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THE VISIBLE RADIATION FROM CARBON.[1] I.

By Edward L. Nichols.

THE law of radiation has for a long time been considered by physicists as a subject of high interest, and numerous investigations looking to the establishment of a general relation between radiation and temperature have been made both from the theoretical and the experimental standpoint. The earliest attempts to determine incandescence in its relation to temperature were made with platinum. Draper[2] in 1847 made observations upon a wire of that metal heated by an electric current. The temperatures were from the expansion of the wire. Zöllner[3] in 1859 compared the light emitted by incandescent platinum with the heat evolved.

E. Becquerel,[4] who made an extensive study of visible radiation from various solids at high temperatures, used thermo-elements of platinum and palladium, calibrated by reference to melting points and with the air thermometer. A partial separation of the rays was effected by means of colored screens. He found that opaque bodies, such as lime, magnesia, platinum and carbon at the same temperature had very nearly equal emissive powers, a conclusion vigorously contested by his contemporaries, but explained in the light of later work, by the fact that the glowing bodies were en-

[1] An investigation carried on in part by means of an appropriation from the Rumford Fund for Research. Read at the meeting of the American Association for the Advancement of Science in New York, June 27, 1900.

[2] Draper, Philosophical Magazine, Vol. XXX., p. 345 (1847).

[3] Zöllner, Photometrische Untersuchungen (1859).

[4] Becquerel, Annales de Chimie et de Physique (3), 68, p. 47 (1863).

closed in a long earthen tube. The conditions for ideal blackness were thus approximately fulfilled. He likewise made photometric observations upon wires electrically heated and found the light to increase much more rapidly than the emitted heat.

Although some of Becquerel's results were at fault, particularly his estimation of temperature above the melting point of gold, his work is especially noteworthy in that he employed many of the methods to which, in the hands of later investigators, our knowledge of the laws of incandescence is due. He established the fact of the direct proportionality of the logarithm of the intensity of radiation to the temperature and pointed out the possibility of optical pyrometry.

In 1878 Crova[1] used the Glan spectrophotometer in the comparison of various sources of light such as candles, gas flames, the lime light, the arc light and sunlight, and proposed an optical method for the measurement of temperatures.

In 1879[2] I published the results of a series of measurements made in this manner upon the visible radiation from platinum at various temperatures. At that time, the measurement of high temperatures by means of thermo-elements, of platinum and platinum-rhodium, or platinum-iridium, had not been developed and the determination of the temperature from the change of resistance of the metal was, as has been previously pointed out by Siemens, a matter of great uncertainty on account of the varying performance of different samples of platinum. This difficulty, which was due to the impurities contained in the metal, has since been largely overcome and platinum thermometry has, through the study of Callendar and others, been advanced to the position of an operation of precision; but at that time I was forced to content myself in the investigation just referred to with an expression of temperature of the glowing platinum in terms of its increase of length.

Work upon the incandescence of carbon was first taken up in a serious manner after the development of the incandescent lamp.

Schneebeli,[3] in 1884, made some observations upon the total

[1] Crova, Comptes Rendus, 57, p. 497 (1878).

[2] Nichols: Ueber das von glühendem Platin ausgestrahlte Licht. Göttingen, 1879; also American Journal of Science, Vol. 18, p. 446 (1879).

[3] Schneebeli, Wiedemann's Annalen, 22, p. 430 (1884).

radiation and candle power of the Swan lamp. He made no estimation of temperatures.

In the same year Schumann[1] published his very complete spectrophotometric comparison of the various incandescent lamps in use in Germany. Lucas,[2] in 1885, heated arc-light carbons in vacuo, estimated their temperature from the current employed and measured the light given in carcels. I shall refer to his work in some detail later.

In 1887 H. F. Weber[3] began his studies of the spectrum of the incandescent lamp. He found that the first light to appear was not that of the region nearest the red end of the spectrum but corresponded in wave-length to the region of maximum luminosity and that at their low temperatures the spectrum was devoid of color. Stenger[4] in the same year corroborated Weber's observations and offered what has since been received as the proper explanation of the phenomenon.

