A NEW METHOD FOR SWITCHING OFF A MERCURY ARC

by

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Abstract

Continuous current control, so familiar in the operation of high-vacuum tubes, has not been possible, except under special circumstances, for gas tubes. Even current interruption has been awkward, except for low currents, for the usual manner of interrupting the current is to decrease the anode potential to zero. The time to switch off the gas tube has been of the order of the deionization time for the gas employed. Now a method is developed for switching off mercury-pool arcs using a third electrode. There is no interference with the main power circuit and, in fact, the potential on the anode causing the electric field aids the dispersal of the charge carriers when the arc has been interrupted. The switching-off time is much decreased because this anode-to-cathode voltage sweeps all the charge carriers out of the tube. Switching off is effected by passing a reverse current of equal or greater magnitude than the arc cathode current through the tube for a time long enough to interrupt the cathode spot. A technical difficulty arises in that the third electrode introducing the reverse current has to have an already formed or an easily formed cathode spot since this third electrode is a cold cathode. Many methods for forming the cathode spot are discussed. The method finally used is probably not the best one but it has the virtue of being easily effected. There appears to be no limit as to the current that can be interrupted if the spot-forming mechanism is altered. Energy used in not an important factor. The amount varies with the time to switch off and does not influence the actual switching process.

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List of Symbols

a = ammeter

A = connecting point, switch circuit

A_s = screen-grid surface area

B = connecting point, switch circuit

C = switching-off capacitor

D = a function of tube geometry

E = connecting point, switch circuit

f = (aperture diameter) ÷ (focal length)

G_A = generator, 100 volts, auxiliary arc

G_1 = generator, 120 volts

G_2 = generator, 100 volts

G_3 = generator, 140 volts

GND = connecting point, switch circuit; = ground

I = arc current

I_A = auxiliary-arc current

I_a = anode current

I_k = cathode current

I_s = switch current

$(I_s)_m$ = peak switch current

J_p = ion current-density

k = Boltzmann's constant

m_e = electronic mass

m_p = ionic mass

M = atomic-mass ratio

N = random-ion concentration

q_p = electronic or ionic charge

Q_s = switching-off charge

$\frac{dQ_s}{dt}$ = rate of change of switching-off charge

r = total resistance in the switching network

r_G = measuring resistor, anode current, 2.1 ohms

r_k = measuring resistor, cathode current, 1.0 ohm

r_p = plasma-edge radius of the sheath

r_r = probe-edge radius of the sheath

r_s = charging resistor, switch circuit, 27,000 ohms

R = switching-off resistor

R_a = arc resistance, anode to cathode

R_A = current limiting rheostat, auxiliary arc

R_G = current limiting rheostat, arc

R_p = plasma resistance, anode to switch probe

t = time

T_p = random-ion temperature

v = voltmeter

v_p = ion thermal-velocity

V = potential difference, anode to cathode

V_s = switching-off voltage

Z = an impedance function

Z_1 = an impedance function

Z_2 = an impedance function

β = a function of r_p and r_r

γ = relay contact, anode current

δ = relay contact, ignition bond

ϵ_o = permitivity for free space

ζ = relay contact, spark-coil primary

η = relay contact, spot formation

θ = relay contact, sopt formation

ξ = relay contact, switch current

σ = relay contact, spark-coil primary

τ_a = switching-off time, anode current

τ_d = deionization time of the plasma

τ_f = minimum spot-interruption time

τ_k = switching-off time, cathode current

τ_s = switching-off time, switch current

ω = relay contact, auxiliary-arc current

A NEW METHOD FOR SWITCHING OFF A MERCURY ARC

1. Introduction

In a high-vacuum thermionic tube there are only electrons present. These electrons travel along the electric-force lines across the tube to the anode when a positive voltage is applied to the anode. Because the current is due to particles of one sign only, a negative space charge is always present and the repulsive forces on the electrons about to leave the cathode limit the current. The current flow can be prevented, and may be interrupted at any time, by making a grid in the tube sufficiently negative. Continuous current control is quite usual.

In a gas tube, on the other hand, the electrons present make collisions with the gas molecules on application of a positive voltage to the anode. The electrons, therefore, although drifting towards the anode, no longer move along the electric-force lines across the tube. If the anode voltage is sufficiently positive, ionization of the gas molecules occurs and the positive ions formed largely neutralize the negative space charge. The voltage drop due to space charge is then much less than in a corresponding high-vacuum tube. The current flow can be prevented by applying a negative voltage to a grid, but because of the presence of positive ions the tube cannot normally be extinguished in the same manner. Continuous current control is not possible except for specially-constructed tubes and then only at low currents (26).

The grid preventing conduction in the gas tube is placed between the anode and the cathode. When the tube is in the non-conducting state a negative grid voltage prevents the electrons from entering the anode-grid region where they would be accelerated to the energy required to cause ionization and produce breakdown of the tube. The ignition condition may be reached by bringing the grid to a more positive value. When the tube is conducting, the grid does not exert any further control. The reason for this is that if; for example, the grid is again made negative, positive ions are attracted to it and electrons are repelled so that a positive-ion space charge forms around the grid. This positive space charge effectively neutralizes the negative grid voltage so that the plasma outside the sheath is unaffected. Similarly, if the grid is made positive with respect to the cathode, a negative space-charge is formed. Thus, once conduction has started, the grid voltage has very little effect on the current flowing between the anode and cathode. The current can only be interrupted by reducing the anode voltage to zero. Once this is done, a negative grid voltage again prevents conduction. This is a severe limitation to the use of gas tubes, particularly at high powers, but many techniques have been devised to obviate the difficulty.

Some attempts have been made to cause current interruption in gas tubes by extending the space charge around the grid to close off completely the anode-grid region from the grid-cathode region. Because of the large negative grid voltage required and the resulting high grid current this method, in general, can only be used at low currents (2) or under particular conditions of pressure, geometry, and gas (1). This has been confirmed by the author using a specially-constructed tube.

In the present investigation, a technique has been developed for switching out mercury-pool arcs using a third electrode. The method is simple and reliable and involves no interference with the main circuit, current interruption is effected with the full anode voltage still applied. The method has the additional advantage of reducing the deionization time by a considerable factor.

The first part of the thesis, Part A, deals with the development of the above technique and forms the main part of the work. Experiments performed using the space-charge-sheath method of switching off are described in Part B.

Part A. The Mercury-pool Tube

The mercury-pool tube was operated in the arc region of the characteristic curve for gas-discharge tubes. The current was high and the voltage across the tube was low.

2. Apparatus

Some of the physical measurements of the mercury-pool tube and various features of the associated curcuitry and connections are described below.

2.1. The Tube

The tube was a mercury-pool type of simple design containing two mercury pools, see Figure 2.1. The three probes and the connections to the anode and cathode, of 0.75-mm radius, projected from 0.6 to 1.4 cm into the tube. These probes were of tungsten and were sealed into the 0.40-in.-thick pyrex-glass walls. The double-probe tungsten electrodes, of 0.75-mm diameter, were covered by a thin glass insulating layer to within 0.3 cm of the ends which projected along the centre line in the opposite direction to the normal-current flow. They were spaced 0.28 cm apart. The large main channel was of $\frac{7}{8}$-in. diameter and the connecting channel was of $\frac{1}{6}$-in. diameter. For an idea of the overall size of the tube and the length of the discharge path see the dimensions in the figure. About 27 ml of distilled mercury filled both the anode and cathode pools.

The connecting channel was for convenience in replenishing the anode pool from the cathode pool since the positive mercury-ion charge-carriers gradually filled the cathode pool as they condensed. The double probe, incorporated to make electron temperature and other measurements, was eventually employed for switching off. The probes were to be used either

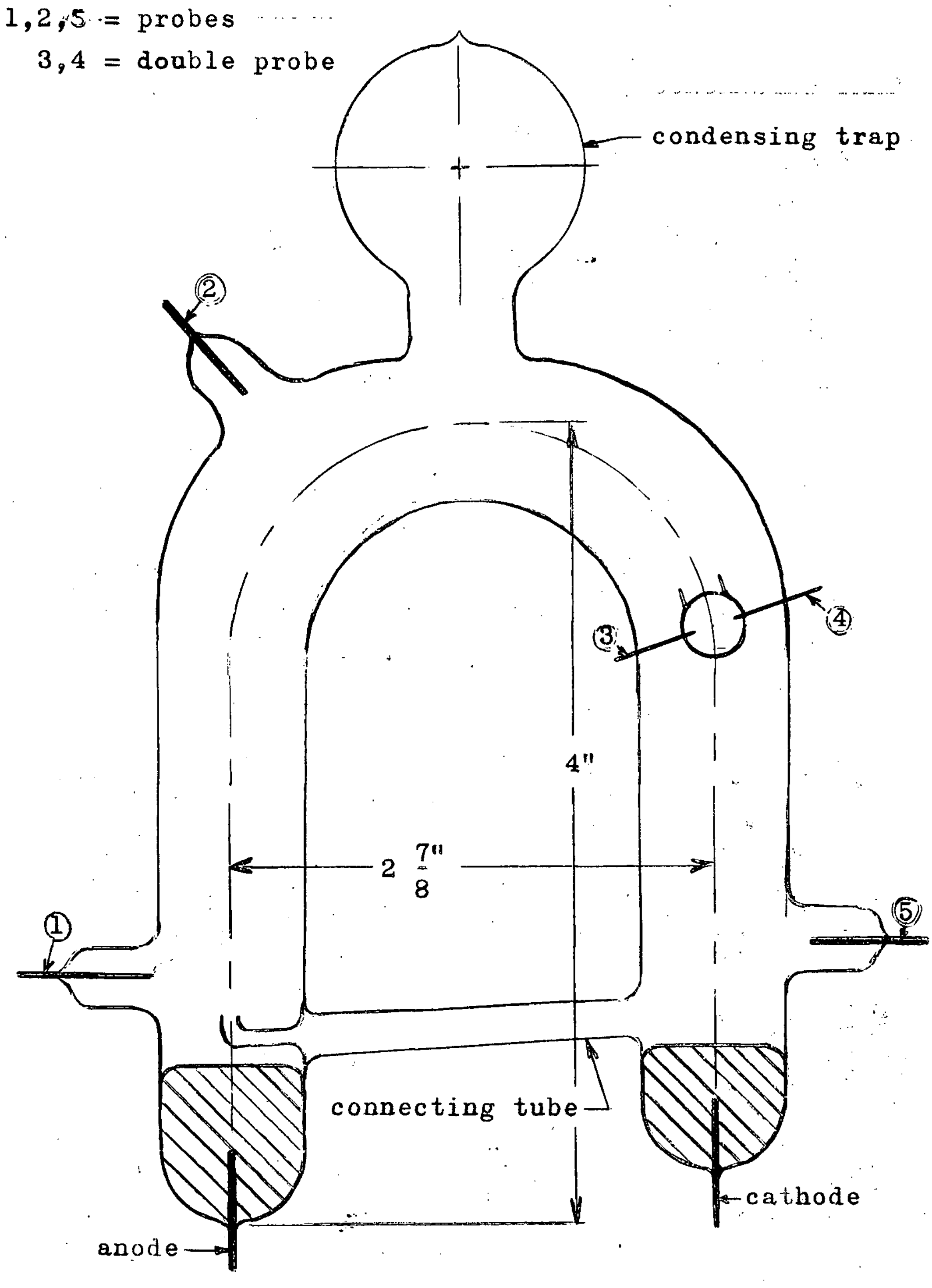


Figure 2.1. The Mercury-pool Tube

for switching off or for obtaining measurements.

Structural changes were made several times and a photograph of the finally modified tube is shown in Figure 8.2.

2.2. The Ignition Method

Thermionic, cold-cathode, and mercury-pool gas tubes are switched on in a variety of ways. A method similar to that for igniting Cooper Hewitt mercury-vapour lamps (3, 5) was used here. The output from a high-voltage spark-coil was applied to a band placed outside the tube at the cathode (7) as shown in Figure 2.2. Most of the potential drop was in the mercury-meniscus-to-glass gap, since glass has a high relative dielectric constant, 5.4 - 9.9 (34). The free electrons from the cathode, produced by the electric field, started ionization when they were accelerated by the positive voltage on the anode,

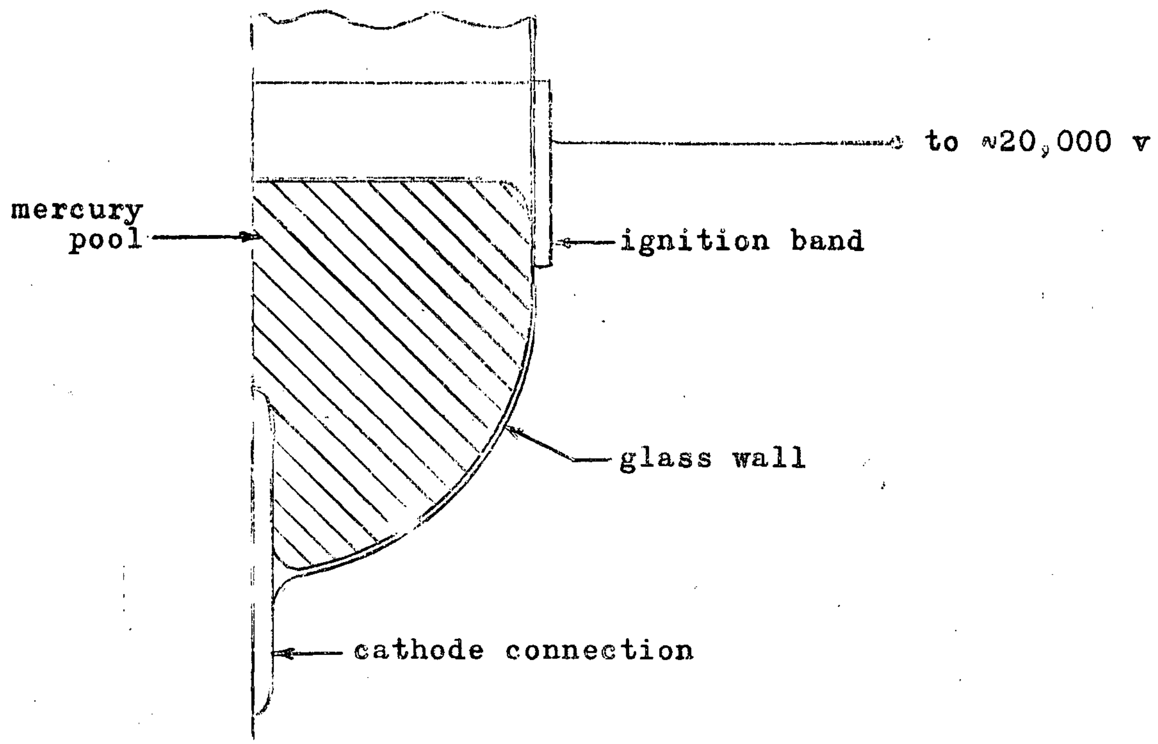


Figure 2.2. A Sectional View of the Cathode

an arc ignited and the cathode spot was formed. Once the electrons were produced, breakdown occurred almost instantaneously, see also Section 5.2.1.

2.3. Variation of Pressure

Initially, the tube was completely sealed and the pressure was $\sim(10)^{-3}$ mm Hg. Then, varying the pressure by changing the temperature (39) would have given different experimental conditions. Accordingly, an enclosure for the tube was built and heaters installed, but a uniform temperature could not be easily maintained due to the air convection streams. It was uncertain that the lowest temperature of the tube was being measured. Finding the position in the enclosure of this lowest temperature would have been difficult, but this temperature value was important since it determined the pressure. As the discharge operated, the overall temperature of the tube increased because of kinetic-energy heating losses, the pressure would then increase, and the arc would extinguish. Heating was discontinued because of these limitations and the tube was redesigned so that a pump, to eliminate the temperature dependence, and a pressure gauge could be installed.

Heating would have been an advantage if it could be ensured that the pools stayed at the lowest temperature. Mercury vapour condenses at the position of lowest temperature in the tube. An unwanted conducting path could be caused by the condensed mercury if the lowest temperature were at the walls. Current would flow along the glass surfaces and the breakdown voltage would be increased to create an ignition problem. Such a condition actually happened, see Section 6.4.

An oil-filled rotary fore-pump connected to a mercury diffusion-pump was chosen for the pumping system. The fore pump was of a standard type; the diffusion-pump design was also quite standard, it had a 365-watt heater and a maximum backing-pressure rating of 0.3 mm Hg. Pumping was continuous on most of the tests made.

