

## THE TEMPERATURE OF THE DIVIDED BUNSEN FLAME.

BY DANIEL W. SHEA.

IN the course of an experimental study of the electrical character of the source of light radiation made with a divided Bunsen flame, in this laboratory, by Dr. T. P. Irving,<sup>1</sup> it became desirable to know the temperature of the different parts of the flame, when in its simple state and when colored by burning in it various metal vapors. As the literature on this flame, so far as we could learn, contained no temperature records of service to us, I measured the temperature at numerous points. The measurements, though made only for the size and form of burner described below, yielded some results interesting in themselves and of importance in connection with Dr. Irving's work. The following pages contain a brief account of the apparatus and measurements, and some discussion of the results.

### I. THE APPARATUS.

The burner used to separate the cones of the Bunsen flame consisted of a brass tube *a*, Fig. 1, 24 cm. long and 1.4 cm. wide inside, and a glass tube *b* shaped like that employed by Fredenhagen,<sup>2</sup> 15 cm. long, 4.8 cm. wide inside at the bottom and 2.7 cm. inside at the top. The glass tube was fitted over the brass tube by means of a bored plug of rubber, 3 cm. thick, inserted 1 cm. into the glass tube. *c* → *Gas* →

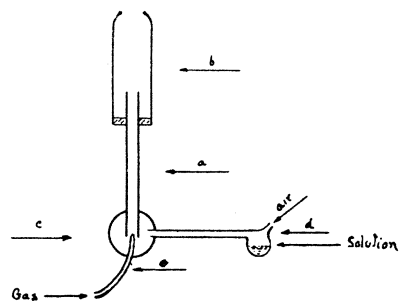


Fig. 1.

By sliding this plug up or down on the brass tube the distance between the bases of the two cones could be varied at pleasure.

<sup>1</sup> PHYS. REV., XXIX., p. 243, 1909.

<sup>2</sup> Physik. Zeitschr., VIII., p. 404, 1907.

The device for mixing the gas, air and metal vapor for the burner consisted of a glass bulb *c*, Fig. 1, of 6 cm. internal diameter, bored at the top for receiving the lower end of the brass tube *a* of the burner, at the side for receiving the neck of a small retort *d* and at the bottom for the introduction of the gas tube *e*. The tube *e* was of glass with an internal diameter of 1.5 cm., but drawn out at the upper end so as to leave an opening only .08 cm. in diameter for the issuing of the gas. This drawn-out end extended up into the brass tube *a* a few millimeters. The retort *d* contained the solution for producing the metal vapor. Through its tubulure the necessary air was admitted. The tubes *a* and *e* and the neck of the retort were sealed hermetically with wax into the glass bulb.

This combination of burner and mixing device gave a steady divided Bunsen flame when the flow of air and gas was properly regulated.

The metal vapor was introduced by the Beckmann<sup>1</sup> method, which consists in putting an acid solution of a salt of the metal, together with some pieces of coppered zinc, into the retort, and allowing the air entering through the loosely stoppered tubulure to carry the metal vapor through the bulb *c* up into the tube *a* of the burner.

The thermometer was an Heraeus Pt-PtRh thermo-element connected with a Weston millivoltmeter. The wires were protected by 12-inch lengths of fire-clay tube near the junction, and their terminals were kept at the temperature of melting ice. The junction was globular, about 1 mm. in diameter. It was glowed by electric current to expel any occluded gases before beginning the measurements.

## II. THE TEMPERATURE MEASUREMENTS.

These were made by inserting the junction of the thermo-element into the various parts of the outer cone, and through the outer cone, into the parts of the inner cone, and into the space between the two cones, reading the millivoltmeter as soon as steady temperature was indicated. The outer cone is so stable that its burning is not interfered with by thrusting through it the protected thermo-element. The inner cone is more sensitive to disturbance than is the outer

<sup>1</sup> Zeitsch. für Angewandte Chemie, p. 561, 1907.

cone, but it is not so sensitive as to make difficult the measurements of its temperature. Several observations were made for each part studied, and the mean of the millivoltmeter readings for each were converted into degrees centigrade by means of the Reichsanstalt certificate accompanying the thermo-element.

