ON THE TEMPERATURE OF CATHODE IN VACUUM ARC

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Abstract

Pyrometric and spectroscopic tests show that the metal cathode spot in a vacuum arc is not at an extremely high temperature. The temperature of a copper cathode is measured by an optical pyrometer and found to be about 3000°K in a 20 ampere arc. Spectroscopic examination of the cathode spot shows only a faint continuous spectrum indicating that the temperature of the cathode is not high. A temperature of the above magnitude is shown to be sufficient to give the rate of vaporization required to account for observed loss of cathode material under extreme assumptions. The results show that the high speed of the vapor stream issuing from the cathode region cannot be due to high temperature of the cathode itself.

Introduction

One of the authors[1] has previously determined the average velocity of the vapor emitted from the copper cathode in a high vacuum arc. Calculations were based upon (1) the observed force of reaction on the cathode, with the loss in weight of the cathode, (2) the force of reaction upon a vane suspended 2 cm in front of the cathode with the increase in weight of the vane. Both methods gave mean velocities around 10^6 cm/sec. In order to emphasize the magnitude of this velocity the transformation was made into equivalent gas temperature by the equation $\frac{1}{2} mv^2 = 3/2\ KT$. The astounding values of 500,000°K resulted from this calculation.

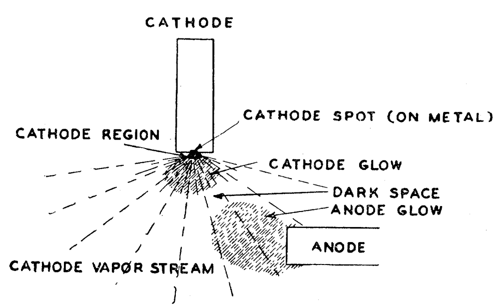

Fig. 1. Nomenclature of vacuum arc.

Recently Dr. K. T. Compton[2] has suggested a mechanism to account for the force of reaction upon the cathode. By means of an accommodation coefficient the incoming copper ions are neutralized at the cathode, but still

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[1] R. Tanberg, Phys. Rev. **35**, 1080–1089 (1930).

[2] K. T. Compton, Phys. Rev. **36**, 706–708 (1930).

retain a fraction of their kinetic energy. These neutralized ions then rebound from the cathode with a random distribution of velocity forming the vapor stream.

Dr. J. Slepian and R. C. Mason[3] have pointed out that while Compton's theory may account for the reaction of the cathode, it does not account for the high speed of the vapor leaving the cathode region.

It is the purpose of this paper to show that the observed high mean velocity of the copper vapor cannot be due to temperature of the metal cathode spot itself.

In order to avoid misinterpretation of terms used, a nomenclature of the vacuum arc is shown in Fig. 1 and will be followed throughout this paper.

A. Distribution of Light in Vacuum Arc

Visual observation of the cathode region of an arc in vacuum reveals a high luminosity on the surface of the cathode, giving the impression that the

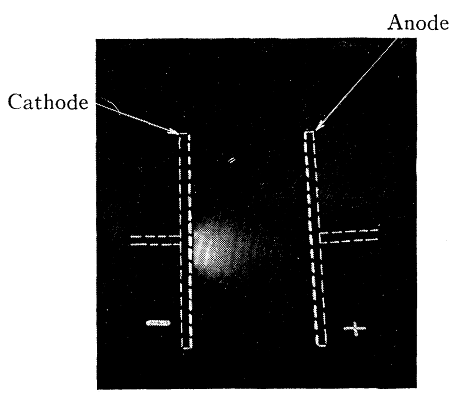


Fig. 2. Low voltage form of 7 amp. D.C. arc between copper plates. The cathode spot moved during the exposure which makes the glow at the cathode surface appear much broader than actually was the case.

the metal surface is incandescent at an extremely high temperature. However, a photographic cross section of the arc, shown in Fig. 2, indicates that the major portion of light comes from a comparatively small region close to the cathode. The light intensity outside this region falls off rapidly to no visible radiation in the dark space. Therefore the real location of the high energy indicated by the cathode vapor speed[1] may not be in the cathode spot on the metal, but more probably in a thin layer of gas immediately in front of the cathode spot.

B. Spectrographic Observations of Arc Cathode

A series of spectrograms were taken of the various portions of arc, with a small Hilger Constant Deviation Spectrograph, Model D. The experimental arrangement is shown in Fig. 3.

[3] J. Slepian and R. C. Mason, Phys. Rev. **37**, 779 (1931).