In 1889 I published in colaboration with W. S. Franklin[5] a series of spectrometric comparisons of incandescent lamps maintained at various degrees of brightness. No attempt was made to determine temperatures. In 1891, H. F. Weber[6] read a paper at the Electrotechnical Congress in Frankfort on the general theory of the glow lamp. By means of numerous measurements through a wide range of incandescence, made upon lamps with treated and untreated filaments, constants were established for his empirical formula for the relation of radiation and temperature.

The infrà-red spectrum of carbon has, since the appearance of the incandescent lamp, likewise been subjected to measurement. Abney and Festing[7] in 1883 published curves for the distribution of energy in the spectrum of such lamps from measurements made with the thermopile. In 1894 I compared with the help of the same instru-

[1] Schumann, Elektrotechnische Zeitschrift, 5, p. 220 (1884).

[2] Lucas, Comptes Rendus, 100, p. 1454 (1885).

[3] Weber, Wiedemann's Annalen, 32, p. 256 (1887).

[4] Stenger, Wiedemann's Annalen, 32, p. 271 (1887).

[5] Nichols and Franklin, Am. Jour. of Science, 38, p. 100 (1889).

[6] Weber, Bericht des internationalen Electrotechnikercongresses zu Frankfurt am Main, p. 49 (1891); also PHYSICAL REVIEW, Vol. 2, p. 112.

[7] Abney & Festing, Philosophical Magazine (5), 16, p. 224 (1883); also Proceedings of the Royal Society, 37, p. 157 (1884).

ment and a highly sensitive galvanometer the infra-red spectra of lamps with black and gray filaments.[1]

Of late years attention has been devoted especially to the problem of the law of radiation from an ideal black body and various formulæ have been proposed by means of which the rise of radiation of any single wave-length upon the one hand and of the total radiation on the other may be expressed as a function of the temperature. Interesting as this phase of the problem is from the point of view of theoretical physics, it is perhaps even more important to know the relation between temperature and radiation for actual surfaces.

APPARATUS AND OUTLINE OF METHOD.

I propose in the present paper to describe an attempt to measure the temperature of carbon rods rendered incandescent by the passage of an electric current, and to make spectrophotometric comparisons of the visible radiation from their surfaces with the corresponding wave-lengths in the spectrum of an acetylene flame.

The carbons used for this purpose were produced by the well-known process of squirting a semi-fluid carbonaceous paste through a cylindrical opening. They were straight cylindrical rods 10 cm. in length and 2 mm. in diameter. Still larger rods would have been preferable but I was unable to obtain any of greater diameter than the above that were capable of withstanding the temperatures to which it was necessary to heat them. The rods were mounted horizontally in a massive metal box 40 cm. in length, 20 cm. wide, and 20 cm. in height. This box, which was made especially for this investigation, had openings at the ends through which, by means of air-tight plugs, the terminals of the rod could be introduced. Through one of these plugs, likewise, the platinum and platinum-rhodium wires of the thermo-element, by means of which the temperature measurements were made, entered the box. In one of the vertical sides of the box was a row of five circular plate glass windows, which could be removed for cleaning, through which the carbon could be seen and the spectrophotometric observations could be made. Other

[1] Nichols, PHYSICAL REVIEW, Vol. 2, p. 260 (1894).

openings in the top of the box and through the opposite sides served to connect it with a mercury air pump of the Geissler type and with manometers for the measurement of pressure. A vertical cross section of this part of the apparatus is shown in Fig. 1.

