[1] It is thus necessary to select a prism whose faces are polished alike.

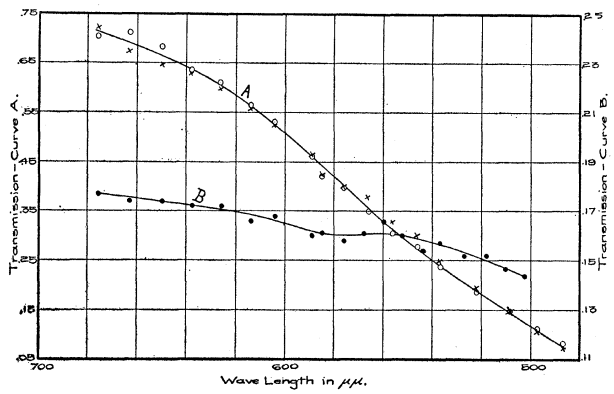


Fig. 6.

## TABLE I.

*Transmission of incandescent lamp film, No.* 15; *thickness,* 0.236 $\mu$.

| Wave-length. | Transmission. | Wave-length. | Transmission. |
|---|---|---|---|
| — | — | 576 | .158 |
| 676 | .177 | 568 | .161 |
| 663 | .174 | 560 | .166 |
| 650 | .174 | 552 | .160 |
| 638 | .172 | 544 | .154 |
| 626 | .172 | 537 | .157 |
| 614 | .166 | 527 | .152 |
| 604 | .168 | 518 | .152 |
| 589 | .160 | 510 | .147 |
| 585 | .161 | 502 | .144 |

## TABLE II.

*Transmission of cathodic film, No.* 9; *thickness,* 4.67 $\mu$.

| Wave-length. | Transmission. | Wave-length. | Transmission. |
|---|---|---|---|
| 676 | .720 | 566 | .380 |
| 663 | .675 | 556 | .330 |
| 650 | .646 | 546 | .304 |
| 638 | .630 | 537 | .250 |
| 626 | .596 | 522 | .199 |
| 614 | .560 | 508 | .148 |
| 604 | .526 | 497 | .106 |
| 589 | .465 | 486 | .074 |
| 585 | .425 | 477 | .054 |
| 576 | .401 | | |

TABLE III.

*Transmission of cathodic film, No.* 9 ; *thickness,* 4.67 $\mu$.

| Wave-length. | Transmission. | Wave-length. | Transmission. |
|---|---|---|---|
| 676 | .702 | 566 | .350 |
| 663 | .711 | 556 | .305 |
| 650 | .681 | 546 | .277 |
| 638 | .635 | 537 | .237 |
| 626 | .611 | 522 | .187 |
| 614 | .563 | 508 | .147 |
| 604 | .531 | 497 | .114 |
| 589 | .461 | 486 | .083 |
| 585 | .422 | 477 | .055 |
| 576 | .397 | | |

maximum in the absorption, such as was found by Nichols[1] for lampblack or by Moore and Ling[2] in the case of incandescent lamp deposits, it is very slight.

The transmission in the ultra-violet was obtained in a qualitative way by means of a Schumann quartz spectrograph. An induction coil arc between terminals of an alloy of cadmium, zinc and aluminium was the source of light. The well-known method of "crossed prisms" was used. Very thin cathodic films on quartz plates were placed before the slit, with the refracting edge of the slightly prismatic film perpendicular to the slit. Under these conditions, photographs were taken with varying times of exposure. If the film over one end of the slit is thin enough to transmit light of a certain wave-length, but thick enough at the other end to be opaque for the same wave-length, the effect upon the photographic plate will be an apparent shortening of the slit. Fig. 7, showing three exposures on one plate, brings out this effect plainly. The faint exposure was a short one, taken before the film was put in place, to locate points in the spectrum. The other two exposures, as well as every other one taken with the film before the slit, show an exposure over the

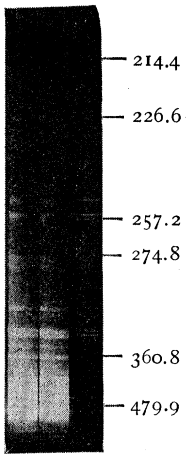


Fig. 7.

