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Magnetically-Controlled Gas Discharge Tubes

R. E. B. MAKINSON, J. M. SOMERVILLE, K. RACHEL MAKINSON, AND P. THONEMANN
University of Sydney, Australia
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Discharge tubes are described in which a low pressure glow discharge is initiated by means of a magnetic field pulse. A tube has been developed in which a glow discharge so triggered leads to the formation of a cathode spot on a mercury pool; this tube will hold off 20 kv until fired and will then pass a current pulse of several hundred amperes. Its use in radar modulator circuits is envisaged.

1. INTRODUCTION

It is known [1–3] that the application of a magnetic field of sufficient strength can initiate a discharge between charged electrodes in certain configurations, such as coaxial cylinders, when the gas or vapor pressure is too low to permit a discharge otherwise. The magnetic field lengthens the electron trajectories so that the average number of ionizing collisions suffered by each electron is sufficient for a glow discharge to be sustained. A detailed study of such glow discharges carrying continuous currents up to several amperes between coaxial cylinders has been made by Penning,[3] who has also used the same principle in the construction of a low pressure manometer and a low pressure ion gun.[4,5]

The work described below was mostly conducted with current pulses, the peak current being of the order of a hundred amperes and the discharge normally an arc, with consequent low voltage drop between the electrodes. The main object was the development of magnetically-controlled discharge tubes which would be suitable for use as modulators in radar equipment. Both permanent gases and vapors were used, tube life in the former case being limited by clean-up of the gas. A satisfactory type of tube was developed having two coaxial cylindrical electrodes, together with a mercury pool as an auxiliary cathode* (Fig. (5a)); a glow discharge in the mercury vapor between the cylinders was initiated by a magnetic field pulse, and bombardment of the pool by ions from this glow discharge produced an arc spot on the pool through which the main current passed. These tubes passed currents up to 200 amperes in 2-megawatt pulses of duration 1 to 10 microseconds at repetition frequencies up to 1200 c/sec. with very small power loss in the tube itself.

Although simple two-electrode concentric cylindrical tubes were not satisfactory as radar modulators it was found that in such tubes, if the glow discharge was not allowed to pass into an arc, currents up to 50 amperes could be switched off against supply voltages of a few thousand volts by removal of the magnetic field. It seems therefore that such tubes may be useful where a rapid high current or high voltage switch is needed.

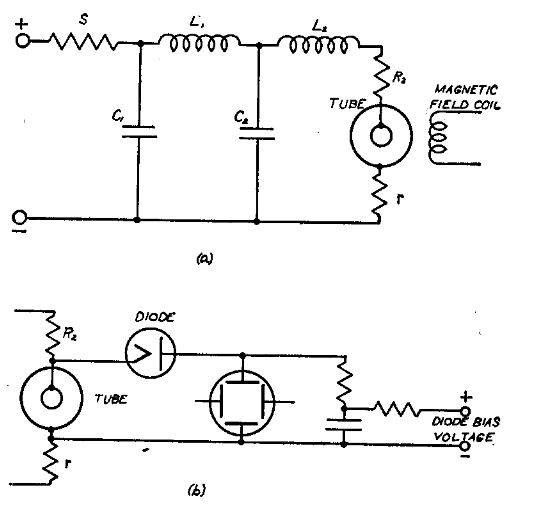

FIG. 1. (a) Showing pulse-forming line and load, R; (b) Arrangement of biased diode to hold off H.T. from oscillograph.

[1] Strutt, Proc. Roy. Soc. **89A**, 68 (1913).
[2] Engel und Steenbeck, *Elektrische Gasentladungen* (Verlagsbuchhandlung Julius Springer, Berlin, 1934), Vol. II, p. 236.
[3] Penning, Physica **3**, 873 (1936).
[4] Penning, Physica **4**, 71 (1937).
[5] Penning and Moubis, Physica **4**, 1190 (1937).
* The name "Hodectron" is proposed for tubes of this type.