3. Initial Attempts to Switch Off

3.1. Extension of the Space Charge

The first attempt at switching off the mercury-pool tube was by biassing a probe negatively. Extending the space-charge sheath across the main channel by application of a high voltage on a probe was an obvious method of trying to cause conduction to cease. Electrons coming from the cathode would not pass through the grid sheath and no further ionization would result. The accelerating potential on the anode would sweep the existing charge carriers out of the anode-grid region. The positive ions would disperse in the grid-cathode region and the current would cease. No influence of the anode would be felt in the grid-cathode region. Biassing a probe positively would have had no interrupting effect since ionization would probably have been aided, not stopped, and the probe would take over as the anode.

Since the current to the probe circuit, supplied by the plasma, is limited by the space charge surrounding the probe, it follows the Child-Langmuir $\frac{3}{2}$-power law (13, 28):

$$J_p = \frac{4}{9}\varepsilon_o\left(\frac{2q_p}{m_p}\right)^{\frac{1}{2}}\frac{V_s^{\frac{3}{2}}}{D^2}. \tag{3.1}$$

In this notation: J_p is the ion-current density; ε_o is the permitivity for free space, $\frac{1}{4\pi 9(10)^9}$ farad/meter; q_p is the electronic or ionic charge, $1.6(10)^{-19}$ coulomb/particle; m_p is the mass of the ion; V_s is the potential difference across the sheath; and D is a quantity which depends on the geometry of the tube. The mass of the ion is calculated from:

$$m_p = 1840Mm_e, \tag{3.2}$$

where: M is the atomic-mass ratio (oxygen is 16); and m_e is the electronic mass, $9.11(10)^{-31}$ kg.

Preliminary calculations were made using cylindrical geometry. Then (28, 29):

$$D = r_p \beta, \tag{3.3}$$

and:
$$\beta = \ln\frac{r_p}{r_r} - \frac{2}{5}\left(\ln\frac{r_p}{r_r}\right)^2 + \frac{11}{120}\left(\ln\frac{r_p}{r_r}\right)^3 - \frac{47}{3300}\left(\ln\frac{r_p}{r_r}\right)^4 + \ldots, \tag{3.4}$$

where: r_p is the plasma-edge radius, and r_r the probe-edge radius of the space-charge sheath. The values used were: M = 201 for mercury vapour; and $J_p = 1$ ma/cm^2, a typical value for the random-ion current-density for mercury vapour (21, 27). See Section 2.1 for the geometry measurements. Since $\frac{r_p}{r_r} = 29.6$, β^2 was taken as 1.09 (29). Therefore, the switching voltage, found from:

$$V_s^{\frac{3}{2}} = \frac{r_p{}^2 \beta^2 M^{\frac{1}{2}} J_p}{5.43(10)^{-8}}, \qquad \text{from (3.1)}$$

was 12,500 volts. Also, using a value of $\sim$0.48 cm^2 for the surface area of a typical probe, the power requirement of the V_s power-supply was found to be 6 watts.

The calculation of V_s was not entirely valid. It was assumed that just extending the space-charge sheath from the end of a probe to the glass wall opposite would be all that was needed to close off the tube. The resulting sheath would be thick along the intersection of the main-channel and probe centre-lines, but would be thin towards the wall in a direction mutually perpendicular to these centre lines. In other words, even higher voltage would probably be necessary to close off the tube with certainty. The critical parameters, J_p and r_p, were difficult to estimate correctly. Because the calculation was only for order-of-magnitude, the limitations were not explored further.

The circuit was connected as shown in Figure 3.1. The arc circuit consisted of the generator, G_1, producing 120 volts; the rheostat, R_G; and the tube. When the discharge was running, the anode-to-cathode potential-difference, V, was 23 volts. Once conduction had started, the current was limited only by the impedance, in this case R_G, in series with the anode. The probe-voltage power-supply, V_s, was connected to the various probes: 1, 2, and/or 5. Probe voltages of up to -1,400 volts, with respect to the cathode, were tested, but the tube did not switch off, as was expected from the preliminary calculations. Note that the negative voltage with respect to the plasma was actually the switching-off voltage value. No distinction has been made between the power supply, V_s, and the switching voltage, V_s, although this becomes significant later, see Part B.

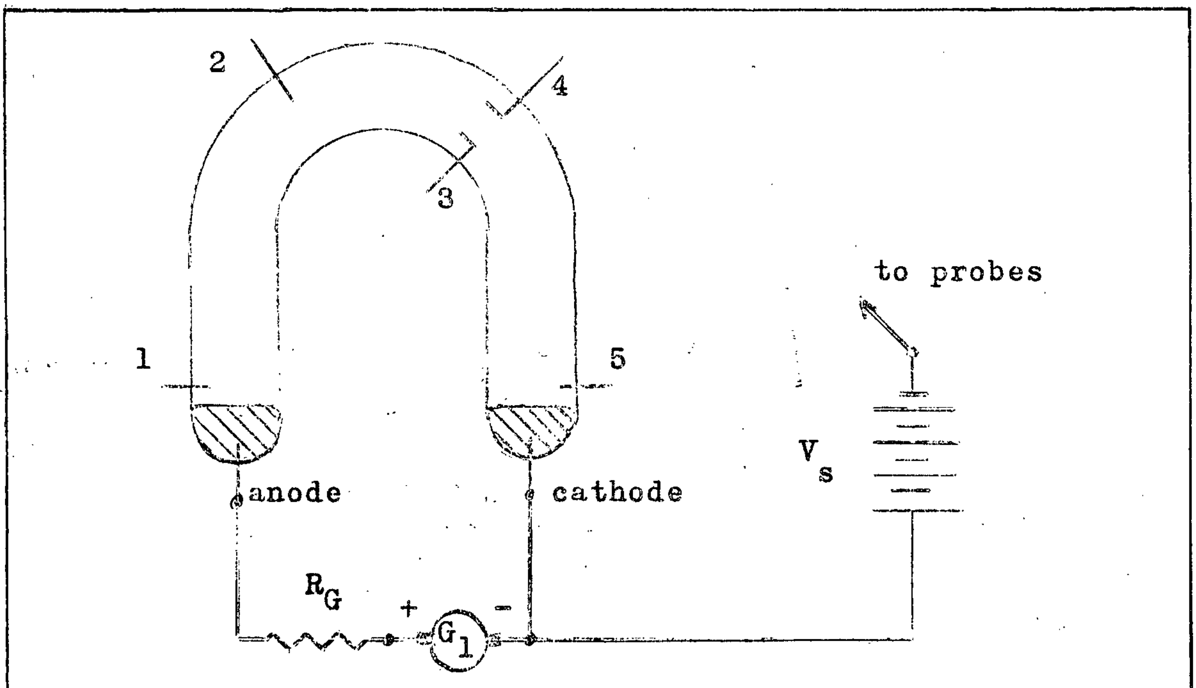


Figure 3.1. The First Switching-off Method

Because the voltage necessary to interrupt the current by extending the probe sheath would be so large, >12,500 volts by calculation, the method was discarded. The calculated power required, however, was not a limitation on the method. The actual energy employed would depend on how quickly the discharge was extinguished. It was thought the tube would switch quite quickly and the energy used then would be small. If a screen-like grid were to be employed with very small holes in it, the switching-off voltage could probably be reduced very markedly.

3.2. Use of a Strap

An attempt was next made at switching off the mercury-pool tube in a similar manner to that employed for ignition.

A strap outside the tube was placed below the double-probe position. The circuit was the same as in Figure 3.1 except that the power supply, V_s, was connected to the strap. Voltages up to 1,400 volts, positive and negative with respect to the cathode, were applied. The tube did not switch off.

The voltage was again probably too low. However, there is doubt whether increasing the voltage would be any more successful, see Section 5.1.2, and, in any event, using a larger voltage would not be practical.

Note that, if a strap of $\frac{7}{16}$-in. diameter were placed inside the tube and the space-charge-sheath method were to be used, the V_s calculated value to switch off would be decreased to -4,800 volts. This switching-off voltage was still large, but the advantage of a suitable electrode construction was apparent, see Part B for further details.

3.3. Use of a Capacitor

The previous methods had not worked at low voltages and would be, at best, not practical when the voltage was increased. Perhaps an entirely different method of switching off the mercury-pool tube by using pulses of current rather than the steady space-charge method would be practicable. Pulse amplitude could be double the value used in the steady-state experiment and still the average-power requirement would be the same or less depending on the pulse-recurrence-frequency.

An obvious way of obtaining a short current pulse is by discharging a capacitor. Accordingly, capacitors were connected to the discharge by either or all of the probes: 1, 2, and/or 5. The circuit is shown in Figure 3.2. The arc circuit consisted of the generator, G_2, providing 100 volts; the current-limiting rheostat, R_G; the ammeter, a; the voltmeter, v; and the tube. In the switching-off circuit were the power

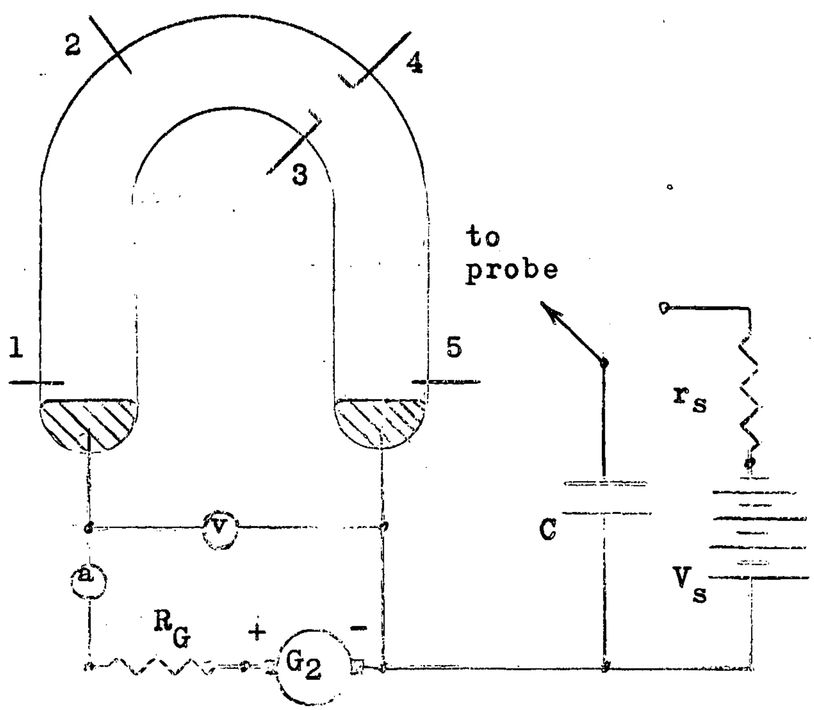


Figure 3.2. Capacitor Switching on a Solid Probe

supply, V_s, the charging resistor, r_s, 27,000 ohms; the capacitor, C; and the tube. Capacitor values of 0.25 to 15 microfarads were tried. The capacitors were separately charged, $6 \leqslant r_sC \leqslant 400$ milliseconds, and then connected to a probe. Various V_s values to a maximum of 1,400 volts, positive and negative with respect to the cathode, were tried. The arc current, I, was ~2.5 amperes.

With the largest capacitor and various negative switching-off voltages, the arc could be extinguished sometimes, but with a smaller capacitor current interruption did not occur. Positive charging of the capacitor, C, caused the arc to switch off only very occasionally when C was connected. Placing a resistor, R, in series with the capacitor increased the switching-off probability for negative switching-off voltages only. Charging the capacitor negatively was a procedure that worked often enough to warrent studying further.

A test made to determine the optimum switching-off voltage for various resistors with constant arc current gave inconclusive results. There were two reasons for this. First, the arc current was ~2.5 amperes. This value was below that of three amperes usually quoted as the minimum for cathode-spot stability on a mercury surface (14). Thus, the arc sometimes extinguished of its own accord even though conditions were not conducive to switching off. This possibly explained why switching occasionally happened when positive pulses were employed. Second, in order to feed a negative pulse from the probe to the cathode, a spot had to be formed at the probe. In other words, the switching-off pulse had to have its own cathode spot. The conditions for cathode-spot formation were not the same on each switching attempt, sometimes the spot would not form, either the capacitor slowly discharged or did not change at all, and switching off was not effected. Earlier switching successes caused sputtering of the electrode material so that the probe surface was continually changing.

The important result was that a current at the cathode in the opposite direction to that of the normal current flow forced arc-current interruption. Establishing this reverse current required establishing a cathode spot on the electrode introducing the pulse. Conditions necessary for formation of a cathode spot and more data collected to isolate the reasons for arc-current interruption are given below.

4. Cathode-spot Formation

Discharges are classified by examining the cathode region. In an arc, the cathode has a fall of potential of the order of the minimum ionizing potential of the gas, a very high current density, and the emitted light shows the spectrum of the cathode material (17). There are several theories of the functioning of the arc cathode in a cold-cathode tube, they all require somewhat the same conditions for cathode-spot formation.

When the cathode spot did not form on the cold-cathode switching probe, the capacitor sometimes discharged slowly, but most often did not change in electrical conditions, and the arc would not extinguish. The current at which transition takes place from a glow, which probably would be the mode used by the switching pulse without interrupting the current, to an arc switching pulse is not easily predictable. In general, the unstable transition region is between 0.01 and 1.0 ampere (20). Then the reverse current has to be greater than one ampere for a cathode spot to form. Some of the other conditions for spot formation will now be stated.

There are several requirements (10, 12) for cathode-spot formation of a cold cathode. First, low-work-function impurities cause the current density to increase in a local region on the cathode. Adsorbed ion and gas layers also have the same effect. The local temperature then increases and electron emission is enhanced, due to ionization more positive ions are formed and the electric-field strength is increased causing even more electron emission, and so forth. Impurities in the cathode enable steady evaporation to result and the formation and ejection of evaporation droplets which act as charge-carrier recombining surfaces and can cause interruption of the arc is avoided. Second, microscopic irregularities (11) on the cathode surface cause high local electric-field gradients which aid emission. Normally, the electric-field strength is not great enough to cause electron emission and a cathode spot would not form on a very clean and smooth electrode. Note that the local currents have to be small, otherwise the irregularities can not survive the high temperature associated with the spot. Third, if it is assumed that the mechanism forming the spot is thermionic, a low thermal conductivity of the cathode is a help. The high temperature in the first two or three atomic layers must be maintained. Fourth, oxide layers on the electrode result in poor electrical contact between the plasma and the cathode. High electric-field gradients result when the positive ions rest on the oxide insulating layer. Emission is increased then and due to ionization more positive ions are formed increasing the electric field strength and the process continues. Fifth, when the cold cathode is a mercury pool, physical agitation causes transient discontinuities increasing local electric-field strengths and formation of a cathode spot is aided.

Of the conditions just described, the last three may be controlled by design. Physical agitation results in spot formation at random time which is not desired. The tube must be shock mounted to stop the effect of vibrations from ancillary equipment and thus eliminate one cause of random variations in the results. Next, unfortunately, tungsten has a rather high coefficient of thermal conductivity, 1.99 watt/cm-°C at room temperature (36), which makes forming a spot on a probe difficult. This limitation was tolerated.

Several techniques for cathode-spot formation were devised and these are described below. It should be made clear that no attempt was made to determine which theory explained the functioning of the cathode spot. All that was of interest was how to form and maintain a spot.

5. Capacitor Switching

Once it had been discovered that the mercury-arc current was interrupted by a pulse of reverse current, various tests were made on the tube to obtain the necessary and sufficient conditions for switching off.

5.1. The Solid Probes

5.1.1. Natural Irregularities Aid Spot Formation

The first method of attempting to switch off the mercury-pool tube depended on the physical characteristics of the switching-electrode material for establishing a cathode spot.

The same circuit as in Figure 3.2 was employed and more data were taken with the arc current at various values. The independent variables were varied according to Figure 5.1; that is, various R values were chosen for certain switching voltage and arc-current values, and the number of current interruptions were counted for 20 switching attempts. A maximum value of 1,000 volts for the switching voltage, V_s, was tried and the arc current, I, was increased to 10 amperes. Even though the probability of current interruption was not great, certain results could be noted. On examining the graphs it was seen: first, that a higher switching-off voltage gave a greater likelihood of switching; second, that a high arc current caused uncertain switching; and third, that there was a possibility of an optimum value for R.