[1] Nichols and Blaker, l. c.

[2] Nichols, Am. Jour. Sc., Vol. 34, p. 277.

whole length of the slit at the red end at a uniform decrease in length for shorter wave-lengths as far as 226.6 $\mu\mu$; beyond this, the absorption is apparently complete as far out as 189.6 $\mu\mu$, the last wave-length detected when the slit is not covered by a film. A true absorption band, if present, would have shown first a decrease in length, then an increase.

## REFLECTION.

The reflection was measured as previously described. No attempt was made to polish any film, — a camel's hair brush will scratch the hardest cathodic carbon surface. In every case, the best reflecting portion of the surface was selected for measurements, which were made on the air surface. These were probably affected very slightly by reflection from the clear glass surface on the back side of the glass plate upon which the film was deposited. A pronounced and puzzling waviness in the reflection curves as first obtained, which varied from point to point on the reflecting surface, was found to be due to interference between the two surfaces of the film. When the reflecting surface of the film is examined with the spectrophotometer without an eyepiece and with the ocular and the collimator slits both very narrow, characteristic interference bands are plainly seen. These bands move across the field of view, when the film is shifted in its own plane toward either a thicker or thinner part. The effect of this interference is eliminated as follows. The telescope objective is diaphragmed by a vertical slit 1.5 mm. wide, approximately wide enough to show one light interference band or one dark band at a time, at the ocular slit. Then the reflection is measured for one wave-length, at one point on the film. The film is next moved in its own plane a very small distance, as described above, and the reflection again determined. This process is repeated until the maximum and the minimum in the reflection can be determined for any one wave-length. The whole procedure is then repeated for other wave-lengths. The average of these values is given in the results as the true reflection. The films are sufficiently prismatic to change the order of interference by one, for a motion as described above, of .35 mm., determined by calculation from the known variation in thickness of the film, and also by trial. Within

this limit, the true reflection is considered a constant, although it varies considerably in going a distance of 10 mm.

The data obtained from film No. 9 are given in Table IV. and

TABLE IV.

*Reflection of cathodic film, No.* 9.

| Wave-length. | Maximum Reflection. | Minimum Reflection. | True Reflection. |
|---|---|---|---|
| 673 | .0695 | .0530 | .0613 |
| 650 | .0530 | .0377 | .0454 |
| 626 | .0604 | .0424 | .0514 |
| 599 | .0477 | .0361 | .0419 |
| 576 | .0395 | .0354 | .0375 |
| 556 | .0351 | .0309 | .0330 |
| 537 | .0367 | .0314 | .0341 |
| 518 | .0380 | .0334 | .0357 |
| 502 | .0370 | .0346 | .0358 |
| 490 | .0333 | .0299 | .0316 |

represented graphically in Fig. 8. Aschkinass [1] gives the reflection of polished gas carbon as 4.4 per cent. at the *D* line, increasing to nearly 100 per cent. for Hertzian waves. The reflection of a cathodic carbon surface, at the *D* line, is seen from the curve to be 4 per cent. There is apparently a very slight rise in the reflection

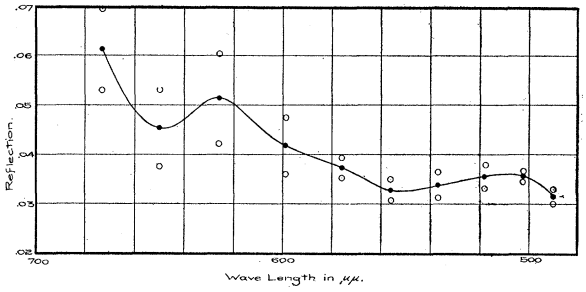


Fig. 8.

curve of cathodic films at 630 $\mu\mu$, corresponding closely to the slight anomaly as shown in curve *A*, Fig. 9. If there is a corresponding variation in the transmission, it is very slight. Nichols and Blaker [2] found a maximum in the rate of increase of radiation

[1] Aschkinass, Ann. d. Physik, IV., Vol. 18, p. 373, 1905.

