

Accommodation Coefficient of Mercury Ions on a Mercury Surface

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The pressure exerted on a mercury surface, to which were attracted mercury positive ions produced in a mercury arc, was measured by a modified form of Chattock micromanometer. The pressures found were entirely too large to be given by the neutralized ions alone, even if they had an accommodation coefficient of zero. The correction for the general heating of the mercury surface was not large. The most probable explanation is that each ion sputtered a large number of atoms and that the reaction on the surface of these escaping sputtered atoms gave the observed forces. If α is the accommodation coefficient, defined as the fraction of the energy of the impacting ions which is not carried away by the sputtered atoms; n , the

number of atoms sputtered per ion; V_s , the electron volt equivalent energy of the sputtered atoms, then the experiments set these limits for 1000 volt ions:

$$100 > n > 7.8; \quad 0.92 > \alpha > 0; \quad 0.78 < V_s < 128.$$

The force exerted on the mercury surface was a linear function of the energy of the ions, represented approximately by

$$(F/i)(\text{dynes/amp.}) = 9V \text{ (volts).}$$

From a critical examination of the sources of error, it seems the true forces must have been greater than the values used above.

AN accommodation coefficient for positive ions neutralized at a metal surface, analogous to the long known accommodation coefficient for neutral molecules, was first discovered by Van Voorhis and Compton;¹ defining the accommodation coefficient α as the ratio of the actual heating of a metal target to the expected heating if all the kinetic energy of the impacting ions were given up to the metal, they found α for A and Ne on Mo, and He on Pt to be 0.75, 0.65 and 0.35 to 0.55, respectively. Later measurements^{2, 3} on the momentum imparted to a metal target by the neutralized ions gave for α , defined in the same way, but with energy translated into momentum, the average values 0.49, 0.84 and 1.0 for He on Mo, A on Mo and A on Al, respectively. Aside from its intrinsic interest, the accommodation coefficient of mercury ions on a mercury surface is of obvious importance in momentum and energy considerations at the cathode of a mercury arc.

EXPERIMENTS AND RESULTS

From the previous experiments and simple theory,³ it was expected that the accommodation coefficient for mercury would be very close to 1; consequently, an extremely sensitive method of measuring the force on a mercury pool was sought. Of several possible ways, the simplest seemed to be the use of a Chattock micro-

manometer.⁴ The usual design had to be altered considerably for the purpose of this experiment, and the water and castor oil commonly used were replaced by liquids of low vapor pressure and low viscosity. The final assembly is shown in Fig. 1, the micromanometer being mounted upon the tilting frame of the standard instrument made by the Cambridge Instrument Company.

Essentially the micromanometer consists of a U-tube employing two liquids of slightly different density. The surface of separation of the liquids occurs in a vertical limb, at the end of the narrow tube O . The interfacial tension of the liquids is large, and the levels are adjusted so that the heavier liquid forms a bubble in the lighter liquid at the end of O . The surface of separation is observed in a microscope M . As a third component, mercury, must necessarily be introduced, the decrease in sensitivity which results may be minimized by making the ratio of the areas of the mercury pools E and P to the area of O , as large as possible. The liquids chosen for the manometer were diethylene glycol, of density 1.1108 at 28.5°C, for the heavy liquid, and dibutyl phthalate, with a chlorinated diphenyl added to bring the density up to 1.0866, for the light.⁵ By freezing the mercury in trap T , it was

⁴ Chattock, *Phil. Mag.* **217**, 96 (1901); Stanton, *Proc. I. C. E.* **156**, 83 (1904); Chattock and Tyndall, *Phil. Mag.* **19**, 450 (1910).

⁵ These were chosen because of their availability in the laboratory; the vapor pressure of the diphenyl compound was high enough, however, that a liquid air trap between

¹ Van Voorhis and Compton, *Phys. Rev.* **37**, 1596 (1931).

² Lamar, *Phys. Rev.* **43**, 169 (1933).

³ Compton and Lamar, *Phys. Rev.* **44**, 338 (1933).