The divided flame in its simple state, that is, in the form of two conical shells of burning illuminating gas, was studied first, and for the distances 11, 8, 6 and 0 cm., respectively, between the bases of the cones. Then studies were made for the same distances when the divided flame was colored by burning in it the vapors of Na, Rb, Cs, Ca, Sr and Ba, produced from the solution of their respective chloride in the retort *d*. The outer conical shell in all cases rested directly upon the top of the glass tube *b*; the inner conical shell directly upon the top of the brass tube *a*, excepting for the distance near zero, when this shell shifted to the top of the glass tube *b*. The gas was taken from the gas mains of Washington.

The height of the outer cone was about 14 cm. and that of the inner cone about 1.75 cm. for all values of the distance between the bases of the cones.

#### 1. *Temperature of the Outer Cone.*

Measurements were made at several points in the conical shell of flame at its base, then at several points in the shell at its intersection with a horizontal plane about 2 cm. above the base, again at the intersection with a plane about 4 cm. above the base, finally at the apex of the cone, 14 cm. above the base. The mean results are given in centigrade degrees in the Tables I.-IV. The grayish color

TABLE I.

*Distance between the Bases of the Cones, 11 cm.*

	At Base.	At 2 cm.	At 4 cm.	At Apex.
Simple flame	563.7	743.8	823.4	884.1
Colored by Na	699.1	793.3	893.1	904.3
Rb	647.8	788.4	881.8	906.1
Cs	629.9	768.2	828.1	901.8
Ca	623.6	753.7	830.1	884.1
Sr	563.7	703.9	803.6	893.1
Ba	647.8	783.2	846.2	897.4

of the outer cone of the simple flame changes to that characteristic of the metal when a metal vapor is introduced. There was so little change in the temperature from about 4 cm. to the apex, and that so regular that measurements made between those points are omitted from the tables.

TABLE II.

*Distance between the Bases of the Cones, 8 cm.*

	At Base.	At 2 cm.	At 4 cm.	At Apex.
Simple flame	614.9	782.6	829.3	891.5
Colored by Rb	716.1	801.8	884.1	910.4
Ca	648.3	770.3	890.1	919.1

Measurements for the simple flame and for Rb and Ca only are given in Table II. and the two following tables, since they are sufficient to show how the temperature varies with variation in distance.

TABLE III.

*Distance between the Bases of the Cones, 6 cm.*

	At Base.	At 2 cm.	At 4 cm.	At Apex.
Simple flame	653.6	793.6	890.4	939.9
Colored by Rb	751.8	873.2	947.9	966.7
Ca	716.9	844.5	927.8	965.2

TABLE IV.

*Distance between the Bases of the Cones, 0 cm.*

	At Base.	At 2 cm.	At 4 cm.	At Apex.
Simple flame	704.0	837.7	937.3	968.2
Colored by Rb	730.4	969.8	993.1	990.0
Ca	880.1	973.6	1,013.0	1,002.5

## 2. Temperature of the Inner Cone.

Measurements were made, as for the outer cone, at the base, at about 0.5 cm., 0.9 cm., 1.3 cm., and at the apex. The results are given in degrees centigrade in Tables V.–VIII. The results for Rb and Ca only will be given in Tables VI.–VIII. The inner cone retains always its greenish color. A solid colored flame burns just above it, characteristic of the metal introduced.

TABLE V.

*Distance between the Bases of the Cones, 11 cm.*

	At Base.	At 0.5 cm.	At 0.9 cm.	At 1.3 cm.	At Apex.
Simple flame	996.5	1,024.6	1,045.2	1,058.9	990.0
Colored by Na	1,000.0	1,048.1	1,090.0	1,085.0	1,000.0
Rb	988.6	1,009.9	1,048.1	1,023.0	988.6
Cs	1,015.8	1,034.3	1,056.6	1,083.3	997.4
Ca	987.3	1,012.7	1,021.4	1,029.3	980.0
Sr	990.0	1,006.4	1,042.9	1,053.2	980.0
Ba	988.6	1,017.0	1,042.2	1,047.0	997.4

TABLE VI.

*Distance between the Bases of the Cones, 8 cm.*

	At Base.	At 0.5 cm.	At 0.9 cm.	At 1.3 cm.	At Apex.
Simple flame	998.9	989.6	1,049.9	1,057.2	993.7
Colored by Rb	997.4	1,028.9	1,047.6	1,038.1	988.6
Ca	1,000.0	1,051.3	1,085.0	1,050.0	988.6

TABLE VII.

