CHAPTER IV

PERSISTENCE OF AFTERGLOW MAINTAINED BY A RADIOFREQUENCY FIELD IN A MERCURY ARC

4.1. INTRODUCTION

Study of the afterglow process in a decaying plasma and the measurements of the coefficient of recombination have been carried out by a large number of investigators. The study has provided us with information regarding the various processes of electron ion, dissociative and radiative recombination and their relative importance in a decaying plasma. The afterglow we are considering here is of a different type than that investigated hitherto in the sense that whereas in a normal afterglow the decaying time is of the order of a few microseconds or less, in our experiments the glow was allowed to continue for a few tens of seconds by applying a radiofrequency field which provided additional ionisation and allowed the plasma to decay at a much slower rate. The object is to study the ionisation and loss mechanism in such a decaying plasma.

Since the ionisation and loss mechanism processes are functions of an externally applied magnetic field, it was thought worthwhile to study the persistence time of such an afterglow in presence of a magnetic field. The perturbation in the deionization processes that will occur due to the presence of magnetic field is expected to help us to identify the main operating factors. Hence in the present investigation, the variation of persistence time of a decaying afterglow plasma in mercury vapour has been investigated in presence of radiofrequency field both in the presence and in absence of external magnetic field.

When a radiofrequency field is applied to the afterglow of a low pressure discharge in mercury vapour the afterglow can persist for upto over a minute. The time (T) for which it is visible depends on certain factors. T is increased by applying a magnetic field. The explanation of these observations is that the r.f. field increases the electron temperature and hence produces in addition active radiating species and the magnetic field directly or indirectly hinders their loss by diffusion to the tube wall. Hopefully a systematic study of how T varies with experimental parameters would permit us to evaluate the various loss mechanisms. This is unfortunately hindered by an apparently unavoidable dependence of the value of r.f. field on the intensity (probably mainly the electron content) of the decaying discharge itself. Incidentally there seems no doubt however that diffusion is an important and at times dominent loss mechanism.

4.2. EXPERIMENTAL SETUP

Investigation has been carried out in the afterglow in a mercury arc. The arc tube is cylindrical of length 38.25 cm (shown in fig. 2.1) and is excited by a d.c. source with a rheostat to control the current which is recorded by an ammeter. The whole mercury arc system is cooled by the external circulation of air and the two mercury pool electrodes by circulation of water. The output from a radio-frequency oscillator of frequency 4.52 MHz was applied to the arc through two coupled coils as shown in fig.4.1. The applied r.f. voltage is tuned by the condenser and the rectified d.c. output voltage is recorded by the d.c. voltmeter. The level of radiofrequency power supplied by the oscillator was low enough so as not to cause any breakdown of the gas. The pressure inside the arc was maintained at 0.05 torr. To maintain the pressure constant, dry air which acts as a buffer gas was introduced by a variable microleak of a needle valve. The arc discharge was run for a few minutes so that a steady condition was reached and the outside wall temperature was noted. Then the primary arc discharge was switched off. A glow which developed in the wake of switching off of the arc persisted for a few seconds and then disappeared. Time of persistence of the glow was recorded by a stop watch. When there was no radiofrequency power applied to the arc, no glow was visible after the switching offof the original discharge. The glow was measured under different conditions of the discharge.

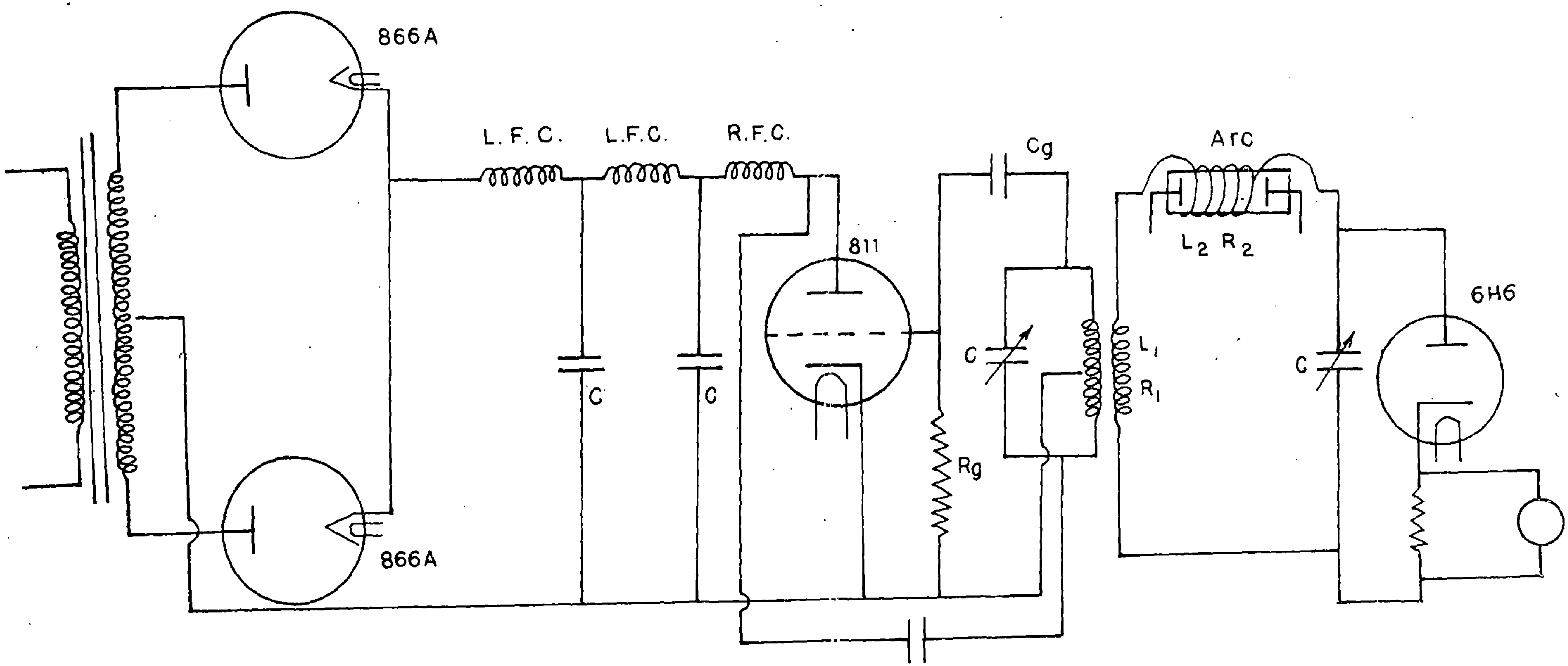

Fig. 4·1 Experimental arrangement

A magnetic field provided by an electromagnet was applied to the positive column of the discharge, to find the effect of magnetic field on the persistence time of the afterglow.

Persistence times have been measured by a stop watch and so an error of $\pm$ 1 sec. in recording times might be present. Nevertheless the persistence times for glow are of the order of tens of seconds so this possible error in the recordings of time is expected to cause not much appreciable error.

When the arc was switched off a greenish white glow existed throughout the whole of the discharge vessel with an r.f. field present. Thereafter the glow in the ends vanished first and ultimately the glow survived only in the central region. Here it was first an ellipsoid, then a sphere and lastly a spheroid. T was taken to be the time interval from the instant when the arc was switched off to the instant when the afterglow finally vanished.

4.3. RESULTS AND OBSERVATION

These are summarised in figures 4.2 to 4.7, the discharges and magnetic parameters being given in the figures and in their captions.

The arc current is fixed at three values of 3A, 3.5A, and 4A, pressure = 0.05 torr, frequency of r.f. field 4.52 MHz. Fig. 4.2 shows the variation of T for a fixed arc currents of 3A, 3.5A and 4A for different periods of

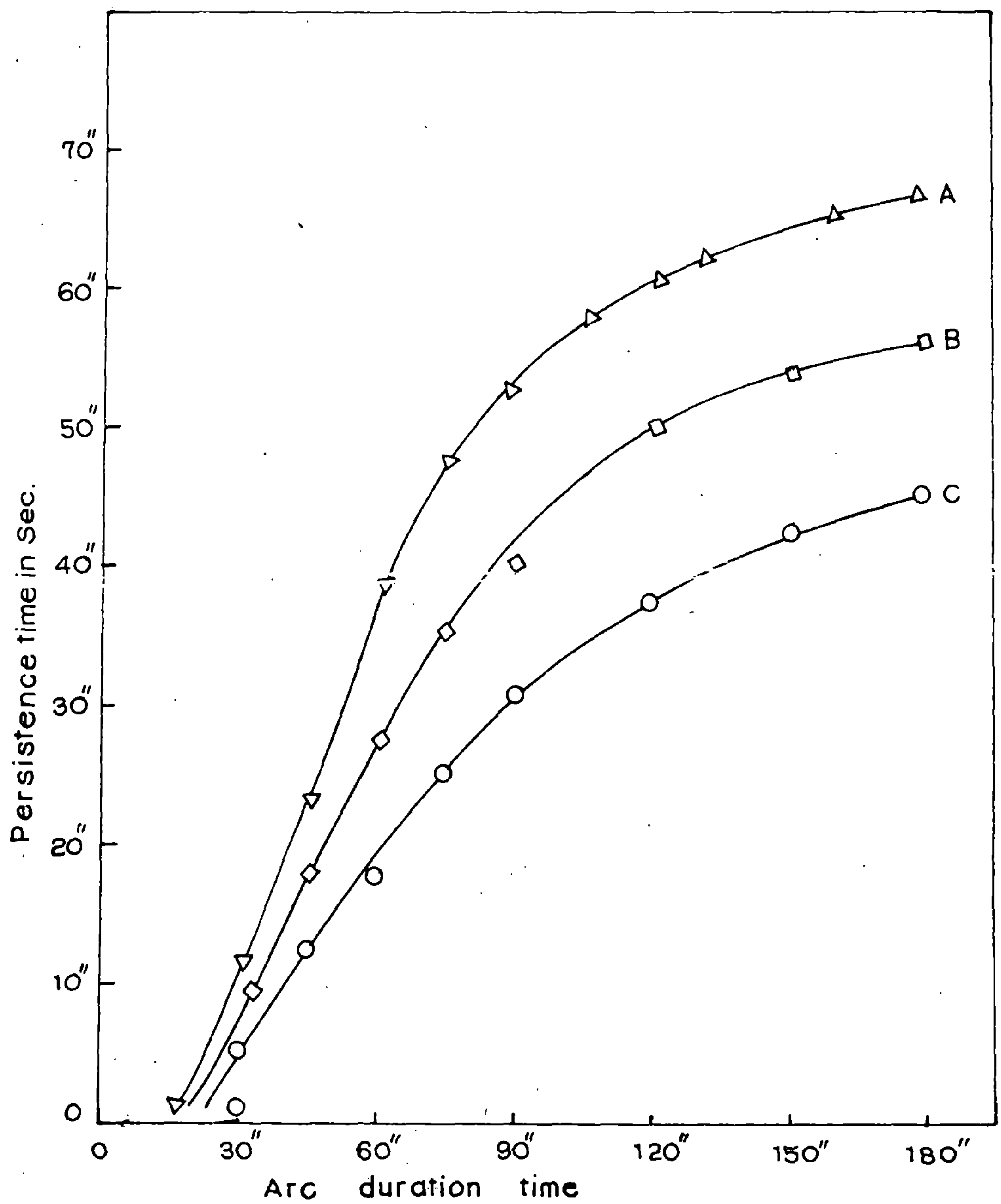

Fig. 4·2. Variation of persistence time with arc excitation time for fixed current A= 4A, B= 3·5A, C= 3A.