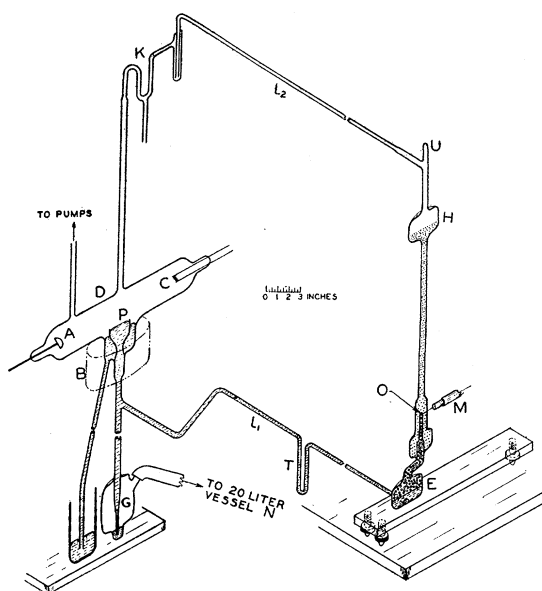


FIG. 1.

possible to introduce the manometer liquids at *U* in the proper sequence, with thorough pumping of the system at each step. The tubes *L*₁ and *L*₂ were sufficiently long and flexible to permit considerable adjustment of the levels of the liquids, and in particular, the surface of separation at *O* could be brought to the desired position, by moving the micromanometer relative to the tube *D* and pool *P*.

Because of rapid changes in atmospheric pressure produced by convection currents in the room, it was necessary to close the vessel *G* by connection to a 20 liter container. Changes in the temperature of *N* also produced pressure changes, but these were slow and could be compensated for by the adjustment of the micromanometer.

The device was calibrated by raising the cut-off *K* so that the pressure on *H* remained constant, and then changing the gas pressure in *D*. The change in pressure on *P*, read directly on a McLeod gauge, produced a change in the position of the surface of separation at *O* which was observed in a micrometer eyepiece in *M*. The sensitivity of the device was such that steady pressure differences could be read to 0.1 dyne

the manometer and discharge tube was necessary. A better choice for the light liquid would seem to be benzyl butyl phthalate or methyl butyl phthalate, as suggested to me by the Commercial Solvents Corp.

per sq. cm, and rapidly changing pressure differences, to 0.5 dynes per sq. cm.

Positive ions were produced by an arc between the thermionic cathode *C* and anode *A*. The electron temperature, electron density and space potential were determined by using *P* as a Langmuir probe. In all tests the residual gas pressure was less than 10^{-4} mm, so substantially only mercury ions were present. It was not possible to bake out the tube or distill in the mercury, but the mercury was double distilled before being put in *G* and the containing tubes were carefully washed out. The surface at *P* was frequently changed by overflowing.

In order to measure the reaction on *P* when it collected positive ions, the bubble at *O* was adjusted to a desired position on the *M* eyepiece scale with *P* insulated; then suddenly, a large negative voltage was applied from *P* to *A*. Any change in the pressure on *P*, due to the impact of the positive ions, resulted in a movement of the surface of separation at *O*, because the pressure on *H* was unaffected by application of voltage to *P*. Ideally, the manometer is supposed to be tilted so as to keep always the same position for the surface of separation at *O*, but practically it was found the magnitude and rapidity of the changes were too great for this. As the best alternative, the deflection of the interface for different pressure changes was determined by direct calibration. Thus, for any change in position on the eyepiece scale, the change in the force acting on *P* was known. That this method was sufficiently accurate was checked by its reproducibility. The manometer was always calibrated immediately after a series of tests, and the calibration changed but little from day to day.

At first, it was almost impossible to keep the bubble at the zero position of the scale, because of the effect of temperature changes in the tube *D*, and particularly because of the thermal expansion of the mercury in *P* and its connecting tube of different diameter. By raising the level of mercury in the overflow tube surrounding *P* almost to the same level as the mercury in *P*, and by placing a cooling bath *B* around both, the drifting of the manometer with *P* insulated was almost eliminated. The most consistent results were obtained with a melting ice bath in *B*.

As the force acting on P proved to be a function of time, the usual procedure was to bring the surface of separation at O nearly to the desired zero position by means of the leveling screws on the micromanometer frame. Then, the position of the interface in the eyepiece scale was read every few seconds, the time being noted on stop watches. After several seconds with P insulated—long enough for the steady drift to be secured—negative voltage was applied to P , and readings continued for perhaps 1 or 2 minutes. Usually, voltage was then removed, and readings obtained for several seconds longer.