[2] Nichols, PHYS. REV., Vol. 13, p. 129, 1901; and Blaker, l. c.

with temperature, using carbon rods and filaments, between the wave-lengths 620 $\mu\mu$ and 700 $\mu\mu$, the exact position varying with the temperature. The reflection of the incandescent lamp films was not obtained, because of their curvature. The refractive index curve

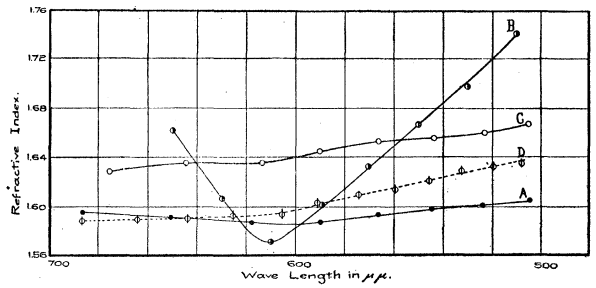


Fig. 9.

for these films, as well as the anomaly found by Wood[1] in similar films deposited on plate glass inside an incandescent lamp globe, suggests the probability of an abrupt change in their reflection.

## REFRACTIVE INDEX OF CATHODIC FILMS.

To obtain the refractive index of a film by interference methods, it is simply necessary to determine the "air thickness" and the "optical thickness" at the same point, in terms of the wave-length considered. The ratio of the latter to the former gives the index.

*To determine the air thickness*, the carbon film is cleaned away from a portion of the glass plate and another plate is put over it, forming a layer of air between the plates on one hand and the front plate and the film on the other. Then if light reflected from these surfaces is resolved by a prism or a grating, two sets of "spectral air bands" will be seen, as when the spectrometer with two collimators is used: one, due to interference between the two inner glass surfaces; the other, to interference between the free carbon surface and the glass surface over it. If these surfaces are slightly inclined to each other, in such a way that the "spectral bands" are parallel to the collimator slit, and are approximately plane, the "air thickness" of the carbon film at any point is readily found by a formula

[1] Wood, l. c.

due to Dr. Brace ;[1] or, by a slightly simpler formula, as follows. Let $n_1$ be the number of "spectral bands" between two definite points in the spectrum, arising from interference between the glass surfaces ; let $n_2$ be the corresponding number, after the reflecting plates have been moved a certain distance in their own plane ; while $m$ represents the number of "spectral bands" that have moved past any wave-length, $\lambda$, during this shift. Further, let $N_1$ be the "order of interference" — twice the distance between the two reflecting surfaces at the initial position — measured in terms of $\lambda$. Then

$$N_1 = \frac{n_1 m}{n_2 - n_1}.$$

$m$ is + or —, according as the shift of "spectral bands" is toward the red or toward the blue. Let $N_2$ be the corresponding "order of interference" between the glass and the carbon surfaces at the same point. Then $N$, the "air thickness," follows directly :

$$N = \frac{N_1 - N_2}{2}.$$

The cathodic films are highly transparent to the longer wave-lengths ; hence, the assumption was made that there is the same change of phase on reflection from carbon as from glass, for these wave-lengths. (There is no evidence of a sudden change of phase, such as Cartmel[2] noticed in the case of fuchsin.) This assumption is the same as was made by Pflüger[3] in the case of reflection of red light from fuchsin, which is many times more opaque than carbon, even for those wave-lengths for which the former is most transparent. Since this assumption requires the choice of dark bands[4] for measurements, these were made in every case by setting upon the dark, rather than upon the light, bands.

*To obtain the "optical thickness,"* two methods were used. The first, or "spectrometer method," is identical in principle with the

[1] Brace, Phil. Mag., V., Vol. 48, p. 350, 1899 ; also Rendtorff, Phil. Mag., VI., Vol. 1, p. 359, 1901 ; and Williams, PHYS. REV., Vol. 18, p. 280, 1904.

[2] Cartmel, l. c., p. 222.

[3] Pflüger, Wied. Ann., Vol. 65, p. 203, 1898.