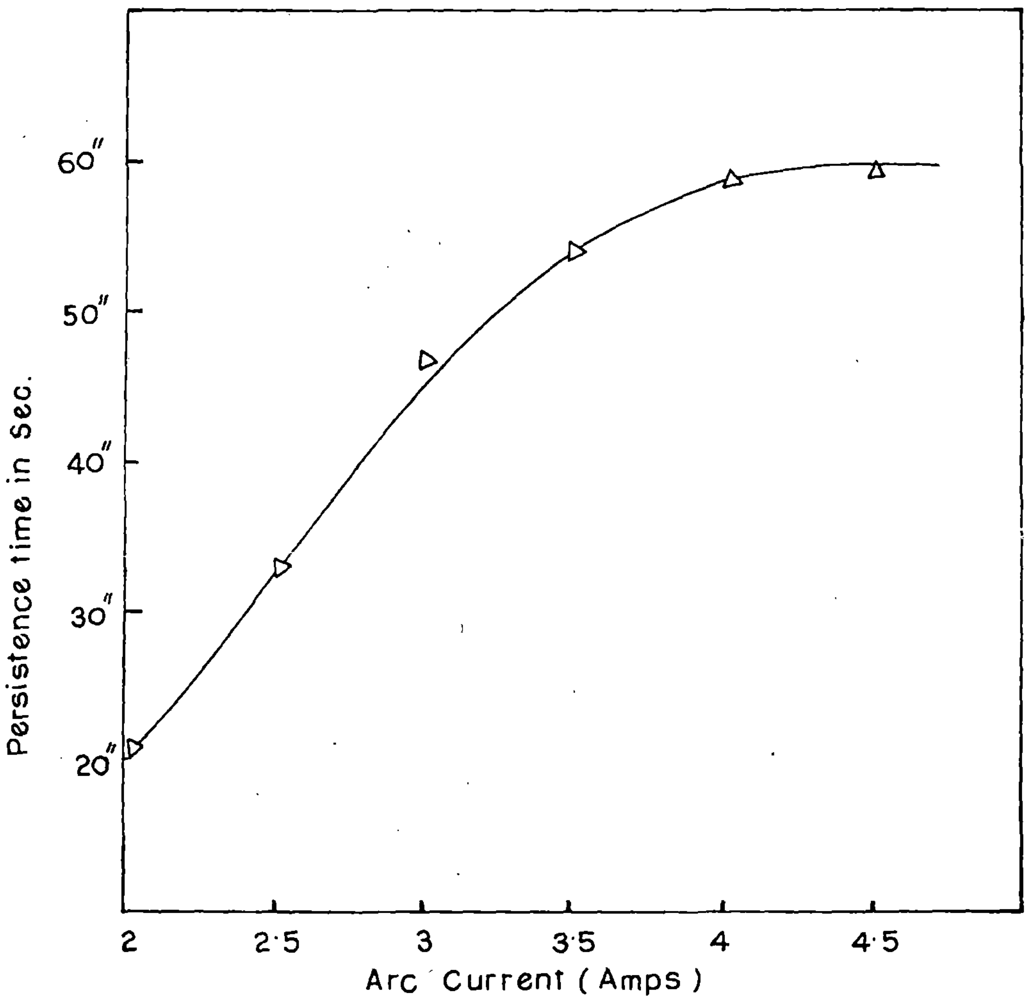

Fig. 4·3. Variation of persistence time with arc current.

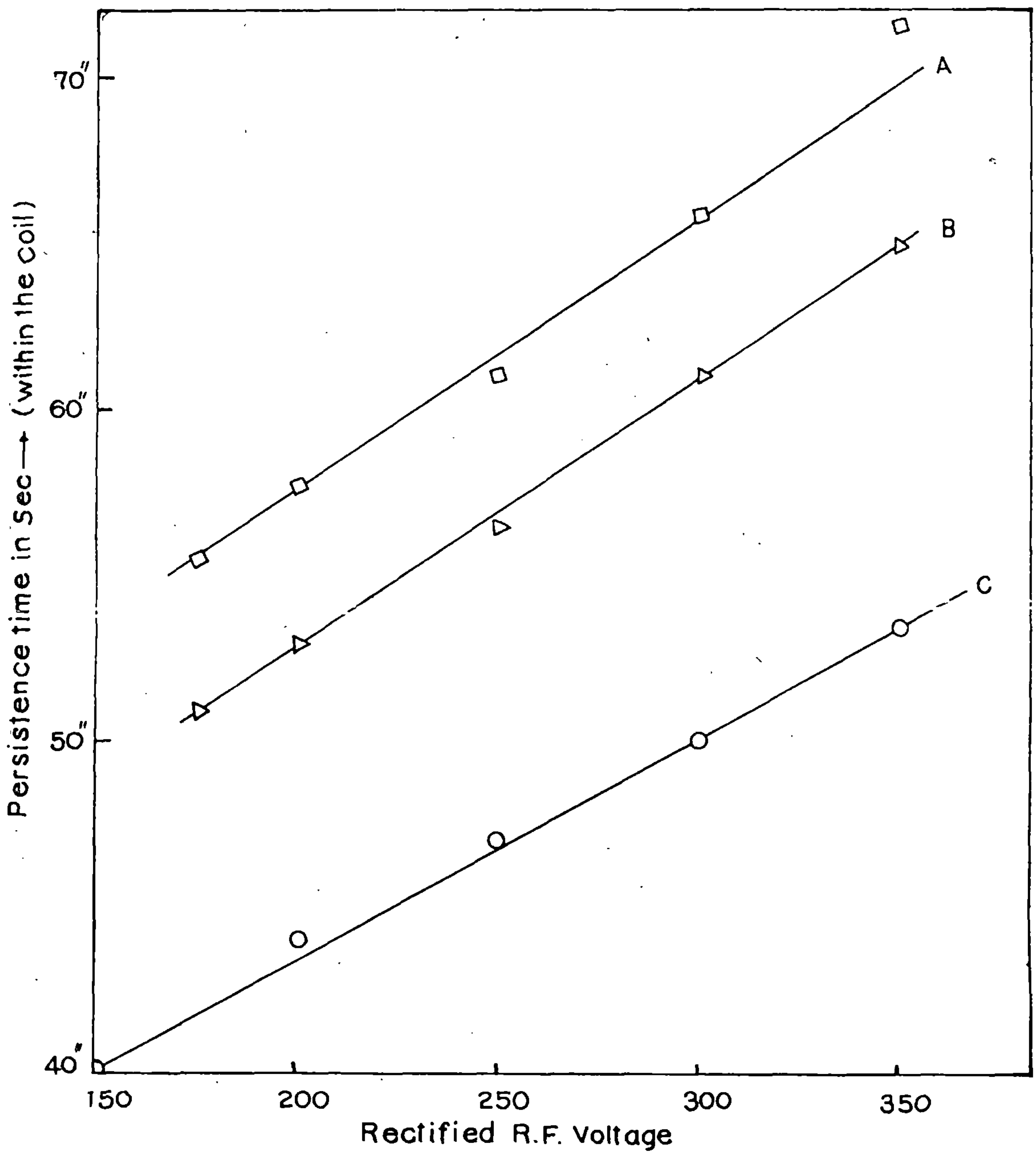

Fig. 4·4. Variation of persistence time with rectified R.F. Voltage.
A = 4 amp., B = 4·5 amp., C = 3 amp.

excitation of arc which varies from 15 sec. to 3 min. It is on the basis of similar tendency towards an asymptote of all three curves that 3 minutes was adopted as the time of switch off in all cases before the afterglows investigation started.

Fig. 4.3.

The arc is excited for 3 minutes. Fig. 4.3 shows the variation of persistence time with arc current varying from 2.0 to 4.5 A. For each current the arc is kept excited for 3 minutes and then switched off. Persistence time is then measured. With the increase of arc current, T, the persistence time increases linearly but near about 4.0 to 4.5A the curves show a tendency of saturation which must some how arise from a corresponding growth in the active species or their precursors in the arc.

Fig. 4.4.

To see how the persistence time is dependent on output voltage of the applied r.f. field, the experiment has been performed with a fixed arc current but the applied field is varied. The figure represents results for three arc currents namely 3A, 3.5A and 4A. The applied radio-frequency field has been varied from 250 to 350 volts, arc excitation time is 3 minutes. The time of persistence becomes a linear function of the applied r.f. voltage. The same nature of variation is observed for all the three cases of arc current (3A, 3.5A, and 4A).

A very important observation has been made with regard to variation of r.f. voltage with time as soon as the main arc current is switched off. It is observed that when there is no arc discharge the measured rectified output voltage of the r.f. oscillator is 260 volts. As soon as the arc is switched on, this rectified voltage drops to 11 volts in case of arc current 2.5A, to 14 volts in case of 3A arc current and to 15 volts in case of 4A arc current. When the arc is switched off it immediately increases to 100 volts and gradually rises with time until the original voltage is restored when the glow vanishes. The nature of variation is almost similar for three different arc currents. The results are plotted in fig. 4.5.

Investigation of the effect of magnetic field on persistence time has been carried out in two ways. In the first set of experiments the magnetic field has been kept fixed at 322 gauss and the arc current has been changed from 2.5 to 4.5A. Arc duration time is 3 minutes in each case. As in the case without magnetic field persistence time increases with the current though the persistence time with magnetic field is higher than that without field. The same nature of variation is obtained from magnetic fields 580 gauss and 725 gauss (fig. 4.6). In the second set of experiments persistence time has been measured keeping the arc current constant and varying the magnetic field. It is observed that persistence time increases with the increase of the magnetic field (fig. 4.7).

