STUDIES OF THE VACUUM CIRCUIT-BREAKER ARC

by

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# List of Principal Symbols

(in order of use)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>s</td>
<td>c.s.a. of cathode spot $m^2$</td>
</tr>
<tr>
<td>I</td>
<td>current $A$</td>
</tr>
<tr>
<td>J</td>
<td>current density $A/m^2$</td>
</tr>
<tr>
<td>$x_{k}$</td>
<td>no. of neutral atoms and ions leaving cathode region and entering column/sec $sec^{-1}$</td>
</tr>
<tr>
<td>W</td>
<td>net evaporation rate into column $kg/C$</td>
</tr>
<tr>
<td>$m_{k}$</td>
<td>weight of one atom of cathode material $kg$</td>
</tr>
<tr>
<td>$n_{k}$</td>
<td>atom concentration (including ions) $m^3$</td>
</tr>
<tr>
<td>$v_{k}$</td>
<td>mean neutral atom radial velocity $m/s$</td>
</tr>
<tr>
<td>$\lambda_{i}$</td>
<td>ionization mean free path $m$</td>
</tr>
<tr>
<td>$\sigma_{i}$</td>
<td>ionization cross-section $m^2$</td>
</tr>
<tr>
<td>$\gamma_{e}$</td>
<td>electron-atom collision frequency $sec^{-1}$</td>
</tr>
<tr>
<td>$\theta$</td>
<td>angle from vacuum arc axis $rads.$</td>
</tr>
<tr>
<td>$x_{e}$</td>
<td>no. of electrons leaving cathode region/sec $sec^{-1}$</td>
</tr>
<tr>
<td>$x_{i}$</td>
<td>no. of ions leaving cathode region/sec $sec^{-1}$</td>
</tr>
<tr>
<td>d</td>
<td>radial distance from cathode spot $m$</td>
</tr>
<tr>
<td>$\rho_{e}$</td>
<td>electron density $m^3$</td>
</tr>
<tr>
<td>$\rho_{i}$</td>
<td>ion density $m^3$</td>
</tr>
<tr>
<td>$v_{e}$</td>
<td>mean radial electron velocity $m/s$</td>
</tr>
<tr>
<td>$v_{i}$</td>
<td>mean radial ion velocity $= v_{k}$ $m/s$</td>
</tr>
<tr>
<td>$\sigma_{e}$</td>
<td>total electron-atom cross-section $m^2$</td>
</tr>
<tr>
<td>$U_{e}$</td>
<td>mean electron thermal velocity $m/s$</td>
</tr>
<tr>
<td>$T_{e}$</td>
<td>electron temperature °K</td>
</tr>
<tr>
<td>$m_{e}$</td>
<td>electron mass $kg$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>recombination coefficient $m^3/s$</td>
</tr>
<tr>
<td>$\varepsilon_{r}$</td>
<td>relative dielectric constant $m^{-1}$</td>
</tr>
<tr>
<td>q</td>
<td>electron line density $m$</td>
</tr>
<tr>
<td>r</td>
<td>radial distance from vacuum arc axis $m$</td>
</tr>
<tr>
<td>$\varepsilon_{n}$</td>
<td>$= 1$ for $n = 0$, and $= 2$ for $n &gt; 0$</td>
</tr>
<tr>
<td>$f$</td>
<td>normalised back-scattered field amplitude $V/m$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>skin depth $m$</td>
</tr>
<tr>
<td>$E_{i}$</td>
<td>incident electric field $V/m$</td>
</tr>
<tr>
<td>$E_{r}$</td>
<td>reflected electric field $V/m$</td>
</tr>
<tr>
<td>C</td>
<td>reflection coefficient $</td>
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\( E_r \) reference electric field

\( f \) degree of ionization in column = \( \frac{x_i}{x_k} \)
CHAPTER 1

Background to this Research

1.1 Introduction

The principles which make the vacuum circuit-breaker attractive to electrical engineers have been recognized for many decades, but it is only very recently that the necessary technology for its manufacture has become sufficiently sophisticated to allow commercial exploitation. One of the most significant features of the recent achievements in the field has been the extent to which success in manufacture has depended on a careful prior study of the physical processes which occur during arcing in high vacuum. In this introductory chapter we shall sketch this development of the vacuum circuit-breaker, often referred to as a "vacuum switch", up to its present-day performance, and then explain the aims of the research work described in succeeding chapters.

1.2 Development of the vacuum circuit-breaker

The excellent dielectric properties of high vacuum were recognized some years before the end of the last century, and Reece (1) refers to a report of a patent filed in 1893 for a vacuum switch. P.H. Thomas, in the discussion following the presentation of the original paper by Sorensen and Mendenhall (4), mentioned work he carried out on vacuum switches with mercury and solid electrodes in 1906, and he noted then the tendency for the solid cathode vacuum arc to "chop" when interrupting alternating current; when the current had fallen to a few amperes just prior to current zero, the arc tended to snap out suddenly. The first major research effort, however, was carried out under Sorensen (4,5) at the California Institute of Technology during 1923-29, and a single sealed-off device successfully interrupted 926 A on a 41.5 kV 60 c/s supply. The patents
for the switches were taken over by the General Electric Company in 1929, but
apart from 3 papers on low power vacuum switches in the 1930's, no work was
published from their laboratories on their efforts to develop high power vacuum
switches until the review paper by Cobine (6) 33 years later in 1962. The
eyear work had had promising results, with switches clearing over 5 kA, but gas
evolution from the electrodes was a major difficulty, and economies brought on
by the Depression caused work to cease in 1931, not to resume as an intensive
effort until 1952.

At the University of California, Koller (7) made a notable attempt to im-
prove physical understanding of vacuum switch operation. He realised that
the very high rate of recovery of dielectric strength in the switch after arc-
ing is due to the high velocity with which the emitted vapour diffuses outwards
from the cathode. For this average velocity, however, he assumed a value based
on thermal motion for a cathode temperature of a few thousand degrees Kelvin,
and thus appears to have been unaware of the considerable discussion in the
1930's which followed the publication of a paper by Tanberg (8) indicating velo-
cities an order of magnitude greater than predicted by kinetic theory. Koller
studied the operation of the vacuum switch for interrupting direct current, and
concluded that for reduced gas evolution and a higher interrupting level, re-
fractory metals such as tungsten were most suitable for the electrodes. He
mentions for the first time how the small contact spacings required in vacuum
allow the design of fast mechanisms which interrupt alternating current close
to current zero, and thus reduce erosion.

Khalifa (9) in 1956 reported experiments to determine the effect of con-
ditioning materials for use as electrodes in vacuum circuit-breakers. Un-
fortunately, he used machine steel for the electrodes, and tested only the
dielectric strength of a static gap, the erosion rate, and the recovery rate
in a continuously pumped switch. That he failed to recognize that despite the conditioning there was considerable gas evolution during arcing is suggested by the relatively low recovery rate of his switch, and also by the mention of anode spots at the relatively low currents at which he worked (less than 220 A).

Vacuum switches originally produced for switching R.F. power in radio and radar apparatus were developed by the Jennings Radio Manufacturing Company into medium power circuit-breakers (10,11) from about 1950, but the literature published suggests a very empirical approach in their design, and does little to further understanding of the vacuum arc. The papers concern mainly applications of the switches, their primary use being to switch in and out sections of high voltage capacitor banks. For this application, microsecond recovery rates are not required, but after one half-cycle a switch which has isolated a unit of the bank must withstand twice the peak bank voltage, and so the switch must achieve full dielectric strength in a few milliseconds, with very high reliability; breakdown of such a switch could have serious consequences. It is clear from the discussion after these papers that by now the phenomenon which Koller had found made the vacuum switch with refractory electrodes attractive for interrupting D.C., namely the tendency to chop at low currents, was proving a hindrance to the application of such switches to inductive circuits, because of the over-voltages produced. Ross (11) claimed that chopping could be reduced with the Jennings switches both by slow initial contact velocity just after break, and also by shunt capacitance across the contacts, but neither method is very attractive.

In a series of E.R.A. reports in 1959, Reece published the first major effort (1,2,3) to relate both previous work and his own studies of the vacuum arc to the design of vacuum switches. He showed that the vacuum arc has two forms. At currents below about 10 kA, the arc consists of a number of
individual cone-shaped columns, emanating from cathode spots which run around the cathode surface at a fairly high random velocity. The electrode erosion is fairly low. Above some critical current, the arc has only a single, stationary, very luminous column, and there is severe electrode erosion. When the arc takes this second form, the vacuum switch fails to interrupt the current. Reece's main efforts were directed towards a high current handling capacity, and minimizing erosion. The highest current interrupted at power frequencies was 10 kA, with simple butt contacts of vacuum cast copper. In this and subsequent work the evolution of gas from the electrodes was significant, the pressure in a 1 litre enclosure rising from $10^{-5}$ Torr to over $10^{-3}$ Torr, implying even higher pressures between the contacts.

In 1962 the results of the extensive efforts over the previous 10 years at the General Electric Company were published in a series of papers, collectively reviewed by Cobine (6) and Lee et al. (12). The switches produced have electrodes which have a high vapour pressure constituent which provides sufficient metallic vapour at low currents to maintain conduction, and since these high vapour pressure materials usually have poor mechanical strength, they are impregnated in or alloyed with a metal such as copper or silver. The resultant switches chop at currents of 2 A or less (13,14), compared with about 4 A for copper alone. The problem of gas evolution was overcome by use initially of single crystal copper, but later techniques were evolved for zone-refining the electrodes. The current interrupting level was improved by rapid movement of the arc over the electrodes under the action of its own magnetic field (15), and by careful design of a vapour-condensing shield around the electrodes (16). This latter patent mentions abnormally high arc voltages which occur at currents of 18 kA and above, and are probably associated with the change of arc type mentioned earlier by Reece.
1.3 Object of this Work

It can be seen from the work summarised above that real progress in the design of vacuum circuit-breakers has only resulted when an attempt has been made to understand the physical processes in the vacuum arc. It is the aim of this present research to investigate the application of a microwave diagnostic technique to a vacuum arc, to provide further data to assist the design of vacuum circuit-breakers. Apart from voltage and current measurements, the following measurements have previously been made to study the arc:

1. Erosion rate at cathode and anode. (1, 7, 9, 24, 29)
2. Vapour deposition rate on a vane between the electrodes. (1, 8, 28)
3. Force exerted on the cathode, and on a vane suspended in front of the cathode. (1, 8, 28)
4. Optical spectroscopy. (21, 22)
5. High-speed photography. (1, 23)
6. Electron beam probing. (60)
7. Mass spectroscopy. (24, 25, 26)
8. Ion energy analysis. (24)
9. Probe measurements outside the arc column. (31)

Although apparently existing in perhaps the ideal environment for uncontaminated arc studies, the vacuum arc has proved a difficult subject for investigation because of its small size, its inhomogeneity, the low luminosity of its column, and its erratic movement. Many of the techniques listed above have given conflicting results, and from the vacuum circuit-breaker point of view have been carried out with very unrealistic electrode structures. Following previous work in this University Department on circuit-breakers and microwave probing of gas discharges, it was decided to investigate how microwave techniques might be applied to the vacuum arc. It was desirable that the arc be as similar as possible to
that which exists in the vacuum circuit-breaker, i.e. it was to be a drawn arc. Measurements on both the burning arc and on the decaying arc products after current zero or after current chop were to be attempted with high time resolution. The first would yield new data on the electron concentration and velocity in the arc column, and the latter information on the rate of decay of the arc plasma.

1.4 Layout of thesis

Chapter 2 contains a summary of existing data on the vacuum arc, which is then used to construct a model for the arc column. This then is used in the next chapter to relate computations on microwave scattering from an idealised plasma cylinder to the realistic arc structure. Chapter 4 describes the microwave measurement technique evolved, and chapter 5 the synthetic test circuit, vacuum system and high speed vacuum switches constructed. The next chapter describes the results of high speed filming and microwave probing of the arc, and finally chapter 7 reviews the measurement technique and recommends some fields in which future work might be carried out.
CHAPTER 2
The Vacuum Arc

2.1 Definition of the vacuum arc

The term "vacuum arc" is somewhat of a misnomer, since no conduction path could occur in a perfect vacuum, because there could be no charge carriers. It refers to low voltage high current discharges, say greater than 0.1 A, which occur in a vacuum when a conduction path is formed solely by evaporation of one or both electrodes between which conduction occurs. The term "vacuum" implies that at ambient temperatures the vapour pressure of both electrodes is very small, say less than $10^{-9}$ Torr. A conduction path can only be formed when the electrode or electrodes are heated to their boiling point by some process, and sufficient vapour is then evaporated to allow passage of large currents. From the above definition we can thus distinguish the vacuum arc from a vapour arc, such as the mercury arc, where the vapour pressure of the mercury is relatively high at ambient temperatures, and also from the gas arc, where the conduction path is not formed solely by evaporation of the electrode or electrodes. Within each of these groups, many sub-divisions may be made, within different ranges of such parameters as current, rate of rise of current, gas pressure, electrode configuration, and so on.

We shall be concerned with a "cold-cathode" arc; Kesaev (17) defines this as an arc in which no part of the cathode is heated to a temperature at which thermionic emission is appreciable. This thus applies to arcs on most common metals, the limitation to achieving appreciable thermionic emission being their relatively low boiling points. The general appearance of such a vacuum arc with copper electrodes may be seen in fig. 2.1. This is a single frame from a high-speed colour film taken during the tests described in section 6.2. While the colour validity is not good when a normal colour film is exposed for such
short durations (the exposure time here was 40 \(\mu\)secs.), the arc shows a blue-green colour which is characteristic of copper, demonstrating that it is in this vapour that the arc burns. We shall consider the arc as having three regions:

(i) The cathode spot on the metal, which is luminous but usually masked by region (ii), is of very small dimensions, typically 100\(\mu\) diam. at 25A, and has a high mobility over the cathode surface. When the current exceeds about 200 A, further spots appear, each carrying 25 - 100 A.

(ii) The cathode high pressure region, which is separated from the cathode spot by a very short cathode fall, and is the region in which evaporated atoms may be ionized. The luminous intensity is very high, as may be clearly seen in fig. 2.1.

(iii) The arc column, which spreads outwards from the cathode region in an ill-defined cone, and is of low intensity. It is this region which microwave probing will investigate.

