also explain the failure of Nasledow and Nemenow[3] to produce a barrier layer cell in which electrons would flow from the metal to the semiconductor, for even though a copious emission of electrons were obtained from the metal, most of the electrons would return to the metal before they lost their kinetic energy.

The author wishes to thank Dr. Felix Bloch and Dr. Robert Oppenheimer for valuable help and criticism.

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[3] D. N. Nasledow and L. M. Nemenow, Phys. Zeits. d. Sow. **3**, 1 (1933).

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Sparking Potentials at Low Pressures

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Sparking potentials were observed between outgassed nickel electrodes in air at low pressures. The spark length d was varied from 2–10 mm and the pressure p reduced from 1 mm of mercury to 0.06 mm. Sparking potentials as high as 80,000 volts were observed, and agreed approximately with Paschen's law. The sparking potential V for $p\cdot d<0.95$ is given by $p\cdot d\cdot e^{V/136,500}=1$.

It is well known that as the pressure of a gas diminishes, the potential difference necessary to produce a spark discharge between flat electrodes, separated by a fixed distance, also diminishes, until at a critical pressure the sparking potential reaches a minimum value. Below this critical pressure the potential required to produce a discharge, rapidly increases as the pressure is lowered.

Many experiments were made by Peace,[1] Paschen[2] and Carr[3] to check Paschen's law, which stated that at a given potential difference, the field being uniform, the product of the pressure at which the discharge occurs and the distance between the electrodes is constant. This law seems to be fairly established experimentally thus far.

Carr[3] who carried the investigation below the critical pressure found that the sparking potential rose extremely fast as the pressure was lowered but he was only able to reach a voltage of 1800 volts due to the restrictions in the design of his apparatus. The portion of the curve beyond this voltage has not as yet been investigated. Many experiments involve the use of electrodes close together, with gas pressures and potentials bordering on those at which a spark takes place; thus it is of interest to know just when such a discharge may occur. This investigation was carried out with this point in view. The experiments described in this paper deal with sparking potentials in air with nickel electrodes. Carr[4] has shown that the sparking potentials of almost all the common gases with the exception of hydrogen are grouped very closely around that of air in the low range of pressures.

Apparatus

A high voltage transformer and a kenotron supplied the rectified high voltage. A microammeter in series with Shallcross high resistances and a Kelvin electrostatic voltmeter served as a means of measuring the potential difference across the discharge tube, that is, between the electrodes. Since no condenser was used in the rectified high voltage, the microammeter resistance method with half wave rectification gave average values of the voltages read, which were multiplied by π in order to give the peak voltages that were interpreted as the sparking potentials.

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[1] L. R. Peace, Roy. Soc. Proc. **A62**, 111 (1889).

[2] E. T. Paschen, Ann. d. Physik **37**, 69 (1889).

[3] W. R. Carr, Phil. Trans. Roy. Soc. **201**, 403 (1903).

[4] W. R. Carr, Phil. Trans. **A201**, 410 (1903).

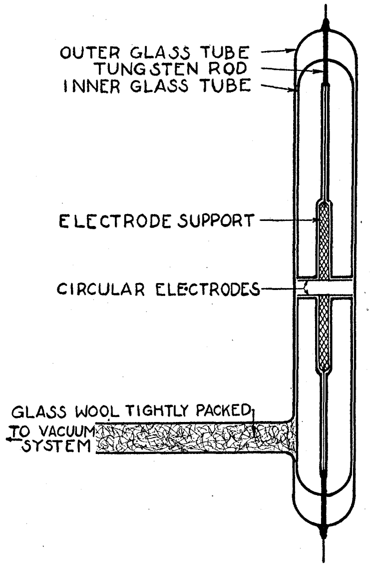

FIG. 1.

A mercury diffusion pump backed by an oil pump was used to lower the pressure to the desired point, a McLeod gauge was used to measure the pressure. The discharge tube was isolated from the rest of the high vacuum system by a trap, thus eliminating mercury or any other vapors that may be in the system. Fractional amounts of dry air were allowed to pass into the discharge tube by a system of stopcocks connected to a reservoir, which could be evacuated to any pressure. This method allowed very small changes to be made.

The design of the discharge tube was the most difficult part of these experiments. Since at the lower pressures the resistance to a discharge is greater for close electrodes than for more distant ones, the discharge will take the easiest, which in this case is the longest, path. In the early stages of this work, this phenomenon was often seen; the discharge going through very small cracks seeking a much easier path, sometimes doubling back to the ground electrode. This was prevented by finally designing the tube as shown in Fig. 1, where the glass tube holding the electrode was tightly telescoped into an outer tube. The tube connecting the discharge tube to the vacuum system was tightly packed with glass wool for several inches thus effectively stopping the discharge from passing to the McLeod gauge or pump.