Again, using the same circuit, more data were collected and these are summarized in Table 5.1. No significance should be given to the particular values of R, V_s, and C used as these values were chosen only to bring about current inter-

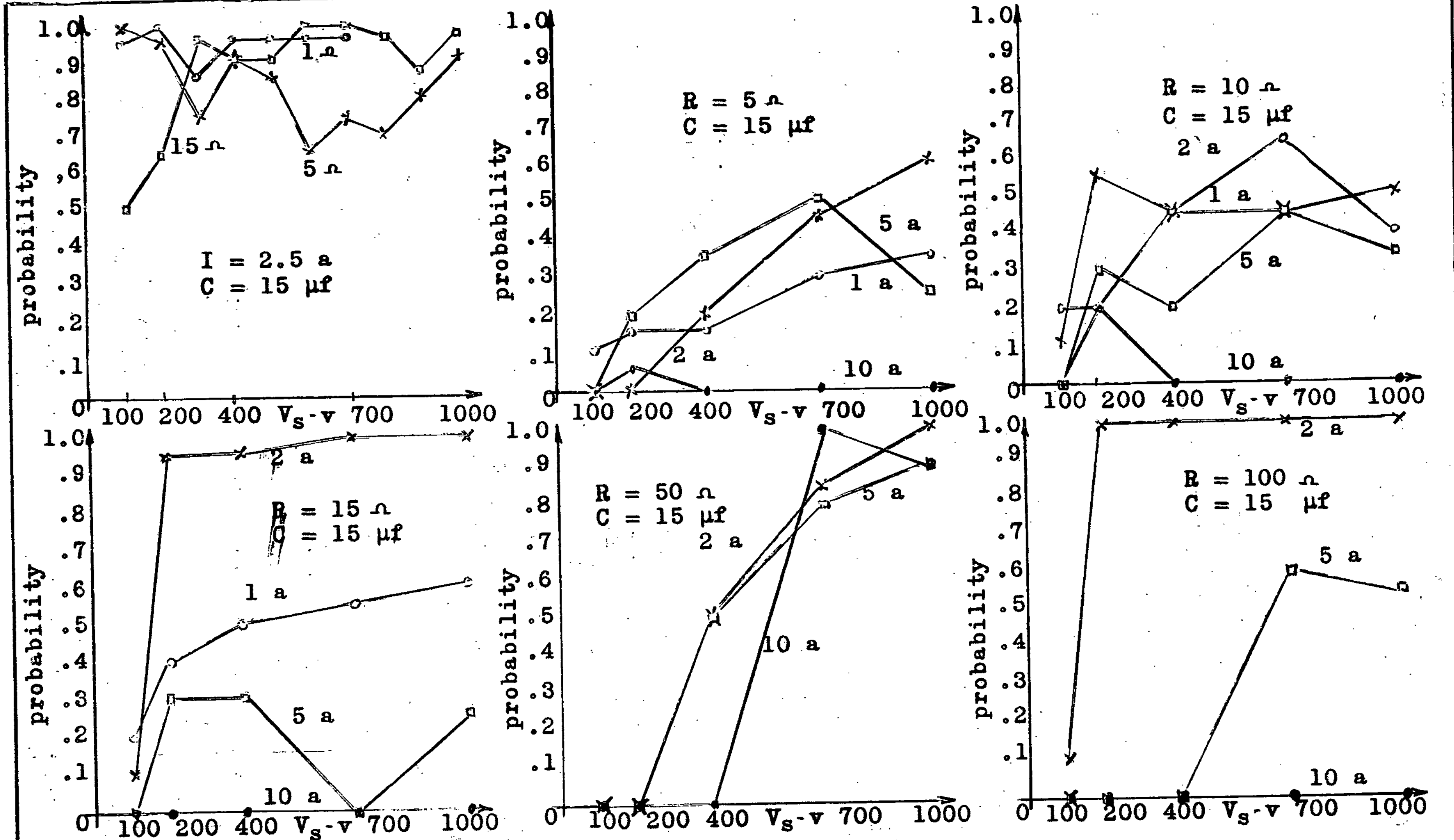


Figure 5.1. Graphs of the Switching-off Probability

Table 5.1. Various Values Important for Switching Off

I - a	R - Ω	C - μf	switch	$(I_s)_m$ - a	τ_s - μs	Q_s - mq	Q_I - mq
1.5	5	15	yes	15.3	91	~1.0	0.7
1.5	5	15	yes	8.2	1400	~1.8	1.0
1.5	10	15	yes	9.4	1350	~2.0	1.0
1.5	10	15	yes	4.0	1900	~1.1	1.4
1.5	15	15	yes	2.1	1960	3.1	1.5
1.5	15	15	yes	4.5	1900	2.2	1.4
1.5	31	19	yes	3.3	2100	~3.0	1.6
1.5	50	15	yes	2.5	2450	~3.1	1.8
1.5	50	15	yes	1.7	2600	~2.5	2.0
1.5	100	19	no	1.1	1400	~1.0	1.1
2.2	5	15	yes	14.7	1300	~3.0	1.4
2.2	10	15	yes	9.1	2100	~4.5	2.3
2.2	15	15	yes	6.7	2400	~4.2	2.6
2.2	31	15	yes	3.6	2300	~2.5	2.5
2.2	100	15	no	1.3	400	~0.4	0.4
5.0	5	15	yes	16.5	360	~2.2	0.9
5.0	5	15	yes	10.6	330	~1.7	0.8
5.0	5	19	yes	21.7	2210	~12.7	5.5
5.0	5	30	yes	17.1	2000	12.0	5.0
5.0	10	15	yes	9.7	420	2.3	1.0
5.0	10	15	yes	7.6	420	~1.7	1.0
5.0	10	19	yes	9.4	1800	~9.9	4.5
5.0	10	30	yes	10.0	1800	~10.0	4.5
5.0	15	15	yes	7.5	540	~2.8	1.4
5.0	15	15	no	5.2	240	~1.0	0.6
5.0	15	19	yes	7.3	1400	~7.1	3.5
5.0	15	30	yes	7.4	1400	~6.0	3.5
5.0	31	15	no	3.3	120	~0.2	0.3
5.0	31	15	no	2.8	480	~0.9	1.2
5.0	50	15	no	2.9	1800	~3.3	4.5
5.0	50	15	no	2.9	1200	~3.1	3.0
5.0	100	15	no	1.3	900	~0.6	2.2

V_s was 700 v except for switching attempts: 1, 3, 5, and 8, when the value was 400 v.

$(I_s)_m$ and τ_s are not very accurate: $\pm 15\%$.

Q_s was obtained by rough calculation of the area under the I_s waveform trace.

Q_I was taken as $\frac{1}{2}I\tau_s$ which will be seen to be greater than the correct value

The tube was continuously pumped.

ruption with a reasonable degree of regularity. It was found from the table that the charge, Q_s, on the capacitor was not an important factor, but $\frac{dQ_s}{dt}$ was. The peak switch current, $(I_s)_m$, had to be greater than the arc current to cause current interruption. The few times switching off occurred when $(I_s)_m$ was not greater than I were dismissed, since I <3.0 amperes on those attempts and would extinguish of its own accord because of instability (14) when any small electrical disturbance was made. With R in series with C, the time to discharge the capacitor, τ_s, increased and, therefore, increased the time $(I_s)_m > I$.

On repeating the switching tests, the probabilities had decreased significantly. This indicated that most of the irregularities on all the probes had been burned off by the high temperature associated with the spot. The probes were now smooth and clean having no irregularities for cathode-spot formation. Probe 5, see Figure 2.1, gave the best control because mercury, splashing from the arc cathode, caused temporary discontinuities aiding the formation of a spot.

A final attempt at using electrode irregularities or contaminating layers for cathode-spot formation was made by connecting all the probes together. The switching-off voltage was applied to the resultant "probe," but no new information was obtained. The switching-off probability remained quite small.

Depending on the microscopic physical irregularities for cathode-spot formation was unsatisfactory. After a few operating cycles, the irregularities were worn smooth and impurities sputtered away so that switching off became random. Provided the cathode spot would form, arc-current interruption would be successful as long as the reverse-current-pulse magnitude was greater than the arc-current value. However, the cathode spot would not form on every switching attempt. This was due to a randomness in the necessary conditions for cathode-spot formation.

5.1.2. Providing the Conditions for Spot Formation

Some method of ensuring that a cathode spot would always be formed when V_s was applied had to be found.

The first way of increasing the probability of switching was by introducing air into the tube. The tungsten probes, contaminated very quickly by a new oxide layer, again had local areas where cathode spots could form. However, the increase in switching probability proved to be only temporary. The oxide layers were worn away too quickly. In any event, the procedure was not practical, periodic opening and closing the tube stop-cock and repumping was clumsy.

It was then remembered that one of the solid probes had given slightly better performance because splashing mercury had provided temporary discontinuities upon which spots could form. Since the double probe, electrodes 3 and 4 in Figure 2.1, was in the discharge path, it was hoped the mercury ions would condense easily on the electrodes, cause discontinuities, and aid spot formation. The fact that the double probe was in a region of high ion concentration (the probes employed previously were out of the direct discharge path) would also help spot formation. Operation was changed to the double probe and switching off became regular. Unfortunately, a varying delay from about 0.1 millisecond to infinite time, between the application of V_s and the time of establishment of the cathode spot, was measured. The tube would switch off on every attempt provided $(I_s)_m > I$, but the time to actual switching off was random. This delay was probably partly a function of the size of the condensed mercury-vapour particles since it was possible that mercury droplets of a critical size were necessary, with large particles not affecting the electric-field strength and small particles causing the gradient to be small. The delay was probably also dependent on the physical irregularities on the electrodes. As the discharge operated, the overall temperature increased and mercury vapour was less likely to condense at the double-probe position, for the double probe would be no longer at a low temperature. Note that the physical irregularities here still played a role in cathode-spot formation.

The delay had to be eliminated. It was decided to try forming a spot by sparking between each electrode on the double probe. If the time of sparking could be controlled, the time of current interruption could also be controlled. The breakdown voltage was 250 volts without the discharge. When the arc was running, the voltage was increased to greater than 450 volts and still no local breakdown occurred between the two electrodes. This was because a space-charge sheath, the same as described in Section 3.1, surrounded the electrodes isolating the voltage applied and the plasma. These electrodes were too far apart on the double probe to make extending the sheath practical since the voltage would have to be increased greatly.

During the tests, one of the double-probe electrodes completely sputtered away. The surface area available for condensed-mercury-vapour deposits was decreased and the switching-off probability also decreased. This, and the fact that the delay-time problem was not solved caused abandonment of the mothod.

In another attempt to force spot formation, the switching electrode again was made a probe. The high-voltage spark coil, also employed for ignition, was connected to a strap placed in turn around the various probes outside the tube. A spot did not form on any probe on application of the strap voltage because the current from the spark coil would take the discharge as a conducting path to the cathode to ground. No influence on spot formation was felt at the probes.

5.1.3. Comments on Solid-probe Switching

The tube could be switched off by using any solid probe, but the performance was erratic. The characteristics of the solid-electrode material determined the action. The physical variations at the switching-off electrode were the main reason for the randomness of current interruption; for example, the probes were always becoming smoother leaving no irregularities upon which a cathode spot could be initiated. Creating an oxide layer on the probes aided spot formation, but the layer was quickly worn away and the irregularities again caused the random behaviour.

Depending on mercury-vapour condensation to provide discontinuities gave results that also were random. The exact cause of the randomness was not known. Condensation effects and physical-irregularity wear probably each played a part. The double probe was not much better than the single probes for switching off.

It was clearly demonstrated, however, that once the cathode spot was established and the electrical condition fulfilled, switching-off would ensue.

5.2. The Mercury-pool Probe

It was evident from the above results that the switching delay would be much reduced if a cathode spot could be formed at the switching probe when the switching-off voltage was applied.

5.2.1. Spot Formation by a Band Igniter

One method of spot formation was to employ a mercury pool as the switching electrode and a band igniter to initiate the spot when V_s was applied; that is, a similar technique as used for igniting the arc was devised for initiating a cathode spot at the switching pool.

The new circuit is in Figure 5.2. Probe 2 was made the arc anode and the former mercury-pool anode became the

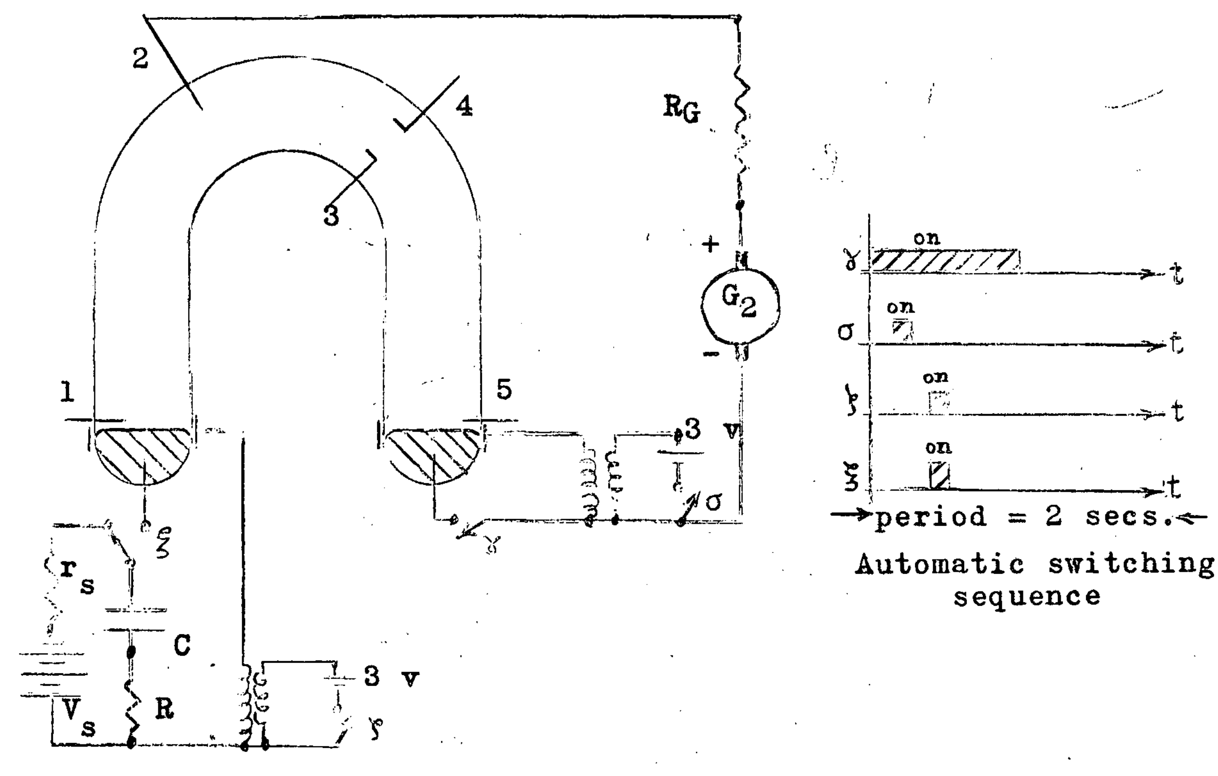


Figure 5.2. Cathode-spot Initiation by a Band Igniter

switching-off electrode. A second band was placed around this pool and a second high voltage spark coil was provided to initiate the switching-off cathode-spot. The other connections remained the same.

Minor modifications to the circuit were made to facilitate the automatic control of the operating cycle. An automatic switching sequence was constructed to prevent over-heating of the anode which was now a tungsten probe. The period of operation lasted two seconds. If the tube did not switch off, the maximum conduction time, controlled by relay γ, was one second; when switching occurred, the conduction time was 200 milliseconds. Care was taken to ensure that relays: γ, β, ξ, and σ, opened and closed in the proper order. The closing of relay ξ determined the time of application of V_s. The relay operating sequence is shown in the figure.

Current interruption was now successful every time when similar circuit values as employed previously were used. The randomness aspect of the problem had been eliminated. However, there was still a delay, much reduced now, of a maximum of ~1 millisecond. This delay was caused by the frequency, ~1 kilocycle/second, of the spark coil. The cathode spot only appeared when the band voltage was sufficiently positive with respect to the switch pool. Since no control was had over the phasing of the band voltage when V_s was applied, the band could be at the correct voltage instantaneously or as much as 1 millisecond later.

The main result obtained was that the switching-off method was sound. Given suitable electrical conditions an arc current could be interrupted regularly.

5.2.2. The Other Attempts at Cathode-spot Formation

The small varying delay between application of V_s and the beginning of the switching-off process when the cathode spot formed was undesirable. Several different techniques were attempted in order to eliminate the delay.

First, the spark-coil igniter was replaced by a Tesla coil. This would not have eliminated the delay time, but would have reduced it to microseconds. Unfortunately, the Tesla coil had too high an internal impedance and not enough useful voltage was available to furnish a spot. The apparatus was discarded.

The contacts on the spark-coil primary were next screwed together in an attempt at providing a "one-shot" pulse. Even though the peak magnitude was probably very great, unreliable operation resulted. The short time duration of the pulse no doubt accounted for the low probability of success.

The band was then grounded in an attempt to have V_s, itself, generate a spot. As was expected, the experiment did not work. The voltage was much too low.