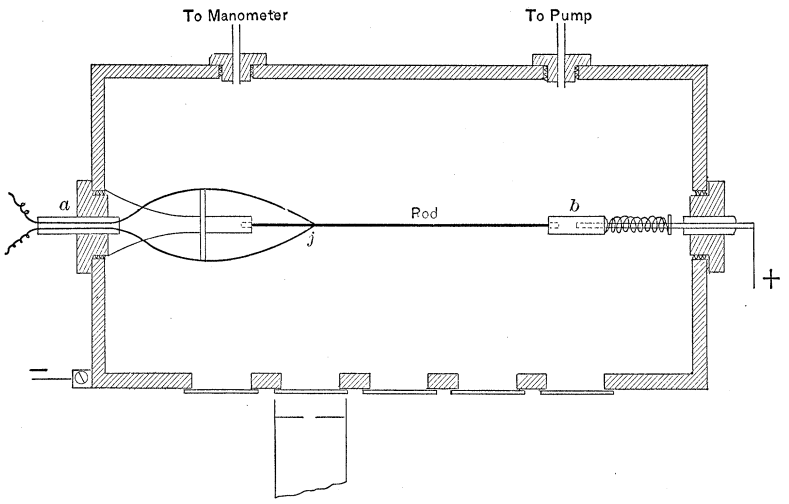

Fig. 1.

Attempts to locate by a variety of methods the hot junction of the thermo-element, by means of which the temperature of the surface of the rods was to be measured, in such manner that it would assume the temperature of that surface, made it only too clear that herein lay one of the chief difficulties of the investigation. It was found that any such junction, however small its size and however carefully it might be brought into contact with the surface of the rod, would not take even approximately the temperature of that surface; and recourse, after the failure of numerous other expedients, was had to the following plan, which although far from being free from objection, was found to be upon the whole the most reliable, and to give, when properly carried out, the most definite and satisfactory result.

By means of a drill made for the purpose from the smallest obtainable size of steel sewing needle, a minute hole was bored radially at the point upon the surface of the rod lying within the field of view of the spectrophotometer. This hole had an approximate

diameter of 0.03 cm. It extended to a depth equal to about one-half the radius of the rod and was conical in form. Platinum and platinum-rhodium wires to be used for the thermo-element were drawn to a diameter of 0.016 cm., and their free ends having been laid together side by side, were fused in the flame of the oxyhydrogen blowpipe so as to form a junction. This junction, which after the action of the blowpipe took the shape of a small bead of the combined metals, was trimmed down into conical form, until it would just enter the hole in the side of the rod, care being taken that the entire junction was beneath the surface. The wires leading from this junction were next sealed into a glass tube of about 2 mm. bore through the interior of which they were carried from end to end; care being taken that they should be nowhere in contact. They were held in place by fusing the glass around them at either end of the tube. This tube was inserted through an opening in the plug *a* (Fig. 1), carrying one terminal of the rod and there made air-tight by means of cement. One end of the carbon rod was then inserted in a clamp attached to the inner face of the plug and the wires at a distance of about 1 cm. from the junction were bent downward at right angles so as to bring the junction into position for insertion into the hole in the rod and to hold it there when inserted by the slight but sufficient spring action of the wires themselves. This arrangement of the junction and rod is indicated in Fig. 2.

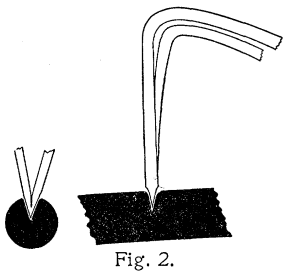

Fig. 2.

The introduction of the thermo-element having been successfully carried out by the method just described, it was possible to insert the plug, carrying the rod and thermo-junction with it, into the end of the box and to secure it in place; after which the free terminal of the rod was introduced between the jaws of a strong clip attached to the opposite plug (*b*, Fig. 1). This operation had to be performed through the open windows in the side of the box. These were then screwed tightly into place, and the box was ready for the exhaustion of the air.

This method of measuring the temperature of the surface, to be

successful, involved the fulfilling of several rather difficult conditions and the application of an important correction. To bore into the material of a carbon rod carrying a current in the manner described, necessarily disturbs more or less the flow of the current; and the changes of resistance thus introduced were likely to bring about decided changes of temperature in that neighborhood. In some instances, this became obvious when the rod was heated, the temperature being higher near the hole than elsewhere. Indeed, it was often possible to note with the eye the increased incandescence of the region in question. In all such cases the mounting was rejected. It was found possible, however, to so nearly compensate for this loss of carbon by the introduction of the platinum junction that no difference in the incandescence of the surface could be detected by the closest observation; and since differences of temperature which cannot be detected by the eye will be negligible in spectrophotometric work, this was taken as the criterion of a satisfactory mounting of the thermo-junction. Measurements were attempted only when this condition was fulfilled. It is likewise obvious that there is danger from the contact of the two wires of the thermo-junction with the sides of the hole in the rod. A branch circuit for the passage of the current is thus formed which includes the galvanometer coils, thus imperiling the integrity of the readings of electromotive force. This could be obviated only by having the wires touch the rod at points in an equipotential surface, and the fulfillment of this condition was determined by the reversal of the current through the rod and the absence of any effect of such reversal upon the galvanometer.