2.2. The cathode spot

For completeness, a brief description is given here of the most probable emission process at the spot, but fuller summaries may be found elsewhere (e.g. ref. 17). In considering theories for the emission process at the cathode, the distinctions between the Richardson-Dushman-Schottky theory for thermionic emission, and the Fowler-Nordheim theory for field emission (18), become blurred. The former theory assumes a low field, so that electrons approaching the potential barrier at the surface from within the metal have a negligible probability of tunnelling through the barrier; those with energies greater than the height of the barrier are emitted with unity probability, those with less are not emitted. On the other hand, the original field emission theory
assumed the metal temperature to be so low that no electron had sufficient energy to pass above the potential barrier. Fowler and Nordheim used the then new wave mechanics to calculate the probability for electrons to tunnel the barrier for a given electric field at the surface. In the cold-cathode vacuum arc, however, it was found that neither the approximations of low field at the cathode, nor low temperature, may be made. In 1956, Murphy and Good (19) developed an expression for the current density at the cathode which made no approximations regarding field or temperature, and Lee (20) showed that this thermionic-field (T-F) emission could explain satisfactorily the emission processes which occur in cold-cathode arcs. The high field is caused by ions formed above the cathode by emitted electrons which have been accelerated in a very short cathode fall region, around $10^{-5}$ to $10^{-6}$ cm. The cathode spot is maintained at a high temperature both by the ionization energy of the incoming ions, and by their kinetic energy gained from the cathode drop. The temperature is somewhat higher than the cathode boiling point, and evaporating atoms supply the vapour for ionization in the region above the cathode.

There have been many other theories for the emission process, mostly concerned with justifying in some way either thermionic or field emission, for example by abnormally high boiling points or insulating layers on the cathode. T-F emission has the merit of fitting experimental data on current density and temperature without recourse to anomalous effects.

2.3 The cathode region

The processes which occur in the high pressure region above the cathode are not well understood, and because of the small dimensions, measurements are difficult. However, some understanding may be gained from data on the particles which are emitted into the arc column. Tanberg (8) in 1930 reported an experiment
in which he suspended a vane in front of the cathode of a vacuum arc, and measured both the rate of deposition on the vane, and the force exerted on it. From this he was able to calculate that the mean velocity of the particles coming from the cathode region was about $2 \times 10^4$ m/sec, and this he attributed to a temperature in the high pressure region of $5 \times 10^5$ K. Spectroscopic measurements (21) directly above the cathode showed strong copper lines superimposed on a weak continuous spectrum. It is believed that the lines originate in the cathode region, and the continuous spectrum at the spot on the metal surface, and so Tanberg's observation that the continuous spectrum was similar to that of a copper wire heated near to its melting point was largely irrelevant, if the particles gained energy in the cathode high pressure region. St. John and Winans (22) have shown that the lines exhibit Stark broadening due to a very high electric field near the cathode, but the only spectroscopic indication of temperature near the vacuum arc cathode is in a footnote to a recent paper by Gurov et al. (23), which states that the temperature does not exceed 40,000 K. Ions are emitted from the region into the arc column, and using a mass spectrometric technique, Plyutto et al. (24) showed that Cu$^+$, Cu$^{2+}$, Cu$^{3+}$, and Cu$^{4+}$ ions exist. By measuring the relative concentrations of these multiply-charged ions, and fitting the distribution to the Saha equation, Franzen and Schuy (25-27) have shown that the lower limit to the temperature is 15,000 K, with a median value of 20,000 K. That these very high temperatures should exist close to the cathode spot, which is at a temperature not exceeding 3,500 K, is surprising, but it should be kept in mind that the spot is always in rapid motion, and gross melting occurs when this motion ceases at very high currents. Further spectroscopic measurements would be valuable, but for this work we will assume that the temperature in the cathode region has an upper limit of 20,000 K.
Measurements of the force on the vane were repeated several times, always with results of around 10^6 m/sec. for the particle velocities from copper, and these have agreed well with kinetic energy measurements (28). That these particles should comprise both atoms and ions is not unreasonable, since if there are no ionizing collisions in the column, and yet there is only a very low electric field, as has been shown by Reece (1), then there must be a plasma with ions supplied, along with the electrons, from the cathode high pressure region. It can also be seen from the measurements of Plyutto and others that the velocities of the ions must be similar to those of the neutral vapour in the column, and this is consistent with the accelerating process occurring in a region where the mean free path is short. Another important effect of the low pressure in most of the column is that the ions and atoms move in straight lines without collisions. They thus tend to move out radially from the high pressure region, and Plyutto (24) concluded from measurements with small vanes that the particles had a cosine distribution around the spot. This confirms the diffuse cone-shaped appearance of the column (fig. 2,1) and is a rather more reasonable distribution than the precise conical shape assumed by Reece. Accordingly, we shall adopt a cosine distribution, and assume a mean radial velocity of atoms and ions of 10^6 m/sec.

The other parameter which has frequently been measured in vacuum arcs is the net erosion rate of the cathode. For copper, this has varied from 17 \mu\text{gm/C} (Tanberg), through 70 \mu\text{gm/C} (Reece), to 200 \mu\text{gm/C} (Burger, Cobine and Vanderslice, 29). What we really require for the column model, however, is the rate at which atoms and ions enter from the cathode region, and this may be very different. Burger et al. quote a net gain in anode weight only 10% of the cathode loss, though this may partly be due to low accommodation coefficient
if the anode heats, and Plyutto claims that 60-80% of the material evaporated from the spot may be scattered at low angles along the cathode surface. The latter author has also compared the cathode loss with the rate of deposition on a vane above the cathode, and quotes a 2:1 ratio. We shall assume that the total mass of atoms and ions entering the column may lie between 10 and 100 \( \mu \text{g/m} \).

The current density at the cathode spot has been estimated from erosion markings to be around \( 2 \times 10^5 \, \text{A/cm}^2 \) (ref. 30), giving a spot diameter of about 0.13 mm. for a 25 A arc. We may estimate the density at the anode side of the cathode region if we assume the region has roughly this same diameter:

\[
S = \frac{I}{J} 
\]

and

\[
\chi_k = \frac{WJ}{m_k} 
\]

Thus

\[
\eta_k = \frac{\chi_k}{S \nu_k} = \frac{WJ}{m_k \nu_k} 
\]

For copper, with \( W = 50 \times 10^3 \, \text{kg/C} \), this gives a concentration of \( 10^{23} \, \text{atoms/m}^3 \), corresponding to a pressure of 206 Torr if the cathode region is at a temperature of 20,000 °K, and 36 Torr if it is at 3,500 °K. Now this concentration must be the lower limit for the concentration in the cathode region, since the vapour is emitted from the cathode spot with a much lower thermal velocity, and some acceleration process occurs in this high pressure region. If we assume an ionization cross-section for copper of about \( 4 \times 10^{20} \, \text{m}^2 \) for 20 volt electrons, and a density within the region of \( 10^{24} \, \text{atoms/m}^3 \), then the extent of the cathode region is of the order of the ionization mean free path,

\[
\lambda_i = \frac{1}{\eta_k \sigma_i} = 2.5 \times 10^{-6} \, \text{m} = 25 \times 10^{-4} \, \text{cm}
\]

Thus for microwave interactions with the arc, we need only consider the arc column.
2.4 The vacuum arc column

Microwave reflections from the arc column will be dependent on the electron density distribution, and it will also be necessary to know something about the electron collision frequency $\gamma_e$, and whether recombination processes are important. While the mean radial ion velocity is well established, there is little information on the mean electron velocity. Tyulina (31) in a recent paper concluded from probe measurements that either the electron and ion velocities are equal, or alternatively that the electron velocity is not greater than 1.5 times the ion velocity. His first conclusion is rather unlikely, since it implies no current flow, and it will be shown later that his alternative conclusion implies improbably high cathode evaporation rates. Reece (1) obtained a figure of $10^6 \text{m/sec.}$ from an energy balance, but it is possible to doubt some of the estimates made in his calculation. In particular, the balance is very dependent on a calorimetric measurement of the distribution of arc energy between the anode and the cathode. From the electrode configuration shown, it would be expected that the arc would run around the edges of the electrodes, and energy not accounted for would then be lost in the vapour reaching the walls of the chamber. The low angle evaporation mentioned by Plyutto would also affect this measurement. The recently reported gross cathode erosion rates of 200 and 130 $\mu \text{gm/C}$ (refs. 29 and 24 resp.), if nearer the correct value than that of 70 $\mu \text{gm/C}$ used by Reece, would also affect the balance considerably, leading to lower values for the electron mean velocity. It was hoped that the microwave measurements described here could provide new data on the electron concentration and velocity.

We shall now derive a model for the column assuming a cosine distribution for the emitted atoms, ions and electrons (see fig. 2.2). This means that any
such particle leaves the cathode region in the direction $\theta$ with a probability proportional to $\cos \theta$. Then it can be shown that in the direction $\theta$, over the angle $d\theta$, the fraction of the emitted electrons travelling in this direction is $\sin 2\theta d\theta$. Thus the number of electrons/sec. in this direction is

$$x_e \sin 2\theta d\theta$$

(2.4)

Thus the total electron current between cathode and anode is

$$I_e = \frac{\pi L}{2} e x_e \sin 2\theta \cos \theta d\theta$$

$$= \frac{\pi}{3} e x_e$$

(2.5)

and since the ion current is

$$I_i = -\frac{\pi}{3} e x_i$$

(2.6)

the total current is

$$I = \frac{\pi}{3} e (x_e - x_i)$$

(2.7)

From (2.4), the electron density at radius $d$, angle $\theta$, is seen to be

$$n_e = \frac{x_e \cos \theta}{\pi d^2 \nu_e}$$

(2.8)

and

$$n_i = \frac{x_i \cos \theta}{\pi d^2 \nu_i}$$

(2.9)

For neutrality, $n_e = n_i$

$$\therefore \frac{x_e}{\nu_e} = \frac{x_i}{\nu_i}$$

(2.10)

Thus in (2.7)

$$I = \frac{\pi}{3} e x_e \left(1 - \frac{\nu_i}{\nu_e}\right)$$

(2.11)
Substituting for $\chi$ in (2.8)

$$n_a = \frac{3/2}{\pi^2} \frac{I \cos \theta}{d \pi^2} \left( \frac{\nu_e - \nu_i}{\nu_k} \right)$$  \hspace{1cm} (2.12)$$

$$\therefore (\nu_e - \nu_i) = \frac{3/2}{\pi^2} \frac{I \cos \theta}{d \pi^2} \frac{\nu_k}{n_a}$$  \hspace{1cm} (2.13)

Thus if $n_a$ can be fixed at any known position $(d, \theta)$ for an arc carrying current $I$, then $(\nu_e - \nu_i)$ can be found. This we will use in Chapter 3.

For microwave measurements, we must consider the electron-atom collision frequency; this is given by

$$\gamma_e = n_k \sigma_e \bar{c}_e$$  \hspace{1cm} (2.14)$$

Now

$$n_k = \frac{-x_k \cos \theta}{\pi d^2 \nu_k}$$  \hspace{1cm} (2.15)$$

using (2.2)

$$= \frac{W I \cos \theta}{\pi m_k d^2 \nu_k}$$  \hspace{1cm} (2.16)$$

Thus

$$\gamma_e = \frac{W I \sigma_e \bar{c}_e \cos \theta}{\pi m_k d^2 \nu_k}$$  \hspace{1cm} (2.17)$$

An absolute upper limit to the collision frequency will be obtained by assuming the electrons to have a thermal velocity corresponding to a cathode region temperature of 20,000 °K.

This is

$$\bar{c}_e = \sqrt{\frac{8}{\pi \mu \frac{k T_e}{m_e}}}$$  \hspace{1cm} (2.18)$$

$$= 8.8 \times 10^5 \text{ m/sec.}$$

The electron energy is $\sim 2.5$ eV, and we assume that the total electron-atom collision cross-section for copper is $3 \times 10^{-19} \text{ m}^2$. For $I = 25$ A, $\nu_k = 10^4$ m/sec., $W = 10 - 100 \mu g m/C$, we may find out how $\gamma_e$ varies along the axis of
the column if $\beta = 0$.

From (2.14) \[ \gamma_e = \frac{53}{d^1} \text{ to } \frac{530}{d^2} \text{ collisions/sec.} \]

The collision frequency along the axis of the column is plotted in fig. 2.3, for a gap of 3 mm. The operating frequency is 9375 Mc/s, as indicated. It will be seen that even with 100 $\mu$gm/C of material injected into the column, and with the electron temperature at its maximum value, $\gamma_e \ll 9375$ Mc/s over most of the column.

Recombination in a plasma may be described by

\[ \frac{dn_i}{dt} = -\alpha n_i^2 \]  \hspace{1cm} (2.19)

where $\alpha$ is the recombination coefficient, which may be taken to lie between $10^{-16}$ and $10^{-14}$ m$^3$/sec. for all recombination processes. The loss rate is seen to be very dependent on the ion density, and in fact proves to be negligible except near the cathode spot. Here the above model breaks down, for it assumes a point source for the emitted particles, and a better model would assume an emitting surface. An analysis of the total recombination loss becomes complex, and so a crude model assuming all recombination occurred in a small cylindrical volume above the cathode spot was used. This gave the fraction of ions lost by recombination in the column to lie between 0.01$p$ and $p$, where $p$ is the degree of ionization, depending on the value of $\alpha$ used. Thus for high degrees of ionization, recombination could be significant, but it will not affect the microwave measurements, which will depend only on the net injection rate of electrons and ions outside the small region where recombination is most likely.
Fig. 2.3

Collision Frequency $\gamma_c$

$r$ (mm.)

$W = 100 \mu g m/C$

$W = 10 \mu g m/C$

$f = 5375 \text{Mc/s}$

$(\gamma_c)_{max}$
CHAPTER 3

Microwave Probing of the Vacuum Arc Column

3.1 Introduction

In this chapter the theoretical basis for microwave probing of the vacuum arc column is developed. In section 3.2 the reasons for the particular microwave probing technique used are discussed, and previous similar work is reviewed. The following section then proposes a model for the dielectric properties of the vacuum arc column based on previous research in the field, and defines the range of electron line densities that might occur. In section 3.4 is outlined the theory for dielectric scattering from a homogeneous arc column, and the results of computations based on this are discussed in the following section. Finally in section 3.6 these results for ideal columns are applied to the vacuum arc, and the likely conditions under which useful data might be obtained are discussed.