[4] Brace, PHYS. REV., Vol. 21, p. 291, 1901.

method just described above, for the "air thickness." The upper glass plate is removed, and interference takes place between the two surfaces of the film, giving "carbon bands" in the spectrum, from which $M$, the "optical thickness," is obtained. The refractive index, $\mu$, for the wave-length $\lambda$, is the ratio of $M$ to $N$, as above. If $\lambda_1$, $\lambda_2$, $\cdots$, $\lambda_k$ are the wave-lengths, from $\lambda$ toward the blue, corresponding to the centers of the successive "carbon bands," the refractive index for each of these wave-lengths is

$$\mu_k = \frac{(M+k)\lambda_k}{M\lambda}\mu \ ,$$

where $M$ is the "optical thickness," in terms of $\lambda$. Table V. gives the refractive index obtained by this method, for cathodic film No. 7, which gave an especially distinct set of "spectral bands." These results are represented by curve $A$, Fig. 9. Film No. 9 gave a similar curve, though about 3 per cent. higher in the red, rising to 4 per cent. in the blue. (See Table VI., and curve $C$, Fig. 9.) Film No. 9 was more highly absorbing than No. 7 for the same thickness; hence was probably denser.

TABLE V.

*Refractive Index of cathodic film, No. 7; spectrometer meth d.*

| Order, $M$. | Wave-length. | Refractive Index. | Order, $M$. | Wave-length. | Refractive Index. |
|---|---|---|---|---|---|
| 19 | 687 | 1.596 | 24 | 545 | 1.599 |
| 20 | 651 | 1.592 | 25 | 524 | 1.601 |
| 21 | 618 | 1.588 | 26 | 505 | 1.605 |
| 22 | 590 | 1.588 | 27 | 487 | 1.609 |
| 23 | 567 | 1.594 | 28 | 472 | 1.617 |

TABLE VI.

*Refractive index of cathodic film, No 9; spectrometer method.*

| Order, $M$. | Wave-length. | Refractive Index. | Order, $M$. | Wave-length. | Refractive Index. |
|---|---|---|---|---|---|
| 19 | 676 | 1.629 | 23 | 566 | 1.653 |
| 20 | 646 | 1.636 | 24 | 544 | 1.656 |
| 21 | 614 | 1.636 | 25 | 523 | 1.660 |
| 22 | 589 | 1.645 | 26 | 505 | 1.667 |

This method is very advantageous, where the films are prismatic and are neither too thick nor too thin to give good bands; because the retardation of one interfering ray over the other takes place entirely in one medium.

The second, or "interferometer method," of obtaining the "optical thickness," in which the interferometer previously described was used, can be used with much thicker films than can the "spectrometer method"; for light traverses the film, which is strongly absorbing, only once in this type of interferometer. It can also be used for much thinner films — films too thin to give "spectral bands" —; for "spectral bands" may be introduced by adjusting the interferometer. As previously described, the instrument is first so adjusted that the retardation in one interferometer path over that in the other is due to carbon, or to air, or to both, and to nothing else. The carbon film, $n$, Fig. 4, is traversed by the lower half of the beam of light in one path; the rotating part of the mica compensator, $k'$, is in the upper part of the same beam. Two sets of spectral bands appear in the spectroscope, $h$, one above the other; as when the spectrometer with two collimators is used. The retardation due to the carbon, in terms of the number of "spectral bands" shifted past any one wave-length, $\lambda$, is measured roughly by slowly pushing along the glass plate carrying the carbon film, from a point where the retardation due to the carbon is zero. The compensator is then turned until the retardation due to the mica is the same at $\lambda$, at the center of a dark band, as that due to the carbon. The process is repeated for other wave-lengths.

The refractive index for any wave-length is

$$\mu = \frac{N + r}{N},$$

where $N$ is the "air thickness" and $r$, the retardation, both measured in terms of $\lambda$. The refractive index of the cathodic films as determined by this method, agrees well with that found by the other method, except in the green and the blue, where the absorption is so great that the spectrometer method is not very accurate. Table VII. and curve $D$, Fig. 9, show the index of film No. 7, obtained by this method. (Compare Table V. and curve $A$.) When the inter-

TABLE VII.

