THE TUNGSTEN ARC UNDER PRESSURE.

By George P. Luckey.

Introduction.

THE present investigation was undertaken to determine, if possible, whether a change in the melting point of tungsten due to a change in pressure could be noted in the case of the tungsten arc. From previous work done on the effect of pressure on the melting point of metals having low melting points[1] it seemed doubtful if any changes could be noticed with the low pressures at which the tungsten arc could be burned in the apparatus at hand, pressures up to 35 atmospheres. On the other hand, work done by Lummer[2] seemed to indicate that in carbon, at least, there was a large pressure effect, even though it could not be attributed directly to a change in the melting point. Due to a lack of data on the latent heat of fusion, and the volume change on melting, the temperature change in the melting point of tungsten could not be calculated.

Apparatus.

The arc was burned in a specially constructed brass tank, designed to hold pressures up to forty atmospheres. A cross-section of the tank is shown in Fig. 1. The central portion is a flanged tube three inches in diameter and four inches long. Brass plates were fastened onto each end by means of twelve bolts which passed from one end of the tank to the other. Lead washers were placed between the end plates and the central portion of the tank to secure air tight joints. Three openings were made in the tank, one in an end plate into which a plate glass window w for observing the arc was fitted, and two in the central portion. One of these was used in evacuating and filling the tank, and through the other an insulated wire was led in. The outside of the tank was wrapped with a coil of copper tubing, through which a stream of water was passed, and which served as a very effective cooling device.

A small holder that could readily be removed from the tank was constructed for holding the electrodes. The electrodes were held in

[1] Johnston and Adams, Am. Jour. of Sci., Vol. 31, p. 501, 1911; Tammann, Zs. Anorg. Chem., Vol. xi, p. 54, 1904; Bridgman, Proc. Am. Ac. of Arts and Sci., 47, pp. 347, 391, 415, 1911.

[2] Lummer, Verflüssigung der Kohle and Herstellung der Sonnentemperatur.

the center of the tank and the arc was burned in an axis parallel to the walls of the tube. The positive electrode, and the one on which the temperature measurements were made, was fastened to the center of the frame, and was insulated from it by several layers of mica. This electrode was connected to the leading-in wire, and the remainder of

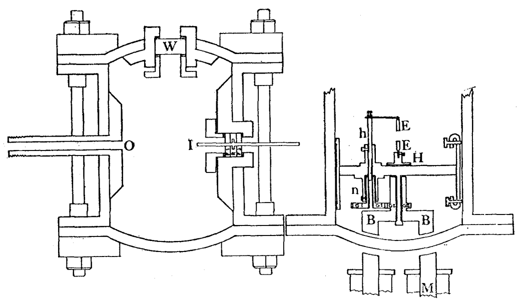

Fig. 1.

Diagram of pressure tank and electrode holder.

Pressure Tank.—W, window; O, gas inlet; I, insulated leading-in wire, held between two layers of fiber, f_1 and f_2 with a soft rubber plug r, in the center.

Arc Holder.—E, E, Tungsten electrodes; h, movable electrode holder; H, stationary electrode holder, insulated from frame by layers of mica; B, soft iron bar, the rotation of which turns nut, n, on the end of the movable electrode holder, h, through gears, g_1 and g_2, and causes electrode holder, h, to move in or out; M, magnet used to rotate soft iron bar.

the circuit was made through the tank and the frame of the holder. The negative electrode was fastened to one end of a shaft which could be moved back and forth. On the other end was a nut which engaged a thread on the shaft. As the nut was turned the shaft was drawn in or thrust outwards. The nut was geared to an iron bar fitted centrally to the back of the electrode holder. The iron bar could be rotated by a magnet outside of the end plate of the tank. Thus by rotating the magnet the two electrodes could be brought together, and on reversing the direction of rotation they could be moved apart.

When measuring the temperatures of the tungsten the negative electrode was set slightly out of the center of the tank, so that an unobstructed view of the whole positive electrode could be obtained through the window, and so that there were no disturbing reflections of the image of the negative electrode from the smooth mirror-like surface of the electrode under observation.

The arc was burned in nitrogen, which was obtained from a tank under a pressure of 1,800 pounds per square inch. The gas had been freed from all impurities, with the exception of water vapor, before it was pumped into the tank. In order to remove the water vapor, before filling the small tank in which the arc was burned, the gas was passed through a steel tube, one end of which was filled with soda lime, and the other with phosphorous pentoxide. The pressures in the small tank were measured by a twelve-inch Ashcroft test gauge graduated to read from 0–500 pounds per square inch.

Method of Determining Temperature.