3.2 Microwave probing technique

The scattering of microwaves by the electrons in an ionized region has for some years provided a useful diagnostic tool for studying the electrical characteristics of the region, stimulated particularly by the increasing interest in large scale plasmas for thermonuclear fusion studies. Microwave diagnostics are particularly suited to the investigation of regions whose dimensions are large compared with the wavelength, since simple free space reflection and transmission experiments may be made, frequently with the assumption of plane wave propagation at and through the ionized region. For smaller scale experiments, such as with some glow and arc discharges, measurements of electron density and temperature have been made either by measuring the change in resonant
frequency and Q of a microwave cavity, by measuring the reflected wave from the discharge, when it appears as a dielectric post across a waveguide, with the axis parallel or perpendicular to the electric field, the so-called TM and TE cases respectively, or by measuring the transmitted wave along a waveguide with the plasma column along the longitudinal axis. It was the success of the reflection technique in this Department by Davidson (32) on measurements on a pulsed glow discharge that led to later work being carried out by King (33) on the application of a similar TM diagnostic method in rectangular waveguide to study the drawn vacuum arc. Davidson had studied a discharge contained in a thin walled precision bore Pyrex tube, but clearly such a method of containment could not be used with the arc because of rapid breakdown of the inter-electrode gap due to deposited metal on the glass. Since it was hoped to measure recovery phenomena under realistic restriking voltage conditions, the insulation between one of the electrodes and the waveguide was a major problem, and King developed a method for reducing the mis-match caused by the large gap between the waveguide wall and the electrode, by attaching a screen to the moving electrode which reduced radiation out of the gap. Although the VSWR varied widely as the electrode was pulled up across the centre of the waveguide, it was possible to have a VSWR as low as 1.25 in the final electrode position, when it was flush with the waveguide wall. However, the screen added considerably to the weight of the moving parts, and the mis-match problem caused by the insulation requirement would have become much more serious as the inside dimensions of the waveguide were reduced to correspond to a more realistic vacuum switch gap.

One method of obviating the insulation problem is to propagate micro-waves between two infinite, insulated, parallel plates, each of which is equal, or close, in potential to that of an arc electrode which is drawn up into it
until the electrode is flush with the inside plate surface. Some work has been done on parallel plate measurements of simple dielectric and metallic shapes by Row (34) and Adey (35,36), and there has been very recent work reported on such measurements with a glass glow discharge tube across the plates, but there has been no known attempt previously to use the d.c. isolation property of parallel plates to measure a free arc column. Effectively this is a return to free space techniques, in which the field distribution around the arc region may be adjusted by the radiation pattern of the coupling arrangements into the plates, and in particular a broad pattern around the arc electrodes will allow the arc position to vary without altering the magnitude of the reflected signal. The major disadvantage of this free space technique is that for a cylindrical Rayleigh scatterer, the scattered field is isotropic, and only a small fraction is reflected back towards the coupling section. Previous practical work with air-spaced parallel plates has mainly been concerned with verification of the calculated scattered field pattern for various obstacles. Row obtained good agreement for the diffracted field of a conducting wedge and thick half-plane, while Adey measured the scattered field around metallic and dielectric columns of circular and square cross-section. In all cases the plates are made to appear infinite by microwave absorbing wedges around their periphery.

It was decided to reflect an incident TEM microwave plane wave from a vacuum arc column produced by separating two current-carrying contacts until they were flush with the surfaces of the plates. The techniques for fabricating the plates and for coupling into them are discussed in Chapter 4.

3.3 Dielectric post model for the arc column

Before any attempt can be made to calculate microwave reflection coefficients of the vacuum arc column, it is necessary first to postulate a structure
for the column, and then to consider in detail the scattering properties of the structure. In Chapter 2 it was shown that over most of the length of the column above a single cathodespot, the mean free path is such that the atoms, ions, and electrons are in free fall, and that the electron-atom collision frequency \( \nu_e \) was less than \( 10^8 \) Mc/s. The column, while possessing cylindrical symmetry, has a very non-uniform electron distribution along its length, and the scattering from even perfect cones between parallel plates would require formidable analysis. However, considerable simplifications can be made by consideration of the expected ranges of values of the parameters.

Eshleman (37), in a thesis in 1952, analysed back-scattered reflections from meteor trails at radio frequencies. His assumption was that such a trail is produced when a small, high velocity particle entering the atmosphere produces a long narrow column of ionized gas, which then increases in diameter but maintains, because there are few collisions, a constant number of electrons per unit length of the column, i.e. a constant line density. The incident wave is of course TEM, and he considered both the TM and TE cases (as defined above), and the effect of various radial distributions. Now while, unlike the column of the vacuum arc, the meteor trail has roughly a constant radial distribution along its length, the two cases do have in common a constant line density of electrons, and this has proved a useful concept when tackling the inhomogeneity problem.

In the absence of collisions, the effective relative dielectric constant of an ionized region is given by the Sellmeier expression

\[
\varepsilon_e = 1 - \frac{\eta_e \varepsilon}{\eta_0 \omega^2 \varepsilon_0}
\]  

Following Eshleman, we replace the electron concentration parameter \( \eta_e \) by that
of the electron line density \( \rho \). These are related by

\[
\rho = \pi a^2 n_e
\]  

(3.2)

where 'a' is the radius of a column with homogeneous electron concentration. Substituting for \( n_e \):

\[
\mathcal{E}_a = 1 - \frac{\varepsilon \rho}{n_e \omega^2 \varepsilon_0 \pi a^2}
\]  

(3.3)

\[
= 1 - \frac{\mu_0 \varepsilon^2 \rho}{\pi m_e (\kappa a)^2}
\]

(3.4)

where \( \kappa = \omega \sqrt{\mu_0 \varepsilon_0} \) is the free-space propagation constant. We continue with the assumption of a homogeneous cylinder, and shall later show that over part of the range of interest the actual radial distribution is relatively unimportant.

Using the expression for the electron density in the column with cosine distribution described in Chapter 2, it can be shown that the line density is given by

\[
\rho = \frac{2 \rho_e}{\nu_e}
\]  

(3.5)

the factor of 2 occurring because \( \nu_e \) is the mean radial electron velocity. The total current was seen to be

\[
I = \nu_e \cdot \varepsilon \rho_e \left( 1 - \frac{\nu_i}{\nu_e} \right)
\]  

(3.6)

and so

\[
\rho = \frac{3 I}{e (\nu_e - \nu_i)}
\]  

(3.7)

Now currents from a single cathode spot are in the range 4 to 100 A, \( \nu_i \) is
fairly well established to be around $10^4$ m/sec., and $V_e$ may lie between $4 \times 10^4$ and $10^6$ m/sec. These give the possible values of $q$ for the burning arc to lie in the range $7 \times 10^{13}$ to $10^{17}$ electrons/m. The other parameter which determines $E_R$ is $k_a$, and a study of vacuum arc photographs suggested this was unlikely to exceed 2 at the microwave frequency chosen, at the broadest part of the column.

3.4 Analysis of scattering from a homogeneous plasma column

In order to study how the reflection coefficient of the column might vary, calculations were then made for back-scattering from long, homogeneous dielectric and metallic cylinders. The scattering theory has been described by Eshleman (37) and Adey (36), and is briefly as follows:-

In fig. 3.1, an infinite plane wave-front polarised as shown propagates in the $+z$ direction towards an infinitely long dielectric cylinder at $z = 0$. The incident electric field may be written:

$$E_{x,1} = e^{-j k y}$$

assuming the amplitude to be unity, and omitting the time-varying component throughout. Transforming to cylindrical co-ordinates

$$E_{x,1} = A e^{-j k r \cos \theta}$$

and Maxwell's equations in cylindrical co-ordinates give

$$H_{\theta,1} = -i \frac{\omega}{\omega_0} \sum_{n=0}^{\infty} E_n(-j)^n J_n(kr) \cos n\theta$$

The scattered wave from the cylinder must satisfy the wave equation in
Fig. 3.1
cylindrical co-ordinates

\[
\frac{1}{kr} \frac{\partial}{\partial (kr)} \left( kr \frac{\partial E_{xz}}{\partial (kr)} \right) + \frac{1}{(kr)^3} \frac{\partial^2 E_{xz}}{\partial \theta^2} + E_{xz}^2 = 0
\]

which has a general solution of the form

\[
E_{xz} = \sum_{n=0}^{\infty} \varepsilon_n A_n H_n^{(i)}(kr) \cos n\theta + \sum_{n=0}^{\infty} \varepsilon_n B_n H_n^{(ii)}(kr) \cos n\theta
\]

where \(H_n^{(i)}\) and \(H_n^{(ii)}\) are Hankel functions of the first and second kind. Consideration of the asymptotic forms of these functions as \(r \to \infty\) shows that the \(H_n^{(ii)}\) summation corresponds to an outward travelling wave, and alone need be considered here.

\[
E_{xz} = \sum_{n=0}^{\infty} \varepsilon_n a_n H_n^{(ii)}(kr) \cos n\theta \quad (3.11)
\]

\[
H_{02} = -\frac{j \varepsilon_0}{\omega \mu_0} \sum_{n=0}^{\infty} \varepsilon_n a_n \frac{1}{n} H_n^{(ii)}(kr) \cos n\theta \quad (3.12)
\]

A similar wave equation, with \(\varepsilon\) replaced by \(\sqrt{\varepsilon_n} \varepsilon_0\) for a perfect dielectric, may be written for fields inside the cylinder, and if the general solution is written in terms of Bessel functions of the first and second kind rather than Hankel functions, then for a finite field strength at \(r = 0\) the solution of the second kind is eliminated, leaving

\[
E_{xz} = \sum_{n=0}^{\infty} \varepsilon_n b_n J_n(\sqrt{\varepsilon_n} kr) \cos n\theta \quad (3.13)
\]

\[
H_{02} = -\frac{j \sqrt{\varepsilon_0}}{\omega \mu_0} \sum_{n=0}^{\infty} \varepsilon_n b_n \sqrt{\varepsilon_n} J_n'(\sqrt{\varepsilon_n} kr) \cos n\theta \quad (3.14)
\]

At the surface of the cylinder, \(r = a\), and the boundary conditions are

\[
\begin{align*}
E_{x_1} + E_{x_2} &= E_{x_3} \\
H_{x_1} + H_{x_2} &= H_{x_3}
\end{align*}
\quad (3.15)
\]
By equating term by term in the series expansions (3.9) to (3.14) the coefficients $a_n$ may be obtained, to give the scattered field $E_{k^2}$. To obtain the field scattered back towards the source, we set $\theta = \pi$, and thus $\cos n \theta = (-1)^n$.

By making suitable substitutions for the differentiated terms $J_n^\prime$, and $H_n^{(2)}$, we obtain the final expression for the back-scattered field in a form suitable for computation:

$$E_{kz} = - \frac{J_0(\sqrt{\varepsilon_R} k \omega) J_1(\sqrt{\varepsilon_R} k \omega)}{H_0^{(2)}(k \omega) J_1(\sqrt{\varepsilon_R} k \omega)} \frac{\varepsilon_R}{\varepsilon_R(\varepsilon_R + \varepsilon_R)} H_0^{(2)}(k r)$$

$$- 2 \sum_{n=1}^{\infty} \frac{J_n(\sqrt{\varepsilon_R} k \omega) J_{n+1}(\sqrt{\varepsilon_R} k \omega)}{H_n^{(2)}(k \omega) H_{n+1}(\sqrt{\varepsilon_R} k \omega)} \frac{\varepsilon_R}{\varepsilon_R(\varepsilon_R + \varepsilon_R)} H_n^{(2)}(k r)$$

When the plasma becomes over-dense, $\sqrt{\varepsilon_R}$ is imaginary, and then $J_n(\sqrt{-\varepsilon_R} k \omega) = I_n(\sqrt{-\varepsilon_R} k \omega)$, where $I_n$ is a modified Bessel function of the first kind.

When the cylinder is metallic, $E_{kz} = 0$, thus $E_{kz} + E_{kz} = 0$, and it is readily seen from (3.9) and (3.11) that

$$E_{kz} = - \frac{J_0(\sqrt{\varepsilon_R} k \omega)}{H_0^{(2)}(k \omega)} \frac{\varepsilon_R}{\varepsilon_R(\varepsilon_R + \varepsilon_R)} H_0^{(2)}(k r) + 2 \sum_{n=1}^{\infty} \frac{J_n(\sqrt{\varepsilon_R} k \omega)}{H_n^{(2)}(k \omega)} \frac{\varepsilon_R}{\varepsilon_R(\varepsilon_R + \varepsilon_R)} H_n^{(2)}(k r)$$

Eshleman used the asymptotic expression for $H_n^{(2)}(kr)$ to calculate the far-field scattered wave, but since in the experimental apparatus the arc was only to be about 3.2 wavelengths from the coupling slot, the expression was evaluated here for a given value of $kr$. Adey (36) gives results for the near back-scattered field from metallic cylinders, but for $ka \gg 2$.

In order to evaluate the expressions, computer routines were first written in Atlas Autocode which calculated $J_n(u)$, $Y_n(u)$, $H_n^{(2)}(u)$ and $I_n(u)$ for any order $n$ and argument $u$, and to any preset accuracy. Two similar programs were then written which evaluated (3.16) for the cases $\sqrt{\varepsilon_R}$ real and $\sqrt{\varepsilon_R}$ imaginary, for input parameters $q$, $ka$, and $kr$; and a third program evaluated (3.17)
for given \( n \) and \( m \). A modified version of the first program was also written which computed \( E_z \) for given values of \( \epsilon_n > 1 \), and the results used in the calibration tests mentioned in section 4.5 for solid dielectric cylinders of known permittivity.

The results from the computer programs are plotted in fig. 3.2, for a value of \( km = 20 \), corresponding to a distance of 4 in. between the coupling slot and the vacuum arc column (see fig. 4.3). The ordinate is the amplitude of the back-scattered field at this distance, relative to the incident wave amplitude at the surface of the cylinder, and from now on this normalised field is given the symbol \( f \). The particular values of \( n \) at which a column of given line density reaches plasma resonance is marked.