In addition to the reaction of the neutralized ions leaving the mercury surface, a force may be imparted to P as a result of the heating of the surface by positive ion impact. The magnitude of the heating effect alone may be found by heating the surface by other means—by electron bombardment, for instance. If P is made slightly negative with respect to space, the electrons reaching it move under a retarding field, so the average energy of the electrons striking the surface is $2kT_e$ where T_e is their temperature in the discharge. The watts input per ampere of electrons is $2kT_e/e + \phi_-$ where ϕ_- is the heat of condensation of the electrons, arbitrarily taken at 4 volts. The mass of the electrons is so small, the momentum involved is negligible. The number of positives striking the surface is practically the same as when a large negative voltage is used, but their energy is so much less (pool 1.5 to 4 volts negative to space as compared to 50 to 1000 volts) that their effect is also negligible.

The effect of heating the mercury is twofold; first, the increase in temperature causes a relatively large increase in the number of atoms leaving the surface, and possibly an increase in the number striking the surface. Consequently, the pressure on the surface is increased. Second, if the surface and vapor were in equilibrium before the heating started, then the number of atoms leaving the surface, after the temperature increases, is greater than the number striking, so a net loss of mass results. This is interpreted by the micromanometer as a *decrease* in pressure on the pool P . If the mean free path were large compared to the dimensions of the tube D , then one could write for the change in force on P when it is heated,

$$\Delta F = (p - p_0)/2 - a \int_0^t (p - p_0) dt, \quad (1)$$

where p_0 represents the pressure of Hg vapor in the tube at $t=0$, when the heating starts; p , the pressure of Hg vapor corresponding to the temperature of the surface at a time t ; and a , a constant given by kinetic theory as 0.034. The temperature of the surface, and consequently p , is an increasing function of the time of heating; it eventually reaches a constant value, however, when all the heat input is lost by conduction or evaporation. Now actually, the vapor density is such that the m.f.p. is short compared to the dimensions of D , so the actual ΔF cannot be represented by an equation as simple as (1): the first term should be greater than given in (1), and the second term should be less, with a no longer constant but a function of both p and p_0 . Eq. (1) does give an indication, however, of what may be expected; the force ΔF is zero for $t=0$, increases to a maximum, and then continually decreases because of the last term. A typical illustration may be found in Fig. 2, where the deflection of the manometer for electron heating of P is plotted against time; the point "on" shows when the electron current to P was initiated.

When positive ions strike the test pool, the force is

$$\Delta F = W(T) + I - St, \quad (2)$$

where $W(T)$ represents the effect of general heating, I is the reaction resulting from an accommodation coefficient less than 1, and S gives the rate of sputtering, to be discussed in the next section. If equilibrium is established before the application of negative voltage to P , then $W=0$ when $t=0$, so the initial value of ΔF

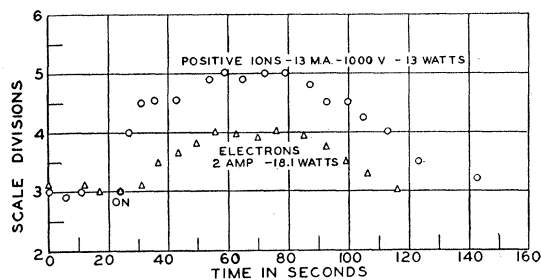


FIG. 2.

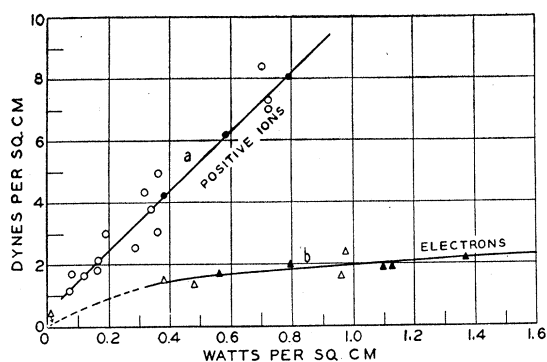


FIG. 3.

