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The Mercury Arc Cathode

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Conduction electrons in the liquid at the arc spot are considered to be heated to about 4000°K by electronic bombardment from the vapor while the atomic temperature of the liquid is near 150°C. Thermionic emission apparently yields the arc current plus that returning from the vapor. An arc spot was driven around a circular mercury track by a radial magnetic field. The spot traveled opposite to the ponderomotive force for fields below approximately 5000 gauss with velocity proportional to field strength and showed a negative temperature coefficient. The Righi-Leduc effect considered as a thermomotive force operative in the hot layer of conduction electrons was assumed to drive the spot. The velocity was evaluated in terms of the vertical thermal gradient and compared with the observed, yielding a gradient of about 5×10^8 degrees cm. Arcs were extinguished by current pulses of about 10^{-7} sec. in the same direction as the arc current. This gave means for calculating the total energy of the hot electronic layer, and finally the vertical thermal gradient in good agreement with the value above. The Thomson heat stops losses along this gradient, and is apparently the factor causing the characteristic arc current density.

To explain the escape of electrons from the apparently non-thermionic arc spot on the liquid cathode, yielding currents of 4000 amperes per square centimeters more or less, the theory has been advanced that most of the electrons bearing the current are pulled from the cathode by the electrostatic force of the field of ions just above the cathode.[1] This well-known extraction theory has been analyzed,[2] and has been apparently the most acceptable for a number of years. However, new phenomena and new considerations to be brought forward lead to a different concept.

We advance the theory that electronic bombardment of the cathode results in an efficient transfer of energy to conduction electrons in the liquid mercury, raising them to a temperature sufficient to cause a kind of thermionic emission great enough to yield the observed arc current plus that coming down from the vapor; and that the atomic configuration is at a very much lower temperature. The Thomson heat is apparently operative to arrest most of the heat flow tending to go down into the liquid by way of the electronic part of the thermal conductor.

We discuss first the relationship between liquid and vapor at the arc spot. In the quantitative discussion that follows we assume a current density of 4000 amperes per sq. cm, which according to our observations given below and in agreement with observations of one other[3] seems to be a characteristic of the ordinary mercury arc.

Probe measurements of electronic temperature and number of electrons in the plasma though generally considered to be very trustworthy in mercury vapor will not be relied upon for the region adjacent the arc spot because of the smallness of the region in relation to the necessary size of the probes and other practically insurmountable difficulties leading to doubts[4] concerning such measurements. We shall have to be content with finding reasonable relationships between plasma and liquid in harmony with the present theory; and shall point out that the plasma factors, cathode drop, electronic temperature, and electronic density, will take on different values for different arcs. Confirming evidence for the general theory will go beyond the fitting of the phenomena in the vapor to the phenomena in the liquid and will come from new considerations of the liquid mercury. We have the following notation:

D = observed arc current density in amp./sq. cm,
L = electronic current in amp. cm^{-2} leaving the cathode,
I = electronic current in amp. cm^{-2} entering the cathode from the gas,
N = number of electrons per cc in the plasma just on the anode side of the cathode fall space,

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[1] I. Langmuir, Science **58**, 290 (1923); Gen. Elec. Rev. **26**, 735 (1923).

[2] K. T. Compton, Phys. Rev. **37**, 1077 (1931).

[3] A. Gunther-Schulze, Zeits. f. Physik **11**, 74 (1922).

[4] R. C. Mason, Phys. Rev. **51**, 28 (1937).

T = electronic temperature of the vapor,

C = cathode drop in volts,

$q = 1.6\times 10^{-19}$ coulomb, being the electronic charge,

ϕ = work function of Hg,

k = Boltzmann gas constant per molecule,

θ = temperature of the conduction electrons in the liquid cathode.

Three equations will be written down involving T, N, I, and L subject to the assumptions of the present theory.

$$L = D + I, \tag{1}$$

$$I = Nq(kT/2\pi m)^{\frac{1}{2}}\mathcal{E}^{-11600C/T}. \tag{2}$$

The energy balance equation:

$$2(I/q)kT + \phi I\times 10^7 = \phi L\times 10^7 + 2(L/q)k\theta. \tag{3}$$

In (3) we have considered the energy brought in due to the kinetic energy of the electrons and the operation of the work function. The energy going out is treated in a similar way. Energy due to ions has been neglected in comparison to that of the electrons. Furthermore, thermal conduction along the electronic medium in the mercury is neglected because we assume the Thomson effect to nullify such conduction. This will be discussed later.