3.5 Discussion of scattering from a homogeneous column

We now consider the results of the computations in the light of the vacuum arc model discussed in Section 3.3. An important parameter in this discussion is the skin-depth for propagation of the field into the plasma. For planewave propagation in a loss-less medium, a field component \( A \) propagates as

\[
\hat{A} = A_0 e^{i \left( \frac{2\pi}{\lambda} \sqrt{-\epsilon_R} \right) t}
\]

where \( \gamma = \frac{2\pi}{\lambda} \sqrt{-\epsilon_R} \) is the propagation constant for the medium. For the case where \( \mu = \mu_0 \), and \( \epsilon = \epsilon_0 \epsilon_R \), and where \( \epsilon_n < 0 \), as in the over-dense plasma, we have

\[
\gamma = \frac{2\pi}{\lambda} \sqrt{-\epsilon_R}
\]

Thus the wave decays in the plasma without phase shift, and by analogy with the skin-depth in metals, we may define a skin-depth

\[
\delta = \frac{\lambda}{2\pi \sqrt{-\epsilon_R}}
\]
Fig. 3.2

kr = 20

BACK-SATTERED FIELD $f$

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$10^{-5}$

$0.01$ $0.1$ $1.0$ $10.0$

$q = 10^{17}$

$q = 10^{16}$

$q = 10^{15}$

$q = 10^{14}$

$q = 10^{13}$

$q = 10^{12}$

$q = 10^{11}$

CRITICAL DENSITY LINE

OVER DENSE

UNDER DENSE

Fig. 3.2
Now we are dealing here with cylindrical geometry, but the same parameter \( \delta \) may be calculated as a guide to the depth of penetration of the field. In particular, the quantity \( \delta_a \) relates the skin-depth to the column radius, thus

\[
\delta_a = \frac{1}{d_a \sqrt{\epsilon_a}} \tag{3.21}
\]

Substituting in (3.4) for \( \epsilon_a \) for various line densities \( q \) enables a graph to be plotted of relative skin-depth versus \( ka \), as in fig. 3.3, again with the assumption of homogeneous density distribution. We note from this the useful fact that for a given line density, the skin-depth is a fixed fraction of the column radius for almost any column radius less than the critical value.

From figs. 3.2 and 3.3 it can be seen that the reflected signal may lie in two main regions:

(a) For \( q \ll 10^{13} \) electrons/m., the skin-depth is always large compared with the radius, and so both for the plasma over-dense and under-dense, the scattering electrons are all subjected to the same incident field. For \( ka < 1 \), the column radius is small compared with the wavelength, and so the electrons radiate practically in-phase. Thus the reflected signal is proportional directly to the number of scattering electrons, and independent of the column diameter, as can be seen in fig. 3.2. It follows that in an inhomogeneous column, line densities in the range \(< 10^{13} \) elecs./m. could readily be interpreted from scattering measurements, since the radial density profile is unimportant. However, such densities will only occur in the arc when the plasma is decaying after the current has ceased, and when the assumption of a constant line density becomes invalid.

For \( ka > 1 \) the column radius becomes large compared with a wavelength, electrons scatter with different phases, causing destructive interference,
Fig. 3.3
and the reflected signal falls sharply.

(b) Above \( q = 10^{13} \) elecs./m. and for \( ka < 1 \), the electron density begins to increase to such a value that the skin-depth becomes appreciable. Thus the incident wave does not penetrate the column completely, and the reflected signal rises less rapidly than before as \( q \) rises. We see from fig. 3.2 that in most of this region the plasma is over-dense, and from fig. 3.3 that the skin-depth becomes a decreasing fraction of the column radius as \( q \) increases. Thus for any column radius the limiting value of \( f \) is reached when the scattered signal \( f \) has the same value as would be produced by a metallic cylinder of the same radius. Now it will also be noted that for the metallic cylinder, the reflected amplitude increases slowly as the radius increases. For the inhomogeneous cylinder, the radius at which the skin-depth abruptly becomes small, i.e. the plasma reaches critical density, increases as the line density increases, and it is this change which allows us still to obtain useful results when the density is high.

3.6 Critical density profiles and vacuum arc scattering

We may next study how to apply the computed results to the very inhomogeneous vacuum arc column. A useful indication of the reflection characteristics of the column may be obtained by plotting, for various line densities, the profiles at which the electron density is critical. For the electron density at any point we had

\[
\eta_e = \frac{3}{2} \frac{I \cos \theta}{\pi d^2} e^{(v_e - v_j)}
\]  

(2.12)

Substituting for \( I \) in terms of the line density \( q \) from

\[
I = \frac{q \cos \theta}{3}
\]  

(3.7)

gives

\[
\eta_e = \frac{q \cos \theta}{2 \pi d^2}
\]  

(3.22)
Now for the electron density to be at its critical value \( (n_e)_c \)

then

\[
d_c = \frac{q}{2 \pi (n_e)_c} \sqrt{\frac{1}{\cos \theta}}
\]

(3.23)

Now from (3.1)

\[
(n_e)_c = \frac{m_a \omega^2 \varepsilon_a}{\epsilon_0}
\]

\[
= 1.21 \times 10^{-2} \, f^2
\]

and for \( f = 9,375 \) Mc/s

\[
(n_e)_c = 1.07 \times 10^{18} \, /m^3
\]

Thus from (3.23), for a given value of \( q \), we may plot the corresponding values of \( d \) and \( \theta \) to obtain the critical density profile for the column. Typical profiles are shown in fig. 3.4.

When \( q \) in the arc is \( 10^{13} \) or less, we see from fig. 3.4 that only a small region around the cathode is over-dense, and since the skin-depth is large compared to the dimensions of the region, scattering is proportional only to the line density, as mentioned previously. We may thus obtain from fig. 3.2 relative values of the scattered field for \( q = 10^{12} \) and \( 10^{13} \), and these are plotted in fig. 3.5. For \( q = 10^{14} \), it is seen that the mean radius of the column is about equivalent to \( ka = 0.45 \). Now for the homogeneous column with this line density the skin-depth is comparable with the radius, and we expect the skin-depth to be rather less than this here because of the increasing density near the axis; thus the reflection coefficient might be somewhat greater. The upper and lower limits of \( f \) are obtained from fig. 3.2 and are plotted in fig. 3.5.

This argument was repeated for \( q = 10^{15} \) and \( q = 3 \times 10^{15} \), assuming mean column radii of \( ka = 1.2 \) and \( k = 1.7 \) respectively. Above \( q = 3 \times 10^{15} \), the assumption of a mean column radius becomes much more doubtful, because the profile assumes a conical form, with a base of large diameter. Computations of the phase angle
Fig. 3.5

LINE DENSITY $q$ (elecs./m.)

BACK SCATTERED FIELD $f$ (V/m.)
of the reflection coefficient at $kr = 20$ for metallic cylinders shows rapid change as the cylinder radius increases above $ka = 2$. Thus the correct reflected amplitude can only be obtained by rigorous solution of the wave equation at the surface of a shallow cone between parallel plates.

Thus under the assumption of constant line density a curve has been derived over the range $10^{12}$ to $3 \times 10^{15}$ elecs./m which relates the reflected signal to the line density. How this is used to gain information on the burning vacuum arc is described in Chapter 6. We may conclude by considering the effect of changing the operating frequency from the value chosen, which had been mainly set by experimental convenience. In fig. 3.4, if the frequency were reduced by a factor of 10, the same diagrams would apply, provided the $q$ value on each profile was divided by 10, and the $ka$-abscissa values were divided by 10. Thus for the higher values of $q$, the profile is then becoming conical more rapidly, and thus there is no advantage.

Similarly increasing the frequency by a factor of 10 is seen to give the higher values of $q$ more cylindrical profiles, but this is with values of $ka \gg 1$, where the deviations from a constant radius along the cylinder length are probably significant. Thus there appears to be little advantage in changing the probing frequency from that chosen.
CHAPTER 4

The Microwave System

4.1 Introduction

The previous chapter described the decision to measure arc characteristics by determining the free-space complex reflection coefficient presented by the column to an incident plane wave at a microwave frequency. This chapter describes the microwave system, and is in two main parts. The first part describes the construction of a parallel-plate system, how the wave is coupled into it from rectangular waveguide, and measurements on the resulting field pattern radiated between the plates. Included in this part are also results of measurements on scattering from simple cylindrical metallic and dielectric obstacles, and a comparison of these results with the theoretical results derived from the methods described in Chapter 3. The second part of the chapter concerns a method developed for rapid display on an oscilloscope of the complex reflection coefficient, to give measurements with microsecond time resolution. The effect of biasing the crystal detectors is discussed, and a brief description is given of the video amplifiers, the diode modulator, and the oscilloscope bright-up circuitry. Finally, results are given of performance measurements on the complete system.

4.2 Absorbing wedges

To avoid problems associated with standing waves existing between the parallel plates, it is necessary that these be made to appear infinite, by arranging that around the extremities of the plate system there is some microwave absorbing medium. Fig. 4.1 (a) shows how absorbing wedges are used. At a similar frequency to that used here, Adey (35) used oak and teak wedges with 4 in. and 5 in. tapers respectively, achieving voltage standing wave ratios of 1.03 and 1.02. Row (34) used carbon-coated wood wedges, achieving a VSWR of around 1.05. However,
Fig. 4.1(a)

Fig. 4.1(b)
in this experiment the water vapour and resins in wood would clearly make it an unsuitable material for use in very high vacuum, and to limit the size of the vacuum enclosure, it is necessary that the absorbing wedges be as short as possible. Conventional waveguide terminations use wedges made by moulding a mixture of resin and powdered carbonyl iron, but here again the use of a resin implies both a temperature and a vapour pressure limitation. Alternatively, it is possible to obtain a high temperature microwave load material composed of Si, Si C, and Ti O₂, which is however very difficult to machine once it has been fired, and would have had to be moulded to a fairly complex shape prior to firing.

One possibility considered was that of not using wedge-shaped load material, but to rely on losses in the plates. For example, fig. 4.1 (b) shows two iron plates, in the central region of which a skin-depth layer of silver or copper has been deposited. A wave propagating outwards from the central region would be attenuated fairly rapidly in the outer regions, with the attenuation constant given by

\[ \alpha = \frac{2.7}{\eta \gamma} \sqrt{\frac{\omega \mu_0 \mu_r}{2 \sigma}} \text{ dB/m} \]

with \( \eta \) the intrinsic impedance of free space, \( \gamma \) the plate spacing, and \( \sigma \) the plate conductivity. The value for \( \mu_r \) for iron at 9375 Mc/s was not known, but a length of nickel-iron rectangular waveguide was available. The value for \( \sigma \) for this material was determined from a simple d.c. measurement, and this value was assumed to be similar at microwave frequencies. By measuring the attenuation along a one-foot length of this waveguide at 9375 Mc/s, it was possible to estimate the value of \( \mu_r \) to be about 8.4, and iron was assumed to be of similar magnitude. Thus a 2 in. width of this material in a parallel-plate line would give, assuming an open-circuit at the plate edges, a return loss of 0.32 dB, corresponding to a VSWR of 55. Thus the iron plate would not be sufficiently
lossy, and this method was not used.

Finally, a method of making suitable wedges which had high temperature and low vapour pressure characteristics, but with the advantage of being easily machined, was found using a mixture of "Eccoceram", a mouldable ceramic-type material based on powdered mica, and finely powdered carbonyl iron. A similar technique is described by Cufflin (38) for a different application. It was necessary to devise a method to determine the effects of relative concentrations of materials, and length of the taper, on the VSWR presented by the termination. A parallel-plate line was not available at this stage, and so the special rectangular waveguide section shown in fig. 4.2 was made. This consists of a 2-section \( \lambda/4 \) waveguide transformer from normal 0.9 in. x 0.4 in. X-band waveguide to 0.9 in. x 0.125 in. reduced height waveguide. Because of the conductivity of the load material, and the requirement to maintain d.c. isolation between the plates, the wedge only rises to 1/16 in. thickness, and so the test section is split across the broad dimension. Half-height wedges were built up in the lower section. The dimensions of the waveguide transformer sections were determined from the data of Young (39) for 2-section maximally flat quarter-wave transformers. The inside surfaces were silver-plated.

Various test wedge-shaped load sections were tried out in the unit, but it was soon apparent that it was difficult to distinguish reflections due to the transformer sections from those due to the load section beyond. Clearly these reflections will add in a manner dependent upon their relative phasing. To overcome this, the load sections were built up on a flat strip of mica, 0.9 in. wide and a few inches long, which could be slid along the waveguide section to vary the relative phasing. Both factors were then found to account for VSWR figures of about 1.07 when the taper was 2 in. long, and work proceeded based on the length of taper. Later on, when the direct display of complex reflection
coefficient was available on an X-Y oscilloscope, it was used to display the locus of the overall reflection coefficient as the load was moved, and the two reflections were easily separated. In this case, at 9375 Mc/s, the reflection coefficient of the transformer was 0.028, and that of the load section 0.051. This latter implies a load VSWR of 1.1, which is rather high, but it was seen that the leading edge of the taper critically determined this figure. Accordingly, both parallel-plate systems built had machined wedges, and it is reasonable to assume their reflection coefficients were considerably lower.

4.3 Slot coupling system

The microwave probing signal and its reflected component must be taken to and from the parallel-plate system by rectangular waveguide, and it was necessary to devise a method for coupling between the two. Two possible methods are shown in fig. 4.3. Row (34) used the simplest form of coupling, by laying the plates over the open end of a rectangular waveguide. Adey (35) used an H-plane horn, with a polystyrene lens for correction of the phase-front, and this butted to the plates. The E-plane transformer shown in fig. 4.3(a) was unnecessary in his system because the plate spacing nearly equalled the waveguide inside height. The requirement for the vacuum arc work, however, was a coupling system which would both be compact, and would preserve the d.c. isolation between the plates. An alternative method of coupling which would achieve these objectives is shown in fig. 4.3(b). Radiating slots are cut in the common wall between a rectangular waveguide and one of the parallel plates. In aerial work, the most common form of slot radiator cut in rectangular waveguide is in the narrow wall, but for such a slot to be "resonant", i.e. to have zero susceptance, it is necessary for the slot to extend into the broad wall. While the dimensions for resonance would clearly alter when the waveguide was set into a large flat plate, it was felt that it might be difficult to achieve resonance. Again, with narrow
Horn Coupling  Fig. 4.3(a)

Slot Coupling  Fig. 4.3(b)
wall slots, the bend away from the surface of the plate would have a large radius of curvature.

Radiating slots in the broad wall may be series (angled, positioned along the centre line), or shunt (longitudinal, displaced from the centre line). Shunt displaced slots were used because some published data exists on their characteristics when radiating from a waveguide face set flush into a large, flat conducting sheet. It will be clear that an array of such slots would have to be broadside, i.e. the slots must radiate in phase; any other arrangement would be complicated because the wavelength in rectangular waveguide differs from that between the plates.