*Distance between the Bases of the Cones, 6 cm.*

	At Base.	At 0.5 cm.	At 0.9 cm.	At 1.3 cm.	At Apex.
Simple flame	996.2	1,000.7	1,011.1	1,027.9	980.0
Colored by Rb	995.2	1,017.3	1,023.8	1,034.1	988.6
Ca	1,006.0	1,047.1	1,062.7	1,037.3	980.0

TABLE VIII.

*Distance between the Bases of the Cones, 0 cm.*

	At Base.	At 0.5 cm.	At 0.9 cm.	At 1.3 cm.	At Apex.
Simple flame	732.5	821.3	950.9	973.2	998.6
Colored by Rb	730.4	839.8	965.2	992.0	1,013.3
Ca	880.1	830.6	958.9	987.7	1,008.4

### 3. *Temperature Along the Axis of the Burner.*

Measurements were made from the apex of the inner cone, at intervals of 1 cm., up along the axis of the burner, to the base of the upper cone, and at the center of the axis of the upper cone. The results are given in centigrade degrees in Tables IX.-XII. The results for Rb and Ca only will be given in Tables X.-XII.

The part of the axis just above the apex of the inner cone is, for the colored flames, in the solid flame of burning metal vapor which rests on this cone, and extends above its apex. The length of the flame is about the same for the various elements, Sr excepted, and for the various distances between the bases of the cones.

The length of these flames of burning metal vapor, measured from the tip of the cone, were about as follows :

Na-flame, 8.0 cm.; Rb-flame, 9.5 cm.; Cs-flame, 8.5 cm.; Ca-flame, 8.0 cm.; Sr-flame, 3.0 cm.; Ba-flame, 8.5 cm.

TABLE IX.

*Distance between the Bases of the Cones, 11 cm.*

	Distance in cm. above Apex of Inner Cone.										
	0	1	2	3	4	5	6	7	8	9	16
Simple flame	990.0	965.9	935.7	910.4	880.1	840.2	788.4	752.7	717.0	703.5	793.3
Colored by Na	1,000.0	972.7	972.7	951.4	937.8	909.1	882.0	893.1	788.4	727.0	793.2
Rb	988.9	972.7	965.9	953.9	935.7	910.4	884.1	860.1	832.5	727.0	788.4
Cs	997.4	972.7	965.9	953.9	932.2	901.8	867.8	832.5	793.3	735.3	815.2
Ca	980.0	972.7	965.9	953.9	927.8	884.1	860.1	832.5	793.2	744.3	788.4
Sr	980.0	972.7	965.9	910.4	860.1	823.2	806.3	793.3	788.4	735.3	727.0
Ba	977.4	972.7	965.9	953.9	945.4	927.8	893.1	867.8	814.9	727.0	762.6

The point on the axis at the distance 9 cm. above the apex of the inner cone coincides with the center of the base of the outer cone; the point at distance 16 cm. with the central point of the axis of the outer cone.

TABLE X.

*Distance between the Bases of the Cones, 8 cm.*

	Distance in cm. above Apex of Inner Cone.							
	0	1	2	3	4	5	6	13
Simple flame	978.5	967.3	950.1	931.2	926.0	874.6	761.5	803.9
Colored by Rb	988.6	972.7	965.9	953.9	935.7	901.8	788.4	806.3
Ca	980.0	972.7	965.9	953.9	927.8	884.1	746.3	806.3

The point on the axis at 6 cm. above apex of the inner cone coincides with the center of the base of the outer cone; the point at 13 cm. with the central point of the axis of the outer cone.

TABLE XI.

*Distance between the Bases of the Cones, 6 cm.*

	Distance in cm. above Apex of Inner Cone.					
	0	1	2	3	4	11
Simple flame	980.0	965.9	884.6	840.2	788.4	832.5
Colored by Rb	988.6	972.7	953.9	932.2	822.3	849.6
Ca	980.0	972.7	965.9	945.6	840.2	867.8

The point on the axis at 4 cm. above apex of inner cone coincides with the center of the base of the outer cone; the point at 11 cm. with the central point of the axis of the outer cone.

TABLE XII.

*Distance between the Bases of the Cones, 0 cm.*

	Distance in cm. above Apex of Inner Cone.			
	-1.75	-1	0	5.25
Simple flame	247.9	471.8	984.1	1,061.6
Colored by Rb	258.5	498.7	997.4	1,070.9
Ca	250.0	483.2	972.7	1,013.5

The point on the axis at - 1.75 cm. from the apex of the inner cone coincides with the center of the common base of the two cones; the point at 5.25 cm. coincides with the center of the axis of the outer cone, and is in the metal flames.