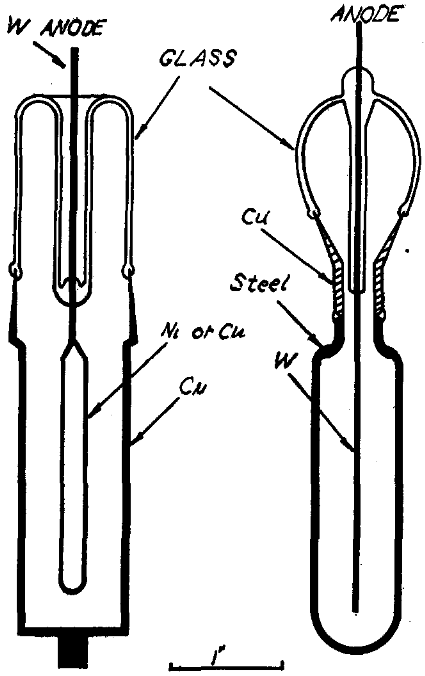

FIG. 2. Examples of two-electrode tubes.

2. CIRCUIT ARRANGEMENTS

The magnetic field was produced by a short coil coaxial with the electrodes and was applied in pulses of about 50 μsec. duration at repetition frequencies which were usually 50 or 100 per second; the peak value of the field was of the order of 500 oersted. The current in the coil was produced by charging a condenser from a d.c. source and discharging it through the coil by means of a vibrator or mercury thyratron.

The performance of the tubes was studied mainly in the circuit shown in Fig. 1 (a), which approximated that in which they would be required to operate as radar modulators. In this circuit the resistive load R corresponded to that placed on the modulator by the radar oscillator. The condensers C, forming with the inductances L_1 and L_2 an artificial line, were charged through the hold-off resistance S to between 1 and 20 kv, and were discharged through the tube and the load R on the initiation of a discharge by the magnetic field pulse. The variation of potential difference between the electrodes was studied by means of a triggered oscillograph, a diode being used as shown in Fig. 1(b) to hold off potentials greater than a few hundred volts. The oscillograph was also used to study the current through the tube, represented by the voltage drop across the small resistance r.

3. GENERAL NATURE OF THE DISCHARGE IN TWO-ELECTRODE TUBES

Examples of two-electrode tubes studied are shown in Fig. 2. Essentially the electrodes were concentric cylinders; with the outer cylinder as cathode a smaller magnetic field was required to initiate the discharge, so this arrangement alone was used. Copper, aluminum, steel, and nickel were used as cathode material, copper, nickel, and tungsten for the anode. Tubes were filled with helium, argon, air, and carbon dioxide and with iodine, mercury, and water vapors.

The tubes were initially studied while still sealed to the vacuum system, so that the pressure could be controlled. The pressure at which a discharge could be initiated by a magnetic field depended on the configuration of the electrodes and the nature of the gas or vapor, but in general was of the order of 0.1 mm for permanent gases. The range of pressures for a controlled discharge in one tube was about 10 to 1.

When the applied magnetic field reached its critical value the potential drop across the tube in general fell rapidly and the condensers C discharged completely in a few microseconds. The line circuit constants determined that the current through the tube should flow as an approxi-

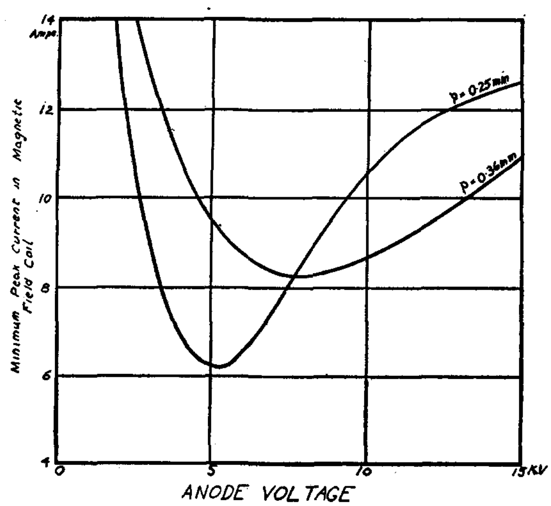

FIG. 3. Variation with anode voltage of the peak current in the field coil necessary to fire a two-electrode tube.