is simply I . Thus if one could measure ΔF for very short times, then I could be found at once. Unfortunately, the micromanometer has considerable time lag, chiefly due to the inertia of the large masses of mercury in pools E and P ; with a suddenly applied force about 8 seconds elapses before the deflection of the manometer reaches 90 percent of its final value. Instead of the positive ion response being a sudden increase, followed by a slow rise to maximum, the time lag of the instrument causes it to show a fairly rapid rise, followed by slower increase to maximum, as shown in Fig. 2. It is impossible to extrapolate such a curve to $t=0$ with accuracy. Consequently, the following procedure was adopted: for positive ion bombardment the value of ΔF at the end of the rapid rise (from 6 to 10 seconds after voltage was applied) was read; this is somewhat less than the true value of ΔF for $t=10$ sec., because of the lag of the instrument and because the readings were often for times a little under 10 sec. For electron heating, the value of $\Delta F=W(T)$ at 10 seconds was determined. Now the true value of I , the reaction due to the impacting ions is greater than the difference between the ΔF for positive ions and the ΔF for electrons giving the same heat input to the mercury surface.

Disturbing factors, such as temperature changes in different parts of the apparatus, drops of mercury falling into the pool, vibration of the building, etc., rendered it necessary to take a large number of readings for each condition. Those in which it was obvious extraneous factors were involved were discarded, and the remainder, usually from 4 to 10, were averaged to get the

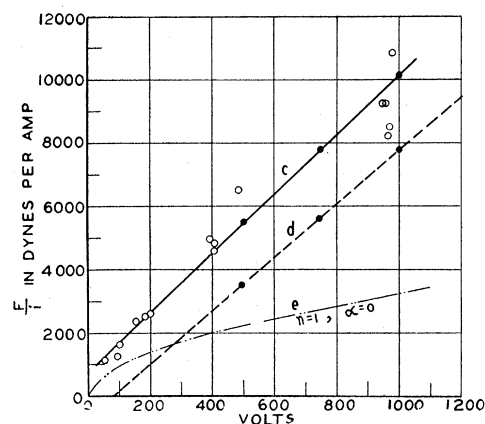


FIG. 4.

data which are plotted in the accompanying figures. Fig. 3 shows the increment in pressure on the pool P plotted against watts per sq. cm input to the pool, both for electron and positive ion impacts. In Fig. 4, the force observed divided by the positive ion current is plotted against the potential of the pool negative to space, for curve c ; for curve d , the observed force for positive ions is first decreased by the ordinate of curve b , Fig. 3, for the corresponding watts input. Curve d , presumably gives the force per ampere of positive ions, resulting from an accommodation coefficient less than 1. The most reliable data are indicated by the solid points.

For voltages less than about 50, the forces for the largest obtainable positive ion currents were too small to be read with accuracy; for voltages greater than 1000 and currents above 1 m.a. per sq. cm the forces were too large to be read by the micromanometer in its present form. Typical data for one particular test are recorded below; the ranges covered in all the experiments are listed in the parentheses.

Test 9-24; arc 10.4 amp. (1.5-20), 26 volts (18-26); electron temp. 29,300°K (9600-30,200); random electron current, over 280 m.a./cm² (33-280); random pos. ion current, 0.805 m.a./cm² (0.09-1.73); space pot. 5.5 volts negative to A (5.5-10.5); dark space thickness, 0.51 cm; temp. cooling bath 4° (2° to 5° when cooled); applied voltage P to A 1000 (60-1000); pos. ion current, 13.1 m.a. (2.74-28.4); initial deflection 1.55 div. = 8.04 dynes/cm² (1.78-8.4); area of P , 16.45 cm².

DISCUSSION OF RESULTS

The momentum delivered to the mercury surface by the impacting positive ion is just balanced by the electrical forces exerted on the mercury; however, if the neutralized ion leaves the surface with some of the kinetic energy it acquired in falling through the space charge sheath, then the momentum imparted to the surface is

$$mv = m(1 - \alpha)^{\frac{1}{2}}(2eV/m)^{\frac{1}{2}},$$

where α is the accommodation coefficient and V is the potential drop in the space charge sheath. If the neutralized ions leave in random directions, then the average normal component of momentum is only $\frac{1}{2}$ the above. If a current i of mercury positive ions flows, then the pressure on the mercury pool should be

$$F_{\text{dynes/cm}^2} = 100 i_{\text{amp./cm}^2} V^{\frac{1}{2}}_{\text{volts}} (1 - \alpha)^{\frac{1}{2}}. \quad (3)$$