Initially, it was decided to find out the field pattern produced between the plates by an array of three similar slots spaced by one guide wavelength. For these three shunt slots to transfer all the incident signal, the normalised slot conductance should be 0.33. Stegen (40) gives a curve which is reproduced in fig. 4.4, which shows how the normalised resonant conductance of a shunt slot set in a plate varies with the slot displacement from the waveguide centre-line. This will indicate in a general fashion how the conductance might vary when another large plate is brought close to the first.

An experimental system was made up to obtain further data, consisting of a pair of silver-plated ground steel plates, each 24 in. x 12 in. x \( \frac{1}{2} \) in. A U-shaped section of waveguide was brazed into a 1 in. wide groove milled in one of the plates, such that its lower surface was flush with the inner side of the plate (see fig. 4.5). As mentioned previously, a machined finish to the load material was essential for a low VSWR. Since the main lobes of the slot radiation patterns are towards the narrow ends of the plates, load material was first cast on to roughened surfaces at these ends, and when the baking schedule for the material had been completed, the surfaces were machined using a vertical mill. Load material was then cast on to the long sides, baked, and hand-finished to
Fig. 4.4

F = 0.375 MHz

1/16" WIDE SHUNT SLOT
0.05 x 0.4" WAVEGUIDE

Normalised Resonant Conductance G/G₀

Slot Displacement (in.)

0.05 0.10 0.15 0.20 0.25 0.35

0.0 0.02 0.04 0.06 0.08 0.1

16.5 cm, 12 cm, 7.2 cm, 5.8 cm, 4.7 cm, 4.5 cm, 3.0 cm, 2.5 cm, 2.0 cm, 1.5 cm, 1.0 cm, 0.5 cm, 0.1 cm
the required shape. The plate was then clamped flat, and the surfaces planed until the wedges rose to a height of 1/8 in., and this set the plate spacing. (The d.c. isolation between plates was not needed here). Finally, hoisting lugs and locating dowels were fitted to the plates. Three slots in all were cut in the first U-section of waveguide (not those shown in fig. 4.5), previous slots simply being plugged when measurements on a new slot were made. Each slot was first made rather shorter than the length expected for resonance, and a Smith chart plot made of its admittance as it was carefully lengthened. Fig. 4.6 shows the typical manner in which the admittance alters as resonance is approached, for a slot displaced 0.35 in. from the centre-line. It is notable that an error of only about 10% in the slot length gives an infinite VSWR, and no power can be transferred into the plates.

Fig. 4.4 shows also the data obtained for the resonant conductance of the 3 slots, when coupled into 1/8 in. spaced parallel plates. The conductances are seen to be considerably lower than for the free waveguide case, but the shape of the curve remains similar. An important conclusion is that it is not possible for a single slot to have a conductance greater than about 0.7, and so there is no slot displacement which will allow all the incident power to be coupled into the plates through one slot, without some form of matching.

From this graph it was possible to decide on the dimensions for three equal shunt slots to have a total conductance of unity, and a new U-section of waveguide was fitted on to the parallel plate, and the 1/16 in. wide slots called; this is the plate shown in fig. 4.5. The first test was to determine the match presented by this 3-slot array. A sliding short-circuit was attached to the end of the U-section away from the source, and was first adjusted until the reflected signal was a maximum. This will occur when there is a short-circuit at the same electrical position as the slots. Moving the short-circuit $\lambda/4$ then effectively presented an open-circuit length of waveguide, shunted by 3 equal conductances,
Fig. 4.6

Normalized Coupling—Slot Admittance

1/8" Parallel Plates
Slot Displacement 0.35"

\[ \frac{\varphi}{2} = 0.30\]

\[ f = 9375 \text{ Mc/s} \]
and the reflected power was then 19 dB smaller than previously. This implies that 99% of the incident power is radiating and being absorbed between the plates without further matching.

### 4.4 Field pattern between the plates

The simple microwave bridge shown in fig. 4.7 was set up to determine the field pattern between the plates due to the 3-slot arrangement, along a line at 4 in. from the slots. This was done by measuring the reflected field from a small metal cylinder, which was moved step by step along the 4 in. line. If the diameter of the cylinder is small compared with a wavelength, then it may be assumed to be an isotropic scatterer, and at all positions the reflected power in any direction is proportional only to the resultant incident field at that point. It must be noted that the reflected power into the rectangular waveguide is proportional to the square of the radiated power distribution pattern, since the same "aerial" is used for transmission and reception. However, it is this two-way pattern which is of importance here; the actual incident field distribution may be obtained from the graphs presented here by taking the square root for power ordinates, and the fourth root for field ordinates.

The most satisfactory method for moving the reflector was found to be by attaching it to a fine thread, and drawing this across the 4 in. line. Reflections from the plate system were first nulled out, with the reflector in the zero-field region in the notch cut in the load material (see fig. 4.5). Successive measurements were then made of the phase and amplitude as the reflector moved. It was found necessary to make allowance for changes in the attenuation of the phase-shifter as its setting was altered, but the phase shift due to the attenuator was negligible. These measurements were only taken from the centre of the plate to one side, but later tests have confirmed that the pattern is symmetrical. The results of these measurements on 3-slot coupling are presented
Fig. 4.7

Diagram showing various components such as hybrid, amplifier, phase shifter, attenuator, tuner, stub, slot, coupling section, movable reflection, and other electrical elements.
in figs. 4.8 and 4.9.

It may be seen immediately that there is little value in using 3 slots to illuminate a central region about ½ in. across, because of the fairly narrow polar diagram of each slot. (Simple theoretical analysis of the expected pattern had assumed, for lack of information, that the slot patterns were nearly isotropic.) ½ of the incident power was being radiated through slots which only very slightly illuminate the central region. Accordingly, two slots were plugged, as in fig. 4.5, the resulting mismatch cancelled using a 3-stub tuner, and the measurements repeated for the single slot, with the results shown. These are considerably more satisfactory, showing a broad central region with amplitude change less than 1 dB, and a narrower central region with phase change less than 20°. Clearly, a ½ in. diam. column will only intercept a small fraction of the incident signal between the plates, but the column may move around over a 2 in. wide region with negligible amplitude changes due to the position changes. Over a 0.8 in. wide region, there are negligible phase errors due to position along the 4 in. line, but of course large phase changes will occur over 0.8 in. in the longitudinal direction, since this represents a change in path length of 1.3 λ. No attempt has been made to make use of that half of the power coupled through the slot, which radiates away from the arc region.

4.5 Calibration using metallic and solid dielectric cylinders

The analysis of Chapter 3 produces a factor f, which is the scattered field from a cylindrical obstacle at some radius r, relative to the incident field at the surface of the scatterer. Experimentally, we measure a reflection coefficient ρ in the rectangular waveguide which is, when mismatches have been tuned out, directly proportional to the scattered field at the coupling slot, and is thus directly proportional to f. This relationship depends primarily on the geometry of the system, and the coefficient of proportionality must be found
Reflected Signal Amplitude (dB below short circuit)

Fig. 4.8

1-SLOT COUPLING
3-SLOT COUPLING

Distance from Centre Line (cm.)
Phase of Reflected Signal (degs.)

Distance from Centre Line (cm.)

1-SLOT COUPLING

3-SLOT COUPLING

Fig. 4.9
experimentally. This was done by measuring $\rho$ for scatterers whose factor $f$ can readily be calculated, e.g. metallic or homogeneous dielectric cylinders, over a range of diameters. The $f$ and $\rho$ values are then converted to decibels, and plotted on the same graph, against the normalised column radius $ka$. This should give pairs of parallel curves, separated by a constant number of decibels, which is the required scale factor.

This was carried out for a range of diameters of cylinders made of brass and Teflon, in the latter case taking $\varepsilon_r$ to be 2.1. The computed values of $f$, and the measured values of $\rho$, are shown in fig. 4.10. Experimentally, care was necessary to obtain consistent results, particularly with the metal cylinders, since the reflection coefficient only varies slowly with the diameter; an accuracy of 0.5 dB was required. A $\frac{3}{8}$ in. diam. bolt was fitted into the top plate, with its lower surface flush with the inner surface of the plate, and the reflectors were introduced through the hole. However, the reflection coefficient was found to be very dependent on the small clearance which had to be allowed between the cylinder and the bolt, the clearance being necessary because distortion of the plates, and hence unbalance, occurred as soon as the two were screwed together. Finally, the results were obtained by pulling each cylinder from the side to the centre of the plates by a thread, as previously described. This method gave the experimental curves for $\rho$ shown in fig. 4.10. From these curves we can deduce the following relationship for the experimental parallel-plate system:

$$f(\text{dB}) = (\text{dB}) + 13 \text{ dB}$$

If this factor is added to each of the experimental values of $\rho$, we obtain "experimental" values of $f$ which lie close to the theoretical $f$ curves, and give a convincing demonstration that simple free-space analysis is valid in the experimental conditions here.
4.6 Principles of impedance bridge systems

In order to measure the reflections from the column of the vacuum circuit-breaker arc, certain requirements were sought from the measurement system used:

(i) It should have a short response time. For the burning vacuum arc, it is known from arc voltage records that the time constant of cathode processes can be as low as $10^7$ secs.\(^1\), and Rich and Farrall (4.1) quote recovery times after forced arc extinction at 250A of the order of microseconds. A technique which could thus resolve changes of column characteristics occurring in a few microseconds was thus required.

(ii) It should be time-resolved; there must be some method for indicating the point in time of each measured reflection coefficient.

(iii) It should have high sensitivity. The mean column diameter is less than one wavelength, and so the scattered signal pattern will approach isotropic; there is also the requirement that the region over which the arc column moves be uniformly illuminated, and both these factors tend to make the back-scattered signal a very small fraction of the total incident power.

(iv) It might be an advantage to measure the phase and amplitude of the reflected signal, rather than just the amplitude, as in a reflectometer. This is because for a steady burning arc, the reflection coefficient would be expected to remain constant, but changes in the distance of the column from the radiating slot would provide phase changes, which could give an indication of the velocity of the arc column (assumed random) over the contact.

Previous work in this Department (33,42) and at RCA Victor (43,44) has concerned the development of a measuring technique originally proposed by Samuel (45), which gives a polar display of complex reflection coefficient on the face of an oscilloscope tube, and which can be adapted to meet the
requirements listed above. The principle of the method will briefly be described, in order that the improvements made to these previous systems to give greatly increased sensitivity, and to give timing information, may be appreciated. Fig. 4.11(a) shows the basic elements of the 4-probe technique, and fig. 4.11(b) shows the hybrid tee arrangement which is analogous to the 4-probe method. Both techniques were mentioned by Samuel in the original paper, but he did not mention one very important feature of the hybrid tee bridge; in view of the limited range of incident powers over which a crystal detector has a square-law characteristic, the independent control of the reference signal and of the signal incident on the discontinuity is a basic advantage with this latter method. We may apply a similar analysis to both systems.

If a discontinuity occurs in a transmission line, then a complex reflection coefficient may be defined by

$$\rho = \frac{E_r}{E_i} = \rho e^{i\phi}$$

where $E_r$ and $E_i$ are the instantaneous values of the reflected and incident fields respectively. Fig. 4.11(a) shows an impedance element $Z$ terminating a transmission line. Both the incident and reflected waves to and from the impedance are sampled by four equi-spaced probes in the transmission line, which are separated by an odd multiple of $\lambda/2$. Each probe element causes a direct current to flow to earth through a diode and a resistor $R$. In fig. 4.11(b), the incident field $E_i$ reaches an impedance element $Z$ through a circulator, and the reflected field $E_r$ is first divided in a 3 dB directional coupler, and each component again divides equally into the collinear arms of two hybrid tees, each arm being terminated by a matched crystal detector. The incident field $E_i$ is also sampled by a directional coupler, and a fraction $E_j$ is first split in a 3 dB coupler, each component again being divided into the collinear arms of the hybrid tees. The method uses the property of a hybrid tee that the electric field
incident on the H-plane side arm appears with equal phase at the two crystal
detectors, assuming these are symmetrically disposed, while the electric field
incident on the E-plane arm divides in anti-phase. Which side arm is used for
the reflected field, and which for the incident, or reference, field is immaterial, but here we assume the reference arm to be H-plane. Included in one arm
of the 3dB coupler on the reference field side is a phase shifter P. Again,
the rectified current through each crystal returns to earth through a resistor R.

Now the rectified short-circuit crystal current \( i \) is assumed to be proportional to the square of the incident total r.f. electric field, i.e. to the
incident r.f. power. This assumption is only valid for incident powers up to
about \( 10^5 \) watts, and will be considered in more detail later. Thus we may
write

\[ i = c E_t^2 \]

where \( c \) is a constant which is different for the two bridge systems, but is the
same for each diode in the same bridge. This assumes that the resistance \( R \)
is small compared to the dynamic resistance of the diode, so that \( i \) is effective-
ively a short-circuit current. The constant \( c \) depends both on the crystal
sensitivity, and on the probe coupling factor in (a), and on the match of the
diodes in (b). It is assumed that these quantities may be adjusted until \( c \) is
the same for each diode.

For each bridge, the resultant fields \( E_t \) at each detector may be found from
the phasor diagrams of fig. 4.12. At the first detector, the phase angle be-
tween the reference field \( E_t^\circ \) and the reflected field \( E_t \) is \( \theta \). For the 4-probe
bridge, the incident signal \( E_t^i = E_t^f \), and the phase of the components increases or
decreases by \( 45^\circ \) from probe to probe. In the bridge using hybrid tees, the
phase of the reference signal at diodes 2 and 4 may be altered relative to the
phase of the reflected signal, and this phase difference \( \gamma \) is adjusted until
Fig. 4.12(a)

Fig. 4.12(b)

Phasor Diagrams for Microwave Bridges
either \( \gamma = 90^\circ - \theta \) or \( \gamma = 90^\circ + \theta \). (In practice, this may be set from the final display, as will be mentioned later). The four diode currents in each bridge may now be written

\[
\begin{align*}
i_1 &= c E_{41}^2 = c (E_r^2 + E_f^2 - 2E_r E_f \cos \theta) \\
i_2 &= c E_{42}^2 = c (E_r^2 + E_f^2 - 2E_r E_f \sin \theta) \\
i_3 &= c E_{43}^2 = c (E_r^2 + E_f^2 + 2E_r E_f \cos \theta) \\
i_4 &= c E_{44}^2 = c (E_r^2 + E_f^2 + 2E_r E_f \sin \theta)
\end{align*}
\]

Thus

\[
i_3 - i_1 = 4c E_r E_f \cos \theta
\]

and

\[
i_4 - i_2 = 4c E_r E_f \sin \theta
\]

Thus if voltages proportional to these two difference currents are applied to the X and Y plates of an oscilloscope, a polar display is obtained with radius proportional to \( E_r \), and thus to \( |\rho| \), and angular displacement \( \theta = \phi + \delta \), where \( \delta \) is a fixed phase shift proportional to the return path between the first detector and the discontinuity. If the display is required to give the absolute phase angle of the reflection coefficient, the angle \( \delta \) may be determined by a simple measurement.