An observation of the spectrum in the visible region from the copper cathode, shows a faint continuous spectrum upon which high intensity emission lines are superimposed. When the cathode is moved to one side so that the cathode spot no longer faces directly into the slit both the continuous and line spectra vanish.

Many years ago J. Stark[4] made a similar observation on the cathode of a mercury arc. His results showed a continuous spectrum when the cathode spot faced directly into the spectroscope and a line spectrum when the slit was faced just outside the cathode spot. His conclusion was that the actual mercury which was acting as the cathode base was at a yellow or white heat.

A three mil copper wire was placed in vacuum and gradually heated by passing current through it. Just before the wire melted the continuous spectrum was about the same intensity as the continuous spectrum in the vacuum arc.

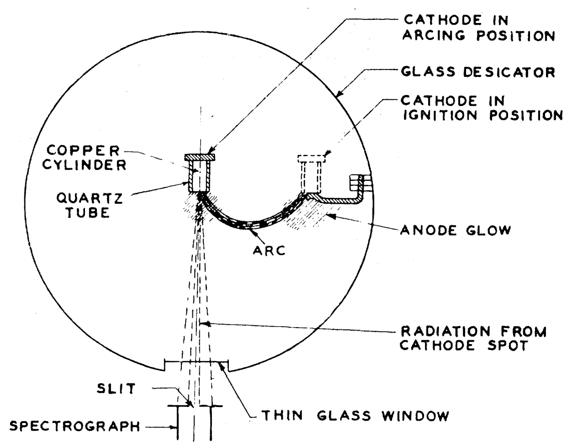


Fig. 3. Arrangement for spectrograms of cathode spot. Cathode was mounted on arm which extended to the outside through flexible bellows.

There may be some reason to believe the continuous spectrum from the cathode spot is due to emission of electrons or neutralization of ions at the cathode surface. But, due to the fact that the arc is drawn in a vacuum of 10^{-4} mm Hg, and that the arc is never held longer than 5 seconds, it seems improbable that the density of copper molecules could be great enough to account for the continuous spectrum.

Fig. 4a is a spectrogram of the high intensity lines from the cathode spot. The continuous spectrum is so weak that it does not show on the plate. Fig. 4b is the reference copper arc at atmospheric pressure, while 4c shows the emission lines of the anode glow. The presence of iron lines in Fig. 4a is probably due to impurities in the copper cathode. The strong mercury lines in the anode glow may be accounted for by mercury distilling over from the pumps.

[4] J. Stark, Phys. Zeits. 5, 550 (1904).

The Fig. 4c shows that the anode glow exists primarily in the residual gases of the arcing chamber, and that the cathode vapor under the condition

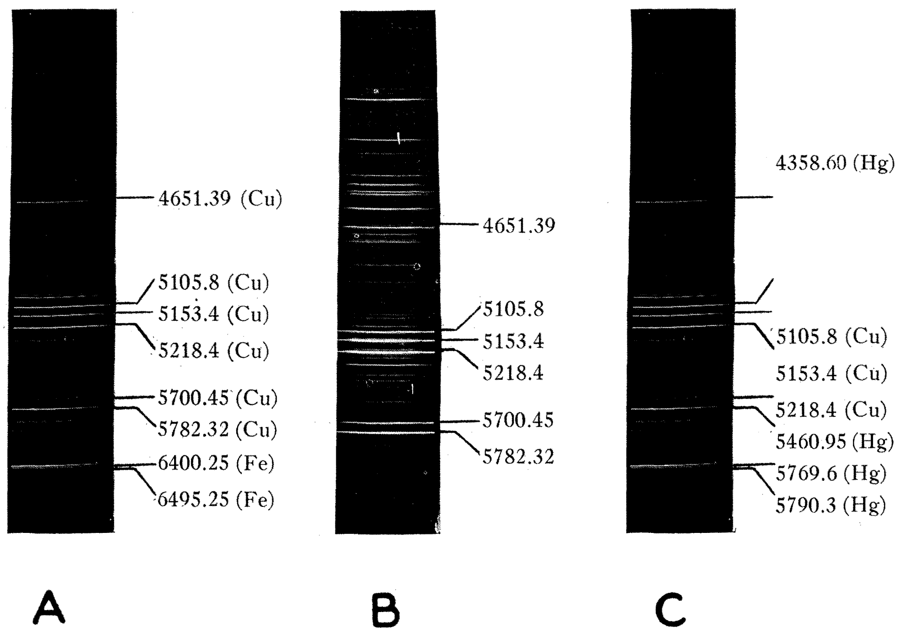


Fig. 4. Spectrograms of vacuum arc. A, cathode spot, vacuum arc between copper electrodes. B, copper arc, atmospheric pressure. C, anode glow, vacuum arc between copper electrodes.