The last term of (3) is relatively small and can be evaluated for our purposes now. θ can be taken from the thermionic equation

$$L = 120\theta^2\mathcal{E}^{-11600\phi/\theta},$$

provided we assume a reasonable value for L. If our estimate of L turns out poor we can use our final results to get a better value and proceed anew. However, as we shall see later, a value of 4000°K will be a good estimate for θ. The work function ϕ is taken to be 4.26 volts. This was obtained from the contact potential between Hg and platinum[5] as observed by Moore and by using the work function of platinum as observed by DuBridge.[6]

Then (3) becomes

$$2IkT/q + \phi I\times 10^7 = (\phi + 0.69)L\times 10^7, \tag{4}$$

or

$$2IkT/q\times 10^{-7} = 4.95D + 0.69I, \tag{5}$$

and

$$D/I = 3.48T\times 10^{-5} - 0.139. \tag{6}$$

T is reasonably expected to be in the neighborhood of 4×10^4. Hence I is approximately equal to D. The electronic emission at the arc spot is therefore approximately $2D$ or about 8000 amperes per sq. cm. Note that the cathode drop is not explicit in Eq. (6). Evidently a change in cathode drop must cause changes in T and N which maintain the validity of (6).

By combining (6) and (2) we have

$$N = \frac{46.2\times 10^{20}}{(T-4000)T^{\frac{1}{2}}}\mathcal{E}^{11600C/T} \tag{7}$$

If there were another relation between N and T known from experiment we could find the value of either. It is known that the cathode is subjected to a mechanical pressure, which by the observations of Kobel[7] upon a given arc was approximately 6.5 cm of mercury. The pressure $p = NkT$ could be called upon provided we accept the idea of Tonks that the mechanical pressure[8] is that of the electrons. The concept seems very reasonable although the kinetic picture of how the momentum is transferred to the cathode must depend upon conditions. However, we shall make only small use of the relation here since the observations are not as extensive as would be desirable, and do not include a value of C. It is of interest, however, to evaluate N from (7) for various values of T and C.

Results are recorded in Table I for cathode drops of 6, 8, 10, and 12 volts and for values of T that seem to cover the expected range. C would not be expected to go below about five volts in any case because of the minimum energy needed to excite the mercury atom. It is known, however, that the cathode drop for a thermionic cathode may be below 7 volts.[9] Measurements

TABLE I. Number of electrons (N) per cc in the plasma. T = Electronic temperature in plasma. C = Cathode drop in volts.

	$C=6$	$C=8$	$C=10$	$C=12$
$T\times 10^{-3}$	$N\times 10^{-15}$	$N\times 10^{-15}$	$N\times 10^{-15}$	$N\times 10^{-15}$
30	10.5	22.7	49.3	105.0
40	3.66	6.54	11.7	20.6
50	1.80	2.87	4.58	7.25
60	1.07	1.59	2.32	3.44
70	710	1.01	1.38	1.93

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[5] D. H. Moore, Phys. Rev. **50**, 344 (1936).

[6] L. A. DuBridge, Phys. Rev. **32**, 961 (1928).

[7] E. Kobel, Phys. Rev. **36**, 1636 (1930).

[8] L. Tonks, Phys. Rev. **46**, 278 (1934).

[9] R. C. Mason, Phys. Rev. **38**, 427 (1931).

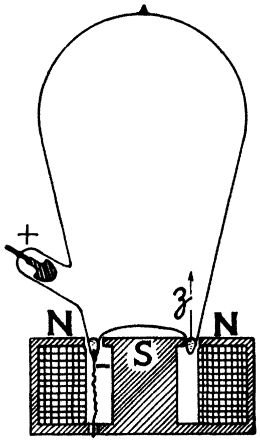

FIG. 1. Arc tube with annular mercury cathode. $N-S$ = concentric poles of electromagnet driving the arc spot around circle 30 cm in circumference. z = coordinate of text.

upon a particular mercury arc have yielded 10 volts[10] for C.

If we assume C was 10 volts when Kobel observed a pressure of about 80,000 dynes per sq. cm and equate this pressure to NkT we find that $T = 37{,}000°\text{K}$ approx. and $N = 15 \times 10^{15}$ electrons per cc. These values seem reasonable. The phenomena in the plasma apparently fit on to those expected in the liquid. The table shows that a smaller N goes with a larger T. We know from experiments with the plasma that a small atomic density usually requires a larger T. The arc for various vapor pressures is visualized, therefore, as accommodating itself to the conditions by variations of C, N, and T. An increase in T is assumed to be caused by an increase in C. The arc according to the present, or *emission theory* is adaptable to a wide range of vapor pressure.