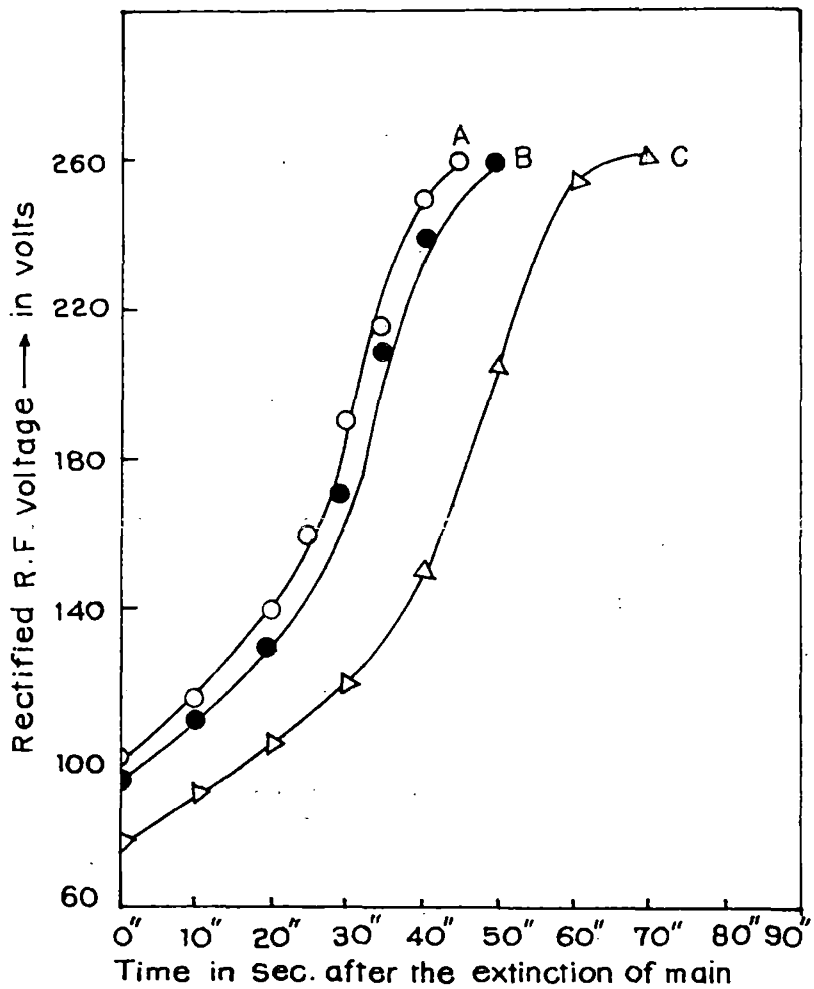

Fig.4·5. Variation of rectified R.F. voltage across the arc in the afterglow with time. A = 4 amp., B = 3·5 amp. C = 2·5 amp.

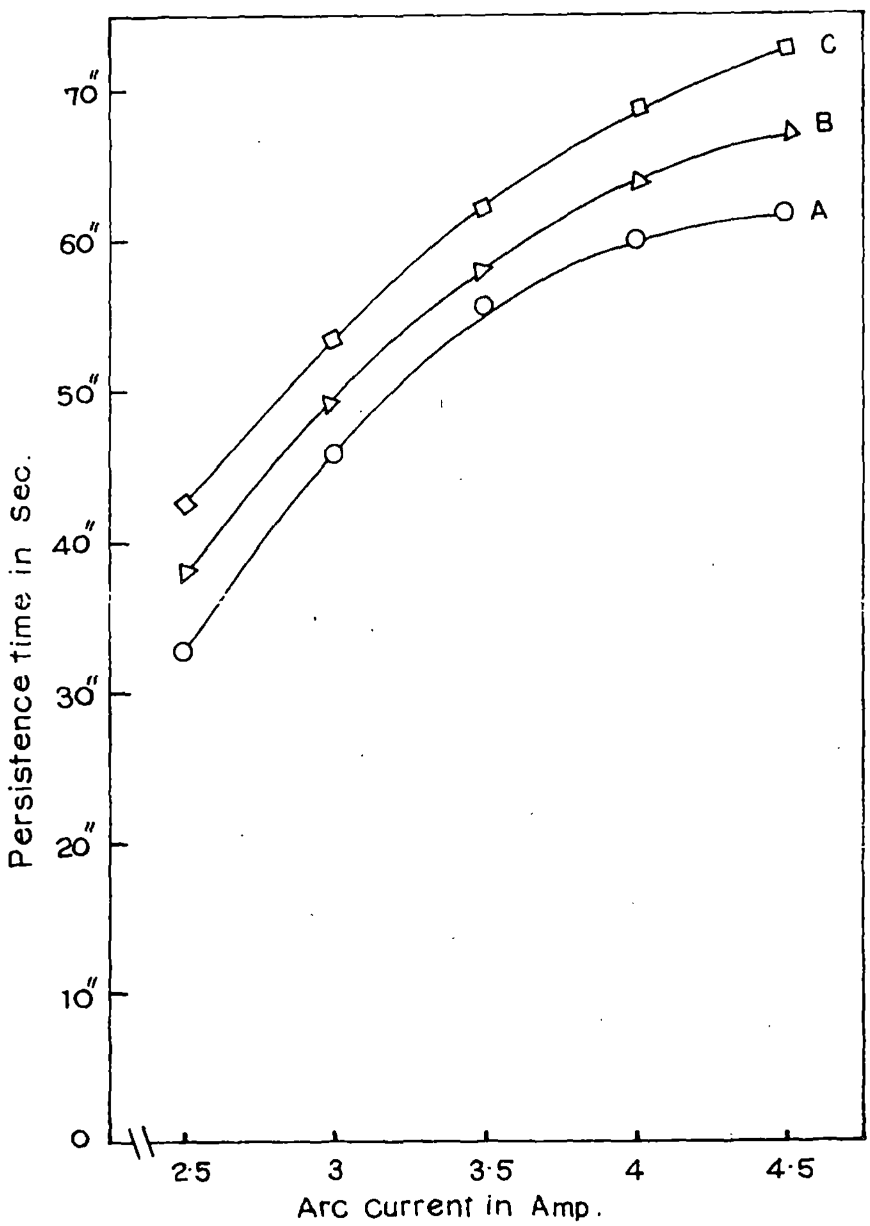

Fig. 4·6. Variation of persistence time with arc current for different magnetic fields. A= 322 gauss, B= 580 gauss, C=725 gauss.

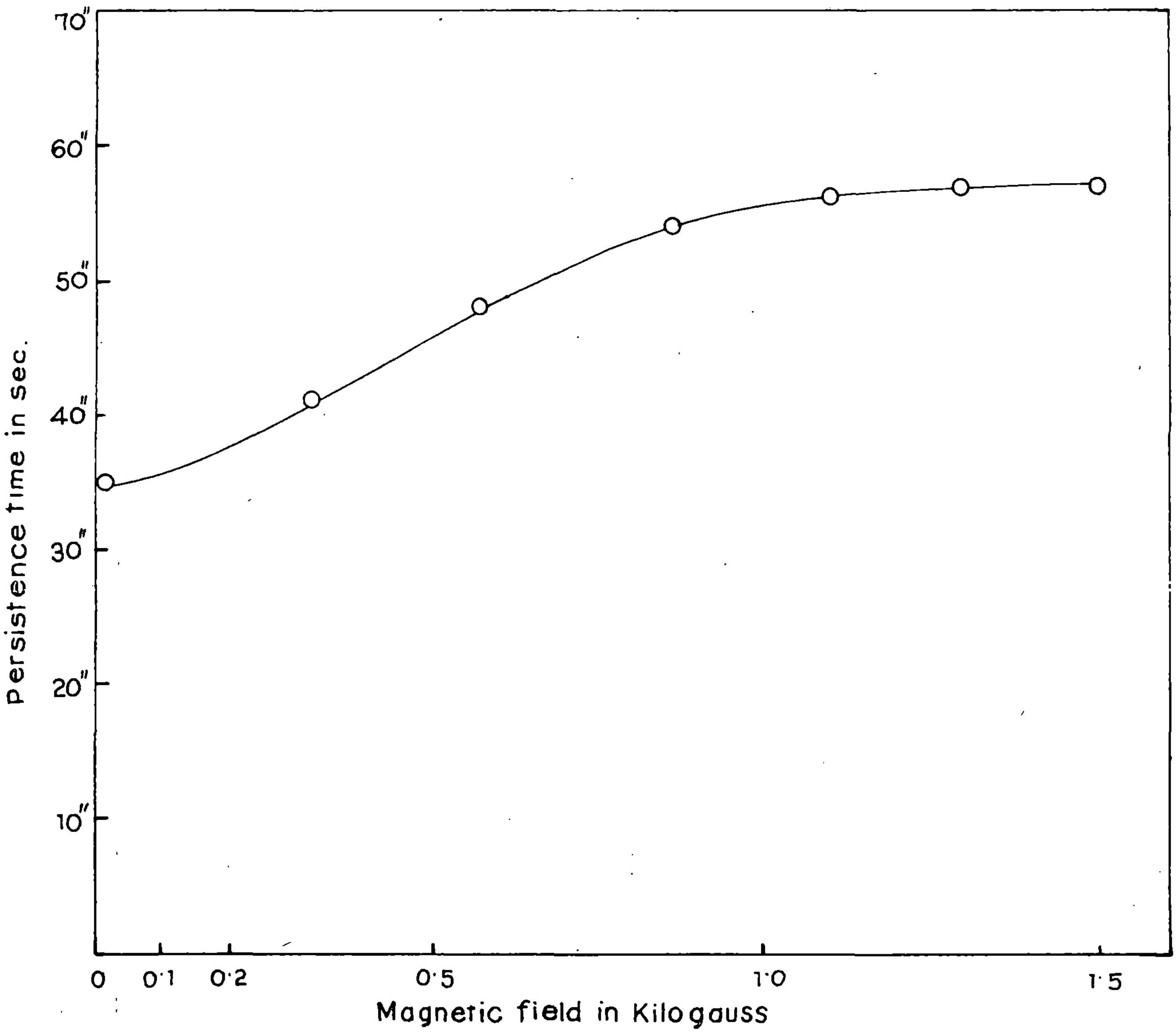

Fig. 4·7. Variation of persistence time with magnetic field.

4.4. DISCUSSION

The reason why after the extinction of the main arc current the glow persists can be ascribed to the fact that due to the flow of arc current a sufficiently high electron density has built up say of the order of 10^{13} electrons per c.c. In absence of the applied r.f. field the glow instantaneously vanishes when the arc current is cut off. We find that the presence of the r.f. field enhances the persistence time of the afterglow to say 50 to 60 seconds depending upon the arc current. We have ascribed this persistence of the glow to the fresh ionisation produced by the r.f. field and the loss of electrons may be due to recombination, diffusion and attachment. In order to understand the variation of persistence time with arc current and other parameters, we have to find the relative importance of various loss processes in different pressure ranges. It is difficult to identify the particular loss process which dominates at a certain pressure range. Dandurant and Holt (1951) studied the electron removal processes in mercury afterglow by microwave technique and also be observing the visible and ultraviolet light intensity and spectrum associated with the afterglow by a gated photomultiplier. It is to be noted that in the afterglow in our present work visible mercury lines were observed through a constant deviation spectrograph specially at low pressure. As concluded by Dandurand and Holt (1951) we can thus conclude that at low pressure the loss is primarily due to recombination. The process is made complex by the presence of metastables in the plasma. According to the observation made by Baibulatov (1966) on the deionisation of a mercury plasma we can conclude that within the pressure range of 0.01 to 0.10 torr deionisation takes place mainly through the diffusion of ion electron gas to the walls of the discharge vessel. Nishikawa, Fujie and Suita (1971) who investigated the atomic collision processes occuring in a flowing afterglow mercury plasma concluded from their observation that at higher pressure range attachment is the major dominating loss process. From the experimental results obtained by Baibulatov (1966) we can assume that within the pressure range of 0.01 to 0.10 torr diffusion dominates as a major factor for loss whereas from the results of Nishikawa et al (1971) it is evident that in the high pressure region $\left[P_{total} > 0.10 \text{ torr} \right]$ major loss of electrons is due to attachment. It is not thus possible to identify the typical loss mechanism which is dominating at a particular pressure. It may be solely due to either one of the processes namely recombination, diffusion or attachment or more than one or two processes may be acting simultaneously.