Another and more serious objection to the method, and one which could only be met by the introduction of a correction, lay in the fact that even with the smallest wires which could be used for a thermo-element a certain amount of heat would be carried away by conduction through the metal; so that the junction would never reach the full temperature of the surfaces with which it was in contact. I was at first inclined to think that this correction would be a small one, but attempts to measure the temperature of the acetylene flame by means of a similar thermo-element indicated that the loss of heat from this source was by no means to be neglected. The numerical value of this correction was accordingly determined

by direct experiment in the following manner. Thermo-elements drawn from the same pieces of wire but differing considerably in diameter were prepared. These were inserted two at a time in holes on opposite sides of a carbon rod and the rod was brought to incandescence by means of the current. The temperatures reached by these junctions were compared by means of the potentiometer and a curve was plotted showing the relation between the cross section of the wire in the thermo-element and the temperature of the junction. This curve, extended in the direction of decreasing cross section, served to indicate with at least a fair degree of accuracy the temperature which would have been reached by a thermo-element of *zero cross section* placed in contact with the surface to be measured. The difference between this temperature and that reached by a junction of any desired size gave the correction which was to be applied. The correction, as will be seen by inspection of the curve, Fig. 3, is a very large one, amounting even in the case

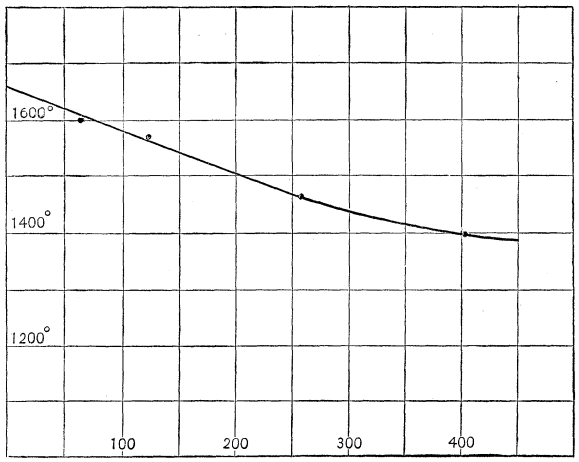

Fig. 3.

of the smallest wires which it was found practicable to use to about 85°. The results of the calibration agreed, however, so well with similar experiments made by placing thermo-junctions of various sizes in the non-luminous outer envelopes of the acetylene flame, of the ordinary gas flame, and of the flame of the candle,[1] that I feel warranted in placing much dependence upon them.

[1] Nichols, PHYSICAL REVIEW, X., p. 234.

This method of correcting for the loss of heat in a thermo-junction was first employed by Waggener[1] in his investigation of the temperature of the flame of the Bunsen burner. I became acquainted with his research, however, only after the completion of my experiments.

Calibration of the Thermo-Elements.

All our modern estimates of very high temperatures may be said to rest in one way or another upon extrapolation. The upper limit of usefulness of the air thermometer has been found to lie in the neighborhood of 1500°. It was at this temperature that Erhardt and Schertel[2] in their admirable but little-known research upon the melting points of alloys of silver, gold and platinum were obliged to abandon direct determination; and very closely, at which Holborn and Wien[3] and Holborn and Day[4] in their latest studies upon thermo-electric thermometry found that the indications of the air thermometer, even when constructed of the most refractory of modern porcelain began to become erratic. We have, it is true, the investigations of Violle[5] upon the melting points of the metals of the platinum group, but these, it must not be forgotten, are based upon an assumed value for the specific heat and this assumption is equivalent to the extrapolation of the curve of the variation of the specific heat with temperature. The observed values, by means of which this value was determined, all lie far below those of the melting points of the metals in question. It is necessary therefore in spite of the accumulation of indirect evidence of their approximate accuracy, to hold in reserve the assignment of absolute values of these melting points until by some means as yet unthought of, we shall be able to obtain direct experimental data. In the meantime they afford us the best present available basis for a temporary scale, our confidence in the approximate accuracy of which must rest upon the fact that the melting points for palladium, platinum, etc., as given by Violle are found to lie upon what may reasonably be

[1] Waggener, Wiedemann's Annalen, LVIII., p. 579 (1896).