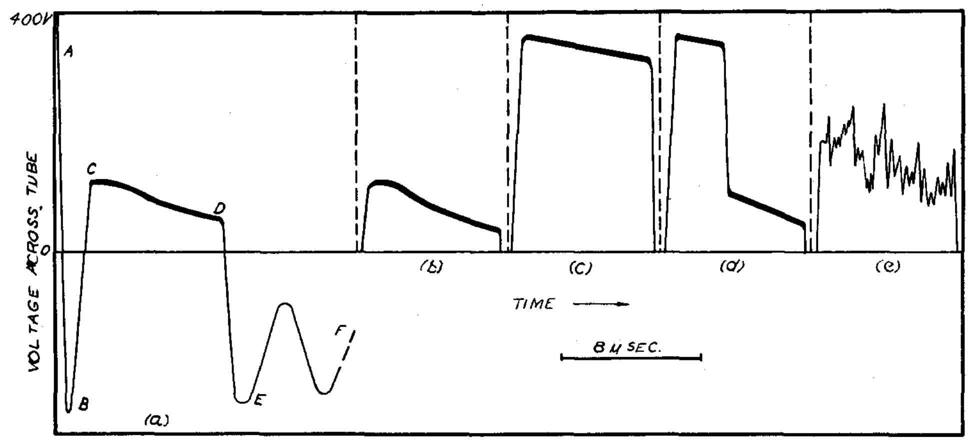

FIG. 4. Typical oscillograph traces of the voltage across the tube during discharge.

mately square pulse of a few microseconds duration; with the circuit used a small reverse current sometimes flowed after the main pulse. The currents passed were of the order of 100 amperes. The hold-off resistance S was large enough to ensure that the condensers did not charge up to breakdown potential twice during the same magnetic field pulse. The variation with anode voltage of the minimum field-coil current necessary to fire the tube is shown in Fig. 3.

Voltage Drop in Tube

When visual inspection was possible the discharge was seen to fill the whole inter-electrode space. It was usually associated with a bright white spot which moved about on the cathode and particularly favored a metal-insulator junction. Most of the current passed through this spot. When the spot was present the voltage drop across the tube was between 30 and 100 volts, in its absence about 400 volts. It was concluded that the presence of the spot meant that the discharge was an arc. Rapid alternation between arc and glow in successive discharges sometimes occurred.

Typical oscillograph traces of the voltage across the tube during the discharge are shown in Fig. 4. The initial deep valley ABC shown in Fig. 4(a) is spurious, and is caused by the rapidly falling anode potential acting through the inter-electrode capacity of the protecting diode. The portion CD shows the potential across the tube while it is conducting (the potential drop across the diode being negligible). When the tube becomes non-conducting, the characteristics of the line produce the portion DEF of the trace. The valley ABC and the portion DEF have been omitted from Figs. 4 (b), (c), (d), and (e). Figures 4(a) and (b) are typical of arc discharges, the voltage dropping rapidly to a value of about 50 volts, which does not vary greatly either with current, over a range of 100 to 1, or with the nature and pressure of the gas in the tube. Figure 4(c) is typical of a glow discharge, the voltage usually falling to between 300 and 600 volts, although much higher values have sometimes been observed; these traces vary markedly with tube conditions and current. Figure 4(d) shows a delayed transition from glow to arc.

The arc discharge in a helium-filled tube with a copper cathode was a characteristic pink color and photographs of the spectrum showed both He and Cu lines. In tubes of this type another kind of discharge was also observed, bright green, with a voltage drop of the order of 700 volts and a spectrum showing more intense copper lines than those of the arc discharge.