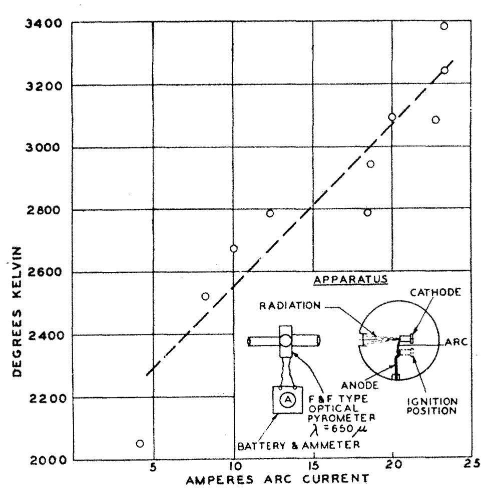


Fig. 5. Apparent temperature—arc current curve. Temperature by optical pyrometer. Emissivity, 0.15.

considered here does not directly sustain the arc in the region next to the anode.

C. Apparent Temperature of Cathode Spot by Optical Pyrometer

An optical pyrometer* F and F Type ($\lambda = 0.650\mu$) was set up as shown in in Fig. 5. This pyrometer was a constant filament current-variable wedge absorption type and calibrated in degrees centigrade against a standard lamp.

Fig. 5 shows the apparent temperature of the cathode spot as a function of the arc current after corrections have been made for an emissivity of 0.15, constant glass absorption of 50°K, and a linear correction for the copper deposit on the glass window. The maximum total correction was 800° and the minimum 379°. The maximum correction for the copper deposit was 250° and the minimum 25°.

Just what temperature the optical pyrometer measures at the cathode of an arc is questionable. The Brown-Boveri Company[5] has measured the temperature of the cathode spot in a mercury arc rectifier as being 2087 ± 25°C, by an optical pyrometer in a similar arrangement. However, they used a green filter and as there are several green emission lines in the mercury spectrum, their results may not be accurate. Other investigators[6] place the temperature of the cathode spot at 500°C in a mercury arc.

It seems unlikely that the temperature of the cathode spot is higher than the temperature measured by the optical pyrometer.

D. Vaporization of the Cathode

The current density at the cathode of a vacuum arc was determined by passing the arc over a highly polished cathode surface. A cross section of the arc path was selected and the width of individual trails measured by a cathotometer. A current density of 14,000 amperes per cm² was found, assuming the cathode spot to be circular. Fig. 6 shows the observed total rate of vaporization plotted against the arc current for a copper cathode. Assuming a current density of 14,000 amps/cm² a constant value of 0.21 grams/cm²/sec is found.

An equation is developed by Jones, Langmuir and Mackay[7] which gives the relation between the absolute temperature and the rate of vaporization of a metal in vacuum. Fig. 7 is plotted from their Eq. (22), namely,

$$\log_{10} M = \frac{A}{C} - \frac{\lambda_0 + E}{CT} - \frac{B}{C}\log_{10} T - \frac{DT}{C} \tag{1}$$

where M = mass of metal evaporated per cm² per sec.

$A = 44{,}638$ for copper
$C = 4.577$ " "
$E = 370$ " "
$B = 3.126$ " "
$D = 0.0008$ " "

* Optical Pyrometer built by Scientific Materials Company. Distributed by Fisher Scientific Company.

[5] Brown Boveri Mitteilungen **16,** 61 (1929).

[6] E. Luebcke, Zeits. f. Tech. Physik **12,** 598, 603 (1929).

[7] Jones, Langmuir and Mackay, Phys. Rev. **30,** 201 (1927).

$\lambda_0 = 82,060$ " " $=$ latent heat of vaporization per gram atom of metal at absolute zero.

T = absolute temperature.

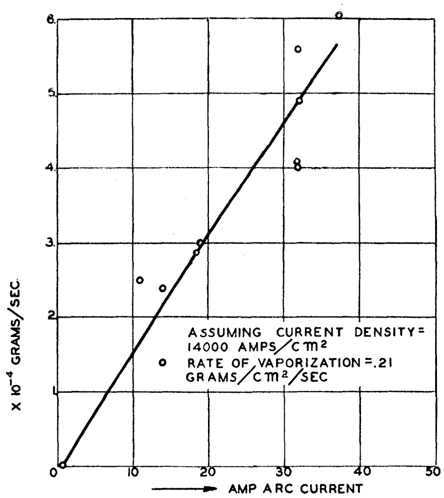


Fig. 6. Vaporization of copper cathode by arc in vacuum.