The rate of generation of fresh electrons will be given by νn where ν is the frequency of ionisation by the radiofrequency field and n is the electron density at the instant of the extinction of the arc, if δ denotes the loss due to various processes then we can write

$$\frac{\partial n}{\partial t} = (\nu n - \delta) \tag{4.1}$$

From the two sets of observations as recorded in fig. (4.2) and (4.3) we can see that the rate of fresh ionisation by the radiofrequency field will depend upon the instantaneous electron density and it will be larger for higher arc current. As the rate of ionisation process will increase with n that is with arc current the time of persistence will naturally increase with arc current.

Besides the increase of electron density with the increase of the arc current another factor namely the heat generated in each case is also increasing. In the first set of observations gas temperature has increased for each observation because time duration has been gradually increased for each observation keeping the current constant at a fixed value. In the second set of observation currents have been increased step by step with the same time duration and hence for each observation the heat developed is proportional to i^2 where i is the current and which has increased the temperature of the gas.

Taking the expression for ν as deduced by Kihara (1952)

$$\nu = N \frac{3\sigma}{C_i} \frac{KT_e}{m} \exp\left[-\frac{mC_i^2}{2KT_e^+}\right] \tag{4.2}$$

where σ and C_i are molecular constants introduced by Kihara, N is the number of molecules at 1 torr, and T_e is the electron temperature. As shown by Persson (1961)

$$T_e = T_g + \frac{M}{3K} \left(\frac{eE}{m\nu_m} \right)^2 , \quad (4.3)$$

where T_g is the gas temperature M and m are the masses of neutral gas particles and electron respectively, K is the Boltzmann constant, ν_m the electron atom collision frequency, which shows that T_e increases with the increase of T_g. With the increase of current and its time of duration as has been done here T_g increases which further increases T_e and hence ν increases. This increases the persistence time. We may further consider how gas temperature enters into the rate processes.

1) In the process of associative ionisation in the formation of Hg_2^+, T_g the gas temperature enters explicitely in the reaction rate. It has been further known (Sadhya and Sen, 1980) that in a mercury arc discharge Hg_2^+ ions are chiefly the ionised species.

2) Quenching rate for heavy particles metastable levels will increase with T_g. An effective quenching process of 6^3P_1 atoms by N_2 is

$$Hg\ (6^3P_1) + N \longrightarrow Hg\ (6^3P_0) + N_2 + 0.218\ \text{eV} \quad (4.4)$$

It has been discussed by Mitchel and Zemansky (1961) that the energy of 0.218 eV in this reaction is taken up by N_2 molecules as vibrational energy. But when neutral particles are hot enough, much of N_2 molecules will be in vibrational state so that the reverse reaction

$$Hg\ (6^3P_0) + N_2^* \longrightarrow Hg\ (6^3P_1) + N_2 \qquad (4.5)$$

may be one of the important processes that populate 6^3P_1 level. This discussion shows how T_g or T_e influences the ionisation process in mercury vapour.

From fig. 4.4, it is evident that as the magnitude of the applied radiofrequency field is gradually increased for a constant value of the arc current, T the persistence time of the afterglow increases linearly. This is true for the three arc currents studied namely 3A, 3.5A, and 4.0 A. Putting the value of KT_e in the expression for ν as deduced by Kihara we get

$$\nu = \frac{eE3\sigma}{C_i(3\lambda P)^{1/2}} \exp\left[-\frac{m\,C_i^2\,N\,(3\lambda P)^{1/2}}{2\,e\,E}\right]$$

$$\simeq \frac{e\,E\,3\sigma}{C_i\,(3\lambda P)^{1/2}}\left[1-\frac{m\,C_i^2\,N\,(3\lambda P)^{1/2}}{2\,e\,E}\right] \qquad (4.6)$$

since in our calculation it comes out that the term $m\,C_i^2\,N\,(3\lambda P)^{1/2}/\,2\,e\,E \ll 1$ with E of the order of tens of volt/cm. As according to our previous argument the persistence time T will be proportional to ν which according to the above approximation is proportional to E for constant arc current. The results give further evidence to the fact that persistence time is proportional to initial electron density produced by the arc. It is evident from fig. (4.3) that for the same radiofrequency field applied the persistence times are almost proportional to strength of current that is proportional to electron density. Hence we can conclude that the two factors which mainly govern the value of persistence time are ν and n (the frequency of ionisation produced by the radiofrequency field depends upon the electron temperature and the magnitude of the radiofrequency field, and the electron density is entirely governed by the arc current). It has however, been pointed out earlier that the electron temperature T_e is directly related with the gas temperature (mercury vapour temperature) which in its turn is dependent upon the arc current and the time for which the current flows. The linear variation of persistence time with the variation of radiofrequency field strength can thus be explained.

An interesting observation that has been made and the results entered in Table (4.1), show that the rectified radiofrequency voltage is maximum when there is no arc current. As soon as the arc strikes there is a sudden fall of r.f. voltage to a low value. As the arc current is switched off, the voltage at once rises and the tabulated results provide the tempo?ral variation of r.f. voltage.

Table 4.1

Time in sec.	2.5 A arc current	3.0 A. arc current	4.0 A arc current
	Rectified r.f. voltage (a) before arcing, (b) after striking.		
	a) 260 V b) 11 V	a) 260 V b) 14 V	a) 260 V b) 15 V
	Rectified voltage in volts (arc current off)		
0	100	95	78
10	118	110	90
20	140	135	105
30	195	170	120
40	215	210	135
50	250	240	150
60	260	250	185
70		260	205
80			255
90			260

A representative curve showing the variation of radiofrequency voltage with time is shown in Fig. (4.5). The circuit diagram of the experimental arrangement has been shown in Fig. (4.1). To analyse the circuit we assume that let E be the voltage induced from the tank coil of the oscillator to the secondary circuit which actually supplies r.f. power to the arc. Then the current through the secondary circuit is

$$I = \frac{E}{\sqrt{(R_1 + R_2)^2 + \{\omega(L_1 + L_2) - \omega C\}^2}} \tag{4.7}$$

where R_1 is the ohmic resistance of L_1

R_2 is the ohmic resistance of L_2

L_1 & L_2 are the inductances of the two coils

C is the untuned (original) capacity. Then the voltage reading across the voltmeter is

$$\frac{E}{\sqrt{(R_1 + R_2)^2 + \{\omega(L_1 + L_2) - \frac{1}{\omega C}\}^2}} \times \frac{1}{\omega C}$$

where ω is the angular frequency of the applied r.f. field. When the circuit is tuned and the new capacity for resonance is C' we get

$$\omega(L_1 + L_2) = \frac{1}{\omega C'} \tag{4.8}$$

so that resonant current is $E/(R_1 + R_2)$ and the resonant voltage is

$$\frac{E}{(R_1 + R_2)} \times \frac{1}{\omega C'} = V_1 \tag{4.9}$$

The plasma column can be assumed to be a cylindrical conductor. The alternating magnetic field associated with the radiofrequency current induces an r.f. electric current within the plasma. The plasma column itself can be considered to act like a secondary coil. It has been shown by a detailed mathematical analysis by Ghosal, Nandi and Sen (1976) that when plasma is excited in the arc the total resistance of the coil surrounding the arc will be given by

$$R_2 + \frac{\omega^2 M^2}{R_0}$$

where $\omega^2 M^2 / R_0$ is the reflected resistance in L_2.M is the mutual inductance between the primary and secondary coil and R_0 is the azimuthal plasma resistance. Hence in the afterglow region of the plasma the radiofrequency rectified voltage will be given by

$$\frac{E}{\left\{ R_1 + R_2 + \frac{\omega^2 M^2}{R_0} \right\}} \frac{1}{\omega C'} = V_2 \qquad (4.10)$$

Then from equations (4.9) and (4.10)

$$1 + \frac{\omega^2 M^2}{(R_1 + R_2) R_0} = \frac{V_1}{V_2}$$

$$\frac{\omega^2 M^2}{(R_1 + R_2) R_0} = \left[\frac{V_1}{V_2} - 1 \right]. \qquad (4.11)$$

Since the right hand side of equation (4.11) can be obtained from experimental data, R_0 can be calculated if the values of

ω , M, R_1 and R_2 can be obtained. The values of R_1 and R_2 have been measured and $R_1 = 10.52\,\Omega$ and $R_2 = 10.3\,\Omega$. M was calculated by assuming the plasma inductance to be a secondary with turn unity and having an average cross section equal to half the inner cross section of the tube (Simpson, 1960). The value of M thus calculated comes out to be $M = 0.359\,\mu H$. Hence $\omega M = 6.28 \times 4.52 \times 0.359$ and

$$\frac{\omega^2 M^2}{(R_1+R_2)} = 5.041$$

Hence

$$R_o = \frac{5.041}{\left[\frac{V_1}{V_2} - 1\right]} \qquad (4.12)$$

It is observed from Table (4.1) that when the arc has not been excited the radiofrequency voltage is 260V, for an arc current of 2.5A, the r.f. voltage drops to 11 volts. We can thus calculate R_o, the azimuthal plasma resistance from the above equation. Putting $V_1 = 260$ V and $V_2 = 11$ V, $R_o = 0.2227\,\Omega$. In the same way values of R_o at different times after the arc has been extinguished can be calculated from the values of r.f. voltage (Table 4.1) at different times. The values of R_o at different t values in the afterglow for an arc current of 2.5 A is entered in Table (4.2).