Finally, a capacitor charged to 1,400 volts, positive with respect to the cathode, was applied to the band. The resultant potential difference between the band and the mercury pool could be as much as 1,900 volts depending on the value of V_s. The method was somewhat similar to one already developed (8), but it did not work. Probably the voltage was too small.

Other band-igniter techniques (4) could have been tried as could entirely different methods, such as the ignitron (6) or the excitron (9) methods. All that was required was that the spot be formed immediately the switching-off voltage was applied. However, these procedures require special construction and modifications to the tube. To expedite the research, the manner of furnishing the cathode spot described below was accepted.

5.2.3. An Auxiliary-arc Discharge Provides the Spot

An instantaneous beginning of the current-interruption process on application of the switching voltage was required. The cathode spot had to be available when V_s was applied. One way of establishing this would be to have a permanent cathode spot or at least one that was always present before connecting the capacitor, C.

An auxiliary-arc discharge was ignited to provide the cathode spot. The circuit is in Figure 5.3. The auxiliary

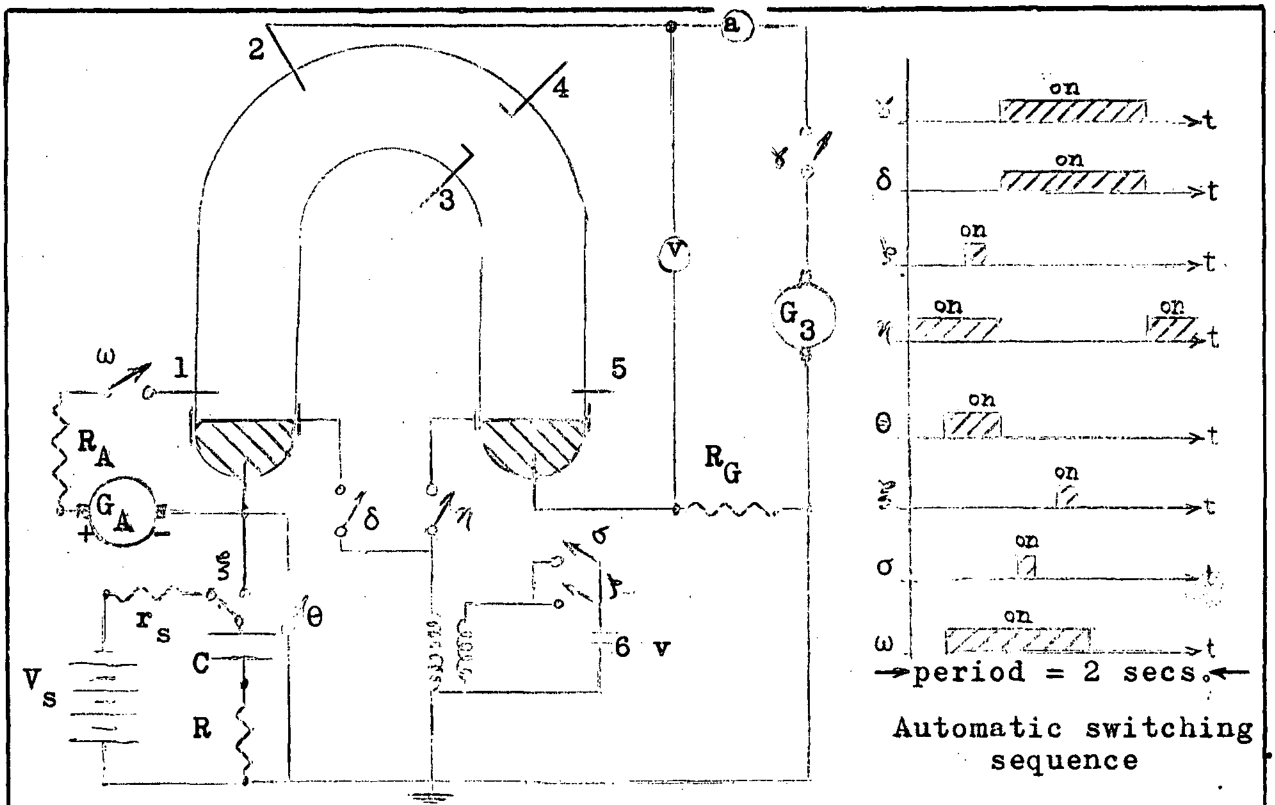


Figure 5.3. An Auxiliary-arc Discharge Provides the Spot

arc connections were to the switch pool, as the auxiliary-arc cathode, and to probe 1, as the auxiliary-arc anode. The rheostat, R_A, was present in order to limit the auxiliary-arc current to ~3 amperes. The generator, G_A, produced 100 volts and the cathode spot was present at the switch pool at all times that the auxiliary-arc discharge was ignited. The switching circuit remained the same as in Figure 5.2. The arc circuit remained similar to previous connections, only R_G was moved to the cathode side of the generator. Having a higher positive potential on the anode, with respect to ground, might increase the switching off probability when there was a greater potential difference between the plasma and the switch pool. The arc circuit values were slightly changed because the generator, G_3, was increased to 140 volts.

Particular attention had to be given to the automatic switching sequence. A relay, θ, connecting the switch pool to ground was necessary to provide a return path for the auxiliary-arc band-igniter-current. This relay had to be disconnected before V_s was applied, via relay ξ, or else a short circuit of V_s would result. Also, the auxiliary-arc band-voltage had to be removed before V_s was applied, to ensure that the influence of the switching-off voltage alone was responsible for current interruption. This was done by opening relay σ. Since only one spark coil was being used, relay sequence was important in order to apply the auxiliary-arc ignition voltage only to the auxiliary-arc band. This was controlled by relays δ and η. No ignition current would then be passed by the low-impedance path provided by the arc already ignited.

The circuit was a success, switching off occurred every time and the reverse-current pulse began to rise immediately V_s was applied; no delay was discovered. The auxiliary-arc discharge apparently did not influence the switching-off circuit behaviour. The method of ensuring certain and almost instantaneous current interruption had been developed. Exhaustive tests were next made to determine the optimum switching conditions.

6. Experimental Difficulties

At various stages of the research, certain experimental difficulties were experienced. Most of these were circumvented in various ways and were not, therefore, too interesting. Other problems, limitations, and curious features of the circuits and apparatus will now be noted.

6.1. The Oscilloscope

There were several problems associated with obtaining accurate waveforms from the oscilloscope. Short persistence of the cathode-ray-tube screen necessitated reading the transient picture very quickly. Accordingly, accuracy suffered on the earlier visual measurements. A wide band oscilloscope was required in order that a correct picture of the signal would be given. A Tektronix Type-531 oscilloscope with a Type-53/54A vertical-amplifier having a 10-megacycle/second pass-band was finally used for all important measurements.

6.2. The Camera

Photographs of certain waveforms at various component and independent variable values were taken. The camera was an Exacta reflex-type having an f-2.8 lens. The film was Kodak Tri-X. The photographs were taken by leaving the camera shutter open for one cycle of the automatic control and the exposures were regulated by varying the oscilloscope trace-intensity and screen-brightness controls.

6.3. The Relays and Contacts

The automatic control sequence was regulated by a motor having mechanical contacts on the rotor. Poor friction contact here and at the relays made frequent repairs and cleaning necessary. This was an equipment cause for the randomness of switching off. The entire randomness problem had to be studied quite carefully to make certain that limitations in the tube were the ultimate cause of randomness and not equipment faults.

Unfortunately, some of the contacts were not rated to control the current or withstand the potential differences required. These contacts then were employed to control other relays which were of higher rating, but which themselves could not be governed by small currents. The reasons for some of the connections in Figure 8.3 should now be apparent.

Arcing at some contacts necessitated placing several relays in oil baths.

Contact chatter occurred in 200 microsecond intervals. It will be seen that the interesting current pulses are finished before the first contact opens because of chatter.

6.4. The Contamination Problem

Due to the sputtering of electrode material and entrance of impurities and oxides, amalgams formed on the tube walls. Occasional attempts were made to have the tube clean itself up by continuously running the discharge between the two pools. This was not effective. Difficulties were met in ignition because of the amalgam near the ignition band (15) and the tube had to be cleaned. The procedure was as follows. Nitric acid was first introduced to clean off any metallic material. Potassium hydroxide was next added to dissolve the amalgam. Repeated cycles of washings with these two chemicals, interspersed with distilled water washings, were carried out to clean thoroughly. A heated sodium hydroxide and methyl alcohol mixture was used to eliminate the stop-cock grease which had entered the tube. Care was taken not to allow this mixture to reach any ground-glass surfaces as these surfaces would be attacked extremely rapidly. Finally, an iron slug was introduced to the tube and the last isolated particles were scraped off by using a magnet to control the slug. After cleaning, operation again became satisfactory.

6.5. The Structural Problem

Twice probe seals cracked due to the stress produced when the probe and glass expanded different amounts because of the high temperature reached when the tube did not switch off. Operating the tube at a nominal value of I, 5.0 amperes, and V, 23 volts, resulted in the probe temperature rising to ~2000 C on these occasions. The temperature is calculable using values easily obtained from handbooks. The glass was then stressed to ~23,000 psi which is in the region of the maximum compressive stress permissible for glass, 20,000 - 50,000 psi (35). Temporary seals of the cracks were made with Glyptal varnish, but both times the glass had to be reworked for final repairs.

6.6. The Connecting-channel Arcs

Sometimes the discharge ignited through the connecting channel. When this happened, the arc which should have ignited around the main channel did not operate. Of course, this only happened when a mercury pool served as the anode. Both arcs would not ignite since two arcs will not work in parallel except at very high currents (23). Since the small-diameter channel was a shorter length path, arcing there must have occurred because of increasing pressure. As the discharge was running the temperature increased, the pressure increased then (39) and the mean-free-path of the electrons decreased (25). This increased the probability of breakdown in the shorter-length path, there could be sufficient collisions for self-maintenance of the arc. Whenever this arcing occurred, the discharge was stopped and the tube allowed to cool. The experiment was resumed after the tube had cooled enough to give normal behaviour.

6.7. The Pumping System

The pumping system had rubber connections throughout, even from the diffusion pump to the tube. These rubber fittings would outgas at $\sim(10)^{-4}$-mm-Hg vapour-pressure (40) making it impossible to attain any lower pressure. Several different oil-filled fore-pumps were used of varying ratings, but did not affect the pressure limit. Pressure gauges used only to detect leaks in the system, were a McLeod gauge (37) and several thermocouple gauges (38).

A mercury-vapour trap was inserted between the diffusion pump and the fore pump. Packing the connection in ice here, prevented, to a certain extent, mercury from contaminating the fore pump.

7. Selecting the Best Connection

Once it was known that the capacitor switching method worked every time as long as a cathode spot was formed, it remained to find the best connection for the switching-current path. The independent variables of interest which would determine the best connection were the time to switch off and the necessary magnitude of the switching voltage.

There were three possibilities for connecting the switching circuit return path. These were obtained, see Figure 7.1, by connecting points A to B to GND; or A to B, E to GND; or A to E to GND. Only the components of the arc and switching circuits, are shown for clarity. The current directions are indicated and distinction is made between arc current, I, and switching current, I_s. Note that the resultant currents into the tube are called cathode current, I_k, and anode current, I_a. Then:

$$I_a = I + Z_1 I_s, \tag{7.1}$$

and:

$$I_k = -I + Z_2 I_s, \tag{7.2}$$

where: Z_1 and Z_2 are functions dependent on the impedance in the circuit.

Estimates of the current waveforms were made in order to better recognise the oscilloscope traces. These are drawn beside the appropriate circuit in the figure. It was seen that only two configurations, A to B to GND and A to E to GND, would be substantially different. Grounding different parts of the circuit would only change dc-voltage levels and, in the case of A to B to GND or A to B, E to GND, the change would probably not be great enough to influence the switching-off probability. The times, τ_a, τ_k, and τ_s, for the three

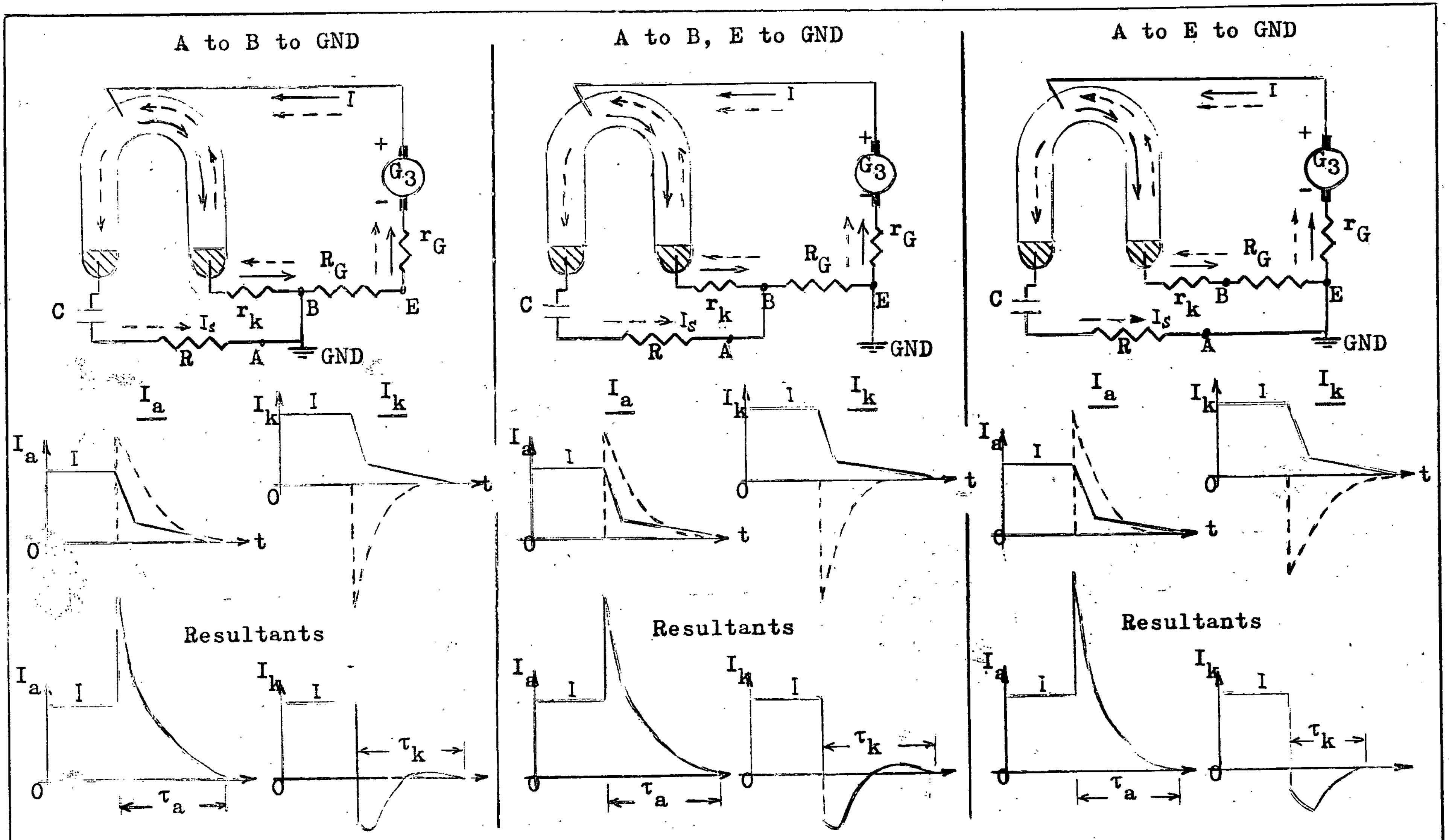


Figure 7.1. The Connections and Current Estimates

currents, I_a, I_k, and I_s, respectively, to decrease to zero would differ for the three configurations. The important switching time for any applications, the time for the anode current to fall to zero, was τ_a.

The connections were tested. Photographs of the waveforms and data obtained are given in Figure 7.2. The parameter values used have no particular significance. They were chosen only to make switching a certainty. Some of the photographs show only the initial rise of the trace. They were included to indicate that the initial part of the waveform was observable. Since the time to switch was approximately the same for the two connections of interest, it did not matter which one was chosen for detailed study. Connection A to B to GND had a smaller resistance path for the component of I_s flowing to the cathode, the major part of I_s would take this path. It was thought then that current interruption would happen at a lower value of V_s for this connection and A to B to GND was chosen for switching.

Legend -applies to all photographs

T. B. = oscilloscope time-base, microseconds/centimeter.

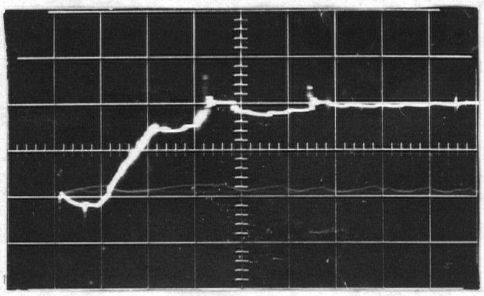
Sens. = oscilloscope sensitivity in the appropriate units.