The temperatures were measured by means of a Holborn-Kurlbaum optical pyrometer of the type in general use in this laboratory.[1]

The pyrometer lamp was calibrated by the use of a tungsten lamp which had been standardized with a black body at the melting point of palladium, taken as 1822° K. The effective wave-lengths of the red glass screen (Jena Rotfilter No. F–4512) between different temperatures were obtained from data calculated by Hyde, Cady and Forsythe.[2] The data for the absorption coefficient of tungsten at the melting point was extrapolated from readings made by Worthing[3] at temperatures up to 3200° K. Below this point the absorption coefficient of tungsten is practically a linear function of the temperature. It was assumed that this function continued up to, and through the melting point without suffering any abrupt changes. The assumption that the absorption as a function of the temperature suffers no abrupt changes between the solid and the liquid states of tungsten seemed justified from the fact that in looking at the surface of the melting tungsten there is no sharp defining line between the solid and the liquid (in case the solid tungsten has a smooth surface) which there would be if the absorption suffered an abrupt change. This result is at variance with the observation of Langmuir[4] (who states) that in the arc the solid tungsten always appeared brighter than the molten tungsten in contact with it. This latter effect was at times noticed in the present experiments in case the solid surface of the tungsten was not smooth, but apparently this was due to the diffuse reflection of the light from the negative electrode.

The value of the absorption as determined from the data of Worthing in the above manner and as used, was 0.393 for $\lambda = 0.661\mu$. This value is much lower than that used by Langmuir,[5] 0.425 at $\lambda = 0.667\mu$. It might be stated in this connection that the method used by Langmuir in determining the emissivity of molten tungsten appears open to doubt, as in the present series of experiments it was at no time possible to

[1] Worthing and Forsythe, Phys. Rev., Vol. IV., p. 163, 1914.

[2] Hyde, Cady and Forsythe, Astrophys. Jour., Vol. XLII., p. 294, 1915.

[3] Worthing, Jour. Frank. Inst., Vol. 181, p. 417, 1916.

[4] Langmuir, Phys. Rev., Vol. 6, p. 138, 1915.

[5] *Loc. cit.*

obtain a pool of melted tungsten in which the temperature throughout was that of the melting point. The temperatures obtained varied from that of melting tungsten at the edges of the pool to a temperature three or four hundred degrees higher near the center. The only time when it was possible to obtain nearly uniform temperatures throughout the visible surface of the molten tungsten was at low pressures when the whole end of the electrode was melted, and the temperatures found under these circumstances were several hundred degrees higher than the melting point.

The Melting Point of Tungsten under Pressure.

A series of readings of the melting point of tungsten were taken under various pressures from one to thirty atmospheres. Electrodes 0.1 cm. in diameter were used, the length of arc varied from 0.1 to 0.2 cm. The results of these determinations are given in Table I. The value found at atmospheric pressure agrees closely with that found by Worthing[1] in the tungsten arc, 3630° K., while it is about eighty degrees higher than the average value of the melting point as determined by Langmuir, 3540° K. The discrepancy between the values determined by Langmuir

Table I.

Apparent Melting Point of Tungsten under Pressure.

Pressure.		Red Black Body Temperature. $\lambda = .661\mu$.	True Temperature.
Atmospheres.	Kilo/Cm^2.		
1	1.03	3138° K.	3623° K.
4	4.13	3129° K.	3611° K.
8	8.26	3116° K.	3594° K.
11	11.36	3113° K.	3590° K.
14	14.46	3107° K.	3582° K.
18	18.6	3099° K.	3572° K.
21	21.7	3092° K.	3562° K.
28	28.9	3093° K.	3564° K.

and those determined in the present investigation is due to the different value of the emissivity of tungsten taken in the two cases. The values of the red black body temperatures obtained in all cases give good agreement. The value as determined by Langmuir for $\lambda = 0.667\mu$ was 3124° K., by Worthing for $\lambda = .666\mu$, 3140° K., while that determined in the present investigation was 3138° K. for $\lambda = 0.661\mu$.[2]

[1] *Loc. cit.*

[2] Various other determinations of the melting point of tungsten are well summarized by Pirani and Meyer (Berichte d. Deut. Phys. Gesel., 14, p. 426, 1912) who compare the values found by other observers with those they obtained. In addition to these might be mentioned the determinations made by Forsythe (Astrophys. Jour., Vol. 34, p. 353, 1911). All of these values are lower than those obtained here.