Before going further with the emission theory more observations are needed. A magnetic field transverse to the arc current drives the spot in a direction transverse to the field but in a sense opposite to the ponderomotive force. We set up a tube having an annular ring of mercury for the cathode. A radial magnetic field was employed as shown in Fig. 1.

With a south pole at the center, the arc spot raced around clockwise as viewed from above. The mercury circulated slowly in the opposite direction. The arc stream curled backward as the spot rushed forward. Velocity was measured by focusing light from the spot upon a photo-cell arrangement and using the amplified current to deflect the beam of a cathode-ray oscillograph. Deflection along the other coordinate was made by the 60-cycle power circuit, or by other known frequency. Definite patterns were observable upon the screen of the oscillograph from which the number of excursions per second made by the arc spot around its track was deduced. Speeds above about 3000 cm per second gave an arc track with very smooth edges and a very definite resulting pattern on the oscillographic screen. Lower speeds showed a ragged arc path and a variable oscillographic indication.

The arc track sought the region where the horizontal component of the magnetic field was strongest (the path where it could go fastest). The spot could be made to race around near the inner glass wall or the outer or could be made to follow a circle half way between the two walls by varying the disposition of the magnetic field to give the strongest horizontal component in the desired region.

A plot of velocity of spot as a function of magnetic field strength is shown in Fig. 2. The result for a constant temperature of the mercury is a straight line through the origin. The velocity has a large but undetermined negative temperature coefficient at any field strength. The steeper straight line was observed with cooler mercury. The magnet was turned on and the speed ob-

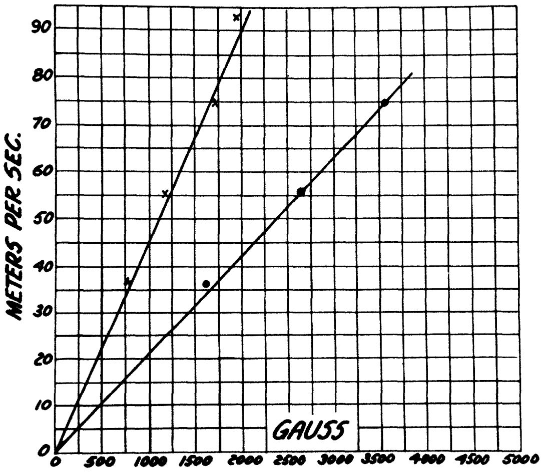

FIG. 2. Velocity of arc spot *versus* horizontal component of magnetic field. Arc current six amp. Steeper line observed with cooler mercury.

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[10] E. S. Lamar and K. T. Compton, Phys. Rev. **37**, 1069 (1931).

served in less than a second. Then the magnet was shut off and after several minutes another reading at a higher field strength was made. In this way the mercury temperature was at about the same low value for each observation. The lower curve was taken by allowing the arc to race around till it reached a constant lower limit of speed, the mercury presumably reaching a constant temperature. We regret that an accurate determination of temperature of the mercury at the arc path was not possible in the time available.

The velocities in the region considered are too high for mechanical effects to cause turbulence of the liquid surface. The large condenser for the vapor insured an inconsiderable pressure everywhere except at the arc spot. We obviously have an arc spot racing over a smooth mercury surface, and going in the direction opposite to that determined by the effect of the field on the arc stream; the speed is accurately proportional to the magnetic field, and has a negative temperature coefficient; the determining temperature is that of the liquid or the hot conduction electrons and probably has little or no connection with that of the vapor, except at very high field strength and low vapor pressure. Phenomena in these regions are dealt with later.

A transverse galvano-magnetic effect suggests itself as a prime cause of the observed phenomena. The Hall effect seems to be too small to be of direct importance. The Nernst and the Ettingshausen effects also seem to be of a low order of magnitude. A negative Righi-Leduc effect, however, seems to be the one involved directly, provided the thermal gradient of the conduction electrons along a vertical line in the liquid is large enough. The magnetic field transverse to the large thermal gradient is visualized as giving rise to a thermomotive[11] force in the liquid at the moving arc spot acting to transfer heat in the observed direction of motion.