The large divisions are centimeters, scaled.

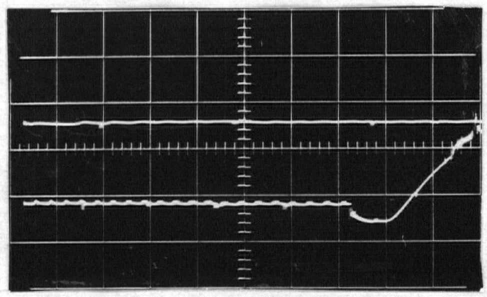
Zero gives x = 0.0 μs and y = ground level.

The positive sense is always towards the top of the picture.

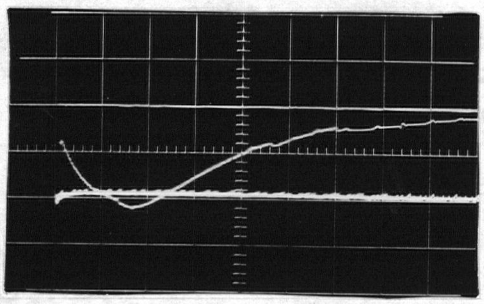
A few pictures have noise and spurious traces present. Since these indications did not obscure the waveform of interest, no attempt was made to eliminate them.



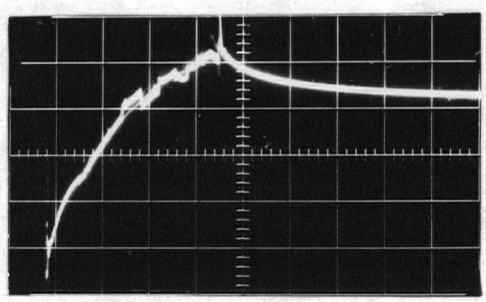
a. I_a - A to B to GND
V_s = 490 v C = 9 μf
R = 4.5 Ω I = 4 a
Zero x =1.1, y = 4.0
T. B. = 200 μs/cm
Sens. = 2.38 a/cm



b. I_a - A to B to GND
V_s = 490 v C = 9 μf
R = 4.5 Ω I = 4 a
Zero x = 0.3, y = 3.6
T. B. = 200 μs/cm
Sens. = 2.38 a/cm

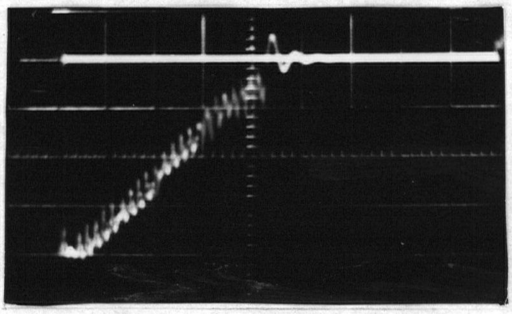


c. I_a - A to B to GND
V_s = 490 v C = 9 μf
R = 4.5 Ω I = 4 a
Zero x = 1.1, y = 4.0
T. B. = 100 μs/cm
Sens. = 2.38 a/cm

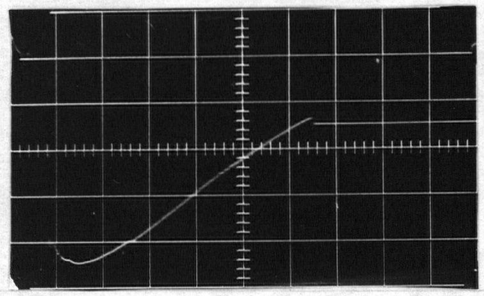


d. I_a - A to B to GND
V_s = 490 v C = 9 μf
R = 5.2 Ω I = 3.5 a
Zero x = 0.8, y = 4.2
T. B. = 200 μs/cm
Sens. = 9.52 a/cm

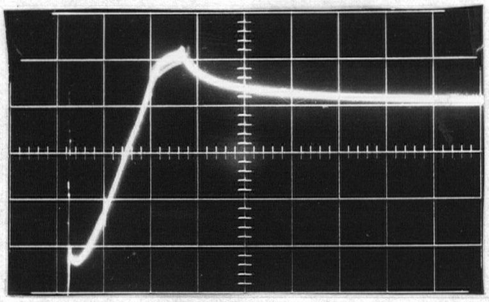
Figure 7.2. Some of the Current and Voltage Waveforms



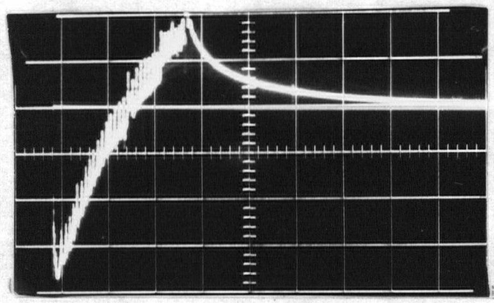
e. I_a - A to B to GND
V_s = 40 v C = 9 µf
R = 5.2 Ω I = 3.5 a
Zero x = 1.1, y = 5.0
T. B. = 100 µs/cm
Sens. = 0.96 a/cm



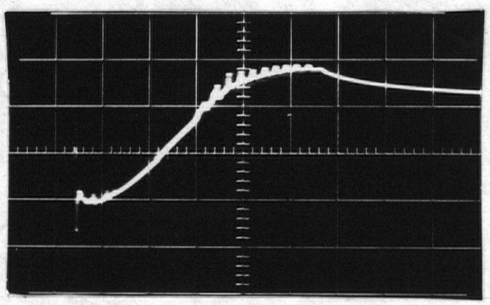
f. I_a - A to E to GND
V_s = 490 v C = 9 µf
R = 4.5 Ω I = 4 a
Zero x = 1.0, y = 3.5
T. B. = 20 µs/cm
Sens. = 4.78 a/cm



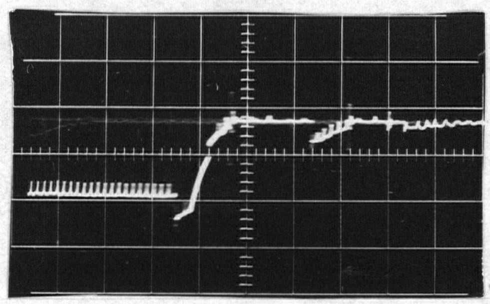
g. I_a - A to E to GND
V_s = 490 v C = 9 µf
R = 5.2 Ω I = 4 a
Zero x = 1.3, y = 4.0
T. B. = 200 µs/cm
Sens. = 11.6 a/cm



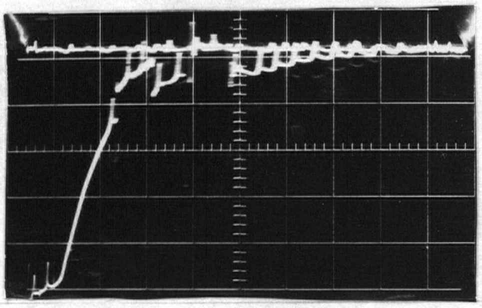
h. I_a - A to E to GND
V_s = 106 v C = 9 µf
R = 5.2 Ω I = 4 a
Zero x = 0.8, y = 4.2
T. B. = 200 µs/cm
Sens. = 2.3 a/cm



j. I_a - A to E to GND
V_s = 150 v C = 9 µf
R = 5.2 Ω I = 4 a
Zero x = 1.4, y = 4.2
T. B. = 100 µs/cm
Sens. = 11.6 a/cm

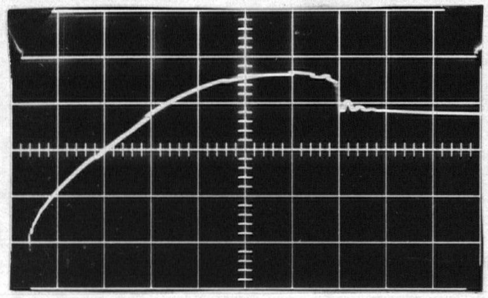


k. V - A to B to GND
V_s = 490 v C = 9 µf
R = 4.5 Ω I = 4 a
Zero x = 0.4, y = 1.5
T. B. = 500 µs/cm
Sens. = 50 v/cm



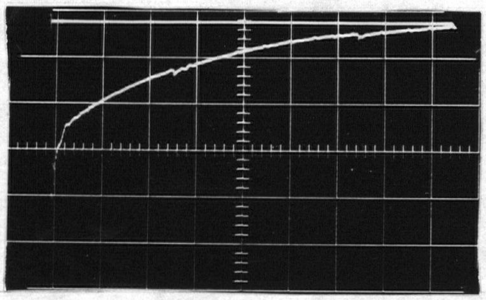
m. V - A to B to GND

V_s = 490 v C = 9 μf
R = 4.5 Ω I = 4 a
Zero x = 0.4, y = 5.2
T. B. = 200 μs/cm
Sens. = 20 v/cm



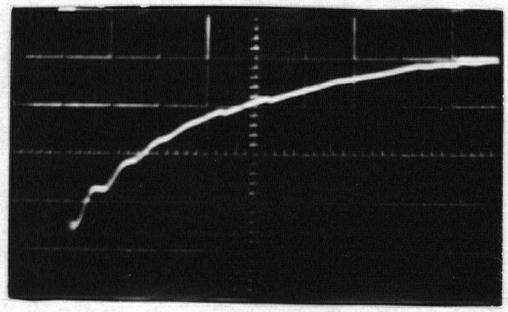
n. V - A to E to GND

V_s = 490 v C = 9 μf
R = 4.5 Ω I = 4 a
Zero x = 0.4, y = 3.2
T. B. = 50 μs/cm
Sens. = 200 v/cm



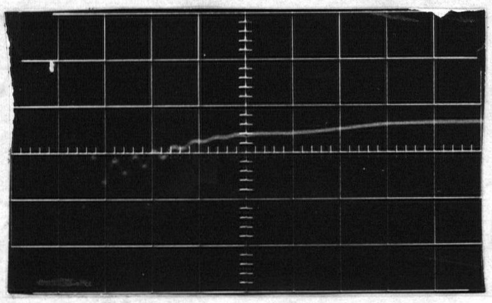
p. I_k - A to B to GND

V_s = 488 v C = 9 μf
R = 5.2 Ω I = 4 a
Zero x = 0.8, y = 5.8
T. B. = 20 μs/cm
Sens. = 23.8 a/cm



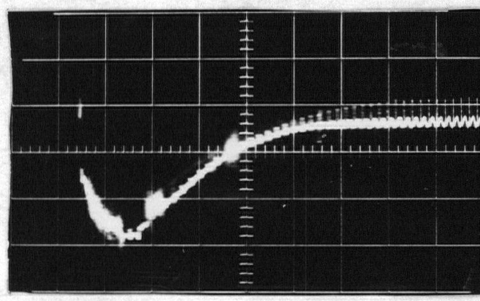
q, A to B to GND - I_k

V_s = 470 v C = 9 μf
R = 5.2 Ω I = 3.5 a
Zero x = 1.0, y = 5.0
T. B. = 20 μs/cm
Sens. = 3.85 a/cm



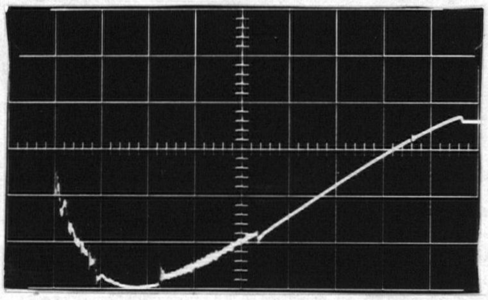
r. I_k - A to B to GND

V_s = 490 v C = 9 μf
R = 5.2 Ω I = 4 a
Zero x = 0.8, y = 4.8
T. B. = 1 μs/cm
Sens. = 47.6 a/cm

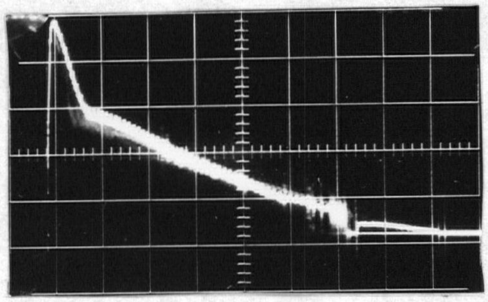


s. I_k - A to E to GND

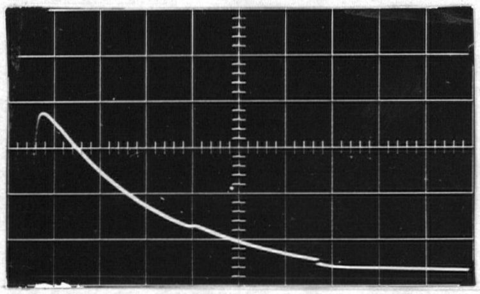
V_s = 95 v C = 9 μf
R = 5.2 Ω I = 4 a
Zero x = 1.4, y = 0.0
T. B. = 100 μs/cm
Sens. = 0.95 a/cm



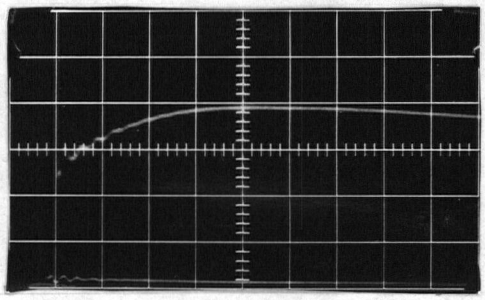
t. I_k - A to E to GND
V_s = 490 v C = 9 μf
R = 5.2 Ω I = 4 a
Zero x = 1.0, y = 3.6
T. B. = 20 μs/cm
Sens. = 2.4 a/cm



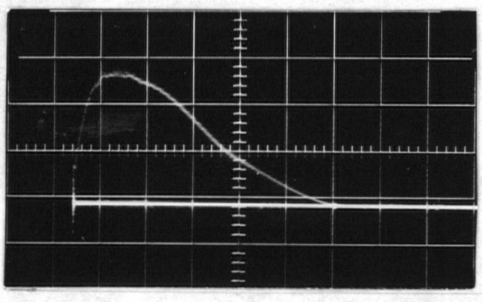
u. I_s - A to B to GND
V_s = 106 v C = 9 μf
R = 5.2 Ω I = 4 a
Zero x = 0.8, y = 1.2
T. B. = 100 μs/cm
Sens. = 0.96 a/cm



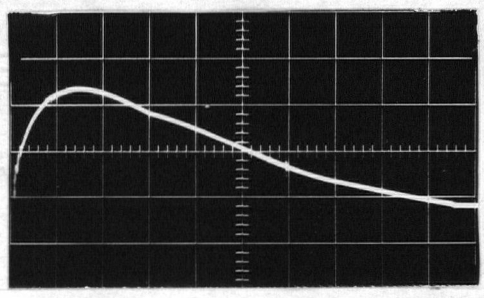
v. I_s - A to B to GND
V_s = 490 v C = 9 μf
R = 4.5 Ω I = 4 a
Zero x = 0.5, y = 0.2
T. B. = 20 μs/cm
Sens. = 2.22 a/cm



w. I_s - A to B to GND
V_s = 490 v C = 9 μf
R = 4.5 Ω I = 4 a
Zero x = 1.0, y = 0.2
T. B. = 1 μs/cm
Sens. = 22 a/cm



x. I_s - A to E to GND
V_s = 232 v C = 9 μf
R = 5.2 Ω I = 4 a
Zero x = 1.4, y = 1.8
T. B. = 100 μs/cm
Sens. = 3.85 a/cm



y. I_s - A to E to GND
V_s = 490 v C = 9 μf
R = 5.2 Ω I = 4 a
Zero x = 0.0, y = 1.8
T. B. = 50 μs/cm
Sens. = 9.62 a/cm

8. The Optimum Conditions for Switching

8.1. The Current-interrupting Circuit

Using the best switching-off connection, A to B to GND, a test was carried out to find if any optimum conditions would result. The switching current was of exponential type and varying C would change τ_s only, however, varying R would change τ_s and the peak value of I_s. This was for a constant value of V_s. In other words, the larger C was, the longer time for which $(I_s)_m > I$, but increasing R would eventually mean the maximum switching current would decrease below the arc-current value and no current interruption would result, and decreasing R would decrease τ_s to such a small value eventually that the arc current would probably not experience any unstabling influence.