Two possibilities exist to obtain the required components. King (33) and Lucas (42) used similar polarity crystal detectors and difference amplifiers to obtain outputs proportional to \((i_3 - i_1)\) and \((i_4 - i_2)\), but a simpler method is to make one crystal of each pair reverse polarity, as shown in fig. 4.11, the difference current flowing through the small resistance \( R \). The voltages across the resistors are amplified and applied to the oscilloscope.

4.7 Choice of bridge system

It is clear from the above analysis that \( E_f \) should be as large as possible for maximum sensitivity, but a limit is set because the incident signal on the
crystal detectors must not exceed about $10^5$ watts. Accordingly, $E_i$ is set, taking into account the probe coupling factor in (a) and the coupling ratios in (b), so that the reference signal power is around this value. In system (a) this has then set the value of the incident probing signal $E_i$. However, in a single frequency system, it is quite possible to match out the residual reflections of the incident power in (a) to a level of $E_r$ so low that the signal at the amplifier outputs falls below the amplifier noise level. Under these narrow-band conditions, the system shown in fig. 4.11(b) has a major advantage; the amplitude of $E_i$ may be raised independently until residual uncancelled signals are greater than the noise level; there is then nothing to be gained by raising $E_i$ further. The ultimate sensitivity is now determined by the spectral purity of the source, since the matching process cannot reject reflected components at frequencies separated from the fundamental. If a broad-band system were being designed, the residual reflection level might be considerably higher, and then perhaps no advantage gained by increasing the probing signal $E_i$; but the 4-probe system is still unattractive because the correct probe spacing depends on frequency, while the hybrid tee system can be designed to be broad-band. Because of its flexibility, the hybrid tee system was chosen for this investigation.

4.8 Measurement of crystal diode characteristics

The sensitivity and linearity of the bridge system depend primarily on the characteristics of the crystal diodes. It is necessary that these have high sensitivity, that pairs of crystals have closely matched sensitivities, and that they be accurately square law. In the first test, each of four crystals was set in turn in an X-band waveguide mount, and an impedance matching arrangement between the crystal and the signal generator adjusted for minimum reflection when the incident signal was $10^{-4}$ watts. At all lower power levels, the crystal was found to be well-matched. For various incident r.f. power levels, the direct voltage
developed across a load resistor was measured on a digital volt-meter; the results are shown in fig. 4.13 for a 220Ω load. Two of the diodes were a nominally "matched-pair" of mixer crystals, but the criterion for matching these was that they have similar i.f. impedances at an incident power level of $10^3$ watts. The other two diodes were backward diodes (46), which were claimed to have a higher short circuit current sensitivity than conventional diodes. From these characteristics the following conclusions may be drawn:

(i) For this value of load resistor, backward diodes were not appreciably more sensitive than point-contact diodes. For lower values of load resistor, one of the backward diodes became significantly more sensitive.

(ii) The "matched-pair" of mixer diodes differ in sensitivity by about 5 dB.

(iii) The point-contact diodes have square-law characteristics for incident powers up to about $10^{-6}$ watts.

The difference in sensitivity between the two point-contact diodes was unfortunate, for the only method by which they could be balanced as they were was to reduce the signal to the more sensitive diode by attenuation or mis-match. In fact, assuming equal video amplifier gains in the X and Y channels, the ultimate sensitivity of the system would be set by the poorest diode.

It is well-known that forward bias may be used to improve the sensitivity of point-contact diodes used as video detectors, but it was not known if this would affect the square-law characteristic. Further measurements were then made to determine the effect of forward bias, and a typical set of results is shown in fig. 4.14. From these may be noted:

(i) A d.c. forward current of about 30 μA gives 8 dB improvement in sensitivity.

(ii) The upward tilt of the zero bias curve at about $10^{-6}$ to $10^{-5}$ watts is a feature of the short-circuit current characteristic of point-contact diodes. Forward biasing removes this kink, and increases the square law region by up
(iii) Variation of the bias current allows a means of matching crystal sensitivities.

(iv) Although not shown, bias currents of 50µA and above caused no further improvement in sensitivity; in fact, sensitivity begins to fall off.

Having proved the necessity for bias, a simple circuit arrangement was made which applied the required direct currents to two opposite polarity diodes, while allowing the rectified currents to flow through a common load resistor. One practical difficulty which arose was that of measuring the bias currents in circuit; this was done by measuring the V-I characteristic of each diode, and adjusting the circuit for the correct voltages using a digital voltmeter. The value of the load resistors finally used, viz. 220Ω, was set by bandwidth requirements of the video amplifiers, and the necessity for the load resistor to be much less than the diode resistances.

4.9 **Video amplifiers**

Since these amplifiers are required to amplify the small reflected signals from the arc column in an electrically noisy environment, it was decided to design transistor amplifiers which were battery-powered, and contained in screened boxes. The low frequency cut-off of the amplifier is set by transistor 1/f noise to about 10 kc/s, and this in its turn requires that the microwave signal be modulated at a fairly high frequency. Since microsecond time resolution was required, the microwave probing signal was square-wave amplitude-modulated at a frequency of 500 kc/s, and a synchronous bright-up signal was applied to the oscilloscope, such that the change in arc characteristics would appear as a series of spots representing the measured arc reflection coefficient every 2 µsecs. To have a rise-time corresponding to that of the modulating pulse, the upper frequency cut-off of the amplifier was set at 7 Mc/s. The gain required was found
experimentally, and was such that the displayed noise level on the oscilloscope at its highest gain setting was just raised when the amplifier was switched on; this was found to correspond to a voltage gain of around 100. The circuit of an amplifier is shown in fig. 4.15, and its frequency response in fig. 4.16.

4.10 Diode modulator and bright-up circuitry

The incoming signal to the microwave bridge is modulated by a p-i-n diode modulator, to give a train of 1 μsec. pulses of r.f. power with a p.r.f. of 500 kc/s. The waveguide component is supplied with a forward current of 100 mA when the switch is "closed", and a reverse voltage of 6 V when the switch is "open", the switching time being about 50 n secs. The modulator circuit is described briefly in ref. 61.

When a difference signal is developed at the diode pairs, a 500 kc/s square-wave is produced, one level of which corresponds to the zero signal condition, and one to the out-of-balance signal. However, since the amplifier is a.c. coupled, this will appear on the oscilloscope display as two bright spots symmetrically disposed about the display centre, joined by a weak line. Methods of d.c. restoring were considered, such that the zero signal condition always caused the spot to return to the centre, but finally circuitry was designed which caused the display to bright-up only on one of the two levels, effectively losing half the signal amplitude. This was found necessary also because the diodes were not well-matched during the switching times, and large spikes were produced every 1 μsec. In the final system, therefore, only the centre 0.6 μsec. of each pulse produced a trace, and this gave a very effective display.

4.11 Final version of microwave bridge assembly

A diagram of the complete microwave bridge is shown in fig. 4.17. The signal source is a VA 2013 klystron, producing about 34 mW at 9375 Mc/s. Two d.c. blocks are incorporated in the waveguide. That adjacent to the circulator
Fig. 4.16

FREQUENCY

VOLTAGE GAIN (expressed as dB)

Fig. 4.15
Fig. 4.17

CIRCULATOR

2
D.C. BLOCK

40 dB

40 dB

10 dB

ROTARY SWITCH

WAVEMETER

E-H TUNER

40 dB

P-1N DIODE SWITCH

THERMISTOR

MODULATOR UNIT

POWER METER

VA-201B KLYSTRON

WAVEGUIDE WINDOW

D.C. BLOCK PLATES

TANK
prevents fluctuations of potential of the vacuum tank during arcing from appearing on the microwave bridge. Inside the tank, the upper plate is left floating at a potential near earth, and since the waveguide is earthed at the waveguide window, a d.c. block is included. Each consists of a thin sheet of mica clamped between two plane flanges; that inside the vacuum tank may be seen in fig. 6.9. The vacuum-tight window for the waveguide on the vacuum tank consists of a triple-iris kovar-glass pressure window mounted on a rectangular flange, which clamps against the baseplate flange with a 0.020 in. gold wire gasket between the two. This window is bakeable to 300°C. A 0.9 x 0.4 in. rectangular hole was broached through the 0.020 in. thick stainless steel baseplate flange; on the upper side this mates with a copper flange and a section of OFHC copper waveguide leading to the slot coupling section. In the final system, the two parallel waveguide plates are 11 in. diam., 0.020 in. thick, and are of OFHC copper. The waveguide load material was cast on to the lower plate, and then machined in a lathe to give a 2 in. long, 1/16 in. high taper at the outer edge. (see fig. 6.9). A 3/8 in. wide groove is cut in the load material to allow viewing of the arc through the viewing port on the tank; this is cut away at a section where the field radiated from the slot is very small, and thus the reflected signal is negligible. The two plates are separated by 13 3/8 in. high PTFE spacers, located in dowels in the lower plate; these can also be seen in fig. 6.9. Round the edges of the plates are 5 3/8 in. radius notches for PTFE leadthroughs, which carry leads to the switch assembly on the upper plate. The plates are supported by 3 3/8 in. diam. stainless steel legs, with short PTFE sections at their upper end to maintain isolation of the lower plate. At the far end of the slot coupling section of waveguide is a short length of waveguide with a short-circuit at the end; this was preset to give maximum coupling through the slot, as described in section 4.3.
The setting-up procedure for the bridge, which is shown in fig. 4.17, was as follows: An initial test was made to set the crystal detector reference signal levels, by substituting a power meter thermistor head for one of the detector mounts, and adjusting attenuator $A_1$ for $10^{-5}$ watts incident on the thermistor. The head was then returned to its normal position, and the corresponding power level there measured. If the generator power output now changed appreciably, a corrected setting for $A_1$ could be calculated to maintain detector reference power levels at $10^{-5}$ watts. With attenuators $A_1$ and $A_3$ set at maximum, each of the detector mounts was set for maximum output at its appropriate d.c. bias level. The diode pairs were then connected into circuit, and small adjustments in the matching made to give zero output on $X$ and $Y$ channels, thus setting the spot to the centre of the display. A sliding short-circuit was then coupled to port 2 of the circulator, and $A_2$ and $A_3$ reduced to give suitable $X$ and $Y$ deflections. Movement of the sliding short-circuit should move the spot in a circular path around the centre. Two errors may need correction: incorrect setting of $P_1$ gives an ellipse with diagonal axes; incorrect equalisation of $X$ and $Y$ amplifier gains gives an ellipse with horizontal and vertical axes. The parallel-plate system was now coupled on to port 2 of the circulator, and the vacuum switch contacts held apart by a small current in the upper solenoid. $A_2$ and $A_3$ were now gradually reduced, the residual reflections being cancelled out using the E-H tuner adjacent to the tank. With $A_2$ and $A_3$ at zero attenuation, the bridge was in its most sensitive condition.

4.12 Performance measurements

Some preliminary tests were made to assess the performance of the system. In the first, a short-circuit was placed on port 2 of the circulator, $A_2$ and $A_3$ gradually reduced, and the corresponding oscilloscope deflections noted. Fig. 4.18 shows how the modulus of the voltage at the oscilloscope $X$ and $Y$ terminals varied with the input signal. From this it is seen that the dynamic range of the
Figure 4.18

Reflected Power (dBm)

Oscilloscope Input Voltage

\[ IV = \sqrt{V_x^2 + V_y^2} \]
measuring system is 50 dB, i.e. from -70 dBm to -20 dBm, the maximum input voltage to the oscilloscope before the video amplifiers show distortion being about 200 mV. This is adequate since the maximum useful dynamic range, for given gain settings, which can be shown on the oscilloscope at one time is about 30 dB. With a maximum incident signal level of about 0 dBm, reflection coefficients in 30 dB ranges can thus be displayed in the overall range of -70 dB to 0 dB.

Fig. 4.19 is an example of the use of this display system to give both phase and amplitude information simultaneously. It shows the results obtained from a multiple exposure photograph of the reflections from the first parallel-plate system of a ½ in. diam. metal cylinder moved in 2 mm. steps across the line 4 in. from the slot. It thus gives fairly rapidly and compactly the results previously obtained for figs. 4.8 and 4.9, but by a more lengthy method.

Finally, a test was made to give a time-resolved display. Fig. 4.20 is a photograph of the changing reflection coefficient as the vacuum switch contact, without any arcing, is pulled up into the upper plate by the solenoid alone. The motion was fairly slow, and so the 2 μsec. bright-up markers were too close, so a technique was used which superimposed another bright-up waveform, to give pips at 500 μsec. intervals. The final position of the spot should have been at the point with X-Y co-ordinates (+1, -1) cm., but slight frequency drift in the klystron causes small changes in the zero position over a few minutes. For single shot applications this is unimportant.
FIG. 4.20

H 10mV/cm
V 10mV/cm
CHAPTER 5

Vacuum System and Vacuum Switches

5.1 Introduction

A major part of the experimental effort in this research has been the construction of a very high vacuum system, and the design, construction and operation of vacuum switches, and this work is described in this chapter. Section 5.2 gives a detailed description of the vacuum system, and the techniques used to achieve very low pressures with fairly limited pump capacity. In the following section are details of a synthetic 50 c/s 150 A current supply. Section 5.4 deals with the design of switch mechanisms for high-speed make and break operations in high vacuum, and the following section discusses their performance. The final section describes an electronic unit which controlled the sequence of operations during experiments, and its associated equipment.