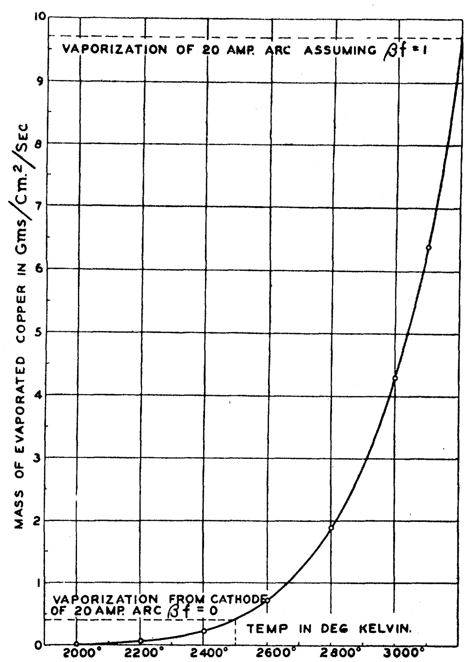


Fig. 7. Rate of vaporization as function of absolute temperature. Plotted from Eq. (22) Phys. Rev. 30, 210, Jones, Langmuir and Mackay.

If the measured rate of vaporization (0.21 gm/cm^2/sec) based upon a current density of 14,000 amps/cm^2, represents the total vaporization at the cathode, then a temperature of 2400°K is found from Fig. 7. However, this measured rate of vaporization may not be the total vaporization rate at the cathode spot.

If there exists a high energy region in the gas just outside the cathode spot, then a molecule emitted from the cathode spot will have a kinetic energy corresponding to the temperature of the cathode spot, until it reaches this cathode region. In the cathode region the molecule is so highly energized that its original kinetic energy is negligible compared to its kinetic energy in the cathode region. The velocity of thermal agitation is so great in the cathode region that the vapor molecules will be emitted in all directions according to their random motion.

Let m_1 = rate of vapor returning to the cathode from the cathode region and m_2 = net rate of loss of vapor away from the cathode. In Fig. 8 this condition is shown graphically.

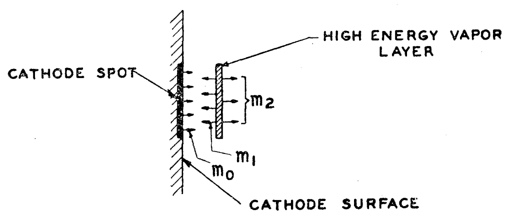


Fig. 8.

As an approximation it is initially assumed that $m_1 = m_2$ because the total surface of the cathode is large compared to the actual area of the cathode spot and the high temperature gas layer is very close to the cathode spot.

It then follows that $m_0 = m_1 + m_2$ where m_0 is the total rate of vaporization at the cathode. The measured rate of loss of cathode material is then $\frac{1}{2}$ the total rate, that is,

$$m_0 = 2m_2 \ . \tag{2}$$

Based upon this reasoning the actual rate of vaporization is 0.42 gm per cm^2 per sec, and the temperature of the cathode spot is 2500°K.

In the above discussion no account was taken of the part the positive ions play at the cathode. A modification of the above theory was suggested by R. C. Mason.

Let αm_0 = fraction of copper vapor which is ionized before it is permanently lost or returned to the cathode. After the arc has reached equilibrium

$$\alpha m_0 = n_+ \tag{3}$$

where n_+ is the number of positive ions returning to the cathode.

The copper vapor lost per second which constitutes the vapor stream previously mentioned is

$$m_2' = \tfrac{1}{2}(1 - \alpha)m_0 \tag{4}$$

while

$$m_1' = \alpha m_0 + \tfrac{1}{2}(1 - \alpha)m_0 \tag{5}$$

where m_2' is the net rate at which the vapor is lost and m_1' is the rate at which copper is returned to the cathode.

$$m_0 = \frac{2m_2'}{1 - \alpha} \tag{6}$$

but

$$\alpha = \frac{n_+}{m_0}$$

therefore

$$2m_2' = m_0\left(1 - \frac{n_+}{m_0}\right) = m_0 - n_+$$

$$m_0 = 2m_2' + n_+. \tag{7}$$

If, however, there is an accommodation coefficient as suggested by K. T. Compton[2] not all the positive ions may be condensed. If β is the fraction of the positive ions actually condensed then

$$m_0 = 2m_2' + \beta n_+ \tag{8}$$

where $1 \geqq \beta \geqq 0$, and $n_+ = i_+/e = f\,i/e$. f is the fraction of current carried by the positive ions at the cathode.