We can write the thermotive force per cm as

$$\Delta\theta/B = SH(d\theta/dz),$$

where B = breadth of arc spot along line of motion; S = Righi-Leduc coefficient; H = magnetic field strength; and $d\theta/dz$ = vertical thermal gradient. $\Delta\theta$ represents the total driving thermomotive force in an element of the spot.

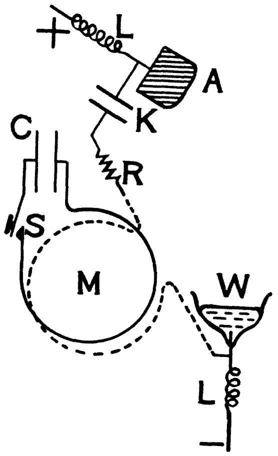

FIG. 3. Arc quenching circuit. S = switch. C = 0.02 μf condenser. M = closely coupled primary and secondary each being one turn of ½″ ribbon about 11 cm in diameter. R = non-inductive resistance of six ohms. K = 0.06 μf. W = Hg cathode. A = carbon anode. LL = r-f chokes.

Let K = the thermal conductivity of the highly excited region in the liquid; E = the energy per unit volume of the excited electrons; and V = velocity of the excited spot. Then $VE = KSH(d\theta/dz)$ = rate of transfer of heat in the direction of motion. Hence

$$V/H = (KS/E)(d\theta/dz).$$

The velocity seems to be independent of B and hence of the size of the spot. Therefore, velocity is apparently independent of changes of arc current. Trebling the arc current suddenly was observed to cause an increase in velocity of about 15 percent. Since the magnetic field due to the arc current has been neglected in its effect upon the thermomotive force, we consider the observations to give a result consistent so far with the formula.

The ratio KS/E may be evaluated approximately from theory.[12]

$$S = \frac{2el}{h}\left(\frac{\pi}{3n}\right)^{\frac{1}{3}}.$$

$$K = \frac{2\pi^3 lk^2\theta}{9h}\left(\frac{3n}{\pi}\right)^{\frac{2}{3}}.$$

$E = \theta C_v$ Approx.

C_v = Specific heat of the electrons.

$$C_v = \frac{4\pi^3 mk^2}{3h^2}\left(\frac{3n}{\pi}\right)^{\frac{1}{3}}\theta.$$

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[11] P. L. Bridgman, *The Thermodynamics of Electrical Phenomena in Metals* (The Macmillan Company, 1934), p. 137.

[12] A. Somerfeld and N. H. Frank, Rev. Mod. Phys. **3**, 1 (1931).

Finally

$$(V/II) = \tfrac{1}{3}(e/m)(l^2/\theta)(d\theta/dz)$$
$$= 5.9\times 10^6(l^2/\theta)(d\theta/dz),$$

where l = mean free path of electron; m = mass of the electron; and e = charge of electron in e.m.u.

The formula as derived is approximate. The quantity l is of the order of magnitude of 2×10^{-6} cm. We take θ to be 4000°K, the value near the emitting or top surface of the spot. Then

$$d\theta/dz = 1.7\ V/H\times 10^8.$$

The observed V/H is between 2 and 4. Hence $d\theta/dz$ is approximately 5×10^8 degrees/cm by this method of evaluation. Fortunately there is an independent method, wherein the total energy of the excited layer of electrons is evaluated from energy necessary to extinguish the arc.

Pulses of current lasting about 10^{-7} sec. were superposed upon the arc current already flowing, by discharging a capacity C of 0.02 microfarad connected in series with one turn of a closely coupled transformer M and a damping resistance R about equal to the critical damping resistance (see Fig. 3). W is the liquid cathode and A is the anode. LL are radiofrequency chokes. K is a condenser about four times as large as C, which served to transmit the pulse but to prevent passage of steady current. The arc was invariably extinguished, when the superposed current was comparable to that already flowing. The voltage of C necessary to extinguish the arc was consistently less if the sign of the charge were such that the first rush of current were added to the arc current. A higher voltage of C was necessary if it were charged to cause a subtraction from the arc current. This observation evidently shows that a superposed added current can extingish the arc. Currents up to twenty amperes were thus interrupted. The mechanism of this action depends upon our ability suddenly to raise the cathode drop of the arc. Evidently the bombarding electronic current I of Eq. (2) ceases for a moment because of a sudden increase of the factor C. The degree of ionization and electronic temperature in the vapor respond relatively slowly as would be expected from other observations.[13] The outflowing current L carries away energy from the spot and it is cooled below that necessary for sustaining the arc. The energy taken away is approximately $4.78\ Lt\times 10^7$ ergs per sq. cm where $t = 10^{-7}$ sec. Hence only about 30,000 ergs are removed. The arc would not have gone out if this were very much less than the total energy involved. We therefore consider the excited region to be limited in energy.