Measurements of the temperature of the solid flame of burning metal vapor which rests on the inner cone were made at various distances from the axis, and they indicated a slight falling off of the temperature as the distance from the axis increased. Thus for the Sr-flame, at a point opposite the apex of the inner cone and just within the surface of the flame, the temperature was 972.7 when it was 980.8 at the axis as given in Table IX.; and it was 935.7 at a point opposite that on the axis 1 cm. above apex at which axial point the temperature was then 972.7, as given in Table IX.

#### 4. *Temperature at Points Outside the Axis.*

Measurements were made at numerous points other than those given in the preceding subsections. Tables XIII.-XV. contain the

results for points at about 0.5 cm. distant from the inner surface of the glass tube *b* and from the top of the plug to the top of the glass tube.

TABLE XIII.

*Distance between the Bases of the Cones, 11 cm.*

	Distance in cm. above Top of Plug.				
	0	3	5	9	14
Simple flame	288.5	450.9	569.1	631.8	653.7
Colored by Na	258.5	425.8	471.8	499.0	554.6
Rb	444.5	544.5	644.5	699.1	752.7
Cs	288.5	471.8	554.6	635.8	725.4
Ca	415.8	453.7	528.2	663.7	790.0
Sr	288.5	480.9	571.8	644.5	663.7
Ba	329.8	429.8	499.0	553.6	635.8

The point 5 cm. above top of plug is opposite apex of inner cone ; the point 14 cm. is at the base of the outer cone.

TABLE XIV.

*Distance between Bases of the Cones, 8 cm.*

	Distance in cm. above Top of Plug.				
	0	3	5	8	14
Simple flame	361.4	560.1	703.8	719.3	767.5
Colored by Rb	338.2	535.4	671.2	725.4	788.4
Ca	355.7	544.5	671.2	780.0	788.4

The point 8 cm. is opposite the apex of the inner cone ; the point 14 cm. is at the base of the outer cone.

TABLE XV.

*Distance between Bases of the Cones, 6 cm.*

	Distance in cm. above Top of Plug.				
		3	5	10	14
Simple flame	379.1	583.2	698.6	825.4	819.9
Colored by Rb	355.7	562.7	663.7	814.9	822.3
Ca	385.5	599.0	725.4	822.3	840.2

The point 10 cm. is opposite the apex of the inner cone ; the point 14 cm. is at the base of the outer cone.

## III. ANALYSIS OF THE RESULTS.

Tables I.-IV. show that: (1) The temperature of the outer conical shell in all cases increases rapidly from the base to about two thirds way up the cone, then falls more rapidly to the apex, so that, if represented graphically, taking temperatures as ordinates and distances above the base as the abscissæ the curve is as shown in Fig. 2, *a*; (2) the temperature of the outer cone is somewhat greater for the

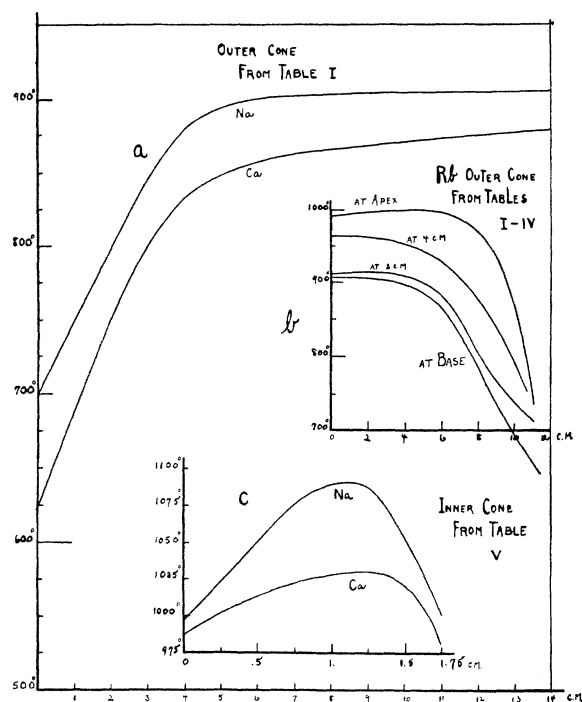


Fig. 2.

colored flame than for the simple flame, the differences being greater near the base, where they average, for Table I., about  $75^{\circ}$ , while near the apex they average only  $30^{\circ}$ ; (3) the temperature of all parts of the outer cone for all cases is greater the shorter the distance between it and the inner cone. If the temperature for a given part of a given outer cone be plotted taking the temperature as ordinates and the distance between the bases of the cones as

abscissæ, the curve is as represented in Fig. 2, *b*, which shows the curves for Rb at apex, at 4 cm. point, at 2 cm. point and at the base; (4) the temperature of the outer cone seems to be somewhat greater for the elements of the first Mendeléeff group than for those of the second group, when the distance between the base of the cone is considerable; the reverse is the case when the distance becomes small.