Table 4.2

t in sec.	0	10	20	30	40	50	60
R_o in Ω	2.017	4.187	5.875	15.1	24.13	126	Infinity

Now $R_o = \frac{1}{\sigma}\frac{l}{S}$ where σ is the conductivity and l is the length of the column and S the area of cross section then

$$\frac{1}{\sigma} = \frac{l}{R_o S}$$

Further $\sigma = \frac{ne^2}{m\nu_c}$ then $\frac{l}{R_o S} = \frac{ne^2}{m\nu_c}$

where ν_c is the electron atom collision frequency. As the observations have been carried out at constant pressure ν_c is constant and we get from the above relation $n_t \propto \frac{1}{R_o}$ Hence if n_t is the instantaneous charge density in the decaying plasma when the azimuthal plasma resistance is R_{ot} we get

$$nR_o = n_t R_{ot}$$

or

$$n_t = n\frac{R_o}{R_{ot}} \tag{4.13}$$

The value of n, the charge particle density has been determined in an arc plasma for a current of 2.5A in this laboratory recently by Hall effect measurement (Sen and Ghosh, 1985) and $n = 3.638 \times 10^{12}$. Taking the corresponding values of R_{ot} the charge particle density in the decaying plasma at different times has been calculated utilising equation (4.13).

Table 4.3

t, time in sec.	0	10	20	30	40	50	60
Particles density.	4.018×10^{11}	1.936×10^{11}	1.379×10^{11}	5.367×10^{10}	3.359×10^{10}	6.431×10^{9}	0

It is thus possible to calculate the temporal variation of electron density in a decaying plasma placed in a radiofrequency field. The variation of electron density with time is shown in fig. (4.8). It is consistent with the time of persistence as has been observed here.

Persistence time in presence of transverse magnetic field -

It is observed from the measurement of persistence time in presence of transverse magnetic field that persistence time increases when the magnetic field is present than in its absence. This is evident for three magnetic fields

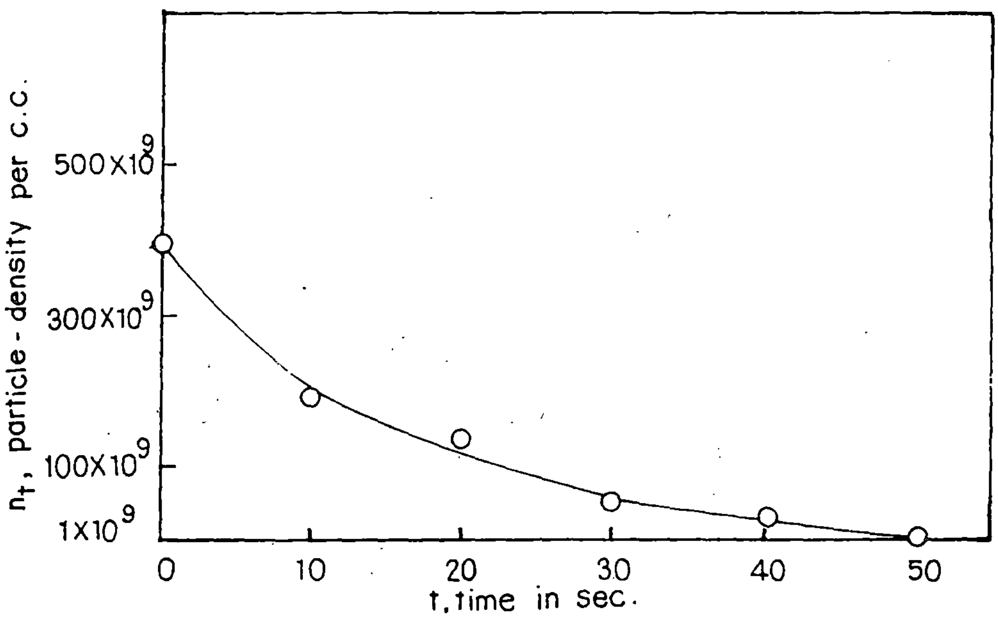

Fig. 4·8. Variation of n_t, particle density with decay time in sec.

namely 322 gauss, 358 gauss and 725 gauss, for the variation of arc current from 2.5 to 4.5 A. The discharge tube was allowed to cool in the same environment during the time of recording. Magnetic field was switched on just before the switching off of the arc current. Visually it was observed that as magnetic field increases the radiofrequency glow becomes brighter. We have observed in a number of experiments that the intensity of spectral line increased in transverse magnetic field, Sen, Das and Gupta (1972), Sadhya and Sen (1980) and the present author (Chap. III) . The enhancement of intensity of afterglow points to the fact that the afterglow is due mainly to the radiofrequency field.

The magnetic field also affects the continuance of the afterglow phenomena in another way. As we have already mentioned the loss of charged particles is due to recombination, attachment and diffusion and it is difficult to ascertain which loss process predominates. If we assume that loss of charged particles is due to diffusion then as is well known the diffusion coefficient decreases in presence of magnetic field according to the relation

$$D_H = \frac{D}{1 + \omega_B^2 \tau^2} \qquad (4.14)$$

where $\omega_B = (eB/m)$ the electron cyclotron frequency and τ is the time for collision between charged particles and neutral atoms and molecules. As diffusion of charged particles towards the wall decreases the energy carried by the charged particles towards the wall where they are neutralised by recombination also decreases. Hence the rate of loss of charged particles decreases whereas the ionisation frequency due to radiofrequency field in presence of magnetic field is not changed by a significant factor (Sen and Jana,1977). Consequently the net life time of charged particles in the afterglow increases which can explain the enhancement of persistence time in presence of magnetic field.

It is difficult to isolate the particular loss process which predominates as has been mentioned earlier. The pressure inside the arc and its size can be so chosen that recombination may dominate over diffusion. In that case the magnetic field should not have any affect on the persistence time and if the losses do not depend on magnetic field, dissociative recombination is the only dominating loss mechanism in the afterglow plasma. This is the same argument that was put forward by Kuckes et al (1961) while investigating the decay of helium plasma in B.1. Stellarator. As they observed that loss rate is independent of magnetic field between 2.9 and 3.5 Kg it was concluded that plasma was recombination dominated and loss due to diffusion can be regarded as negligible. In this investigation, we have however, recorded the persistence times only. Generally for a fuller information of afterglow, densities of different particles are measured as a function of time. The results are then analysed with the rate or continuity equations of particles and with a knowledge of electron temperature relaxation, different macroscopic coefficients for the particles are measured. Simply a knowledge of persistence time cannot give a clear picture of the decay rates of particles. Lastly the disappearance of occurance of a discharge was inferred usually by observing the glow. So when the glow vanished we considered that afterglow ceased to exist. But the decay rates of charged particles may be different from the decay rate of excited atoms which are responsible for creating the visual picture of the glow. Generally it is believed that during the decay, production of new charged particles ceases and concentration of charged particles then decreases by different loss mechanism such as recombination and ambipolar diffusion approaching finite but very small value. However, for an analysis of the experimental data we have correlated the visual glow with the plasma since the radiation is definitely an electron atom process (either it is recombination radiation or an electron excitation radiation).

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INT. J. ELECTRONICS, 1987, VOL. 63, NO. 1, 55–59

Persistence of afterflow maintained by a radiofrequency field in a mercury arc

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Afterglows in low pressure mercury arc vapour which remain visible for many seconds (T, which is defined as the time of persistence) can be produced by applying a radiofrequency field to the decaying discharge. T has been measured for different arc currents and also for different times of excitation of the arc. T increases if there is a longitudinal magnetic field, indicating that part of the decay, which may be substantial in some instances, is due directly or indirectly to diffusion of charged particles to the wall. The effect on T of varying the radiofrequency power and the strength of the magnetic field are described and discussed briefly, together with a retroactive effect of the decaying discharge on the voltage of the oscillator.

1. Introduction

When a radiofrequency field is applied to the afterglow of a low pressure discharge in mercury vapour the afterglow can persist for over a minute. The time (T) for which it is visible depends on various factors. T is increased by applying a longitudinal magnetic field. The explanation of the observations is that the rf field increases the electron temperature and hence produces additional active radiating species, and the magnetic field directly or indirectly hinders their loss by diffusion to the tube wall. Hopefully a systematic study of how T varies with experimental parameters would permit the evaluation of the various loss mechanisms. This is unfortunately hindered by an apparently unavoidable dependence of the value of the rf field on the intensity (probably mainly the electron content) of the decaying discharge itself. There seems no doubt, however, that diffusion is an important and at times dominant loss mechanism.

2. Experimental arrangement

Investigations have been carried out in the afterglow of a mercury arc. The arc is cylindrical, of length 38·25 cm, and is excited by a DC source with rheostat control. The arc is cooled by the external circulation of air. The output from a radiofrequency oscillator of frequency 4·52 Mc/S. was supplied to the arc through two coupled coils, as shown in Fig. 1.

The applied rf voltage is tuned by the condenser and the rectified DC output voltage is recorded by the DC voltmeter. The level of radiofrequency power supplied by the oscillator was low enough not to cause on its own any breakdown of the gas. The pressure inside the arc was 0·049 torr. To maintain the pressure constant, dry air, which acts as a buffer gas, was introduced by a variable micro-leak needle valve. The arc discharge was run for a few minutes so that a steady condition

Received 9 January 1987; accepted 22 January 1987.

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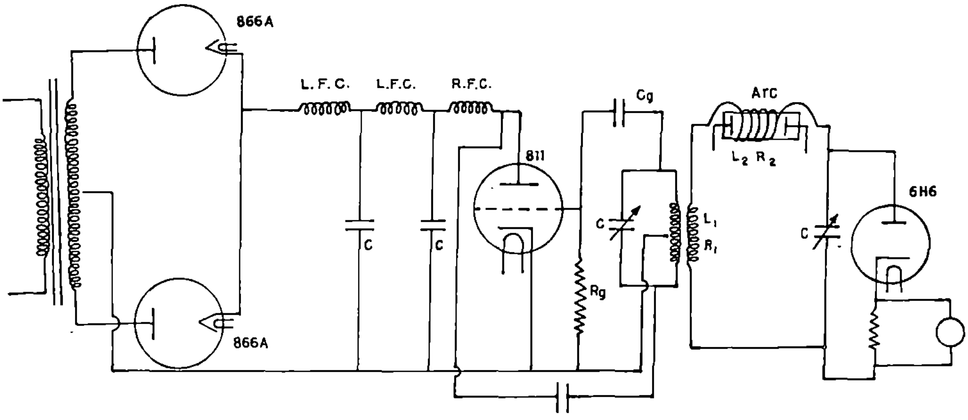

Figure 1. Experimental arrangement.

was reached, and the outside wall temperature noted. When the primary arc discharge was switched off an afterglow appeared and T was recorded by a stop watch with an error of ± 1 s. When there was no radiofrequency power supplied to the arc, no glow was visible. T was measured for different discharge parameters and magnetic fields.

When the arc was switched off, a greenish white glow appeared throughout the whole of the discharge vessel with an rf field present. Thereafter glow in the ends vanished first and ultimately the glow survived only in the central region. Here it was first an ellipsoid, then a sphere and lastly a spheroid. T was taken to be the time interval from the instant when the arc was switched off to the instant when the afterglow finally vanished.

3. Experimental results

These are summarized in Figs. 2–6, the discharges and magnetic parameters being given on the figures and in their captions.

Figure 2 shows how T varies with the time that the arc has been switched on. It is on the basis of the similar tendency towards an asymptote of all three curves that 3 minutes was adopted as the time of switch off in all cases before the afterglow's investigation started.