5.2 Vacuum system

The parallel-plate waveguide system and vacuum switch mechanism are contained in a stainless steel tank with internal dimensions 12 in. diam. and 15 in. high. The tank was designed to give flexibility for future experiments, and has four 3 in. diam. side-ports at different heights above the base. A 2\(\frac{1}{2}\) in. diam. bakeable window is fitted to one of these ports, and a mass spectrometer analyser head is fitted to another. The tank has a \(\frac{7}{8}\) in. thick, 15 in. diam. baseplate, which may seal with a flange on the tank either by a rubber O-ring, or by a 0.020 in. gold wire gasket. There are nine ports in all on the baseplate; two of these are 2 in. diam. pump ports, two which are diagonally opposed were intended for waveguide leadthroughs for transmission experiments (only one is used here), and the remaining five are \(\frac{3}{8}\) in. diam., and are fitted with high-voltage leadthroughs rated to 20 kV. The second waveguide port was fitted with an 8-wire low-voltage leadthrough, which carries the solenoid connections, and could also be used for thermocouples to
check temperatures inside the tank during bake-out.

The aim in designing the system was for all parts to be capable of being baked to about 400°C, since high-temperature baking is known to be very desirable for processing vacuum switch electrodes. Any form of rubber O-ring thus being excluded, a study was made of other materials suitable for compression gaskets. Some relevant data is shown in the following table:

<table>
<thead>
<tr>
<th>Material</th>
<th>Melting Point (°C)</th>
<th>Brinell Hardness No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indium</td>
<td>156</td>
<td>0.9</td>
</tr>
<tr>
<td>Lead</td>
<td>325</td>
<td>3.2-4.5</td>
</tr>
<tr>
<td>Aluminium</td>
<td>660</td>
<td>17</td>
</tr>
<tr>
<td>Copper</td>
<td>1083</td>
<td>40</td>
</tr>
<tr>
<td>Gold</td>
<td>1063</td>
<td>25</td>
</tr>
</tbody>
</table>

Indium and lead have too low melting points for this application, and of the other materials, gold has the greatest resistance to oxidation, and it was decided to use this for gaskets. The gold was obtained in the form of 0.020 in. diam. wire, and was made into rings by carefully cutting the ends, annealing the wire, butting the ends together on a carbon block, and then carrying a molten zone across the junction using a very fine oxy-coal gas flame. With experience it was possible to produce a joint without change in diameter of the wire. One face of all flanged joints was cut with a 0.010 in. deep V-groove, into which was laid the gold wire ring. Because the soft wire altered in dimensions when handled, each ring was made 5% under size, and then stretched immediately prior to use on truncated-cone-shaped mandrels. For the baseplate gasket, which was 12 1/2 in. diam., it was necessary to have a brass annulus cast and machined. Later experience showed that with well-finished surfaces, the V-groove was unnecessary, and a gold wire clamped between two flat surfaces was equally successful. All flange bolts were of the same material as the flanges, to avoid differential expansion on heating.

One of the pumping ports is connected through a 1 in. bakeable metal tap and
liquid nitrogen cold trap to a 25 l/sec. oil diffusion pump, backed by a 25 l/min rotary pump. The other port is connected to a 5 l/sec getter ion pump. The net pumping speeds of the two pumping systems are, of course, reduced if the conductance of the tubing is taken into account. Using the expressions for pipe conductance assuming molecular flow found in most vacuum textbooks (e.g. 47), the net pump speeds for the ion and oil diffusion pumps are approximately \( \frac{4}{3} \) and 2.9 l/sec respectively. The poor diffusion pump speed is due to the necessity of including a cold trap and tap in this pipeline, and in practice it did not prove to be a limitation. Although such low pumping speeds for a vessel of some 30 litres capacity would be very undesirable in systems frequently opened to atmosphere, it was not serious in this work because the time scale of pump-down was always set by the slow heating and cooling processes in bake-out. A compensatory advantage of low pump speeds is that there is less danger of neglecting contamination by relying on a high pump speed to achieve the pressures required.

Two methods are available to measure pressure; the ion pump current gave an indication of pressure down to \( 10^{-6} \) Torr, and a Penning gauge between the diffusion pump and the cold trap indicated pressures in the range \( 10^3 \) to \( 10^6 \) Torr. In each case corrections are necessary due to low pipe conductances; the pressure in the tank was about 1.1 times the ion pump indicated pressure, and about 1.8 times the Penning gauge pressure.

The whole tank and baseplate may be baked to remove water and adsorbed gases by a large oven, which contains heating elements rated at 4.5 Kw, which is lowered over the tank and mass spectrometer head. During the bake, the temperature was always raised slowly, and the system allowed to cool naturally under the oven, to avoid leaks caused by different rates of cooling of adjacent flanges. Thermocouples were used to monitor the temperature at various points on the tank. The maximum bake-out temperature which was used during initial tests with an empty tank
was 250°C, and pressures of $10^{-8}$ Torr were reached with a non-operational vacuum switch in the tank. In later tests with the full waveguide and switch assembly in the tank the pressure was not less than $2 \times 10^{-7}$ Torr, but always the limit was found to be due to a leaky gasket, and the pressure could have been further reduced if time had permitted.

An A.E.I. MS10 mass spectrometer was used with the vacuum system. This instrument consists of an analyser head based on the principle of the Dempster mass spectrometer, with magnetic deflection produced by a 1800 gauss permanent magnet, and an electrostatic accelerating field which is varied between 2000 and 40 volts as currents due to ions with m/e ratios between 2 and 100 are measured on an electrometer. The spectrometer was used both as a leak detector, using mineral Helium as a tracer gas, and to analyse the gases evolved during arcing. The time constant of the electrometer circuit is one second, which did not permit any rapid scanning techniques of the spectra of evolved gases. The instrument can detect partial pressures down to $10^{-10}$ Torr, and thus this was a very effective method of detecting leaks over the range of total pressures used, viz. down to $10^{-8}$ Torr.

The normal precautions concerning choice of materials for ultra-high vacuum applications were used in the design of all apparatus. Brass was avoided, and all metal parts were either of stainless steel, OFHC copper, vacuum-cast nickel-iron alloy, or pure aluminium. It was originally planned to use "Alsil", an alumina silicate, as a high-temperature insulator, but as will be mentioned later, it proved to have poor resistance to mechanical shock in the switch, and was replaced by "Fluorosint", a sintered PTFE material filled with powdered mica, which distorts much less than PTFE at elevated temperatures and under load, but with a similar melting point limitation. Having accepted this limitation, all further insulating parts were made of either PTFE or Fluorosint. All parts were degreased in trichloroethylene, and then washed in warm water, smaller parts being cleared
in an ultrasonic bath. The copper contacts of the switch were cleaned by etching for a few minutes in the ultrasonic bath in a solution of 60% Formic acid, 10% Hydrogen peroxide, and 30% water (ref. 48).

In the design of mechanical parts, care was taken to avoid trapped volumes of gas in blind holes, in some cases by drilling out the centre of bolts. Holes were drilled in the centre of the broad wall of the part of the waveguide section between the baseplate flange and the d.c. block.

5.3 Vacuum arc power supply

For the purposes of interpreting the microwave reflection coefficient of the vacuum arc, it was convenient to ensure that only one cathode spot was present at a time; it is known that multiple spots appear in the current range 100 - 150 A, and so the power supply for the arc in this experiment need not supply greater than this current. In order to simulate a switch working on a high-voltage system, a circuit was used in which the switch operates on a zero power factor supply, a situation which creates large restriking transients. More sophisticated synthetic test circuits can be devised (e.g. 49) than the method described here, but this technique is adequate for the measurements required. The power supply circuit is shown in fig. 5.1. The main capacitor bank $C_c$ is charged to a voltage up to about 12 kV, and may be discharged through the inductor $L$ and the initially closed contacts of the vacuum switch VS. The inductance of $L$ was chosen so that the circuit would oscillate at a frequency of around 50 c/s if VS remained closed. The peak current which flows during each half-cycle, if there were no losses, is given by

$$\hat{I} = \sqrt{\frac{C_c}{L}} \hat{V} = 12.9 \times 10^{-3} \hat{V}$$

for the circuit shown, where $\hat{V}$ is the initial capacitor voltage. Current flow in the circuit is begun by triggering the trigatron $T_c$, and simultaneously firing the mechanism which closes the mechanical back-up switch BS across the trigatron.
The use of a trigatron alone to carry the main current is avoided for two reasons: to prevent the uncertainties of operation with two arcs in series, and to minimise erosion in the trigatron. Although high accuracy of timing can be achieved with the mechanism developed for the back-up switch, jitter could occur because of erratic breakdown of the switch contact gap as it closed, if the trigatron were not used. The back-up switch closes after about 3 msecs, and the vacuum arc may now be drawn out by triggering the vacuum switch mechanism VS at any required moment. At the first current zero the switch normally clears, leaving the capacitor bank charged at some negative voltage. If the switch fails to clear, arcing could continue for a few half-cycles, but the Q of the inductor L is fairly low, and the peak current rapidly diminishes (fig. 6.1). After 100 msecs, the back-up switch is opened, and \( C_c \) continues to be charged. After 2 seconds, the vacuum switch closes again, and the cycle may be re-commenced when \( C_c \) is fully charged.

The vacuum switch and back-up switch mechanisms are operated by discharging the appropriate capacitor banks \( C_v \) and \( C_b \) through the trigatrons \( T_v \) and \( T_b \) into spiral-wound coils on the switches, as described in the next section. In the circuit diagram the three trigatrons are triggered from a thyatron bank through d.c. blocking capacitors \( C_T \), and the large resistors A ensure that prior to triggering no voltage is developed between the trigger pin and the adjacent electrode, as the voltage on the latter rises during charging. The resistors B are bleeder resistors, and the three switches across the capacitor banks are knife switches which close when the high voltage cage door is opened. The inductor L was made up of 12 sections wound over a removable iron core, and was rated to 25 kV peak with all sections in series, and the capacitor \( C_R \) was included to limit the over-voltage when the current chopped. The spark gap \( S_2 \) prevents an excessive negative voltage appearing on the thyatron of the trigger unit when the voltage on \( C_c \) falls; it is set to break down at about 5 kV.

The main capacitor bank \( C_c \) is charged from a 3-phase selenium rectifier bridge,
supplied from 3 50 kV X-ray transformers, whose primaries are fed from a 3-phase motor-driven Variac. The capacitor bank and rectifiers are rated to 20 kV. All the high voltage supplies are contained in a wire mesh cage, both doors of which are fitted with inter-locks and the system for short-circuiting the capacitor banks.

In the top left-hand corner of fig. 5.1 may be seen one of the three similar thyatron circuits used to supply a trigger pulse to the trigatrons. The hydrogen thyatron is made conducting by a 200 V positive pulse applied to its grid, and discharges a 0.01 μF capacitor charged to 5 kV into the trigger electrode.

The three trigatrons are similar in construction; two are shown assembled and disassembled in fig. 5.2. Two flat stainless-steel disc-shaped electrodes are separated by a thick disc of plate glass, which has a 1½ in. diam. central hole. The steel discs seal with rubber O-rings against the glass, so that the central region may be evacuated by a ½ in. pumping port in one of the discs. The same disc is also fitted with a trigger electrode, whose face is flush with the disc face, and spaced from it all round by 3/32 in. The discs are clamped together by Tufnol plates and nylon screws. The two low voltage trigatrons have an electrode spacing of ½ in., while the other trigatron gap is ⅝ in. The characteristics of trigatrons for applications up to 300 kV have been described by Sletten and Lewis (50) for 15 cm. diam. hemispherical electrodes in air at atmospheric pressure. Their experimental results show that for voltages less than about 30 kV in air, the minimum voltage at which a given gap can be triggered is independent of both the polarities of the main gap and the trigger gap voltages, but that a negative trigger voltage gives a considerably shorter time lag of operation than a positive trigger voltage.

Tests were made on our trigatrons for the condition of negative-trigger and negative main gap polarity, to determine the natural breakdown voltages and minimum trigger voltages for the two main gap spacings, and how these varied with
pressure; the results are shown in figs. 5.3 and 5.4. From these graphs it is seen that at the lower pressures, the shorter gap trigatron has the much greater dynamic range of operation, and that even at higher pressures, the minimum trigger-ed voltage of the 3/8 in. spaced trigatron is still over 80% of the natural breakdown voltage. With 10 times greater trigger energy, Sletten and Lewis were able to operate a trigatron at 50% of its natural breakdown voltage, but greater energy could not be used here because of the peak current limitation of the thyatron. Changing the pressure proved to be a convenient method of controlling the breakdown characteristics of the trigatron, and during use the pressures were kept constant by pumping through fine leak valves to a single small rotary pump.

The arc current is measured using a coaxial non-inductive current shunt, as described by Park (51). It consists of a 4 mm. outside diameter, 3 mm. inside diameter, 2 1/2 in. long stainless-steel tube, over which are a PTFE sleeve 0.006 in. thick, and a copper tube. The two tubes are joined at one end by a boss, and their other ends are connected in the supply line. The voltage drop across the ends of the stainless-steel tube is taken by twin screened leads to the oscilloscope amplifier. The shunt resistance is 13.1 mΩ.

5.4 Break and make switches

For some years this Department has had an interest in synchronous operation of circuit-breakers (52, 53). It has been demonstrated on a plain air circuit-breaker that under conditions where normally in all but a few cases the switch would fail to clear completely, careful adjustment of the time at which the switch mechanism is actuated, taking into account previously determined switch characteristics, allows the switch consistently to clear the circuit at the first current zero. As with all conventional high-voltage circuit-breakers, however, the contact separation must be relatively large before the switch can withstand the restriking transient, and in the demonstration it was necessary artificially to
reduce the normal rate of rise of restriking voltage to prove the principle.
Because of the relatively large contact separations required before arc extinction
methods normally used become effective, it is necessary that the switch carry
several half-cycles of fault current before interruption, with consequent severe
erosion of the contacts under fault conditions. For first current zero interrup-
tion, it is necessary that the switch attain its full dielectric strength in a
time short compared with a half-cycle. Due to mechanical limitations, contact
speeds in conventional circuit-breakers are unlikely to be increased significantly,
and so the application of synchronous switching has had to await the availability
of a sufficiently effective dielectric medium, to reduce the required contact
separation. Since in the vacuum switch only small contact movements of the order
of $\frac{1}{4}$ in. are required, the possibility occurs here of making a mechanism with very
high speed action and precise operation.