The theory was checked by experiment. Data was collected using the circuit in Figure 8.1 and the results tabulated in Table 8.1. Various R and C values were employed and the minimum switching voltage for each combination of R and C was measured. It should be noted again that the switching voltage value, measured with respect to the plasma, was always greater than the power-supply value, V_s, because of the plasma potential with respect to the cathode. The arc current was kept at an approximately constant value, 3 amperes. The switching-off times τ_a and τ_s, were measured and the stored energy in the capacitor was calculated. The circuit is similar to that employed in Figure 5.3. Capacitors were connected across the generators to suppress noise.

The tube had now been modified to its final shape, see Figure 8.2 for a photograph. Probe 1 had been

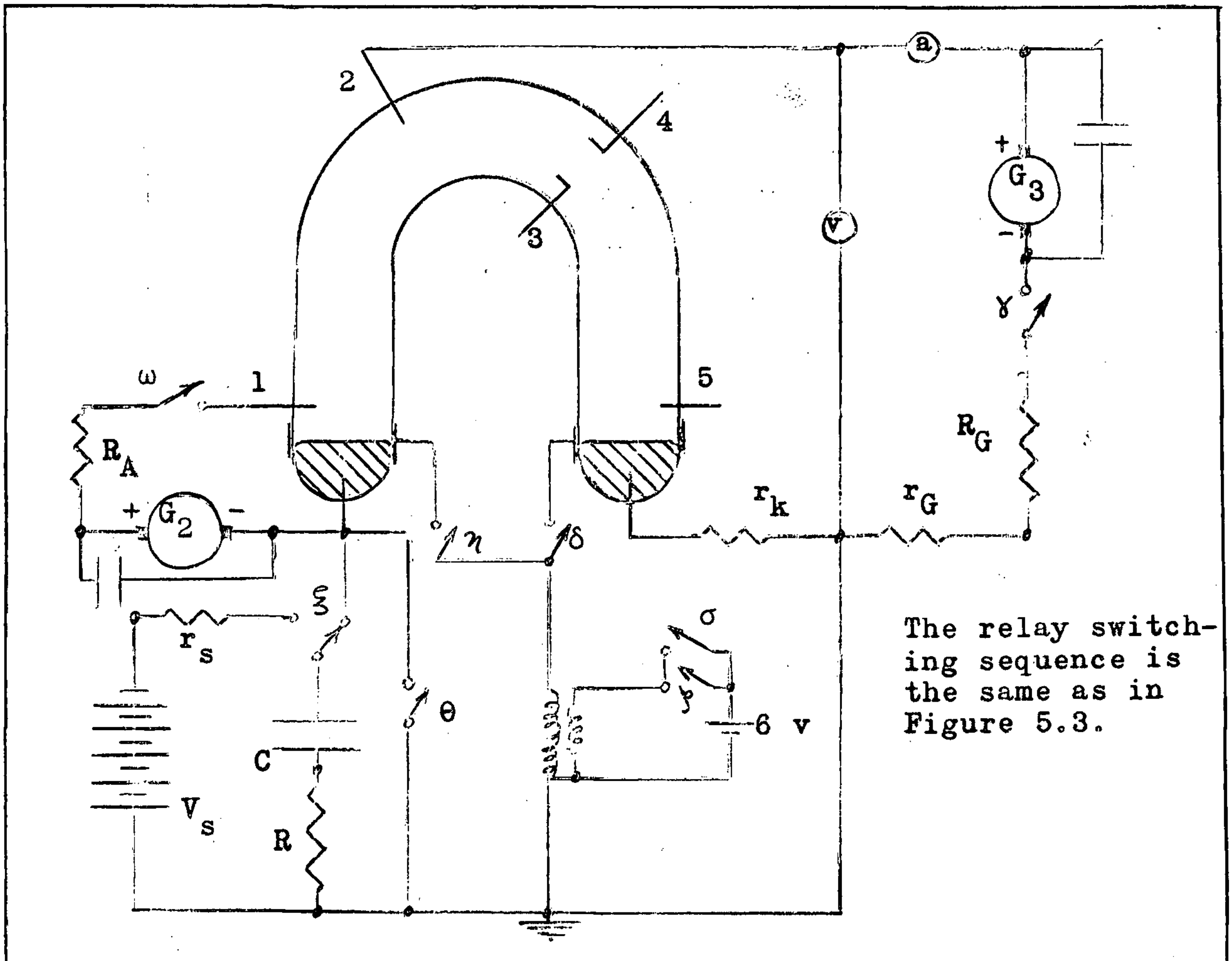


Figure 8.1. The Switching-off Circuit

replaced by a mercury pool. Since the auxiliary arc had to be running for 1 second, an auxiliary arc anode of larger surface area had to be employed in order to dissipate the heat.

In all the circuit diagrams given, only the essential connections are shown for the sake of clarity. The complete switching circuit, including the controlling motor, is shown in Figure 8.3. This is drawn only for general interest. Reference will not be made to this figure in the text.

Results from Table 8.1 indicated that an optimum switching-off condition existed, as was expected. The important data were graphed, see Figure 8.4. It was difficult to tell

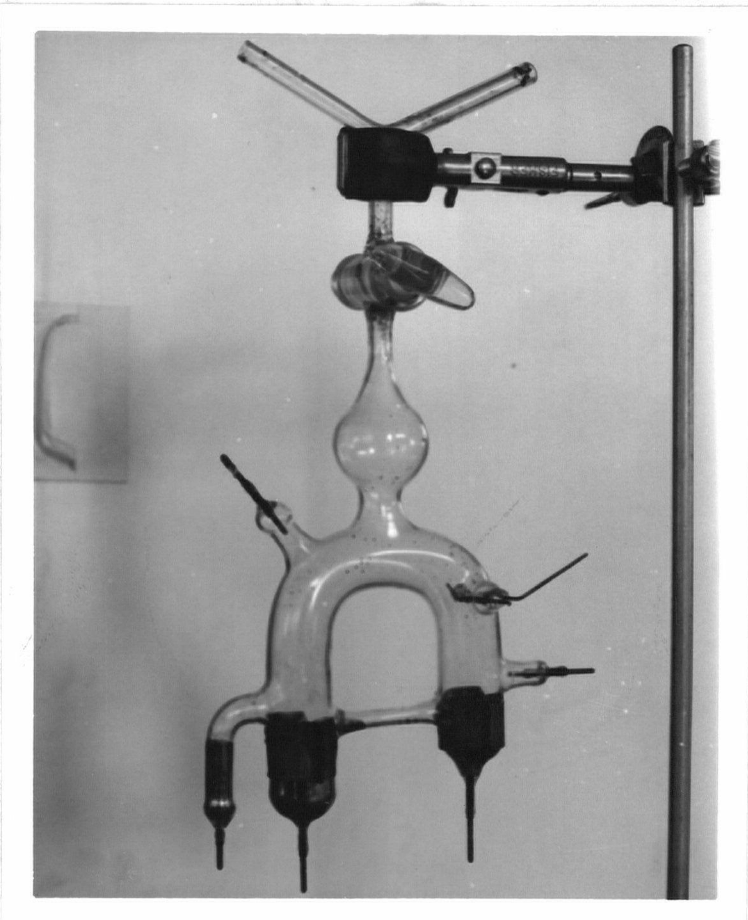


Figure 8.2. The Modified Mercury-pool Tube

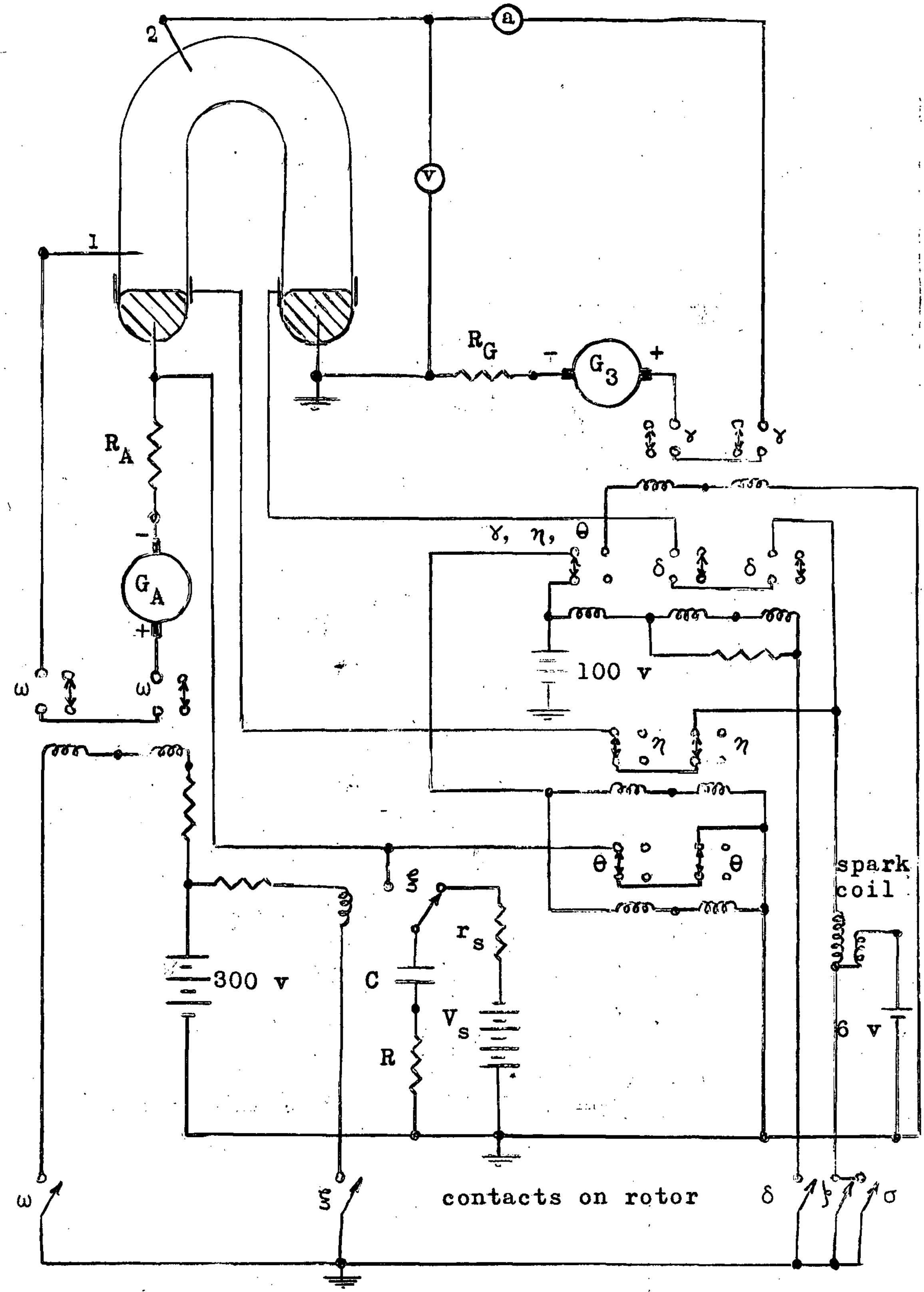


Figure 8.3. The Complete Circuit for Switching Off

Table 8.1. The Minimum Values for Successful Switching

C - μf	R - Ω	V_s - v	I - a	$(I_s)_m$ - a	τ_a - μs	τ_s - μs	$\frac{1}{2}CV_s^2$ - j
9	9.7	45	3.3	5.6	760	425	$91.1(10)^{-4}$
9	5.2	40	3.3	—	700	—	72.0
5	1.6	12	3.0	2.9	430	325	3.6
2.2	100	250	3.0	2.7	1400	1100	625.0
2.2	9.7	39	2.9	2.9	300	300	15.2
2.2	5.2	30	2.8	2.6	300	300	$9.9(10)^{-4}$
2.2	1.6	17	2.8	2.7	300	300	3.2
2.2	.1	24	3.3	42	275	12	6.4
2.2	.05	500	4.4	32	no switch	2	—
0.25	100	280	2.8	2.7	120	120	98.0
0.25	9.7	66	3.0	3.7	70*	48	$5.4(10)^{-4}$
0.25	5.2	34	2.6	1.7	70*	44	1.4
0.25	1.6	21	2.8	5.0	70*	44	0.6
0.25	.1	23	2.9	19	70*	10	0.7
0.25	.05	49	3.1	260	70*	10	3.0
0.025	100	445	2.9	.45	60*	24	$24.7(10)^{-4}$
0.025	9.7	98	2.8	1.3	60*	60	1.2
0.025	5.2	67	2.6	2.1	60*	20	0.7
0.025	1.6	58	3.2	3.0	60*	18	0.4
0.025	.1	65	3.2	250	60*	15	0.5
0.025	.05	65	3.1	640	58*	10	$0.5(10)^{-4}$
0.002	9.7	430	2.8	—	55*	80	1.9
0.002	5.2	330	3.0	—	55*	40	1.1
0.002	1.6	200	3.0	—	55*	—	0.4
0.002	.1	275	3.0	380	56*	8	0.8
0.002	.05	300	3.1	1360	65*	7	$0.9(10)^{-4}$
235 μμf	9.7	500	2.6	—	no switch	60	—
235 μμf	5.2	500	3.1	—	no switch	60	—
235 μμf	1.6	500	2.9	—	58*	—	0.3
235 μμf	.1	500	3.4	720	no switch	3	—
235 μμf	.05	500	3.4	2000	no switch	3	—

*Oscillated--crossed zero at 18, 40, and 60 μs.

The values are reasonably accurate: ±10%.

exactly what the optimum value of R was. The value was independent of C and measured approximately $0.1 < R < 2$ ohms. The fact that V_s increased so quickly as R decreased from one ohm to fractional values indicated the lower limit on τ_s was important.

Another result was that the switching-off time, τ_a, of the arc current was $\sim 60(10)^{-6}$ second. The deionization time for mercury vapour in thyratrons is a function of pressure, arc current, grid voltage, and tube geometry (21). For conventional thyratrons, the deionization time is $\sim (10)^{-3}$ second

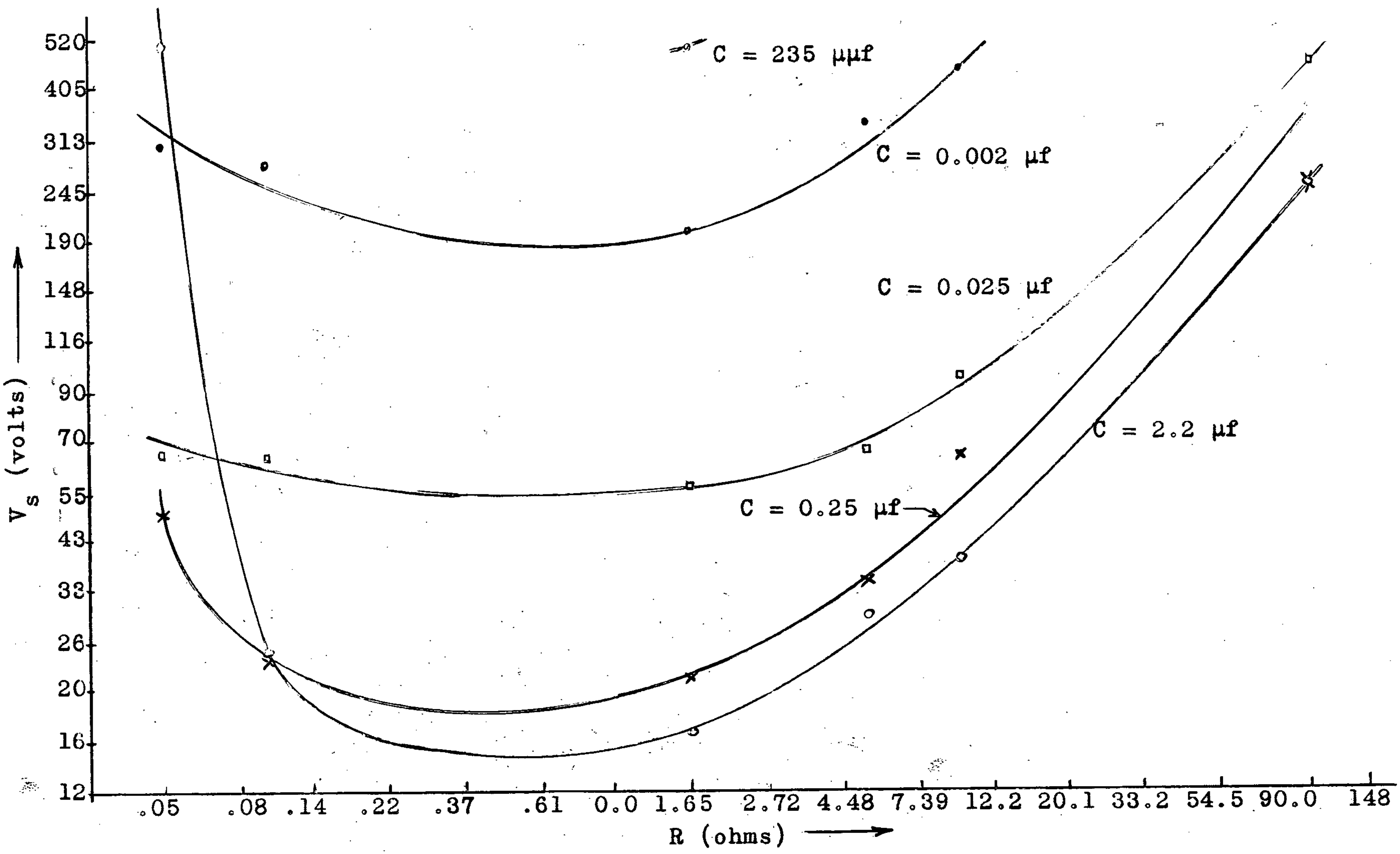


Figure 8.4. A Graph of the Optimum Switching Conditions

and for inverter tubes, when special construction has been used, the deionization time is reduced to $\sim 100(10)^{-6}$ second (16, 33).