Figure 3 shows how T varies with arc current. There is a tendency towards saturation which must somehow arise from a corresponding growth in the active species or their precursors in the arc.

Figure 4 shows how T varies with rectified radiofrequency voltage; with an increase in the latter the electron temperature will increase, leading in a variety of ways to an increased concentration of the active radioactive species.

Figure 5 gives an example of how T increases with an increase in the magnetic field; the origin of the tendency to saturation is not entirely clear. It could arise in a number of ways (*cf* Franklin 1976).

Finally, Fig. 6 gives an example (*cf* § 1.) of the disturbing effect of the afterglow (almost certainly the electrons in it) on the rectified radiofrequency voltage.

We have also observed in a number of experiments that the intensity of spectral lines increases in a magnetic field (Sen *et al.* 1972), but a far more detailed analysis

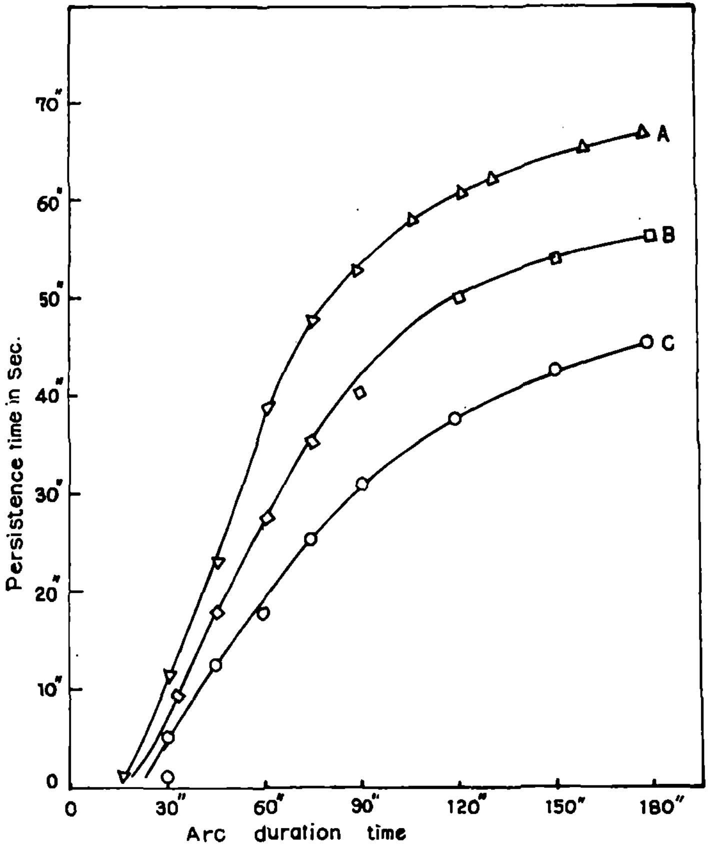

Figure 2. Variation of persistence time T with arc excitation time for fixed current. Curve A—4 A; curve B—3·5 A; curve C—3 A.

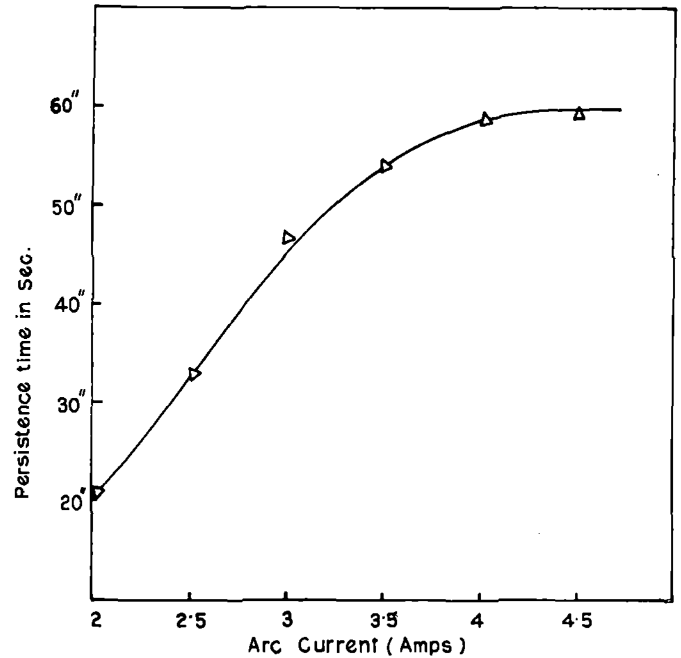

Figure 3. Variation of persistence time T with arc current.

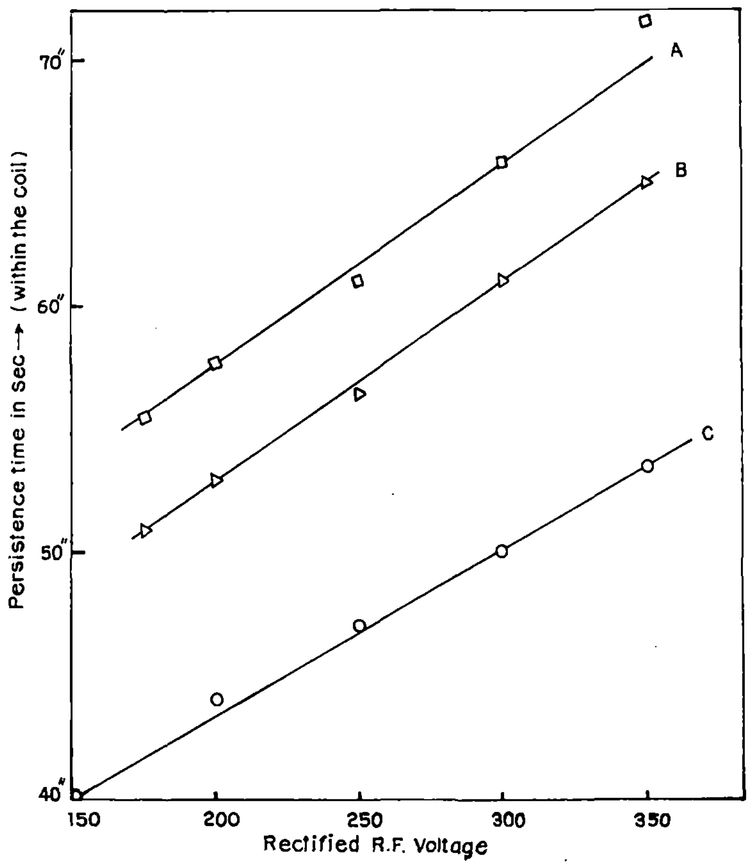

Figure 4. Variation of persistence time T with rectified rf voltage. Curve A—4 A; curve B—3·5 A; curve C—3 A.

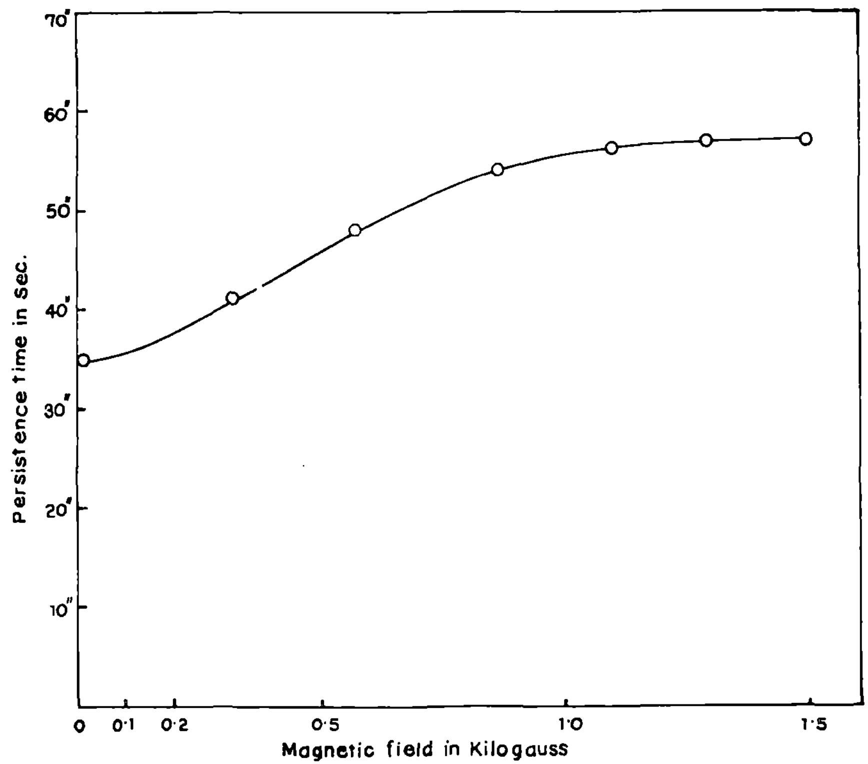

Figure 5. Variation of persistence time T with magnetic field for fixed arc current.

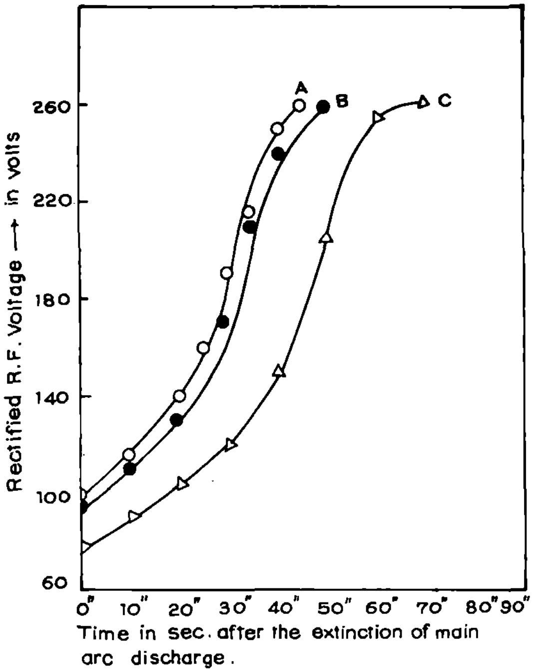

Figure 6. Variation of rectified rf voltage across the arc in the afterglow with time. Curve A—4 A; curve B—3·5 A; curve C—3 A.

of the decaying plasma by the standard techniques will be required before the role of the different possible decay processes, e.g. dissociative recombination, (Kuckes *et al.* 1962) can be ascertained.

ACKNOWLEDGMENT

The authors are indebted to Professor K. G. Emeleus for valuable comments and suggestions for the preparation of the paper.

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© Proc. Indian natn. Sci. Acad., 53, A, No. 4, 1987, pp. 469–477.
Printed in India.