The transition from the glow to the arc was favored by irregularities or discontinuities in the electrodes or the magnetic field and by an increase in the supply voltage (and consequently in the tube current). The glow-arc transition showed no marked dependence on the nature and pressure of the gas.

Owing to the low power dissipation in the tube with the arc discharge, this mode is to be preferred. Consistent striking of the arc during the whole life of the tube was not obtained using a solid cathode. Tubes are described in Section 4 in which this difficulty was overcome by using a mercury pool as cathode.

Figure 4(e) shows an unstable type of voltage trace, frequently observed, in which the voltage was subject to rapid, apparently random fluctuations, no two consecutive traces being the same. Because of its appearance on the oscillograph such a trace has been called "grass." The height of the peaks varied from a few volts to about 200 volts. In tubes of the mercury pool type shown in Fig. 5(b) (see Section 4), grass occurred only when the tube temperature was below about 40°C. With permanent gases the appearance of grass was unaffected by changes in pressure and was also insensitive to changes in the magnetic field strength. No satisfactory theory of its occurrence has been evolved, but it is suggested that it may be associated with the motion of the cathode spot; alternatively its cause may be in the mechanism of formation of the arc spot.

Clean-Up of Gas

Considerable clean-up of gas took place during the discharge, severely limiting the life of any sealed-off tube which depended for its satisfactory operation on the presence of permanent gas. Some reduction of the clean-up was obtained by

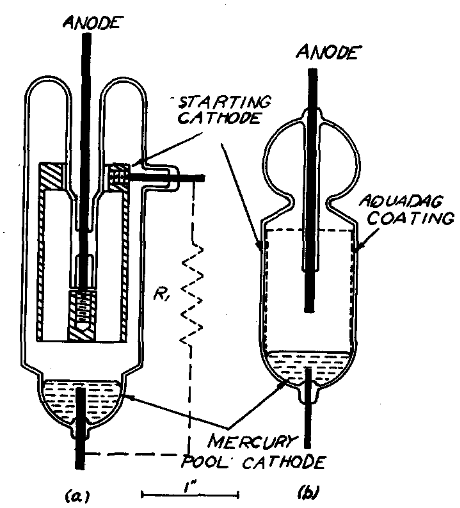

FIG. 5. Three-electrode tubes with anode, starting cathode, and mercury pool cathode; (a) with external resistance, (b) with internal resistance.

preliminary saturation of the walls with gas and by the addition of a buffer volume, but the longest life so achieved was only 50 hours. The effects of clean-up were avoided in tubes described in Section 4, which would start running on mercury vapor at room temperature. Attempts to run tubes on iodine and water vapor were unsuccessful.

4. ARC DISCHARGES IN MERCURY POOL TUBES

By addition of a mercury pool to the coaxial cylinder electrodes described in the preceding section a tube was obtained which operated on mercury vapor at room temperature and in which the discharge always took the form of an arc. Such tubes are shown in Fig. 5. The mercury pool acted as the cathode taking the main current and the outer cylindrical electrode merely as a starting cathode. Between the starting cathode and the anode a glow discharge was initiated by the magnetic field; bombardment of the mercury by ions from this discharge caused an arc to strike on the mercury surface.

These tubes operated satisfactorily at ambient temperatures between a few degrees C and 80°C, but below about 30°C unsteadiness occurred in the current trace on first switching on, disappearing as the tube warmed up. To ensure that the arc regularly formed on the mercury and not on the starting cathode, a resistance was placed in the starting cathode circuit. This was either an external resistance as in Fig. 5(a), or an internal resistance as in Fig. 5(b) where the starting cathode was a thin coat of Aquadag or sputtered tungsten. The latter type of tube had a life of only a few hours under the test conditions, i.e., as in a radar modulator, failure resulting from one of two causes; sometimes the action of the arc spot as it moved around the line of contact of the mercury and the glass separated the coating from the mercury pool; sometimes sputtering from the anode during current reversal after passage of the main pulse so lowered the resistance of the starting cathode that the arc spot formed on it instead of the pool, the voltage drop in the tube being then much higher and arcs sometimes forming again between the magnetic field pulses.