Let us assume about 4×10^{22} electrons per cc and let Z be approximately the thickness of the activated layer. Then the total energy is roughly $Z\times\theta C_v = 550\ Z\theta^2$. θ is an average, taken here to be 2000°K. Then $2.2\times 10^9\ Z = 30{,}000$ and $Z = 1.4\times 10^{-5}$ cm. A reasonable estimate of Z of the order of magnitude seems to be about 10^{-5} cm.

The thermal gradient downward among the conduction electrons is therefore approximately 4000×10^5 or 4×10^8 degrees per cm. The experiments with the moving spot and those involving blowing out of arcs are each in harmony with the emission theory and each yields essentially the same value for the thickness of the excited region of conduction electrons.

Such an enormous thermal gradient in the liquid would cool the spot and extinguish the arc if the ordinary thermal conduction had free play. Arcs were also extinguished within 10^{-7} sec. by pulses of current in the direction opposite to the arc current. The arc spot in the absence of arc current cools down to an inoperative value within the 10^{-7} sec. Evidently the arc current normally prevents the cooling. The convection of heat upward with the electronic current must approximately equal the thermal conduction downward. Therefore, we assume the Thomson heat to counteract the thermal conduction. We look first at the order of magnitudes necessary and write $10^7\sigma D(d\theta/dz) = -K(d\theta/dz)$ approx., or, $\sigma = -(K/D)\times 10^{-7}$ volt, where σ = Thomson coefficient; D = current density = 4000 amp./sq. cm; K = thermal conductivity = 8×10^5 ergs/cm sec. deg. Hence $\sigma = -2\times 10^{-5}$ volt. We can evaluate σ approximately from the theory[12] of metals.

$$\sigma = 300\,U_E = \frac{-8\pi^2 mk^2\theta}{3eh^2}\left(\frac{\pi}{3n}\right)^{\frac{2}{3}}\times 300 \text{ volts.}$$

Here U_E is the Thomson coefficient in e.s.u. as calculated for a case of no variation of electronic free path with temperature. The formula

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[13] C. G. Smith, Phys. Rev. **59**, 997 (1941).

is therefore not expected to yield a correct result. Nevertheless, it is of some interest to note that for $n=4\times 10^{22}$ and $\theta=2000°$ we find $\sigma=-1.1\times 10^{-5}$ volt, a magnitude close to that required by the arc theory. Evaluation of σ from observation is possible from the relation

$\sigma_m-\sigma_r=\theta(dQ/d\theta)$ = difference in Thomson heats of two metals, m and r.

Here Q equals the thermoelectric power. From the *International Critical Tables 6*, page 214, we find data for mercury and lead, which give

$$\sigma=-3.3\times 10^{-8}\theta.$$

Extrapolation to $\theta=2000°$ gives a value of the order of magnitude needed for the arc theory.

At this point we cannot feel sure that our procedure is correct in detail, although it evidently indicates that we are dealing with factors of real significance. We have not explained why the current density is 4000 amperes per sq. cm. If it were more than this the Thomson coefficient could be less. In view of the present theory we feel that the current density is a characteristic of the liquid mercury and is determined among other things by the behavior of the Thomson heat. Evidently currents below some limit are too small to nullify the possible thermal losses. The 4000 amperes is probably this minimum current. There is a back e.m.f. associated with the Thomson heat and proportional to the thermal gradient, which must tend to limit the current density since it supplies a spreading tendency for the arc spot. We shall not make mental constructions now to fit the situation in more detail, since experimental results to accompany them are not at hand. We therefore return to other observations.

The rapidly moving arc spot in a definite track when viewed through a filter that transmits only the red, appears like a red hot streak whose width is readily measured by optical means. Measurements were made for currents ranging from 2 to 12 amperes, and the resulting current density evaluated by assuming the moving spot to be circular. Values only slightly below 4000 amperes per square centimeter were found.