$$1 \geqq f \geqq 0$$

$$m_0 = 2m_2' + \beta f \frac{i}{e}\cdot$$

The previous assumption that $m_1 = m_2$ will be true only if

$$\beta f = 0$$

Assuming the other extreme $\beta f = 1$, then the rate of vaporization is

$$m_0 = 2m_2' + \frac{i}{e}$$

assuming singly ionized copper molecules

$$\frac{i}{e} = 9.30 \text{ gm/cm}^2\text{/sec.}$$

$$m_2' = 0.21 \text{ gm/cm}^2\text{/sec.}$$

$$m_0 = 9.72 \text{ gm/cm}^2\text{/sec.}$$

Extrapolating the curve of Fig. 7 shows that this rate of evaporation corresponds to a temperature of 3200°K, about 100° over the boiling point.[7] Thus the difference in temperature caused by choosing $\beta f = 0$ and $\beta f = 1$ is only 700°.

Conclusions

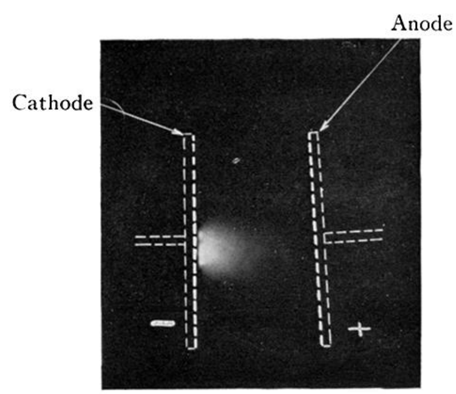
(1) Spectroscopic observation of the cathode spot discloses a weak continuous spectrum, which is of a strength comparable with that given by a 3 mil copper wire heated in vacuum just before the wire melts.

(2) Pyrometric readings of the temperature of the cathode spot give a temperature which may be too high due to the unknown effect of the ionized gas in front of the cathode spot.

(3) Temperatures calculated under extreme assumptions as to actual rates of vaporization are shown to agree in order of magnitude with those measured by an optical pyrometer.

(4) Further experiments have confirmed the existence of the high velocity vapor and since this high energy of the vapor cannot be attributed to the temperature of the cathode spot, then the vapor stream must acquire its high velocity in the cathode region.

The writers wish to express their appreciation to Dr. J. Slepian and Mr. R. C. Mason for helpful suggestions.



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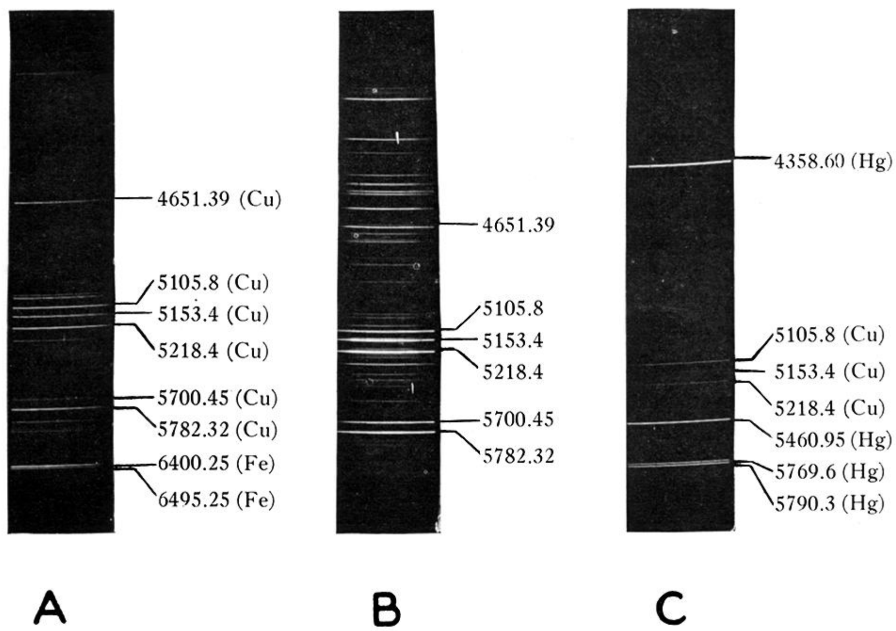

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