*Refractive index of cathodic film, No. 7; interferometer method.*

| Wave-length. | Retardation, $r$. | Refractive Index. | Wave-length. | Retardation, $r$. | Refractive Index. |
|---|---|---|---|---|---|
| 687 | 3.49 | 1.589 | 576 | 4.32 | 1.610 |
| 665 | 3.61 | 1.590 | 560 | 4.46 | 1.614 |
| 645 | 3.73 | 1.591 | 546 | 4.63 | 1.621 |
| 626 | 3.86 | 1.594 | 533 | 4.80 | 1.629 |
| 605 | 4.00 | 1.595 | 520 | 4.95 | 1.633 |
| 591 | 4.15 | 1.603 | 508 | 5.09 | 1.635 |

ferometer is used, the method of mixed bands[1] should be applied. However, with the order of thickness used in this work, the error due to neglecting this correction is very small, since the mixed bands include air and carbon bands only.

REFRACTIVE INDEX OF INCANDESCENT LAMP FILMS.

The incandescent lamp films were but very slightly, if at all, prismatic and were on curved surfaces; consequently, the methods of measurement used in determining the refractive index of cathodic films, need some modifications. Obviously, the spectrometer method could not be used; hence, the interferometer method was employed. A lamp was broken into bits, and a piece selected that gave approximately straight "spectral bands" when placed in the interferometer, the light being resolved by a spectrometer with a very short, narrow narrow slit. The incandescent lamp films not being sufficiently prismatic, the order of retardation could not be obtained roughly, as it was for the cathodic films. Instead, the interferometer is set for the central white band in one half of the field, as seen in the spectrometer; then, one of the interferometer plates is moved until the same condition is obtained in the other half of the field, and the consequent shift of bands past any wave-length is counted. This shift, for lamp films, was always less than one band. The exact retardation was determined from the mica-compensator readings as follows. The compensator was carefully calibrated throughout the spectrum, for a shift of each whole band from 1 to 5. The retardation caused by rotating the compensator is

[1] Brace, PHYS. REV., Vol. 21, p. 294, 1905.

$$r = \frac{t(\mu - 1)}{\lambda}\left(\frac{1}{\cos\theta} - 1\right),$$

where $t$ is the "air thickness" of the mica; $\theta$, the angle through which the compensator is turned for the wave-length, $\lambda$; and $\mu$, the refractive index of the mica in the direction of the ray. $\mu$ is constant for values of $\theta$ from 0° to 20°, corresponding to values of $r$ from 0 to 5, as can be shown by plotting values of $r$ and $(1/\cos\theta - 1)$. This makes

$$r = K\left(\frac{1}{\cos\theta} - 1\right),$$

in which $K$ is calculated from the observed values of $r$ and $\theta$ within the limits just given. From this equation, calibration curves were calculated and plotted for values of $r = 0, 0.05, 0.1, 0.2, \cdots, 1.0$, since $r$ was always less than unity in practice. The actual retardation caused by the lamp films was then obtained by interpolation from these curves.

To determine the "air thickness" of lamp films, Newton's rings were used. Upon the film side of the bit of glass selected above — from a part of which the film had been cleaned away — was placed another selected piece of the same globe, carefully cleaned all over, and the whole illuminated with strong sodium light. This arrangement gave two sets of Newton's rings, shifted past one another slightly, just as were the "spectral bands" above. This shift was measured for light at nearly perpendicular incidence, by means of a low-power micrometer microscope; and from it, the "air thickness" of the film was calculated. There was a little uncertainty at first, whether the shift of the sodium bands was a part of a band only, or a certain number plus that part of a band. This is settled definitely, however, by the fact that, if the shift is assumed to be a part only of a band, the index becomes 1.602; while, if the shift is assumed to be one whole band plus that fraction, the resulting index is only 1.3, — an improbable value. The "air thickness" of incandescent lamp film No. 15 is thus determined to be .402 wave-length, at the $D$ line. $\mu_D$ is then determined from the equation given above,

$$\mu = \frac{N + r}{N}.$$

The refractive index for other wave-lengths is obtained from the equation,

$$\mu_x = 1 + \frac{r_x \lambda_x}{N_D \lambda_D}.$$

The results from the above film No. 15, are shown in Table VIII. and are represented by curve $B$ of Fig. 9.

TABLE VIII.