PERSISTENCE OF AFTERGLOW MAINTAINED BY A RADIOFREQUENCY FIELD IN A MERCURY ARC

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(*Received 22 July 1985; after Revision 19 December 1986*)

By applying a radiofrequency field to a mercury arc it has been observed that the persistence time of afterglow increased manifold after the main arc current is switched off. The persistence time has been measured for (*a*) different arc currents (2amp. to 4.5amp.), (*b*) for a fixed current but for different excitation times of the arc discharge (from 15 seconds to 3 minutes) and (*c*) also for different output voltages of the radiofrequency oscillator. The variation is linear over a wide range and the increase of persistence time in afterglow has been ascribed to additional ionization produced by the radiofrequency field and assuming various loss mechanisms such as diffusion, attachment and recombination and utilizing Kihara's theory[1] of radiofrequency discharge, a qualitative explanation of the results has been provided. The imposition of magnetic field increases the persistence time which has been ascribed to the diminution of loss of charged particles due to decrease of diffusion in a magnetic field. It is concluded that loss due to diffusion in such an afterglow plasma dominates over the loss due to recombination and attachment.

Key Words : Afterglow; Radiofrequency Field; Mercury Arc; Plasma Decay

INTRODUCTION

STUDY of the afterglow process in a decaying plasma and the measurements of the coefficient of recombination have been carried out by a large number of investigators. The study has provided us with information regarding the various processes of electron ion, dissociative and radiative recombination and their relative importance in a decaying plasma. The afterglow being considered here is different from that investigated hitherto in the sense that whereas in a normal afterglow the decaying time is of the order of a few microseconds or less, in our experiments the glow was allowed to continue for a few tens of seconds by applying a radiofrequency field which provided additional ionization and allowed the plasma decay at a much slower rate. The object is to study the ionization and loss mechanism in such a decaying plasma. Since the ionization and loss mechanism processes are functions of an externally applied magnetic field, it was thought worthwhile to study the persistence time of such an afterglow in presence of a magnetic field as well.

EXPERIMENTAL ARRANGEMENT

Investigation has been carried out in mercury afterglow in a mercury arc. The output from a radiofrequency oscillator of frequency 4.52Mc/S was applied to the arc

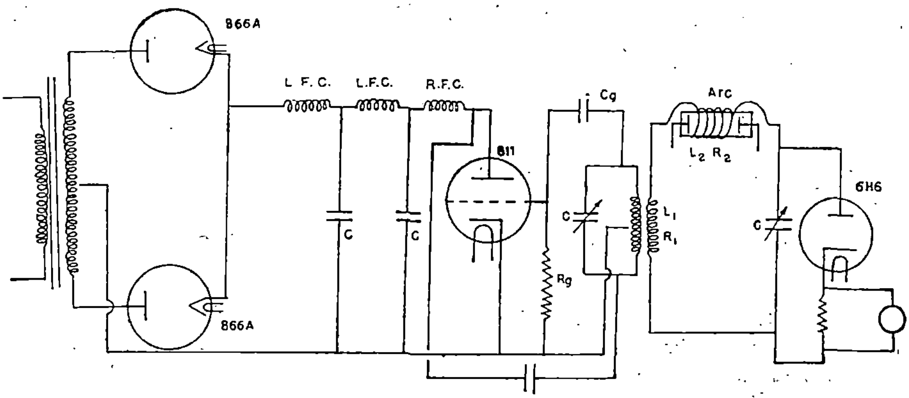

FIG 1 Experimental arrangement.

through two secondary coils as shown in the Fig. 1. The applied r.f. voltage is tuned by the condenser and the rectified d.c. output voltage is recorded by the d.c. voltmeter. The level of radiofrequency power supplied by the oscillator was low enough so as not to cause any breakdown of the gas. The arc discharge was run for a few minutes so that a steady condition was reached. Then the primary arc discharge was switched off. A glow which developed in the wake of switching off of the arc persisted for a few seconds and then disappeared. Time of persistence of the glow was recorded by a stop watch. The glow was measured under different conditions of the discharge and in presence of transverse magnetic field.

RESULTS AND OBSERVATION

The arc is excited for 3 minutes, frequency of the r.f. field is 4.52MHz. Pressure = 0.05 torr. Fig. 2 shows the variation of persistence time T with current varying from 2.5 amp. to 4.5 amp.

The arc current is fixed at 4 amp. Fig. 3 shows the variation of T the persistence time for arc currents 3amp, 3.5amp and 4amp. for different periods of excitation of the arc which varies from 15 seconds to 3 minutes. The variation is initially linear and then shows a tendency of saturation.

To see how the persistence time is dependent on output voltage of the applied r.f. field, the experiment has been performed with a fixed arc current but the applied field is varied. The figure represents results for three arc currents namely 3amp., 3.5amp., and 4 amp. The applied radiofrequency field has been varied from 250 to 350 volts, arc excitation time 3 minutes. The time of persistence becomes a linear function of the applied R F voltage. The same nature of variation is observed for all the three cases of arc current (3amp, 3.5amp and 4amp).

A very important observation has been made with regard to variation of r.f. voltage with time as soon as the main arc current is switched off. It is observed that when there is no arc discharge the measured rectified output voltage of the r.f.

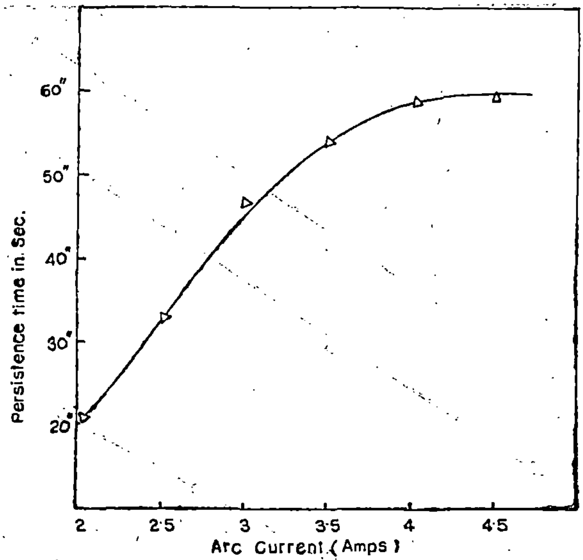

FIG 2 Variation of persistence time with arc current.

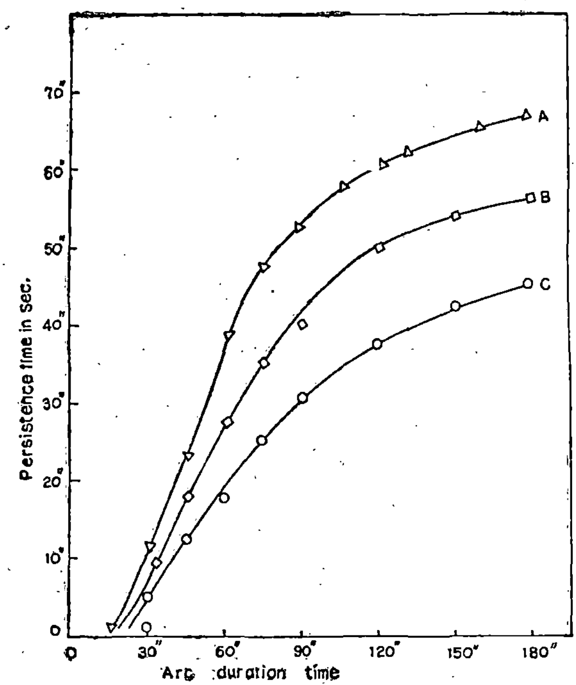

FIG 3 Variation of persistence time with arc excitation time.
A — 4 Amp., *B* — 3.5 Amp., *C* — 3 Amp.

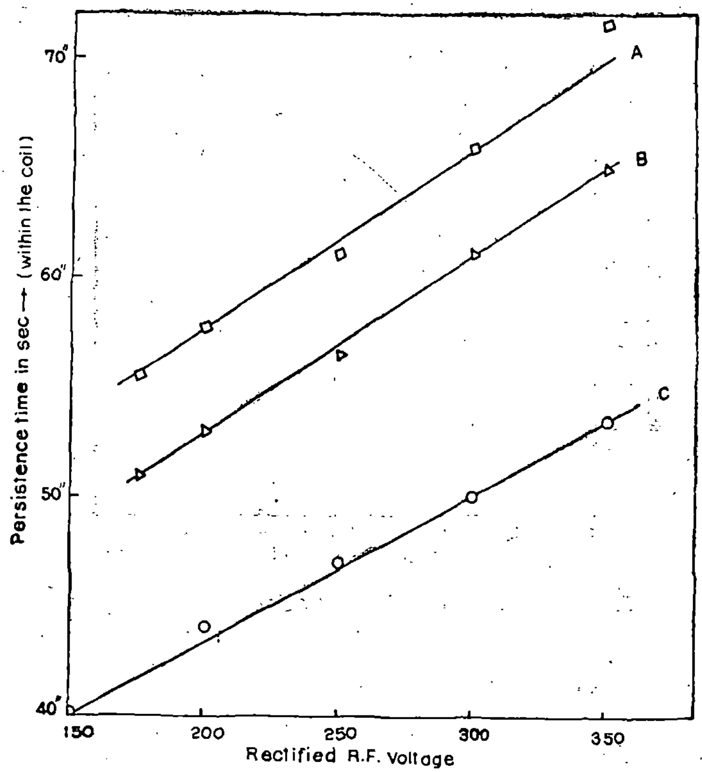

FIG 4 Variation of persistence time with R F Voltage.
A — 4 Amp., *B* — 3.5 Amp., *C* — 3 Amp.

oscillator is 260volts. As soon as the arc is switched on, this rectified voltage drops to 11 volts in case of arc current 2.5amps, to 14 volts in case of 3amps arc current and to 15 volts in case of 4 amps arc current. When the arc is switched off it immediately increases to 100 volts and gradually rises with time until the original voltage is restored when the glow vanishes. The nature of variation is almost similar for three different arc currents. The results are plotted in Fig. 5.

Investigation of the effect of magnetic field on persistence time has been carried out in two ways. In the first set of experiments the magnetic field has been kept fixed at 322 gauss and the arc current has been changed from 2.5 to 4.5amps. Arc duration time is 3 minutes in each case. As in the case without magnetic field persistence time increases with the current though the persistence time with magnetic field is higher than that without field. The same nature of variation is obtained for magnetic fields 580 gauss and 725 gauss (Fig. 6). In the second set of experiments persistence time has been measured keeping the arc current constant and varying the magnetic field. It is observed that persistence time increases with the increase of the magnetic field (Fig. 7).