The most interesting observation, however, is that the intensity of the red streak seems to be exactly the same regardless of the angle between the mercury surface and the line of vision. This suggests the operation of Lambert's cosine law of brightness, and shows clearly that the red light is coming from the liquid mercury. If it were coming from the gas immediately above the liquid, then the brightness when viewed along a line nearly parallel with the surface would be greater than that observed when looking normal to the surface; just as an end on view of a discharge tube yields greater brightness than that encountered across the tube. The inference is that the electrons in the liquid in the activated arc region are emitting the light, and any such emission from the adjacent vapor is of secondary importance. Time was not available for determining the color temperature of the streak, although the spectrum was observed to be continuous.

The arc spot appears to be incandescent. However, the vaporization from the spot has been estimated[2] to be that expected from a liquid surface at approximately 200°C. Our observations with the transverse magnetic field confirm this. With a strong field, an electron leaving the liquid to enter the vapor will in general start along a cycloidal path which will lead back to the cathode unless the trajectory is disturbed by a collision with atom or electron in the vapor. A field of 5000 gauss stopped the contrary motion of the spot attributed to the Righi-Leduc effect and reversed it, giving rise to a very slow opposite motion. If the vapor pressure were allowed to rise, this new motion ceased and the direction changed back to that characteristic of a lesser magnetic field. Apparently the electronic free path for a spot barely stopped is nearly that of the expected cycloidal path. It appears that we can evaluate approximately the electronic free path. The length of the cycloid expected is about 0.008 cm for an electron whose kinetic energy at the crest of the cycloid is about nine electron volts. The free path of an electron in normal mercury vapor[14] at 1-mm pressure is approximately 0.015 cm. We infer that the vapor density just above the arc spot under the conditions above corresponds very roughly to that of vapor at 2-mm pressure under standard condi-

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[14] K. T. Compton and I. Langmuir, Rev. Mod. Phys. **2**, 123 (1930).

tions. The liquid surface is therefore estimated to be about 150°C by this independent method.

The conduction electrons in the liquid at the arc spot are at a temperature of 4000°K according to this emission theory. The observations indicate they emit light as an incandescent body. The atomic constituent of the excited region is at approximately 150°C. If these things be true, then the cooling of the liquid by evaporation and by ordinary thermal conduction along the atomic constituent plus losses due to convection are together able to keep pace with the energy transfer from the excited electronic medium over to the atomic matrix. This rate of transfer is expected to be low but no attempt at a theoretical estimation of it will be made at this time.

For the sake of clarity, however, we recall in this connection the well-known fact that sputtering of a cathode is readily produced by bombardment with masses of atomic magnitude, namely, ions; whereas the plate of a radio tube bombarded by electrons suffers little or no sputtering. Evidently the transfer of energy to the atomic lattice is direct in the ionic case but indirect in the electronic. Where the mass of colliding particle and target particle are nearly equal the efficiency of direct energy transfer would be considered greatest. The electronic bombardment must heat electrons in the metal first and these in turn transfer energy to the atoms.

The emission theory, therefore, seems to introduce ideas in harmony with those previously acceptable. It fits in with known factors in the vapor above the arc spot. It seems to be the only theory compatible with the characteristic behavior of the arc spot in a transverse magnetic field and the extinction phenomena cited, and leading to an explanation of the characteristic current density. The lack of equilibrium between the hot electronic medium and the relatively cool atomic matrix involves an account that can possibly be elaborated upon later.

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The Loss of Energy of Hydrogen Ions in Traversing Various Gases

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The loss of energy of hydrogen and deuterium ions having initial energies in the range from 60 to 340 kev has been measured as a function of their path in various gases at various pressures. The measurements are expressible in terms of the energy loss in kev per cm of path per mm of pressure as well as in terms of stopping power relative to air. The gases examined are air, water vapor, hydrogen, deuterium, and helium.

APPARATUS

FIGURE 1 shows the general plan of the apparatus. The hydrogen or deuterium ions after being accelerated by means of a Cockcroft-Walton voltage quadrupler pass into the field of the resolving magnet. Here a mass beam is selected and properly deflected so as to pass on through the gas absorption chamber. After traversing the gas the beam is again brought into a high vacuum and passed through the field of a measuring magnet. This magnet is so adjusted as always to bend the beam a definite amount as determined by the ion beam fluorescence on the observation screen. Thus the magnetic field of the measuring magnet measures the energy of the ions after passing through the gas.

Figure 2 gives a detailed sketch of the absorption chamber. The gas is confined by means of a fine capillary system of diaphragms at each end of the chamber. The gas which does escape through these capillaries is removed by a liquid air trap and a system of high speed pumps.

Several features in the design and operation of the apparatus have been given special attention. Energy measurements are all made in