Tables V.–VIII. show that: (1) The temperature of the inner conical shell for the simple and the colored flames and for distances between the bases of the cones not near zero increases from the base to a maximum value in a zone about 3 or 4 mm. broad, just above the middle of the cone, then decreases to a value at the apex which is about the same as at the base. These maxima for Table V. average about  $70^{\circ}$  higher than the minima. Near the zero of distance between the bases of the cones, the temperature distribution for the inner cone becomes similar to that of the outer cone, and the values are smaller than for longer distances. Fig. 2, *c*, shows the temperature curve for the inner cone when the distances between the cones are large; (2) the temperature of corresponding parts of the inner cone for the simple flame and for all the colored flames has practically the same value for all distances between the bases of the cones. As noted elsewhere in this paper, the characteristic greenish color of the inner cone for the simple flame remains unchanged through the burning of metal vapor, while that of the outer cone is changed, and a characteristic solid flame of the metal vapor appears between the two cones.

A comparison of Tables I.–IV. with V.–VIII. shows that the temperature of the inner cone is higher than that of the outer cone until the distance between the bases of the cones is nearly zero. Then the outer cone becomes the hotter, and the hottest point of the flame, which is then the ordinary Bunsen flame, is above the apex of the inner cone and near the center of the outer cone. The highest temperature found there,  $1070.9^{\circ}$ , occurred when burning Rb vapor. The highest temperature of the flame of an ordinary Bunsen burner using the same gas was found at about the same distance above the inner cone as in the case just mentioned, and it had the value  $1186.6^{\circ}$ , the mean of a large number of observations. The

temperature near the base of the same flame measured  $361.3^{\circ}$  and was the lowest temperature found in that flame. A comparison of all the Tables I.–XV. shows that the highest temperature attained in the divided Bunsen flame is that of the zone of the inner cone just above its middle. The highest temperature found there,  $1090.0^{\circ}$ , occurred at the time the flame was burning Na-vapor (see Table V.). In Fig. 3, *a*, the two cones and the flame of burning metal vapor are shown, and in Fig. 3, *b*, this zone of highest temperature is indicated by the heavy parts of the lines.

Tables IX.–XII. show that: (1) The temperature along the axis of the burner decreases regularly up to the base of the upper cone, then increases to the apex of the upper cone; (2) the temperature is about the same for the corresponding points of the first three centimeters of this axis for all the colored flames, and is only slightly larger in the average than that for the simple flame. At points higher up the temperature differs considerably for the different flames, and averages for the colored flames considerably higher than for the simple flame, until the base of the outer cone has been reached; (3) the temperature for the simple and for the colored flames remains about the same for each corresponding point of the axis below the outer cone, as the distance between the bases of the cones is shortened, but it increases rather rapidly in the outer cone; (4) the temperatures for the elements of the first Mendeléeff group average about the same as for the elements of the second group.

Tables XIII. to XV. show: (1) At points in the space outside the inner cone, and outside the flame between the cones, the temperature increases considerably as the distance between the bases of the cones decreases; (2) for any given point it is practically the same for both simple and colored divided Bunsen flames.

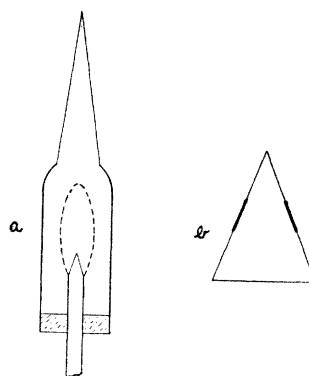


Fig. 3.