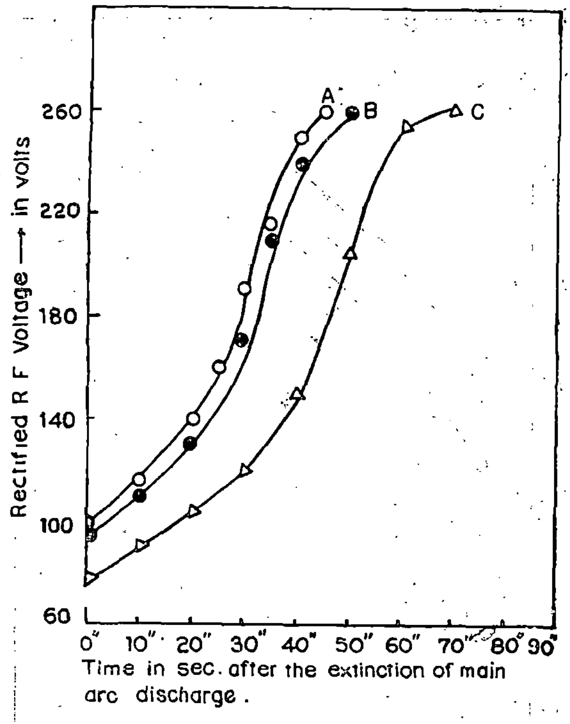

FIG 5 Variation of rectified voltage across the arc in the afterglow with time.
A — 4 Amp., B — 3.5 Amp., C — 3 Amp.

DISCUSSION

The reason for persistence of the glow after extinction of the main arc current may be due to the fact that the flow of arc current has built up a sufficiently high electron density say of the order of 10^{13} electrons per c.c. Since in the absence of the applied r.f. field the glow instantaneously vanishes when the arc current is cut off, we find that the presence of the r.f. field enhances the persistence time of the afterglow to around 50–60 seconds depending upon the arc current. We have ascribed this persistence of the glow to the fresh ionization produced by the r.f. field and the loss of electrons may be due to recombination, diffusion and attachment. It is however not possible to identify the typical loss mechanism which dominates at a particular pressure. It may be solely due to either one of the processes namely recombination, diffusion or attachment or more than one or two processes may be acting simultaneously.

The rate of generation of fresh electrons will be given by νn where ν is the frequency of ionization by the radio frequency field and n is the electron density at the instant of the extinction of the arc; if δ denotes the loss due to various processes then we can write

$$\frac{\partial n}{\partial t} = (\nu n - \delta). \qquad \text{...(1)}$$

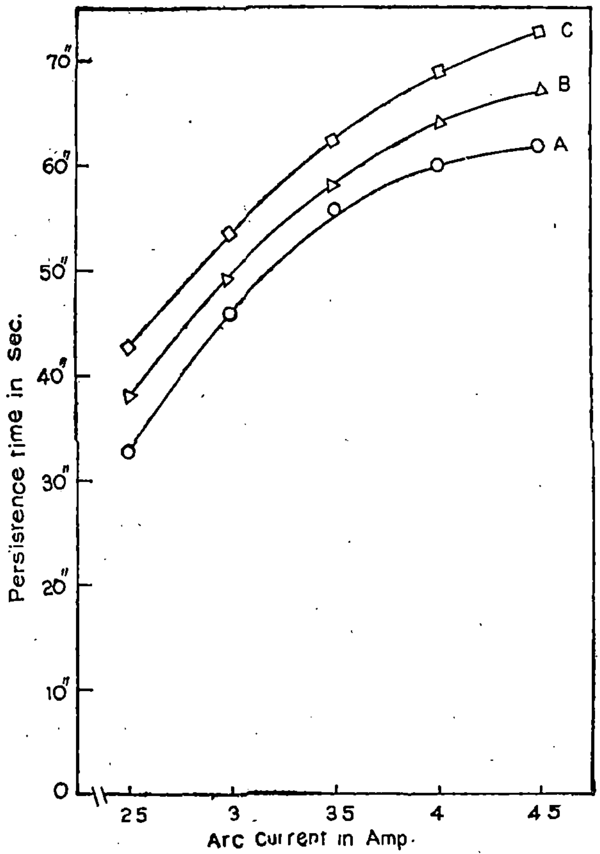

FIG 6 Variation of persistence time with arc current for different magnetic fields. A — 322 gauss, B — 560 gauss, C — 725 gauss.

From the two sets of observations recorded in Figs. 2 and 3, the rate of fresh ionization by the radiofrequency field is seen to depend upon the instantaneous electron density and the same will be larger for higher arc current. As the rate of ionization process will increase with n that is with arc current the time of persistence will naturally increase with the arc current.

Besides the increase of electron density with the increase of the arc current another factor namely the heat generated in each case is also increasing. Because in the first set of observations, currents have been increased step by step with the same time duration and hence for each observation the heat developed is proportional to i^2, where i is the current and which has increased the temperature of the gas. In the second set of observations gas temperature has also increased for each observation because time duration has been gradually increased for each observation keeping the current constant at a fixed value.

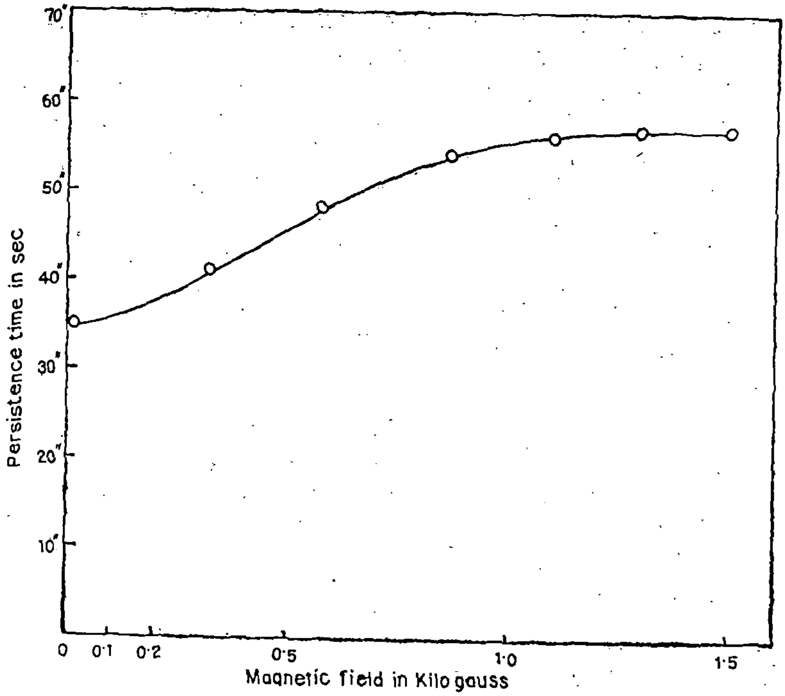

FIG 7 Variation of persistence time with magnetic field for a fixed arc current.

Taking the expression for ν as deduced by Kihara[1]

$$\nu = N \frac{3\sigma}{C_i} \frac{KT_e}{m} \exp\left[-\frac{mC_i^2}{2KT_e}\right], \qquad \ldots(2)$$

where σ, C_i are molecular constants introduced by Kihara, N is the number of molecules at 1 torr, and T_e is the electron temperature. As shown by Persson[2]

$$T_e = T_g + \frac{M}{3K}\left(\frac{eE}{m\nu_m}\right)^2, \qquad \ldots(3)$$

which shows that T_e increases with the increase of T_g and hence ν increases, which increases the persistance time. From Fig. 5, it is evident that as the magnitude of the applied radio frequency field is gradually increased for a constant value of the arc current, T, the time of persistance of the afterglow increases linearly. This is true for the three arc currents studied; putting the value of KT_e in the expression for ν as deduced by Kihara we get

$$\nu = \frac{3eE\sigma}{C_i(3\lambda\rho)^{1/2}} \exp\left[-\frac{mc_i^2 N(3\lambda\rho)^{1/2}}{2eE}\right] \qquad \ldots(4)$$

and since according to our previous argument the persistence time T will be proportional to ν which to a certain approximation is proportional to E it is evident that persistance time will be proportional to E, for constant arc current.

It is observed from the measurement of persistence time in presence of transverse magnetic field that persistence time increases when the magnetic field is present than in its absence. This is evident for the three magnetic fields namely 322 gauss, 580 gauss and 725 gauss, for the variation of arc current from 2.5 to 4.5 amp. The discharge tube was allowed to cool in the same environment during the time of recording. Magnetic field was switched on just before the switching off of the arc current. Visually it was observed that as magnetic field increases the radiofrequency glow becomes brighter. We have observed in a number of experiments that the intensity of spectral lines increased in a transverse magnetic field.[3,4] The enhancement of intensity of afterglow points to the fact that the afterglow is due mainly to the radiofrequency discharge created by the externally applied radio frequency field.

The magnetic field also effects the continuance of the afterglow phenomena in another way. As we have already mentioned the loss of charged particles is due to recombination, attachment and diffussion and it is difficult to ascertain which loss process predominates. If we assume that loss of charged particles is due to diffusion then as is well known the diffusion coefficient decreases in presence of magnetic field according to the relation

$$D_H = \frac{D}{1+\omega_B^2\tau^2}, \qquad \ldots(5)$$

where $\omega_B = \left(\frac{eB}{m}\right)$ the cyclotron frequency and τ is the time for collision between charged particles and neutral atoms and molecules. As diffusion of charged particles towards the wall decreases the energy carried by the charged particles towards the wall where they are neutralised by recombination also decreases. Hence, the rate of loss of charged particles decreases whereas the ionization frequency ν_H due to radiofrequency field in presence of magnetic field is not changed by a significant factor.[5] Consequently the net life time of charged particles in the afterglow increases which can explain the enhancement of persistence time in presence of magnetic field.

It is difficult to isolate the loss process which predominates as has been mentioned earlier. The pressure inside the arc and its size can be so chosen that recombination may dominate over diffusion. In that case the magnetic field should not have any effect on the persistence time and if the losses do not depend on magnetic field dissociative recombination is the only dominating loss mechanism in the afterglow plasma. This is the same argument that was put forward by Kuckes *et al.*[6] while investigating the decay of helium plasma in Bi Stellarator. As they observed that loss rate is independent of magnetic field between 2.9 and 3.5 kilogauss it was concluded that plasma was recombination dominated and loss due to diffusion can be regarded as negligible. In this investigation, we have however, recorded the persistence times only. Generally for a fuller information of afterglow, densities of different particles are measured as a function of time. The results are then analysed with the rate or continuity equations of particles and with a knowledge of electron temperature relaxation different macroscopic coefficients for the particles are measured. Simply a knowledge of persistence time cannot give a clear picture of the decay rates of particles. Lastly, the disappearence of occurrence of a discharge was inferred visually by observing the glow. So when the glow vanished we considered that the afterglow ceased to exist. But the decay rates of charged particles may be different from the decay rate of excited atoms which are responsible for creating the visual picture of the glow. Generally, it is believed that during the decay, production of new charged particles ceases and concentration of charged particles then decreases by different loss mechanisms such as recombination and ambipolar diffusion approaching a finite but very small value. However, for an analysis of experimental data we have correlated the visual glow with the plasma since the radiation is definitely an electron atom process, (either it is a recombination radiation or an electron excitation radiation).

Attempts are being made to put forward an analytical explanation of the observed results.

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