*Refractive index of incandescent lamp film, No.* 15 ; *interferometer method.*

| Wave-length. | Retardation, $r$. | Refractive Index. | Wave-length. | Retardation, $r$. | Refractive Index. |
|---|---|---|---|---|---|
| 650 | .241 | 1.662 | 570 | .263 | 1.633 |
| 630 | .228 | 1.607 | 550 | .287 | 1.667 |
| 610 | .222 | 1.572 | 530 | .312 | 1.698 |
| 589 | .242 | 1.602 | 510 | .344 | 1.741 |

The refractive index of every film examined shows anomalous dispersion, although it is very slight in all of the cathodic films. In these, the anomaly probably corresponds to a "point of inflection"[1] in the refractive index curve. There is a corresponding variation in the reflection of cathodic films, but little or no evidence of a variation in the absorption, even in the case of incandescent lamp films, in which the anomaly is most prominent. The lamp films examined were somewhat thicker and more porous than is usual with such films. Wood's films[2] were deposited on plate glass inside a lamp globe ; hence the deposit was formed at a place much nearer the incandescent filament than in the case of mine. His were, in consequence, probably much denser than mine. This would account for his higher value of the refractive index, 2.2 for the $D$ line, as compared with my value of 1.6.[3] Amorphous carbon absorbs nitrogen so strongly that it probably is really a solution of nitrogen and carbon, as Stark[4] suggests for smoke films.

[1] Brace, PHYS. REV., Vol. 21, p. 293, 1905.

[2] Wood, l. c.

[3] Professor F. Braun, of Strassburg, has kindly sent me a number of carbon films made by "flashing" a filament near a glass surface. He has shown (Ann. d. Physik, IV., Vol. 17, p. 359) that these films are deposited directly from the vaporous condition. Consequently, they are much denser than those I have thus far examined. I hope to be able to determine the optical properties of these later.

[4] Stark, l. c.

Its properties, therefore, are those of a solution, and not of pure carbon.

Different samples examined thus far vary so much, that it appears conclusive that the optical properties of carbon films, and probably of other substances as well, are not constant ; but are complex functions of the conditions and methods of deposit. This is to be expected from the work of Kundt,[1] Hagen and Rubens,[2] Stone,[3] Longden,[4] Patterson,[5] Beilby,[6] and others, upon both the optical and the electrical properties of thin films of metals. The suggestion of Kundt and of Hagen and Rubens, that this variation for certain metals may be due to the formation of oxides, is not so satisfactory in the case of carbon, since its oxides are gases.

## Recapitulation.

1. The reflection, the absorption, and the refractive index of carbon films vary with the conditions and method of deposit.

2. There is a slight anomaly in the refractive index of cathodic carbon films, and a more pronounced one in the case of incandescent lamp films, at the wave-length $\lambda = 610\ \mu\mu$. The reflection curves of the former show a corresponding variation. Scarcely any variation, however, has been detected in the transmission curves of either class of films.

3. The transmission of cathodic films decreases almost uniformly from the red of the visible spectrum to the wave-length $\lambda = 226.6\ \mu\mu$, beyond which the films are completely opaque. Thus there is no pronounced absorption band.

4. The reflection of cathodic films *decreases* from a maximum in the red to a minimum in the blue of the visible spectrum. A slight rise, however, occurs at the wave-length $\lambda = 630\ \mu\mu$.

In conclusion, I wish to express my grateful appreciation of the assistance and inspiration given me in this work by the late Dr. D. B. Brace, and also of the excellent laboratory facilities placed at my disposal in the University of Nebraska, where it was done.

Syracuse University, June, 1906.

[1] Kundt, Phil. Mag. V., Vol. 26, p. 1, 1888.
[2] Hagen and Rubens, Phil. Mag., VI., Vol. 7, p. 164, 1904.
[3] Stone, Phys. Rev., Vol. 6, p. 1, 1898.
[4] Longden, l. c.
[5] Patterson, Phil. Mag., VI., Vol. 4, p. 652, 1902.
[6] Beilby, Proc. Roy. Soc., Vol. 72, p. 226, 1903.

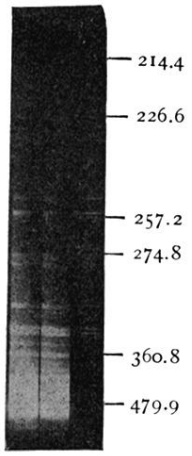


Fig. 7.