What probably happened in the switching-time measurement was the following, see Figure 8.5. The reverse current pulse extinguished the arc cathode-spot. A cathode spot only needs to be interrupted for a time, τ_f, of $(10)^{-8}$ second and it remains extinguished (18, 31). The remaining period is the time, τ_d, to disperse the charged particles in the plasma. Then:

$$\tau_k = \tau_f + \tau_d, \tag{8.1}$$

and, practically:

$$\tau_k \sim \tau_d. \qquad \text{from (8.1)}$$

If the resistance, R, was too small, the time, τ_f, that $(I_s)_m \geqslant I$ would be too small, less than $(10)^{-8}$ second, and current interruption would not happen. Unfortunately, the exponential current was superimposed on I, as shown, and this

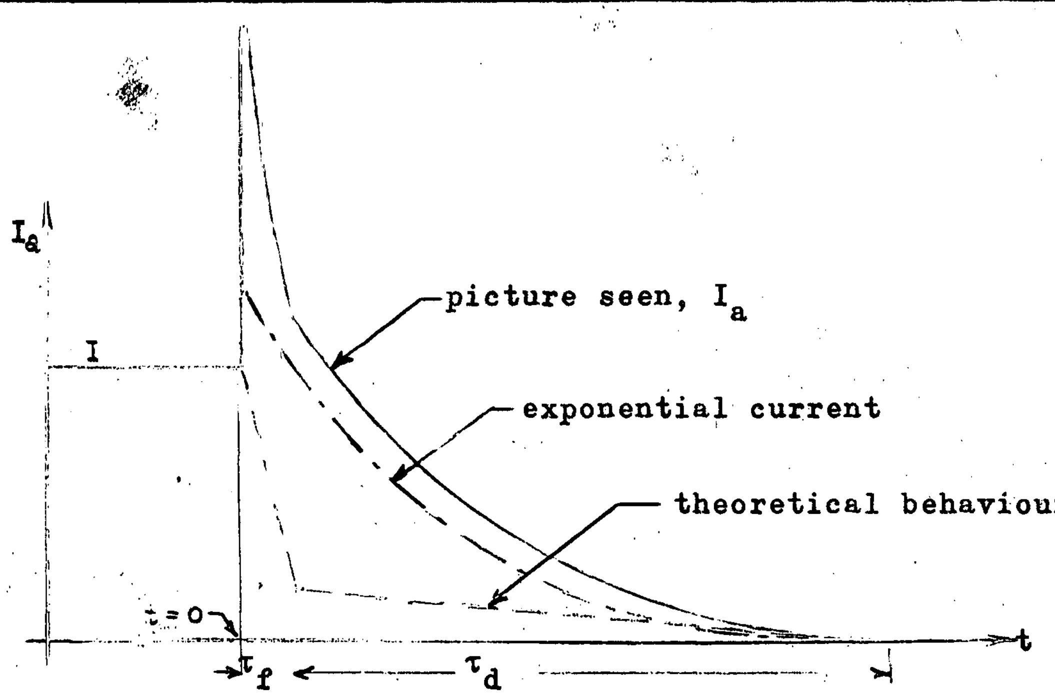


Figure 8.5. The Theoretical and Actual Arc-current Waveforms

theory was not verified. The somewhat low result of $\sim 60(10)^{-6}$ second for the fall to zero of the arc current could be due to one of two reasons. Either the anode-to-cathode potential difference, still causing an electric field, could affect the recombination process and decrease the deionization time by sweeping all the charge carriers out of the tube, or the noise level in the circuit was such as to obscure any signal beyond the 60-microsecond time-to-zero, even when examining the waveforms at high oscilloscope sensitivities. If the latter is the case, from a practical point of view the current still present after $\sim 60(10)^{-6}$ second is so small it may be neglected. However, the waveforms were examined carefully and it is felt that the former supposition is correct.

The current waveforms oscillated with approximately the same period, $\sim 40(10)^{-6}$ second, for every successful current interruption at the low capacitance values. The use of inductive resistors and the fact that C discharged to zero then charged up to the anode voltage and discharged again probably accounts for the oscillations. With the large C values, the oscillations did not occur since this capacitance would be large with respect to the inherent circuit capacitance and would play the dominant role.

The energy needed for switching off was small, see Table 8.1 for values. However, the energy was not an important factor for switching other than that it was small, as can be seen from the table. The energy amount varied with the capacitor employed. The only important electrical requirements were the magnitude of the reverse current and the time, τ_f, that $(I_s)_m \geqslant I$.

8.2. Analysis of the Circuit

A mathematical analysis of the switching-current path was made in order to better understand the results. The network is in Figure 8.6 and the symbols are the same as used previously. It was assumed that the auxiliary-arc discharge

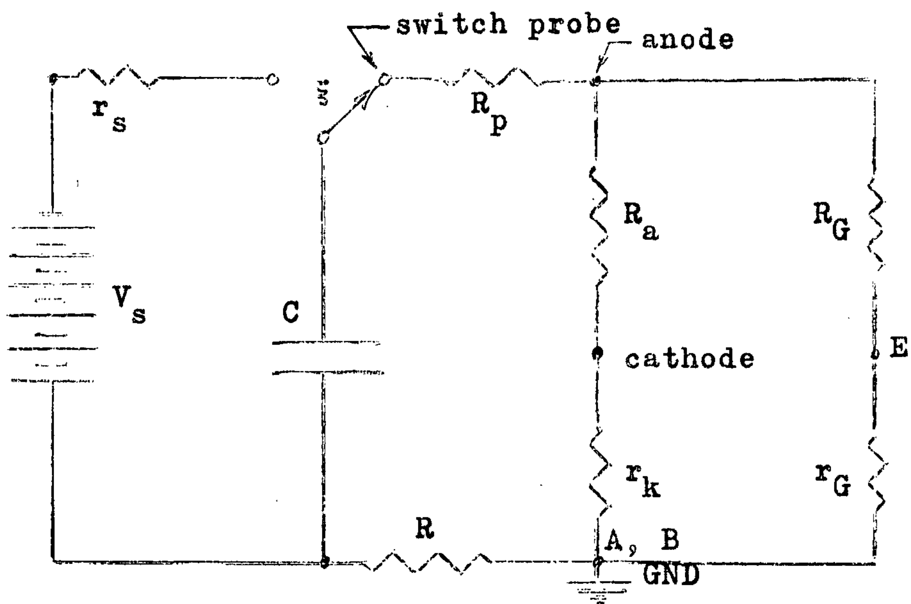


Figure 8.6. The Switching-off Network

did not affect switching except in that a cathode spot was provided.

The switching current was:

$$I_s = \frac{V_s}{r}\exp\left(- \frac{t}{rC}\right), \qquad (8.2)$$

where:

$$r = R + R_p + \frac{R_a + r_k}{1 + \dfrac{R_a + r_k}{R_G + r_G}}. \qquad (8.3)$$

The symbols are: R_p, the resistance between the probe anode and the switching-off pool; R_a, the arc resistance; r_k, the small measuring resistance for I_k; R_G, the current-limiting resistance; r_G, the small measuring resistance for I_a.

The anode and cathode currents were:

$$I_a = I + \frac{R_a + r_k}{R_a + r_k + R_G + r_G}\cdot\frac{V_s}{r}\exp\left(-\frac{t}{rC}\right), \qquad (8.4)$$

and:

$$I_k = -I + \frac{R_G + r_G}{R_a + r_k + R_G + r_G}\cdot\frac{V_s}{r}\exp\left(-\frac{t}{rC}\right). \qquad (8.5)$$

The times of interest, when $I_a = I_k = 0$, were:

$$\tau_a = rC\ln\left(\frac{1}{-\frac{R_G + r_G}{R_a + r_k} - 1}\cdot\frac{V_s}{rI}\right), \qquad \text{from } (8.4)$$

and:

$$\tau_k = rC\ln\left(\frac{1}{1 + \frac{R_a + r_k}{R_G + r_G}}\cdot\frac{V_s}{rI}\right). \qquad \text{from } (8.5)$$

Examining these equations showed that the condition for a physical solution was: when $r > 0$, $(R_a + r_k) < 0$, and $|R_a + r_k| < |R_G + r_G|$. When $r > 0$, $(R_a + r_k) > 0$, and when $r < 0$, the solutions were impossible.

Note that:

$$r = Z(R, R_p, R_a, r_k, R_G, r_G), \qquad \text{from } (8.3)$$

and R_a and R_p are functions of time, t, and arc current, I. No calculations of τ_a and τ_k were made since the functional relationship was not known; R_a was a dynamic arc-resistance and equations were available only for a static arc-resistance (32). However, R_a and R_p would probably be constant for the time, τ_f, that $(I_s)_m \geqslant I$. Therefore, an order-of-magnitude calculation was made using Equation 8.2. It was assumed that increasing-$I_s = I$ at $t = 0$, and decreasing-$I_s = I$ at $t = \tau_f$. Then:

$$\tau_f = rC(\ln\frac{V_s}{I} - \ln\cdot r). \qquad \text{from } (8.2)$$

It was also assumed that $R_p = 0$ ohms and $R_a = -1$ ohm. When a general tube characteristic is examined (22, 24), these resistances will be seen to be near the values used at the arc currents involved. Note that r had to be of positive value for the solution to have physical meaning. The calculations are given in Table 8.2. As can be seen, the time that $(I_s)_m \geq I$ was $\sim(10)^{-6}$ second. Analysing the equation indicated that this was an upper limit for τ_f. Comparing τ_f with the interruption time for extinction, $(10)^{-8}$ second, indicated that the theory possibly was correct.

Table 8.2. Theoretical Limits on Cathode-spot Stability-time

C - μf	R - Ω	rC - μs	V_s - v	I - a	V_s/I	$\ln\frac{V_s}{I}$	ln·r	# 9*	τ_f - μs
9	9.7	87.3	45	3.3	13.6	2.61	2.27	.34	29.7
9	5.2	46.8	40	3.3	12.1	2.49	1.65	.84	39.4
5	1.6	8.0	12	3.0	4.0	1.39	.47	.92	7.4
2.2	100	220	250	3.0	83.4	4.42	4.61	—	—
2.2	9.7	21.5	39	2.9	13.4	2.59	2.27	.32	6.9
2.2	5.2	11.6	30	2.8	10.7	2.37	1.65	.72	8.4
2.2	1.6	3.6	17	2.8	6.1	1.81	.47	1.34	4.8
2.2	.1	.22	24	3.3	7.3	2.03	-2.31	4.34	.95
2.2	.05	.11	500	4.4	113.7	4.72	-2.99	7.71	.85
0.25	100	25	280	2.8	100.0	4.60	4.61	—	—
0.25	9.7	2.4	66	3.0	22.0	3.09	2.27	.82	1.97
0.25	5.2	1.3	34	2.6	13.1	2.57	1.65	.92	1.20
0.25	1.6	.4	21	2.8	7.5	2.01	.47	1.54	.62
0.25	.1	.03	23	2.9	7.9	2.07	-2.31	4.38	.13
0.25	.05	.01	49	3.1	15.8	2.77	-2.99	5.76	.06
0.025	100	2.5	445	2.9	153.7	5.03	4.61	.42	1.05
0.025	9.7	.24	98	2.8	35.0	3.56	2.27	1.29	.31
0.025	5.2	.13	67	2.6	25.8	3.25	1.65	1.60	.21
0.025	1.6	.04	58	3.2	18.1	2.89	.47	1.42	.06
0.025	.1	.003	65	3.2	20.3	3.01	-2.31	5.32	.016
0.025	.05	.001	65	3.1	20.9	3.04	-2.99	6.03	.006
0.002	9.7	.02	430	2.8	157.2	5.06	2.27	2.79	.056
0.002	5.2	.01	330	3.0	110.0	4.70	1.65	3.05	.031
0.002	1.6	.003	200	3.0	66.7	4.20	.47	3.73	.011
0.002	.1	.2 mμs	275	3.0	91.7	4.51	-2.31	6.82	1.36 mμs
0.002	.05	.1 mμs	300	3.1	96.9	4.57	-2.99	7.56	.76 mμs
235 μμf	9.7	2.3 mμs	500	2.6	192.2	5.26	2.27	2.99	6.87 mμs
235 μμf	5.2	1.2 mμs	500	3.1	161.4	5.08	1.65	3.43	4.12 mμs
235 μμf	1.6	.4 mμs	500	2.9	172.3	5.15	.47	4.68	1.87 mμs
235 μμf	.1	.02	500	3.4	147.1	4.99	-2.31	7.30	.14 mμs
235 μμf	.05	.01	500	3.4	147.1	4.99	-2.99	7.98	.08 mμs

*# 9 is $\ln V_s/I - \ln \cdot r$.

The term r reduces to R when values are substituted.

The table is arranged in the same order as Table 8.1.

There were many intangibles in the analysis that were difficult (if not impossible) to estimate. Nothing has been rigorously proved. The values were calculated in order to show that interruption of a necessary arc cathode-spot, by the introduction of a reverse-current pulse of equal or greater magnitude than the arc current, for a short time interval could be all the mechanism required to switch off the tube.

9. Increasing the Current and Voltage

The current interruption method had been proved successful at low currents. It now had to be checked when the arc was running at higher voltages and currents.

9.1. High Voltage

The arc supply-voltage was changed to a 25-kilowatt 500-volt mercury-arc rectifier. Naturally, R_G was increased to keep the arc current, I, between 3.5 and 4.5 amperes. The remainder of the circuit was the same as in Figure 8.1. When the arc was ignited, the already operating auxiliary-arc discharge extinguished. A 3-kilowatt 220-volt mercury-arc rectifier replaced the generator, G_A, in the auxiliary-arc circuit and R_A was appropriately increased to keep I_A = 3 amperes. The behaviour was the same. Using the 100-volt and 140-volt generators, G_2 and G_3, respectively, resulted in normal operation. A test was made using 240-volt and 120-volt generators for arc and auxiliary-arc voltage-supplies, respectively. It was seen that the circuit with the greater current flowing remained ignited after the second band-ignition-voltage was applied. These voltage supplies were interchanged and the same result was obtained.

Apparently, increasing the voltage of the arc and auxiliary-arc supplies increased the current instability. When the 140-volt and 100-volt generators were employed, the arc current could be increased to ~10 amperes with the auxiliary arc remaining at three to four amperes and operation was normal. As soon as the 240-volt and 120-volt generators were used or the 500-volt and 220-volt rectifiers connected, variations of one to two amperes between the currents determined which circuit would stay in operation. The connections were thoroughly checked, but were found to be completely independent of each other except for the switching-off circuit.

Using the procedure here to switch required three stable arcs in the tube, the auxiliary arc provided the cathode spot, the main arc was where the normal current flowed, and the reverse-current arc extinguished the main arc. These arcs were approximately at the same conditions except for the currents flowing and the power supplies used. The arcs had to be stable in order to obtain reproducable results. As has been shown, changing the power supplies so that they differed significantly caused a marked change in the current stability of the auxiliary and main arcs. It will be shown that instability was also involved when the arc current was increased. It is felt that using a different method to provide the cathode spot necessary for immediate switching would eliminate the instability problem.

9.2. High Current

An experiment was made to determine if the method was successful at high currents. The same circuit as in Figure 8.1 was employed. The arc current was increased to a maximum of 30 amperes by changing R_G. The capacitor method of supplying the reverse-current pulse for current interruption still worked. The results are tabulated in Table 9.1. Here also, the auxiliary-arc current had to be increased as I was increased. Otherwise, the arcs were not stable. There was considerably more insensitivity to current differences at the low power-supply voltages. Currents higher than 30 amperes were not obtained because the probe anode was destroyed due to the very

Table 9.1. Switching Off at High Arc Current

V_s - v	I - a	$(I_s)_m$ - a	I_A - a
55	6.5	8.8	4
55	7.5	10.2	4
60	9.0	9.5	4
72	10.5	11.2	10
25	14.0	15.0	25
109	19.5	19.5	25
130	23.8	24.2	25
180	27.5	29.5	25

R = 1.6 ohms, C = 0.25 μf.