The usual appearance of the positive electrode during temperature measurements may be described as follows. There is a bright spot in the center where the main arc discharge falls, around this is a pool of melted tungsten, which in turn is surrounded by solid tungsten. If the tungsten on the end of the electrode is melted and allowed to cool slowly by gradually decreasing the current through the arc the surface remains smooth after the tungsten has become solid, if, however, the tungsten is cooled very rapidly by suddenly decreasing the current the surface is roughened. This roughened condition of the solid surface was of great advantage in determining the boundaries of the pool of melted tungsten. By increasing the current the melted pool of tungsten is made larger, and the pyrometer lamp filament may be matched with the tungsten in the moment at which it changes from the solid to the liquid state. Or the current may be left constant, and it may be assumed that the temperature of the tungsten at the boundary line between the solid and the melted portions has a value very near to that of the melting point. Readings made by these two different methods gave the same values or the melting point. It is necessary that the regions of solid and melted tungsten should be sharply differentiated in order to get accurate results. The roughness of the solid portion and the mirror-like surface of the melted tungsten gave a very sharp differentiation at low pressures. Above twelve atmospheres, however, the refraction of the light by the heated gas near the electrodes created such disturbances in the image that the position of this dividing line could not be determined with any great accuracy, so that a rather large uncertainty is introduced into the measurements.

Assuming no change in the emissive power of tungsten with pressure the melting point of tungsten as found apparently decreases slightly as the pressure increases. The change observed, however, is large in comparison with the changes found by previous experimenters (*loc. cit.*) in the case of metals having a low melting point, on the other hand it is very small in comparison with the changes found by Lummer in carbon, and has the opposite sign. It is also open to doubt whether the observed change is due to an actual change in the melting point, or whether the apparent diminution in brightness might not be due to a layer of cooler tungsten vapor above the electrode, the absorption of which would increase as the density of the vapor was increased at higher pressures. Unfortunately the apparatus used would not allow this point to be investigated further, but the order of such an effect might well be the same as that observed.

THE HIGHEST ATTAINABLE TEMPERATURES.

As has been previously noted, that part of the electrode on which the main arc discharge falls is much more brilliant than the surrounding melted tungsten. A series of readings were made on the red black body temperature of this portion of the arc, and temperatures were found which varied largely with the pressure, the current through the arc, and the area over which the discharge took place. The highest attainable red black body temperatures found at each pressure are given in Table II. Owing to the melting of the whole tungsten electrodes by the high currents that were necessary to obtain these temperatures only a few readings were possible at each pressure. If it be assumed that the absorption coefficient, as determined by Worthing, maintains the same relationship with respect to the temperature up to the temperatures here obtained, then the true temperature of the tungsten would be given by the values in the last column of Table II.

TABLE II.

Highest Attainable Temperatures.

Pressure.		Red Black Body Temperature. $\lambda = .661\mu$.	Assumed Absorption Coefficient.	Computed True Temperature.
Atmospheres.	Kilo/Cm.^{2}			
1	1.03	3559° K.	0.374	4235° K.
8	8.3	3794° K.	0.363	4602° K.
15	15.5	3907° K.	0.358	4782° K.
22	22.8	3982° K.	0.354	4912° K.
29	30	4022° K.	0.352	4978° K.
33	34.1	4086° K.	0.349	5084° K.

There is a question as to what this temperature represents. It is doubtful whether it can be assumed to be the boiling point of tungsten, as at a given pressure the temperature varies with the current strength through the arc. It is more probable that it represents some temperature lying between the melting and the boiling points. The observed increase in the temperature with the pressure is possibly due to either an increase in the boiling point of tungsten, or to an increased density of the arc discharge, which would tend to concentrate the heating effect, or to both of the above causes. For a given current as the pressure was increased the arc discharge became more concentrated, till at high pressures the whole discharge fell upon a very small portion of the electrode surface.

ELECTRICAL CHARACTERISTICS.

In connection with the temperature determinations of the tungsten arc, measurements were also made of the electrical characteristics in nitrogen under pressures from one to thirty-three atmospheres.

Rapid fluctuations of the current and especially of the voltage, made it necessary to use an instrument with which both readings could be taken simultaneously. For this purpose a Siemens and Halske Oscillograph was used, and exposures of about two minutes were made, during which time the current was varied throughout the range of possible currents. The variation, however, was made slowly enough to enable the arc to reach stable conditions after each change.

Direct currents of from one to ten amperes, with an outside potential on the circuit of 225 volts were used. The length of arc was varied from 0.06 to 0.24 cm. At the highest pressure the longest arc that could be maintained stably with the voltage used was about 0.06 cm. With the exception of the characteristics taken at atmospheric pressure, electrodes having a diameter of 0.14 cm., and about 1 cm. long were used. At atmospheric pressure the positive electrode melted down when currents larger than three amperes were sent through the arc. In order that characteristics for larger current values could be obtained a positive electrode of 0.38 cm. diameter and a negative electrode 0.14 cm. in diameter were used. This change in the size of the positive electrode apparently made no change in the form of the characteristic.