Of all types tested, the tube of Fig. 5(a), with the external resistance between starting cathode and pool, gave the most satisfactory operation. Its life was limited by the formation of a conducting path of sputtered material and mercury between the pool and the lead to the starting cathode, with consequent arcing on the starting cathode as described above. Such tubes have handled powers up to two megawatts from a power supply of 10–20 kv at repetition frequencies up to 1200 c/sec. with pulse lengths from 1 to 10 μsec. One had a life of 150 hours; the conducting path mentioned above could then still be broken up by shaking. The interval between the beginning of the magnetic field pulse and the beginning of the current pulse through the tube, which was from 20 to 50 μsec., never varied from pulse to pulse by more than 2 μsec.; the variation decreased as the supply voltage was increased, its average value being less than 1 μsec. with a supply voltage of 10 kv. A magnetic field pulse of peak intensity 350 oersted was sufficient to fire the tube.

The value of the resistance R_1 was not critical, values from 0.01 to 0.5 megohm being satisfactory. Operation was not affected by tilt of the tube so long as the mercury did not touch the starting cathode. Alignment of the electrodes was not critical, nor was that of the field coil.

Graphite, which does not amalgamate with mercury and sputters at a slow rate in mercury vapor, was found to be a suitable material for starting cathode and anode. The clearance between these two electrodes and the pool was made greater than $\frac{1}{4}''$, since "stalactites" of mercury sometimes grew downwards from them towards the pool. For a similar reason, the clearance between the starting cathode and the glass was kept greater than $\frac{5}{32}''$.

In operation of the tube, gases are cleaned up and it was found that rigorous outgassing or very low pressures were not necessary before sealing off.

Figure 6 shows the oscillograph traces of tube current, anode potential, and starting cathode potential; these may be interpreted as follows. When the magnetic field reaches the critical value a glow discharge is initiated between the anode and the starting cathode, and the potential of the latter rises. About 0.7 μsec. later the arc strikes on the mercury, and the starting cathode potential drops nearly to the cathode potential (zero), remaining at this value while the discharge continues, and afterwards so long as the anode is negative. When the anode becomes positive the starting cathode potential also rises until deionization in the inter-electrode space is complete, when it falls again to zero.