Arc generator = G_3, auxiliary-arc = G_2.

high temperature reached.

9.3. Comments on Switching High Currents and Voltages

To maintain the cathode spot required for the switching off pulse, I_A had to be of the same order of magnitude as I. The two arcs would not run simultaneously unless this condition was met. This was the limitation on using an auxiliary-arc discharge to provide the cathode spot for switching. Unfortunately, no more measurements at higher current or voltage could be taken since a further increase in the auxiliary-arc current would have been necessary and this increase together with the high arc-current value being tested would have meant operating the tube close to or above the temperature limit for safety, see also Section 6.5.

Using an auxiliary-arc discharge was not too satisfactory for another reason. As has been mentioned, see Section 2.2 or Section 5.2.2, the cathode spot could be provided in various ways. Many of these ways require only a small energy output. Using the auxiliary arc to provide only a cathode spot for switching off was a rather great waste of energy.

The switching method was successful for currents up to 30 amperes. The theory explaining current interruption was still valid, but some other manner of ensuring cathode-spot formation has to be found; for example, the ignitron method (6). Because an auxiliary arc was being run in the tube a problem in arc stability resulted. This was not a defect in the switching-off method, but just a poor choice in the cathode-spot-forming technique.

10. Conclusions About Switching Off a Mercury Arc

Only two requirements are the necessary and sufficient conditions for switching off a mercury-arc discharge without opening the main circuit. First, a pulse of current must be fed into the cathode in the reverse direction to the arc current, and this reverse current must be equal to or greater than the arc current for a minimum time. This minimum time was not measured, but it was indicated to be less than $(10)^{-6}$ second and probably was the minimum time, τ_f, usually quoted as $(10)^{-8}$ second, that a mercury-arc cathode-spot may be interrupted without reignition. Once the cathode spot has been interrupted, the arc will not reignite and the charge carriers quickly disperse under the influence of the electric field in the tube so that the current ceases. One switching time, τ_k, is the time until $I_k = 0$, this time includes τ_d, the deionization time of the gas, and τ_f. The important switching-time is τ_a, the time until I_a or I falls to zero. The two times differ depending on how the switching circuit is connected. The second requirement for switching off is actually necessary only to control the exact time of switching. The reverse current "cathode" must have either a cathode spot already formed or an easily provided cathode spot at the instant the switching-off voltage is applied. If the spot is not instantaneously present when V_s is applied, a random delay will make it uncertain just when the arc will be switched off.

The power required to switch off the arc is small, and the energy is also small since application of the switching circuit need only be necessary for $\sim(10)^{-8}$ second. However, from a practical point of view, this time is probably difficult to attain because of stray inductance and capacitance.

Higher currents and voltages were not attempted because of the limitation in the mechanism for providing the spot. There appears to be no reason why the switching method should not work at very high current and voltage provided formation of the cathode spot is effected in a different manner. A better way to form the spot is necessary for another reason. The technique of the auxiliary-arc discharge was employed only for expediency. The power and energy used were very high. On the other hand, the ignitron method (6) should be very satisfactory. Only low energy output is required and one arc would be eliminated.

The main point to be made is that there was no interference with the main circuit. Switching was effected not by open-circuiting the main power circuit, but by passing a short pulse of current in the reverse direction through the mercury-pool tube.

11. Projects That May Be Examined

The reverse-current pulse method has been developed now for extinguishing mercury-pool tubes and the complete switching-off is accomplished faster than by conventional methods. Since the smallest switching time, τ_a, was $60(10)^{-6}$ second, the main limitation in the circuit now is the spark-coil band-ignition technique. The time to ignite can be as much as $(10)^{-3}$ second, but when ignition is changed, perhaps also to the ignitron method (6), it will probably decrease to the order of a microsecond.

A project that could then be examined is the building of a high-frequency power oscillator. High-power short pulses could be easily generated and a tuned circuit would give the frequency desired. The present power oscillators in induction-heating apparatus are limited in frequency because of the deionization time of the gas employed in the tube. It should now be possible to increase the frequency markedly.

High-power control-circuits can also be devised. Faster on-and-off control is now possible.

Part B. The Hydrogen Tube

The hydrogen tube was operated in the arc region of the characteristic curve for gas-discharge tubes; that is, the cathode fulfilled the conditions for an arc. The voltage and current were relatively low.

12. The Tube

A description and some of the physical dimensions of the hydrogen tube will be given below. The tube was specially constructed. It was a hot-filament tube filled with hydrogen under a pressure of $(10)^{-3}$ mm Hg. The tube was baked and thoroughly outgassed before filling and all water vapour and oxygen was removed from the gas. The distance between the anode and cathode was 6.0 in. and the tube diameter was 1.0 in., see Figure 12.1. The remaining electrodes were spaced at one-inch intervals between the anode and cathode. The tungsten probes, 1 and 6, of 1.0-mm diameter, extended one-third of the distance across the tube. The double-probe electrodes, 3 and 4, were 0.5 mm in diameter, spaced 2.0-mm apart, and 3.0-mm long, and lay longitudinally in the centre of the tube. The cathode was oxide coated and the heater was rated at 9.0 amperes at 6.3 volts. The anode was a nickel disc of $\frac{3}{4}$-in. diameter and 0.5-mm thick. The discharge could be studied by using the nickel screen-like grids, 2 and 5. The holes in the grids were 0.1-cm square.

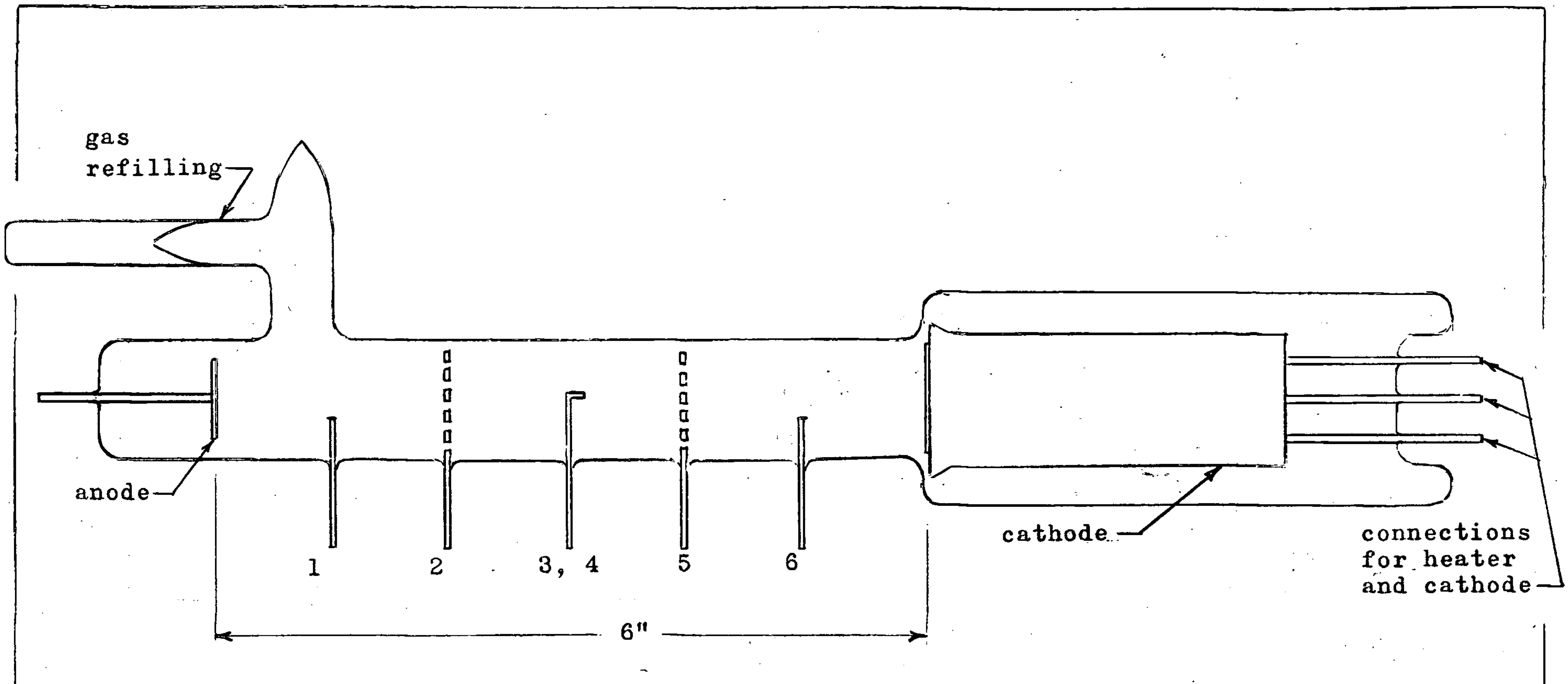


Figure 12.1. The Hydrogen Tube

13. Switching Off

The switching-off method employed involved extending the space-charge sheath until the anode was closed off from the cathode. This was the same method as that attempted in Section 3.1, but the tube construction, with fine-mesh-screen grids filling the tube cross-section, was now more propitious and the use of the space-charge switching method appeared practical. Hydrogen gas was employed in order to make use of the shorter deionization time, $\tau_d = (10)^{-5}$ second (19), and switching could be expected to be much faster.

The circuit is shown in Figure 13.1. To ignite the discharge it was necessary to apply $\sim$850 volts to the anode, positive with respect to the cathode, but operating the tube required only 200 volts. The current flowing was 100-150 milliamperes. The arc was interrupted by a switching-off voltage of 500 volts, negative with respect to the cathode. The plasma at the grid-2 position was $\sim$120 volts, positive with respect to the cathode, so that V_s was $\sim$620 volts because V_s was the potential difference between the grid and the plasma edges of the space-charge sheath. Switching off occurred and the current supplied by the switching power-supply was 21 milliamperes.

The space between the tube wall and the grid was larger than any holes in the grid. This space was the limiting factor on how small V_s could be and still effect switching off. The discharge current flowed, via the plasma, through any hole that was not closed off by the space-charge sheath. Sometimes when a large value of V_s was applied to the grid, a narrowing of the plasma at some random position

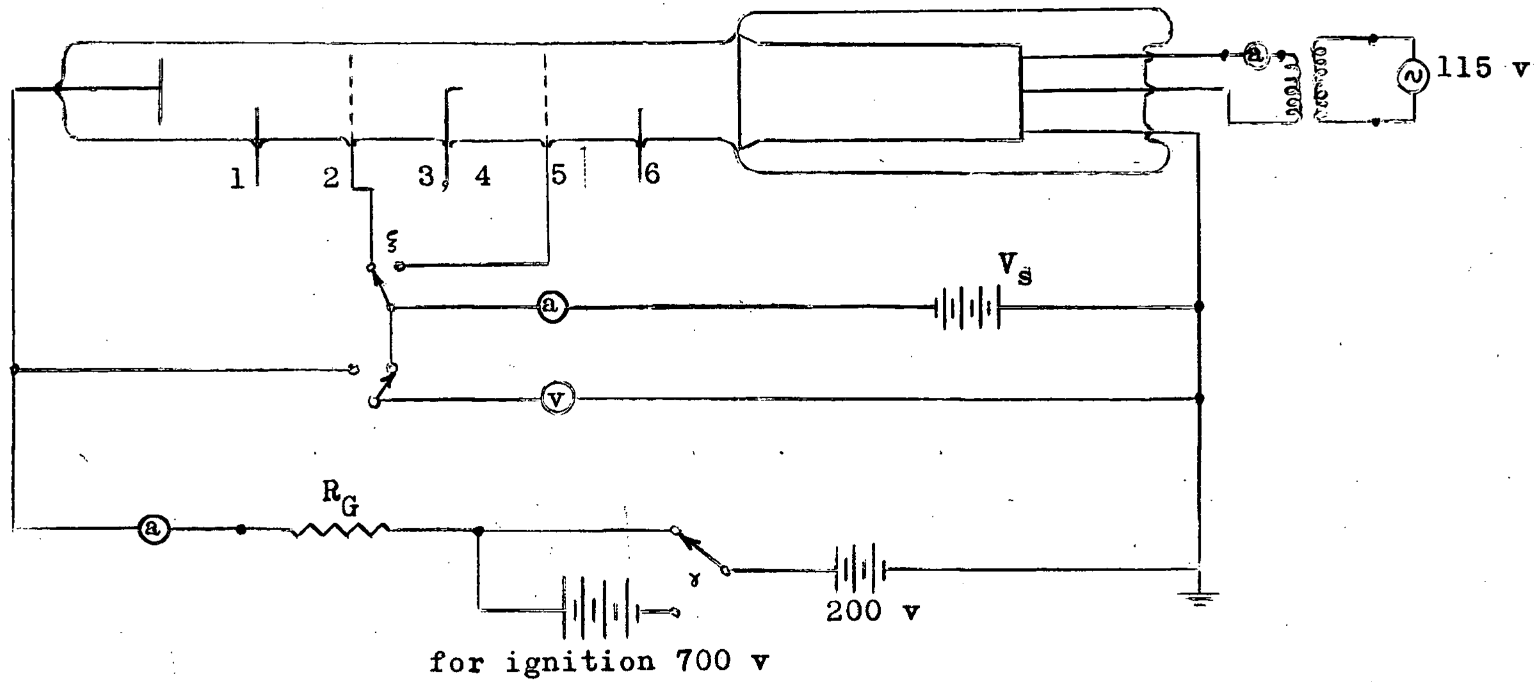


Figure 13.1. Switching Off the Hydrogen Tube

on the grid resulted and large current was delivered by the switching-voltage power-supply. The negative grid voltage probably caused the grid to act as a cathode. The plasma in the anode-grid region appeared to deionize, but the current was still flowing in the grid-cathode region. The switching voltage was removed very quickly or the grid would have been partially destroyed due to the high temperature reached at the narrowed position. Either this occurred, or switching resulted, or the current continued to flow between the tube wall and the grid, each at the same value of V_s, ~620 volts. Whichever one of these three situations happened was unpredictable. The behaviour was random.

The measurements made soon changed due to a deterioration inside the tube. The cathode emission was found to decrease over a period of time and finally became negligible, $I < (10)^{-6}$ ampere. This could be due to either the gas gradually cleaning-up or the cathode oxide-material slowly sputtering away, or even a combination of both these affects. Accordingly, the experiment was abandoned.

A calculation was made, using Equation 3.1, to determine the current delivered by the switching power-supply. The values were: V_s ~620 volts; and M = 2.0, for hydrogen gas is molecular. The geometry measurements were: $r_p = 0.15$ in., the largest space to cover; and $r_r = 0.125$ mm. Then $\frac{r_p}{r_r} = 30.5$ and β^2 was taken as 1.09 (29). Therefore, J_p was calculated to be 3.78 ma/cm^2. Since:

$$I_s = J_p A_s, \qquad (12.1)$$

and A_s, the screen-grid surface-area, was ~5.7 cm^2, the grid current was calculated to be ~22 milliamperes. This was an excellent, but fortuitous, agreement between theoretical and experimental values.

Also calculated was the random-ion concentration, assuming most of I_s was due to the random-ion current. This was an aid to see if the tube was operating correctly before deterioration affected the measurements. The random-ion concentration was obtained from:

$$J_p = Nq_p v_p, \qquad (12.2)$$

where: N is the random-ion concentration, and v_p the thermal velocity of the ions. Since:

$$\frac{1}{2}m_p v_p^2 = \frac{3}{2}kT_p, \qquad (12.3)$$

where: k is Boltzmann's constant, $1.38(10)^{-23}$ joule/°K; and T_p is the temperature of the random ions. The other symbols have been explained previously. Then:

$$N = 3.98(10)^{13} J_p \left(\frac{M}{T_p}\right)^{\frac{1}{2}}. \qquad \text{from } (12.1)$$

Using $T_p \sim 75$ C, since the random-ion temperature would be approximately the same as the gas temperature, the random-ion concentration was calculated to be $1.14(10)^{10}$ ions/cm^3. This was a reasonable value (30).

14. Conclusions About Switching Off the Hydrogen Tube

Although the hydrogen tube switched off by the space-charge method, the voltage and current required were rather high. The power supply had to be rated at 10 watts. Also, the random behaviour was not good.

The method was not novel (1, 2), except for the fact that hydrogen gas was employed no new information would be contributed by further study. It was disappointing that no measurements of time to interrupt the current could be taken.

Part C. References

The bibliography is sectionalized so that the reader is quickly directed to the references on a given topic.

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