It was found that the discharge would occur between the sides of the electrodes rather than between the flat faces as desired in this case. To prevent this they were made very thin and pressed very tightly to the glass tube holding them. It would probably have been much better if they could have been imbedded into the glass itself. The corners were rounded off to prevent concentration of the field at the edge of the electrode. The faces were flat, smooth and parallel. The electrodes were thoroughly out-gassed by heating in vacuum to a red heat with an inductance furnace to prevent any spurious gases from being liberated while the field was being applied, which by increasing the pressure between the electrodes would cause a premature discharge.

In the operation of this discharge tube the electrode which came out of the closed end A was connected to the high potential, while the other electrode connection B was grounded. The voltage was applied to the terminals of the discharge tube and if after a few minutes no discharge started, the voltage was raised and applied again and again in a similar manner until a discharge was formed. After making at least two more such observations, this potential was recorded as the sparking potential for that particular pressure. One-half hour was allowed to elapse between readings at different pressures.

The time delay of the discharge, first observed by Warburg,[5] was especially pronounced in the vicinity of the critical pressure, but seemed to diminish as the voltage was increased. It was rather difficult at first to determine the exact sparking potential, for the longer the application of the potential, the lower the spark occurred. However this was controlled by having a constant maximum time delay. Also this tendency diminished rapidly as the voltage was increased, in fact it was replaced at the high voltages by small premature electrical breakdown sparks. These were attributed to very small impurities in the electrodes themselves and were disregarded since a self-sustaining spark discharge did not form. The data in this range were slightly irregular presumably for that reason, although the irregu-

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[5] Warburg, Ann. d. Physik **62**, 385 (1897).

larity also might be caused by a small error in the pressure which would make a very large error in the potential difference.

Results

The data are plotted in Fig. 2. The pressure in mm of mercury is plotted on a logarithmic scale in order to cover the range and illustrate all the curves together. The points for the lower portions of the curve are averages for two or three readings while those for the higher voltages are single readings. This was due to the fact that at the higher voltages when the discharge occurred, it did so with a hot, bright flash that finally burned the electrodes and sputtered the inner walls of the glass tube between them, thus ruining the discharge tube. Some of the curves are shortened for this reason, and because tubes with exactly the same characteristics could not be built. The life of the tubes was prolonged by taking readings with spark discharges of very short duration after the point had been approximately determined.

The points for the higher pressures and low sparking potentials agree with those of Carr[6] as far as he went, while the points of the upper end of the curve, i.e., for $p\cdot d<0.95$ fall approximately on a straight line. The equation of this line is $V=18-314{,}000\log_{10}(p\cdot d)$, where V is the sparking potential in volts, p is the pressure in millimeters of mercury and d is the spark gap in millimeters. As $V\gg 18$ for all cases to which the formula may be applied, we may neglect the constant term on the right and say that for $p\cdot d<0.95$; the sparking potential is connected with the pressure and spark gap approximately by the formula $p\cdot d\cdot e^{V/136{,}500}=1$.

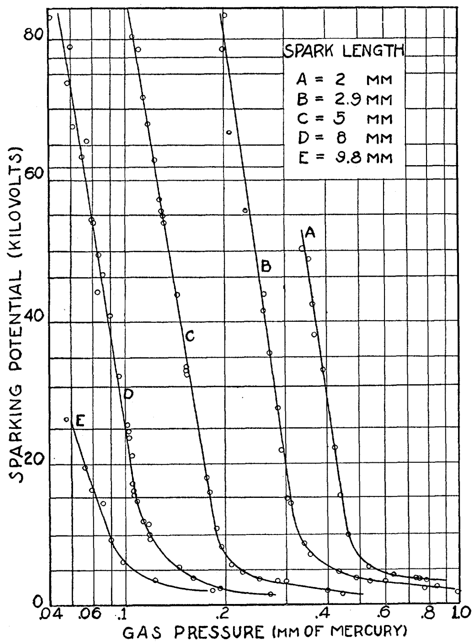

Fig. 2.

According to Paschen's law the sparking potential is a function of the product of the pressure and the spark length. To the extent that the observations agree with the above formula, it is seen that the law holds. The sparking potentials were plotted against the products of pressure and spark length and were found to fall approximately on one curve. The points showing disagreement were those for the highest voltages where the irregularities in Fig. 2 are greatest.

The author wishes to acknowledge the many essential suggestions and constant helpful advice, which Professor A. J. Dempster, who suggested this problem, has given in the course of this work.

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[6] W. R. Carr, Phil. Trans. **A201**, 414 (1903).