[2] Erhardt and Schertel, Jahrbuch für das Hüttenwesen in Sachsen, 1879, p. 154.

[3] Holborn and Wien, Wiedemann's Annalen, XLVII., p. 107 (1892), and LVI., p. 360 (1895).

[4] Holborn and Day, American Journal of Science, VIII., p. 175 (1899).

[5] Violle, C. R., LXXXIX., p. 702 (1879).

supposed to be an extension of the curves experimentally determined for lower temperatures by means of the air thermometer. As for the various formulæ for the variation of electromotive forces of thermo-elements with the temperature, we must not lose sight of the fact that they are simply analytical expressions for experimentally determined relations and that the extensions of them to temperatures lying far beyond the experimental range is not to be regarded as more trustworthy than the extension of a curve by graphical methods. Under these circumstances I decided to content myself with the provisional acceptance of the following values for the melting points of gold, palladium and platinum, namely:

Gold,[1] 1064° C.
Palladium, 1500° C.
Platinum, 1775° C.

and to ascertain as accurately as possible the electro-motive force given by the thermo-elements used at these points. It was thought that by drawing a curve through them, and reading intermediate temperatures from this curve the values thus obtained would be as close as our present knowledge of the subject will admit. The platinum-platinum-rhodium wire used for my elements was obtained, as has already been stated, from Heræus in Hanau and was supposed to be of the same stock as that employed by Holborn and Wien. The fact that the electromotive force given by these thermo-elements when exposed to the temperature of melting platinum agreed very closely indeed with that obtained by extrapolation of their data, seems to indicate that the metals were identical with those used by them.

For the purpose of calibrating the thermo-elements, I employed a very simple method, the results of which, however, proved highly satisfactory. This method, which consists in exposing the hot junction to the layers of heated gas surrounding the acetylene flame and lying just outside the luminous envelop of that flame, has been described in some detail in a separate communication.[2]

[1] This value is that given by Holborn and Day in their second paper (American Journal of Science, X., p. 171 (1900).

[2] Nichols, On a New Method of Calibrating Thermoelectric Elements for Use in the Measurement of High Temperatures. [Livre Jubilaire dedié à H. A. Lorentz; La Haye, 1900, p. 339.]

The method is easily carried out and it is free from many of the most serious difficulties of the cumbersome operations usually employed, which involve the use of furnaces and of the porcelain bulb air thermometer. Fig. 4 contains the calibration curve of the thermo-

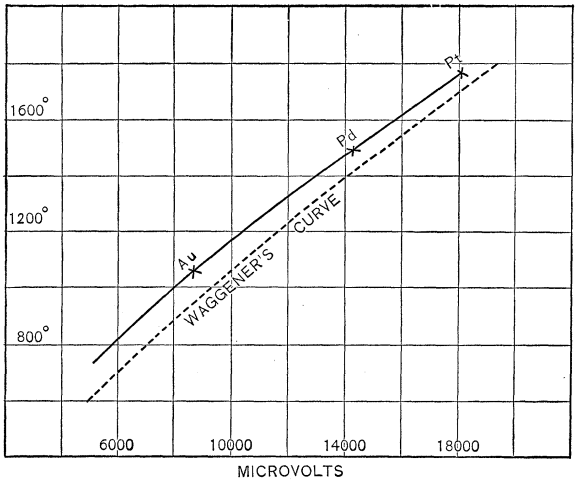

Fig. 4.

elements used in this investigation and likewise, for the purpose of comparison, a curve reproduced from Waggener's paper and extrapolated by him from the data given by Holborn and Wien. It will be seen that while the two curves are not identical, they are of the same general character and that the differences are not greater than experience would lead us to expect in the case of different thermo-elements, even where these are of platinum and of platinum-rhodium of the same manufacture. It is not a question of absolute electromotive forces but rather of the form of the curves; since what we really need is a criterion by means of which we can determine whether temperature readings based upon Violle's values for palladium and platinum are in reasonable agreement with those obtained by the extension of the curve of Holborn and Wien.