For α independent of V as previous experimenters have found approximately true, then F/i should be proportional to $V^{\frac{1}{2}}$. The maximum possible value of F/i is given by putting $\alpha = 0$ (i.e., assuming the ions are elastically reflected upon neutralization); such a maximum is plotted in curve e , Fig. 4. One sees that e lies below all of the uncorrected experimental points; and if $\alpha = 0$, then no energy is given to the mercury surface, and no correction for heating of the surface should be applied to the measured forces. Only possibly for positive ion energies less than 100 volts can the experimental points agree with Eq. (3); and for energies of 1000 volts, the discrepancy is wide. Furthermore, the experimental data show F/i is proportional to V and not to $V^{\frac{1}{2}}$ as Eq. (3) would require. Thus both in magnitude and way of variation with energy of the positive ions, the observed forces cannot be exerted by the neutralized ions alone.

For a given total energy, the momentum is proportional to the square root of the mass involved; so, one can account for the observed forces by supposing many atoms react upon the mercury surface for every ion measured. This can occur if an ion makes several collisions in passing through space charge sheath. With momentum conserved, the total momentum given to the mercury surface by all the impacting particles,

both the ion and the neutral atoms with which it has collided, is still balanced by the electrical force on the mercury. If, however, the neutral atoms also have an accommodation coefficient less than one, then the reaction of these atoms and the neutralized ion leaving the mercury yields a net force on the mercury. The question thus arises, is the mean free path of the mercury ion less than the space charge sheath thickness?

The mercury vapor density in the discharge tube is not known precisely, but it may be estimated as follows: in order to carry away the heat input to the mercury, in the steady state with the pool insulated, a temperature drop of less than 20° between the surface of the pool and the outside of the discharge tube, is estimated from the dimensions and geometry of the mercury pool P and the mercury surrounding it in the overflow reservoir. The temperature of the outside tube wall was perhaps 50° in the early tests, but when a cooling bath was used, as was the case for all the data plotted in Figs. 3 and 4, the temperature of the bath was between 2° and 15° ; when the best data were obtained, the temperature was 2° to 4° . The temperature of the mercury surface, then lay between 20° and say 40° ; the corresponding vapor pressures are 0.0012 and 0.0061 mm. At these pressures, the mean free path of the mercury atom would be 1.37 and 0.27 cm. For many of the trials, the m.f.p. of the mercury ion was certainly greater than 1 cm. The space charge sheath thickness was observed visually in a number of cases, and could be calculated of course; the measured values were about 30 percent higher than the calculated (see below). The greatest thickness, for 1000 volt applied to the probe, was only 0.76 cm. Though some collisions undoubtedly occurred within the sheath, it seems very unlikely that a sufficient number of collisions were made to account for the large forces.

The other alternative is that many atoms leave the surface of the mercury for each positive ion which strikes, or as one may say, the *sputtering* of the mercury surface is large. This is reasonable from the v. Hippel theory⁶ which attributes sputtering to local vaporization from a limited area, raised to a high temperature

⁶ v. Hippel, Ann. d. Physik **81**, 1043 (1926); Blechschmidt and v. Hippel, Ann. d. Physik **86**, 1006 (1928).

for a very short time by the impact of a positive ion. The time the temperature remains high enough for rapid vaporization is inversely proportional to the thermal conductivity of the material. The rate of vaporization depends upon the vapor pressure of the material, which can be approximated by $p = A e^{-\lambda/kT}$, where λ is the heat of vaporization per molecule. Sputtering thus is influenced to some extent by the thermal conductivity, but to a much greater degree by the latent heat of vaporization, since the latter occurs in the exponential. The v. Hippel theory does not attempt a quantitative explanation of sputtering, but it is successful in predicting the relative order in which the metals sputter. Data for the sputtering of mercury are not available, but the sputtering of other metals by 1000 volt mercury ions is between 1 and 5 atoms per ion.^{7, 8, 9} Consider the value for platinum, 1.75 atoms per ion:⁸ the thermal conductivity of platinum is about 8 times that of mercury, while the latent heat of vaporization of platinum is almost 10 times that of mercury; the sputtering rate of mercury must be far greater than that of platinum. The thermal conductivity, and particularly, the heat of vaporization are so much less for mercury than for the metals for which little sputtering is found, that it would not be surprising to find the sputtering of mercury to be greater by one or two orders of magnitude.