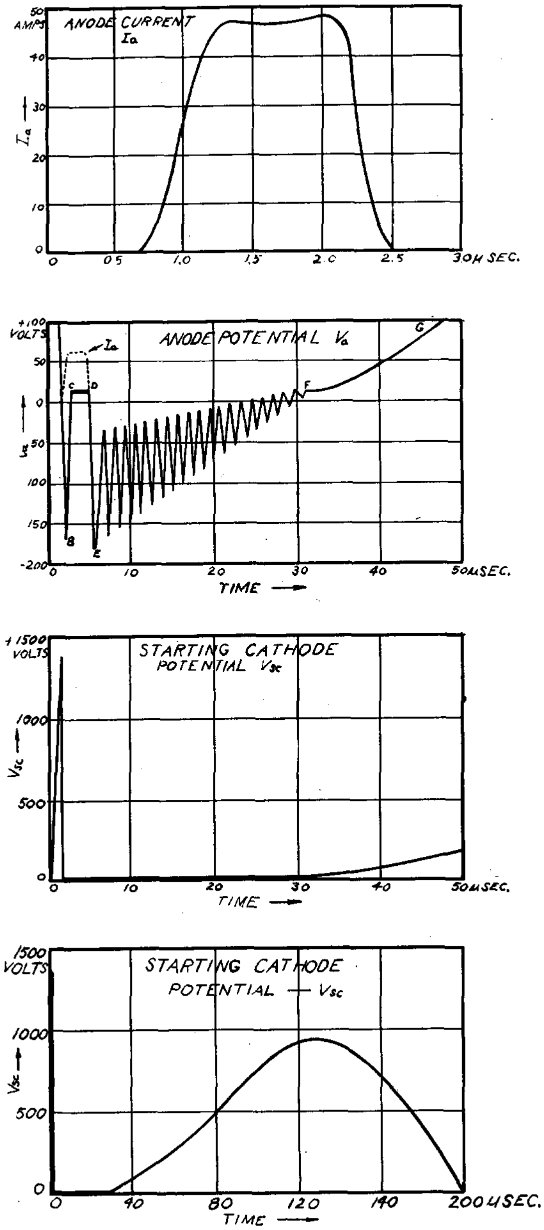

FIG. 6. Oscillograph traces of tube current, anode potential, and starting cathode potential.

It was observed that on first operating new tubes of this type the arc spot at first formed on

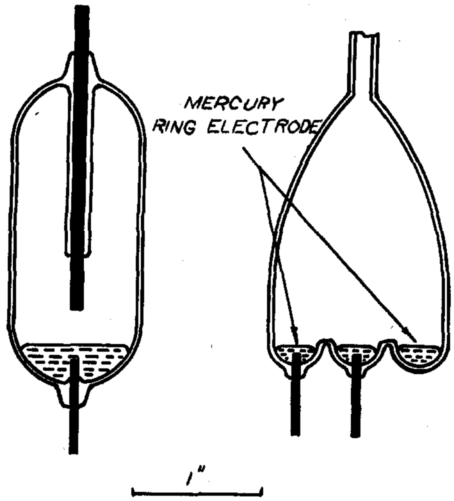

FIG. 7. Tubes with electrodes other than coaxial cylinders.

the free surface of the mercury pool, then formed only with difficulty until (after about 10 minutes) the mercury had begun to wet the glass; the spot then formed regularly at the meniscus.

Other Mercury Pool Tubes

During work leading up to the design of the tube just described, it was found that discharges could be initiated between electrodes whose geometry differed widely from the concentric cylindrical types and the configurations used by Penning.[4,5] Some examples are shown in Fig. 7, all of which required a permanent gas in addition to mercury vapor for operation at room temperature and were thus subject to clean-up troubles.

5. INTERRUPTION OF CURRENTS BY REMOVAL OF THE MAGNETIC FIELD

The general features of the glow discharge initiated by a magnetic field have been discussed in Section 3. It was found that, so long as the discharge did not pass into an arc, reduction of the magnetic field below the critical value interrupted the current through the tube, causing it to fall to a negligibly small value in less than one microsecond. Once the arc had been formed, however, removal of the magnetic field caused no change in the tube current, which continued to flow until the condensers were discharged.

Some attention was given to the production of a tube which would switch moderate or heavy currents off as well as on. It will be seen that the chief problem involved in this was to prevent the transition of the discharge from a glow to an arc. Concentric cylinder two-electrode tubes were used, and to prevent arc formation it was found necessary to keep the supply below about 3000 volts; this limit did not depend much on the current. Currents up to 50 amperes were interrupted in this way.

It is possible that in a tube with a large cathode area, containing a gas such as nitrogen, which has a large normal cathode current density, large currents could be switched on and off, passing with a few hundred volts drop across the tube. A cold cathode tube might thus be obtained which would do what is now only done with difficulty by high vacuum hot-cathode tubes.

We wish to acknowledge the extensive cooperation and help of Professor V. A. Bailey, the C.S.I.R. Radiophysics Laboratory, Sydney, and of Professor L. H. Martin, L. G. Parry, and W. R. Watson. While this work was being carried out, one of us (J.M.S.) was a holder of a Commonwealth Research Fellowship and another (K.R.M.) was employed by the Radiophysics Laboratory.