The Spectrophotometer.

The spectrophotometer used was a copy of the instrument designed by Lummer and Brodhun for the Imperial Institute in Char-

lottenburg. It consists of a one-prism spectroscope with two collimator tubes, placed at right angles to each other as shown in Fig. 5. Each of these tubes carries a slit the width of which is regulated by means of an accurate micrometer screw with a drum head divided into one hundred parts. By estimating tenths of a scale division, the width of the slits could be estimated to one one-thousandth of a revolution.

The essential feature of this photometer consists in the Lummer-Brodhun device (D), placed between the objective lenses of the two collimators and the prism, in such a position that the beam of light from one of the tubes is transmitted directly to the latter, while that from the other tube is bent through 90° by total reflection. The instrument was set up with collimator A in such a position that a portion of the surface of the incandescent rod lying nearest to the

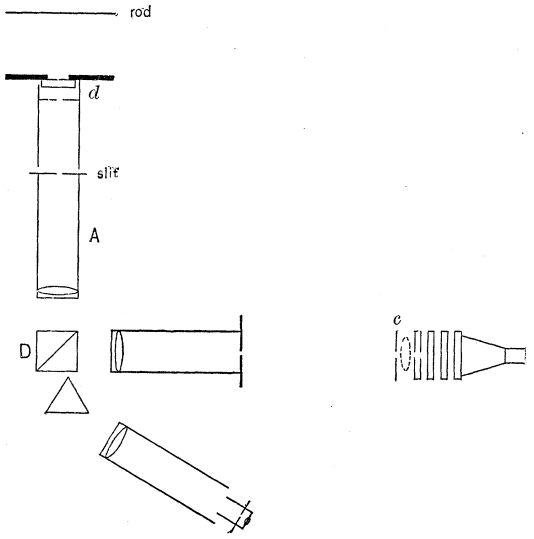

Fig. 5.

point at which the thermo-element had been inserted formed a field of illumination for the slit at a distance of about 25 cm. The region under observation was limited by means of a vertical diaphragm (d) 5 mm. in width which was mounted in a tube in front of a window of the metal vacuum box. The comparison source was the spectrum

of the brightest part of an acetylene flame set up in the axis of the other collimator at a corresponding distance and viewed through a circular aperture (c) 5 mm. in diameter, cut in a metal screen interposed between the flame and the slit and as near the former as practicable.

The acetylene flame was adopted as a comparison standard for the following reasons :

1. It possesses a continuous spectrum brighter in the less refrangible regions than that of any other controllable source of light.

2. The radiating material is finely divided carbon, presumably of a character not unlike that of the surface of the untreated rod.

3. The acetylene flame is the result of the combustion of a definite fuel (C_2H_2) burning under reasonably constant conditions. It is preferable in this regard to any of the ordinary gas or candle flames in which the fuel is of an undetermined and more or less variable character.

4. When supplied with gas under constant pressure, an acetylene flame of the type used in these experiments, that, namely, obtained by means of a burner composed of a single block of steatite, is more nearly constant in its intensity and color than any other flame with which I am acquainted, with the exception of that of the Hefner lamp. It is indeed questionable whether the latter is superior to acetylene in this respect and its comparative weakness in the blue and violet renders it very undesirable as a comparison source in spectrophotometry.

Method of Checking the Constancy of the Acetylene Flame.