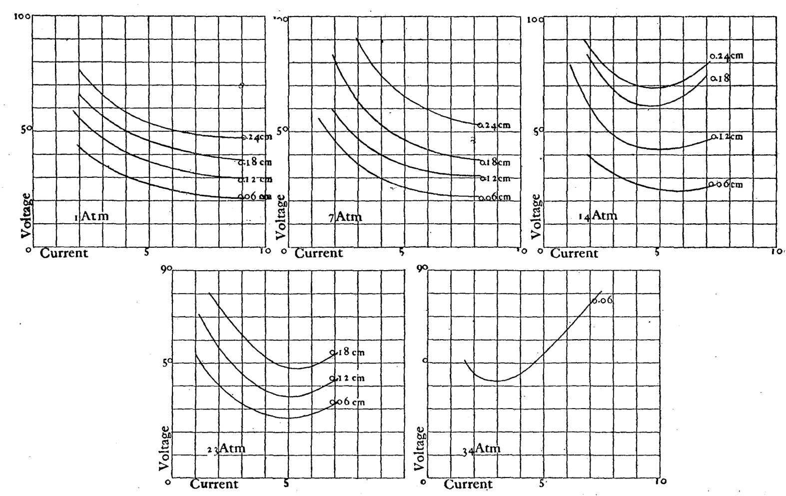

Fig. 2.

The characteristics of the arc are shown in Fig. 2. Owing to the large fluctuations of the voltage and current averages were made of several determinations, which are plotted above. The characteristics of the arcs of the same length tend to have higher values of voltage throughout the whole range of current as the pressure increases. This effect of pressure is similar to that noticed in arcs burned under pressures lower than atmospheric, an effect especially predominate in the mercury vapor arc, and to that found by Duncan, Rowland and Todd[1] in the carbon arc burned at pressures up to ten atmospheres.

It will be noticed also that at high pressures the characteristics, instead of falling continuously, as is the case in the usual metal arc, have a tendency to rise. That is, as the current increases the voltage does not drop continuously, but after a certain current has been reached tends to rise if the current through the arc is made larger. A rising characteristic similar to this was noted by C. D. Child[2] in the case of the flaming carbon arc. He attributed this increase in voltage with larger currents to a tendency of the arc to flare out to one side. This would have the same effect as increasing the length of the arc. The rising characteristic found in the tungsten arc is probably partly the result of this same effect. The convection currents in the gas tending to blow the arc out of its normal path would become more marked as the pressure was increased, thus causing a higher potential drop across the arc for greater pressures, other conditions being the same. The effect of these convection currents in the gas at high pressures was seen in the fact that when all the external resistance was removed from the arc circuit, the current through the arc would not rise indefinitely; instead, after the current had reached a value of ten or twelve amperes, the arc would flare up and go out. The effect of the increase in the pressure in the tank due to the heating of the gas by the larger currents would have a similar effect on the characteristics. However, as this change in pressure was never very large, the increase in voltage from this cause would not wholly account for the large change observed.

Summary.

Measurements were made of the temperature of the melting point of tungsten in the electric arc under pressures from one to thirty atmospheres. The melting point found at one atmosphere was 3623° K., and the apparent melting point decreased to 3564° K. when the pressure was raised to twenty-eight atmospheres. It is doubtful whether this decrease is due to a change in the melting point or merely to an increased absorption of the vapor surrounding the arc.

The highest temperatures attainable in the arc were measured, and a large increase in this temperature as the pressures increased was noted. At atmospheric pressure a probable temperature of 4235° K. was found, while at thirty-three atmospheres the highest temperature in the arc

[1] Duncan, Rowland and Todd, Electrot. Z. S., 14, 603, 1893.

[2] C. D. Child, Electric Arcs, p. 60, D. Van Nostrand Co., N. Y.

was increased to 5084° K. It is probable that these temperatures represent a value somewhere between the melting and the boiling points of tungsten in each case.

The electrical characteristics of the tungsten arc were investigated. The drop in potential across the arc, other conditions being the same, was found to increase with the pressure. At high pressures the voltage dropped as the current increased until values of current of about five amperes were reached, after which the voltage rose with increasing current. This latter effect might be ascribed to the tendency of the arc to flare out to one side with larger currents, as well as to the increase of pressure in the tank caused by the heating of the gas.

In conclusion I should like to take this opportunity to express my appreciation to the director and the members of the staff of the Nela Research Laboratory for the suggestion of this problem and for their valuable assistance.

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