A distinction should be made between the local vaporization or sputtering and the general vaporization, which occurs uniformly over the surface. Any reaction due to the latter is included in the correction made for the effect of heating the mercury surface; the former is directly attributable to the positive ion impacts.

If many atoms leave the mercury surface near the point of impact of a positive ion, it is useless to inquire which is the neutralized ion and with what velocity it leaves; experiment gives only the reaction of all the atoms. The definition of accommodation coefficient may be generalized, to cover the present case, with the following simplifying assumptions: suppose the sputtered atoms, including possibly but not necessarily the

neutralized ion as one of their number, all have the same velocities which are distributed randomly in direction away from the surface; let $n = \text{No. of sputtered atoms per incident ion}$, $v = \text{velocity of emission}$, $m = \text{mass of individual atom}$. Define α , the accommodation coefficient, as

$$\alpha = (eV - \frac{1}{2}mnv^2)/eV. \quad (4)$$

The pressure exerted on the surface will be

$$F = i/e \cdot \frac{1}{2}mnv. \quad (5)$$

Now, from Fig. 4, the force on the mercury surface is seen to be almost directly proportional to the energy of the impacting ion, with a small uncertainty involving the correction for general heating. Approximately, then

$$F/i_{\text{dynes/amp.}} = 9V, \quad (6)$$

where V is the energy of the ion in electron volts. Substituting in the expression for α , and changing to practical units

$$\alpha = 1 - 7.8 \times 10^{-3} V/n. \quad (7)$$

The kinetic energy of an individual sputtered atom,

$$\frac{1}{2}mv^2 = eV_s \quad \text{say, is} \quad V_s = 7.8 \times 10^{-3} (V/n)^2. \quad (8)$$

Now α defined in this way must be positive, so

$$n \geq 7.8 \times 10^{-3} V. \quad (9)$$

An idea of the upper limit of n may be obtained from the rate of change of ΔF with t ; in Eq. (2), if none of the sputtered atoms return to the mercury pool $S = n(i/e)mg$. Since W is also a function of t , through the temperature, S cannot be greater than $-d\Delta F/dt$. For $V = 1000$, the experimental data show that n must be less than 100. So these rough limits may be fixed, for $V = 1000$

$$100 > n > 7.8, \quad 0.92 > \alpha > 0, \quad 0.78 < V_s < 128.$$

It seems likely the true values are nearer the left-hand limit than the right.

SOURCES OF ERROR

The micromanometer could be read with an error of not over 0.5 dyne per sq. cm; the percentage error thus was large at very low voltages

⁷ Meyer and Guntherschulze, *Zeits. f. Physik* **71**, 279 (1931).

⁸ Henderson and Gidéon, *Phys. Rev.* **43**, 601 (1933).

⁹ Compton and Langmuir, *Rev. Mod. Phys.* **2**, 188 (1930).

but became about 5 percent at the highest voltages.

The energy the positive ions acquired in the accelerating field at the mercury surface was known to within 2 volts. Some doubt exists, however, as to the number of positive ions. The measured current included both the positive ions and any secondary electron emission from the mercury surface. For 1000 volts applied to the probe, the space charge sheath thickness calculated from the Langmuir space charge equation upon the basis of no collisions by the positive ions was less than the measured value by almost 30 percent. The tube was so constructed that the sheath thickness could not be measured accurately but it seems the error in measurement must have been less than 30 percent. Edge effects would make the average current density, used in calculating the sheath thickness, greater than the actual current density at the center of the pool, where the thickness was measured; thus the calculated thickness would be too low. The effect of collisions of positive ions within the sheath would tend to make the actual thickness less than the calculated,¹ rather than greater. The secondary electron emission would have to be almost 80 percent of the positive ion current, in order to bring up the calculated thickness to the measured. This is larger than the secondary emission found for Hg ions on Ni, W and Pt by other investigators,⁸⁻¹² who report values from less than 10 to 40 percent. From the work of Sonkin¹³ it seems unlikely that any large emission by metastable atoms occurred. Possibly some photoelectric emission occurred. The force per ampere calculated above, being based on the measured current, is less than the actual force per ampere of positive ions, if electrons were emitted from the mercury surface.

The heating effect of electrons is uncertain to the degree that the heat of condensation differs from the assumed value of 4 volts. In calculating the heating by positive ions, merely the product of measured current and voltage to space was used; the unknown heat of condensation of the positive ions was neglected. More important

considerations, and effective in the opposite direction, are the heat carried away by the sputtered atoms and the inclusion of any secondary electrons as heating current. The actual heating must be considerably less than the measured iV used, so the correction subtracted from the observed positive ion forces is too large.