To secure as complete a check as possible upon the constancy of the flame the following method, based upon the assumption that so long as the radiation from the flame remained constant, its light-giving power would not vary, was employed. A diaphragm d (Fig. 6) similar to that interposed between the slit and the flame and having an aperture of the same size, was mounted on the opposite side of the latter and a thermopile p was placed at a distance of about 15 cm. from this opening. A second diaphragm d', with an intervening air space served to cut off, in large part, the radiation

from the heated metal. Two thin sheets of glass forming the sides of an empty glass cell c of the kind used in the study of absorption spectra, etc., were placed between the cone of the thermopile and the second diaphragm; so that only those rays from the flame which were transmitted by the glass fell upon the face of the pile.

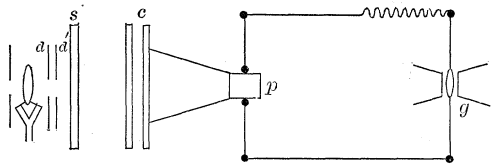

Fig. 6.

The thermopile was connected with a sensitive d'Arsonval galvanometer (g), the circuit being kept permanently closed, and a double metallic shutter s, which could be raised or lowered so as to open or close the opening in the diaphragm next to the flame was so mounted that it could be readily operated by an observer at the telescope of the galvanometer. When a reading of the radiation from the flame was to be made, the zero point of the galvanometer was noted and this shutter was raised during the short interval of time necessary to bring the needle, which was not strongly damped, to its first turning point. The shutter was immediately closed in order to prevent further heating of the face of the thermopile. This throw of the galvanometer was taken as an indication of the intensity of the flame. It was found that the thermopile would cool sufficiently within two minutes to admit of the repetition of the reading. These observations were taken by an assistant simultaneously with each setting of the spectrophotometer, the intention being to reject any spectrophotometric readings made at a time when the flame showed marked deviation from its standard intensity, and to reduce the readings to a uniform flame intensity under the assumption that for the small range of variation occurring from reading to reading, the changes in the brightness of the flame would be proportional to the variations of this galvanometer reading from the mean of the whole set. In point of fact it was found that the flame rarely varied by more than two per cent. from the mean in the course of a set of observations and remained most of the time within one per cent. From day to day its intensity was usually within the limits stated above although occasionally a larger variation was detected. None

of these variations in the course of the present investigation reached values so great as to lead me to hesitate to apply the correction already referred to, and all the observations described in this paper have been reduced to a constant flame intensity by means of a correction factor obtained from the readings of the galvanometer.

Control and Measurement of the Temperature of the Carbon Rod.

The carbon rod having been brought to the desired degree of incandescence by means of the current from a storage battery, was held at a constant temperature by varying the resistance placed in the battery circuit. The indications of the thermo-element inserted in the rod were noted by means of a potentiometer consisting of an accurately adjusted resistance box of 100,000 ohms, the smallest coils in which contained one ohm each, a sensitive galvanometer of the d'Arsonval type and a large Clark cell of the old Feussner type, against which the electro-motive force of the thermo-element was balanced in the usual manner. The arrangement of this potentiometer has been described in my recent paper[1] on the temperature of the acetylene flame. The cells used in the measurement of the temperature of the carbon rod were the same as those employed in that investigation and the same precautions were taken to preserve constancy of temperature and to control and check their electro-motive force. It was found that at the temperature of 18°, which was very closely the mean temperature of the room, the electro-motive force of the Feussner cells was 1.430 volts.

The potentiometer having been balanced by looping the circuit containing the thermo-element around a sufficient portion of the resistance box to balance its current against that of the Clark cells, a condition which was indicated by the reduction of the galvanometer deflection to zero, the current was maintained at such a value as to hold the carbon at a constant temperature during the time necessary to complete measurements of the intensity of eight different portions of the spectrum, ranging from the extreme red to the violet, with the corresponding portions of the spectrum of the acetylene flame. In order to insure the maintenance of this con-

[1] Nichols, Physical Review, 10, p. 237 (1900).

stant temperature in the rod, an assistant made repeated observations with the potentiometer and readjusted the resistance in the battery circuit whenever necessary. Excepting at very high temperatures where the rod was subject to rapid disintegration, it was rarely necessary to make any adjustment during the progress of a single set of observations. Readings of the current flowing through the carbon and of the fall of potential between its ends were made at the beginning and end of each experiment.