## IV. SUMMARY.

The most interesting results of the measurements are these : (1) The highest temperature in a divided Bunsen flame is confined sharply to a small zonal segment of the inner conical shell, no matter what substances are used to color the flame, nor what the distance is between the bases of the cones, provided that that distance is at least a few centimeters ; (2) the temperature of the inner conical shell is not changed by varying its distance from the outer conical shell, provided that the distance is more than two or three centimeters, nor by introducing through it metal vapors that burn in a flame above it and in the outer cone ; (3) the temperature distribution of the inner conical shell changes to one that increases from base to apex when the distance between the cones approaches zero ; (4) the temperature of the flames of metal vapor burning just above the inner cone is the same for all the vapors used, excepting near the tips of these flames, and it is not changed by varying the distance between the cones ; (5) the temperature of the outer conical shell increases from the base to the apex and it is always greatest at the apex ; (6) the temperature of the outer conical shell increases when its distance from the inner cone decreases ; also when it burns metal vapors introduced through the inner cone.

## V. RELATION TO IRVING'S RESULTS.

Irving found the negative electrical wandering of the inner cone stronger than that of any other part of the divided Bunsen flame, so strong that it "was torn off the brass tube on the side towards the negative plate" even by weak fields. The temperature measurements show that this inner cone is much the hottest part of the divided Bunsen flame. There are no distortions of the inner cone, in an electrical field, definite enough in location to say that they are at the hottest zone. The wandering was about the same for all distances between the bases of the cones. The temperature of the inner cone is also the same for all distances between the cones, if the distances are not too small. The magnitude of the negative wandering of the flames of metal vapor burning just above the inner cone Irving found to be the same for all the metals and for all distances between the cones. The tempera-

ture of these flames is the same for all the metals and for all distances between the cones. The electrical wandering of the flames towards the negative plate is less violent than is that of the inner cone. The temperature of these flames is less than that of the inner cone.

Irving found no wandering of the simple outer cone, nor for this cone colored with Li, but he found wandering towards the negative plate, when the cone was colored by the other metals, ranging from  $9^{\circ}$  for Na to  $45^{\circ}$  for Ca and Ba. The temperature of the simple outer cone is less than that of the inner cone and of the flame, for like conditions, ranging from about  $100^{\circ}$  to  $500^{\circ}$  cooler for different parts. Its temperature is higher when burning metal vapor than when in the simple state.

In Irving's experiments it was found that the outer cone wanders as soon as the metal flame burning above the inner cone reaches it, on decreasing the distance between the cones. Table IV. shows that the outer cone is then at its highest temperature.

The foregoing comparisons would indicate that the electrical wandering of the parts of the Bunsen flame is greatest for the hottest parts. This does not hold, however, for the metal vapor before it enters the inner cone. Its temperature there is about that of the room, yet it is even more electro-positive than is the hot inner cone. Further it does not hold in all respects for outer cones when compared with one another, for, although the temperatures given in Table I. for Ca, Sr and Ba are in the same order, excepting at the apex of the cone, as that given by Irving for the respective electrical wanderings, yet the temperatures for Na, Rb and Cs, excepting at the apex, are in an order the reverse of that given by him for the electrical wanderings. Further the temperature given for Rb and Ca in Tables II. and III. are in an order the reverse of that for the electrical wanderings, while the temperatures given for the same elements in Table IV. are in the same order as that of the wanderings. Nevertheless, the parts having the higher temperatures show the larger electrical wanderings for any given divided Bunsen flame, whether it be a simple flame, or one colored by any one of the elements studied.

The correspondence of magnitudes of electrical wanderings and

magnitudes of respective temperatures may be mere coincidences, not due to any relationship of the two phenomena. But it seems probable that the changes in magnitudes occur simultaneously in the same direction necessarily. Irving offers an explanation of the decrease in the magnitude of the electrical wandering on passing from the inner to the outer cone, by supposing that the negative electrons from the cones neutralize the positive metal ions in the formation of oxides, which takes place chiefly in the flame above the inner cone. The formation of oxides would also explain the observed differences in the temperatures of the inner cone, metal flame and outer cone, if we suppose, as we must, that the parts are hottest where the oxidation is most extensive. The oxidation in the metal flame above the inner cone takes place to such an extent for all the metals studied that the flame is equally positive for all of them. At the same time the extent of oxidation is such that the flames are equally hot for all these metals.

To Dr. Irving and Mr. Louis H. Crook, I acknowledge my obligation for valuable assistance.

PHYSICAL LABORATORY,  
THE CATHOLIC UNIVERSITY OF AMERICA,  
October 20, 1909.