Some of the pressure attributed to the effect of heating when electrons are attracted to the pool might conceivably be due to sputtering by the electrons. The energy contributed by an electron is more likely to be generally distributed, so no local high temperature occurs, than the energy would be for a positive ion. Furthermore, the kinetic energy of the electrons was less than 5.2 equivalent volts. Experiments of Bariess¹⁴ showed no electron sputtering for 800 volt electrons; though his data are incomplete, from approximate calculations it seems that the sputtering in his case must have been less than 10^{-3} atom per 800 volt electron. Other experiments¹⁵ record a disintegration of a sputtered deposit by electrons only for energies greater than 2000 volts. General heating of the mercury seems to be the only possible effect when electrons strike the surface.

Calculations show that any direct change in surface tension through the presence of an electric field or the change in temperature of the mercury surface caused an entirely negligible deflection of the micromanometer. The effect of a change in the angle of contact between the mercury pool and the glass tube P , due to the above factors, is not so easy to estimate, but it also appears to have been inconsiderable.

Changing the arc current by 2 amp., or applying a large negative voltage to the mercury in the overflow reservoir surrounding P , caused no deflection when the test pool was insulated; thus any effect of change in current distribution in the tube when electrons or positive ions were collected by P must have been negligible.

The electron pressure to which Tonks¹⁶ has called attention, is negligible; when the mercury surface was changed from insulated to 1000 volts negative, the electrons reflected from the surface,

¹⁰ See Rev. Mod. Phys. **2**, 177 (1930).

¹¹ Oliphant, Proc. Roy. Soc. **A132**, 631 (1931).

¹² Chaudhri, Proc. Camb. Phil. Soc. **28**, 349 (1932).

¹³ Sonkin, Phys. Rev. **43**, 788 (1933).

¹⁴ Bariess, Zeits. f. Physik **68**, 585 (1931).

¹⁵ Johnson and Harris, Phys. Rev. **45**, 630 (1934).

¹⁶ Tonks, Phys. Rev. **46**, 278 (1934).

and the electron pressure, changed by about 1 part in 400; when the mercury was changed from insulated to a few volts negative to space, so a large electron current was collected, the electron pressure decreased by less than a factor of 2. Since the total electron pressure, which was calculated from the measured temperature and density of electrons, was just below the limit of sensitivity of the micromanometer, consequently its effect could never be detected.

When the pool was insulated, it was actually about 5 to 15 volts negative with respect to space; thus, when a larger negative voltage was applied, the positive ion current remaining about constant, the *change* in pressure, which was the quantity measured, was smaller than the actual pressure which would be produced by ions of the applied voltage. The difference became considerable only for low negative voltages; as for these voltages, the uncertainties in the measurements were so large, a correction cannot be obtained.

Finally, if the sputtered atoms, before reaching the tube walls or before being scattered, communicated their momentum to other mercury atoms directly above the mercury pool, then the pressure of mercury vapor on the pool was reduced. Thus, the measured change in force actually was less than that corresponding to the reaction of the sputtered atoms.

Of all the factors mentioned above, a preponderance indicates the actual force on the mercury surface was greater than that given by curve *d* in Fig. 4. The approximate linearity of the relation between F/i and V shows that if the number of sputtered atoms is proportional to the energy of the positive ions, as many experiments indicate, the energy of the sputtered atoms must be constant. The data are not accurate enough to decide whether a minimum voltage exists below which sputtering does not occur. From Fig. 4, such a minimum must be less than 75 volts, as curve *d* is certainly too low. Consequently, direct application of these results to the cathode of an arc is not possible. As sputtering of tungsten has been found for 25 volt A ions,¹⁷ it seems quite possible that mercury ions cause sputtering of the mercury cathode of a mercury arc with a 10 volt cathode fall. If the data reported herein can be extrapolated so far, then it appears an accommodation coefficient certainly less than 0.9 must be used in energy and momentum balance calculations for the mercury arc.

The writer is indebted to his associates in the Westinghouse Research Laboratories for advice about the choice of materials and the performance of the experiments.

¹⁷ Holst, *Physica* 4, 68 (1924).