Koller (7) in 1946, and many others since, have recognised the particular
suitability of the vacuum switch for synchronous operation. Cobine (6) mentions
unpublished demonstrations by Hull and Gallagher in 1950-51 of such operation to
circumvent the problems of high-current vacuum interruption. It was with the
vacuum switch particularly in mind that a patent application for controlled switch-
ing was made by Farvis (5). Since for the microwave probing technique it was
also necessary for the contacts to be drawn up into the plates in a time short
compared with the time for a half-cycle of current, a technique of rapid switching
was thus developed here which might have application to synchronous switching.

Two rapid switches were required, one back-up make switch, and one break
switch. Both were originally intended to be operated inside the vacuum tank, but
in fact due to a shortage of leadthroughs into the tank, the make switch was opera-
ted in air. Most previous designs of vacuum switches have operated with the
contacts inside an envelope, a bellows arrangement allowing movement of one or both
contacts by mechanisms outside the envelope. Since the bellows and associated linkages might appreciably increase the inertia of the moving parts, the complete switch action was here to be actuated electrically through vacuum lead-throughs.

The basis of the rapid action was used by Gorowitz, Moses and Gloersen (55) for injection of a pulse of gas into a high vacuum system. A sketch of the break switch is shown in fig. 5.5, and there can be seen a flat spiral coil of copper embedded near the surface of an insulating medium, and directly above this is a 3 in. diam. disc of aluminium. The coil is ¾ in. inside diam. and 3 in. outside diam., and there are about 10 turns of ¼6 in. square section copper. A high-voltage capacitor is discharged through a trigatron into this coil, and the very large current pulse induces eddy currents in the disc directly above, such that the disc is repelled violently. The moving contact of each switch is mounted on this disc. The capacitor discharges in a few tens of microseconds, so the force exerted on the disc is impulsive, and the velocity of the disc during most of its upward movement is constant. To ensure maximum coupling, the coil is constructed so that the current flows as near to the surface of the insulator as possible, while avoiding electrical breakdown. One problem was that of fabricating the copper spiral. This was done by cutting a deep spiral in the face of a sheet of copper, using a lathe modified to have a very rapid cross-motion of the tool-post. The cut surface was then immersed face down in a mould of Eccoceram, and when this material had set, it was gripped in the chuck of the lathe, and the reverse side of the copper machined off to leave the embedded copper spiral. Leads were then brazed on, and the back of the coil built up, and finally the front surface was machined to leave a ½32 in. layer of insulation covering the copper. The aluminium disc was made from ⅛ in. thick material, milled away on one side to leave eight webs supporting a ¼6 in. thick skin on the lower side.
Originally it had been intended that a spring toggle mechanism could hold the switch in its open or closed positions, but problems were encountered with the small movements involved, and of obtaining high temperature springs. Solenoids are used as latches in both switches, and the wires in the solenoid coils are of anodised aluminium wire, which meets temperature and vacuum requirements. They are ring shaped, as shown in fig. 5.5, and act on thin nickel-iron rings riveted on to the aluminium disc. The lower solenoid pulls the disc downwards to maintain a positive contact pressure prior to arcing on the vacuum switch.

The moving copper contact on the break switch is screwed to a stainless-steel lead, in an insulating sleeve, which originally was made of Alsi, but had to be replaced by Fluorosint for greater resistance to the shock of the spiral coil impulse. This upper electrode is slightly narrower than the insulating sleeve, and so does not make contact with the upper waveguide plate; since this electrode is always the cathode, this allows a method of anchoring the arc. The lower electrode is held flush with the lower waveguide plate by a simple leaf spring, which is deflected downwards by the pressure of the upper contact when the lower "hold-on" solenoid operates. A photograph of the switch in position on the upper waveguide plate is shown in fig. 5.6.

The back-up, or make switch is similar in principle to the switch described above, and is seen in fig. 5.7. Here the moving contact is situated above the disc, and only one solenoid is required to keep the contacts closed against a leaf spring on the upper contact, which deflects about \( \frac{1}{32} \) in. to maintain contact pressure. To prevent contact bounce, a 3-body technique was used. Above the upper contact was a mass, free to slide upwards, similar in weight to the moving disc and contacts. When the two contacts make, the momentum of the moving parts is transferred through the upper contact to the movable mass, and the now almost stationary disc is pulled up by the solenoid the remaining \( \frac{1}{32} \) in.
The solenoid current is switched on the moment the contacts make.

5.5. Performance of the switches

Once the bounce problem had been solved, the back-up switch would consistently close in 3.0 ms, when a 10 µF 3 kV capacitor was used, the total weight of the moving parts being 88.6 gm. The switch could be used in air at normal pressure up to 9 kV, and in a tank which was adapted for the purpose, up to 20 kV at 3 atmospheres in nitrogen with an increased switching time.

Several tests were made to determine optimum operating conditions for the break switch. The upper solenoid has little influence on the switching time, and was normally energised as the spiral coil supply was triggered; the lower solenoid was switched off 0.5 msec prior to this. With a 25.5 µF 3 kV capacitor bank, the electrode crossed the \( \frac{1}{8} \) in. gap in 2 ms; a plot of its position versus time was derived from one of the high-speed films described in section 6.2, and is shown in fig. 5.8. Since no acceleration process could have occurred at mid-travel, it is assumed that the slightly concave shape of the curve in its lower half is due to the contact rod stretching when the aluminium disc is thrown upwards. If this is the correct explanation, then the disc moves with constant velocity. The mean velocity was determined for various capacitor bank voltages in the range 2.45 to 3.0 kV, and fig. 5.9 shows the velocity plotted against the square of the voltage. This is linear because the disc is impulsively accelerated. The usual impulse equation is of the form

\[
\int F \, dt = mv
\]

The dimensions of the force are those of \((\text{current})^2\), and is thus proportional to \((\text{capacitor voltage})^2\). Thus the velocity achieved is proportional to the square of the capacitor voltage, and other things being equal, for a given stored energy it is better to operate at as large a voltage as possible. However, insulation problems in the spiral coil limited the allowed voltage.
Checks were also made of the time jitter of the moment that the contacts actually parted, and it was found that this was less than 10 μsecs. Both this very low jitter, and the high initial contact speed, would make the mechanism very suited to a synchronous switch.

5.6 Digital delay sequence generator and associated equipment

The complete cycle of operations is controlled by the digital delay sequence generator, a block diagram of which is shown in fig. 5.10. When the 'start' button is pushed, or a relay across its terminals closes, the gating circuit allows a train of pulses from the 10 kc/s oscillator to feed into three scale-of-10 binary adders. When the count on the adders reaches 999, they are reset to zero, and a pulse is returned to the gating circuit which prevents further input unless the gate is in the continuously open mode. As the circuit counts, the binary-decimal decoders convert the count to output pulses on one of each of the three sets of 10 output lines. These lines connect to a matrix board, in such a way that on each of 12 output channels, a single pulse is produced when a particular count on the decoder output lines is sensed by the corresponding AND-gate. Any of the 12 outputs may be set to give a pulse at any one time during the count. This unit controls the complete sequence of operations of trigatrons, solenoids, and oscilloscope triggers.

Associated with the sequence unit are three solenoid current supplies. Each of these supplies about 8 A to one of the three solenoids on receipt of a start pulse from the sequence generator, and switches this off at some later time on receipt of a second pulse. If for some reason no stop command is received, the supplies automatically turn off after about 2 secs., to protect both their own output transistors and the solenoids.

Another associated piece of equipment has 3 channels which provide the three thyratrons with a 200 V 10 μsec spike on receipt of a trigger from the
Digital Delay Sequence Generator

Fig. 5.10
sequence generator. The output pulse is delayed by 30 \( \mu \text{sec} \) on the input to facilitate oscilloscope measurements of thyatron and trigatron breakdown times, and jitter.
CHAPTER 6

Experimental Results and Discussion

6.1 Current, voltage and pressure measurements

After the characteristics of the trigatrons and the switches had been determined as described in chapter 5, tests were then made on the complete synthetic a.c. supply. Fig. 6.1 shows the current waveform as the 34 μF capacitor bank, charged to 7.1 kV, was discharged through the 0.3 H choke, with the peak current 67 A. In the lower trace the trigatron Tc in fig. 5.1 was fired, but the back-up switch was not energised; the arc in the trigatron struck for several half-cycles. The upper trace shows the same system with the back-up switch operating, and the ringing is continuous. The back-up switch was triggered here at the same instant as the trigatron, and so the arc in the latter would extinguish after 3 msecs.

In view of the large circuit inductance, it was decided to make the initial vacuum arc tests with the inductor L and capacitor C_{R} replaced by a resistor, to minimise the over-voltages occurring while the chopping characteristics were established. This produces a decaying exponential current waveform, and a typical vacuum arcing characteristic is shown in fig. 6.2. The switching sequence, which was typical of that for all tests, was as follows:

<table>
<thead>
<tr>
<th>Time (msecs)</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Vacuum switch lower solenoid ON</td>
</tr>
<tr>
<td>20</td>
<td>Oscilloscope trigger</td>
</tr>
<tr>
<td>21</td>
<td>Trigatrons T_{C} and T_{B} fired</td>
</tr>
<tr>
<td>23</td>
<td>Vacuum switch lower solenoid OFF</td>
</tr>
<tr>
<td>23.5</td>
<td>Trigatron T_{V} fired and vacuum switch upper solenoid ON</td>
</tr>
<tr>
<td>24</td>
<td>Back-up switch solenoid ON</td>
</tr>
<tr>
<td>99.9</td>
<td>Back-up switch solenoid OFF</td>
</tr>
<tr>
<td>2000</td>
<td>Vacuum switch lower solenoid OFF</td>
</tr>
</tbody>
</table>

The current is seen to rise abruptly to a peak value of 33.7 A. The moment when
the current chops, and in fig. 6.5 the same situation is shown with higher sensitiv-
ity in order to estimate the arc voltage. The transient from the vacuum
switch mechanism appears at the onset of arcing because of inadequate oscillos-
cope common-mode rejection, and the current in the second picture falls from
34 A to 11 A during arcing. Note the increasing instability as the current falls.
It is difficult to estimate the arc voltage accurately; Reece (1) estimates the
high frequency components of arcing to be 10% of the mean, but clearly they are
much higher here. Initially the mean voltage is about 21 V, when the arc is
most stable, and this compares well with the results of other workers. The
short-term steps in arc voltage which can be seen may be associated with gas evolu-
tion, or with deposits on the cathode, but the contacts used for this measure-
ment were zone-refined, and were unlikely to contain gas pockets.
Outgassing during arcing was still a problem, despite the care taken over
choice of materials. It was unfortunate that it proved necessary to use PTFE
in the switch, because a high temperature bake at, say, 450°C was not then poss-
able. During a series of tests with the zone-refined contacts, the ion pump
was switched off during arcing, and its initial pressure reading when it was
switched on gave an indication of the gas evolution. The contacts had drawn
only two or three prior arcs, and the first arc of this set caused the pressure
to rise from $2 \times 10^{-7}$ to $2 \times 10^{-6}$ Torr; in a 30-litre tank, this represents an
appreciable quantity of evolved gas, since vacuum switches are typically con-
structed in 1-litre enclosures. After 30 similar arcs, the pressure rose
from $2 \times 10^{-7}$ to $10^{-6}$ Torr. It was possible to determine the composition of the
evolved gases with the mass spectrometer; the relative concentrations of the
main gases in the tank after the 30th of these arcs, with the ion pump off, was
as follows:
In addition to these gases, some other hydrocarbons were present in smaller quantities. The carbon compounds are almost certainly due to inadequate trapping of back-streaming vapours from the diffusion pump in the liquid nitrogen trap. They could have been driven from the contact surfaces by a higher temperature bake. We may check if this gas evolution is likely to affect the model for the arc column which was proposed. A pressure of $2 \times 10^6$ Torr implies $7 \times 10^{16}$ gas molecules/m$^3$, and in a 30-litre tank this is $2.1 \times 10^{15}$ molecules. If these are released at a constant rate as the arc runs over the cathode, during 8 msecs, then the emission rate is $2.6 \times 10^{17}$ molecules/sec.

Now assuming a net erosion rate of 70 $\mu$g/cm/s for copper, and a mean current of 25 A, the vapour evolution rate into the column is $1.8 \times 10^{18}$ molecules/sec.

Thus while the gas evolution would be fairly serious in a sealed-off switch, it is negligible for the measurements made here. If, as is believed, the gas was released by scouring by the arc of adsorbed gas on the contact faces, rather than from below the contact surface, then it would be expected that as time went on, the pressure rise would become smaller. Although quantitative measurements were not made once microwave measurements had begun, it was noticed that the pressure rises did become markedly less.

### Table

<table>
<thead>
<tr>
<th>Gas</th>
<th>m/e ratio</th>
<th>Relative concentration</th>
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<tbody>
<tr>
<td>H$_2$</td>
<td>2</td>
<td>22.8</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>16</td>
<td>8.8</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>18</td>
<td>11.6</td>
</tr>
<tr>
<td>CO</td>
<td>28</td>
<td>18.4</td>
</tr>
<tr>
<td>N$_2$</td>
<td>28</td>
<td>28.5</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>44</td>
<td>10.0</td>
</tr>
</tbody>
</table>

6.2 **High-speed filming of vacuum arcs**

Visual observations of the vacuum arc as the contacts are drawn apart gives
little information other than the arc colour. It was known (1) that the arc moves over the contact rapidly, and so high-speed cine films were taken using an 8,000 f.p.s. Fastax camera. To enable the arc to be photographed more readily, the switch was constructed on 2 5 in. x 5 in. copper plates, at the same spacing as the waveguide plates. This allowed the arc to be nearer the window on the vessel. The camera accelerated the film over about 0.6 sec, and then the digital sequence generator was triggered, to draw out an arc which occupied about 60 frames on the film. Each frame was exposed for 40 $\mu$secs, and the interval between frames was 125 $\mu$secs. Timing marks on the film enabled the arc picture at any time to be related to the current waveform recorded simultaneously on an oscilloscope camera.

From these films, it was seen that the arc could move rapidly around the electrode, in some cases moving from one side of the electrode to the other between frames, implying velocities as high as 50 m/s. Projecting the film at 8 f.p.s. helped to confirm that the arc moved around the periphery of the contact, and when the upper electrode (the cathode) was drawn completely up into the copper plate, the cathode spot often ran up the gap between them and out of sight.

An interesting phenomenon which was studied was the appearance on some frames of bright radial streaks coming from the cathode spot; Fig. 6.6 shows one spectacular example of these, the upper electrode being the cathode, and the inter-electrode gap $\frac{1}{2}$ in. In some cases they seemed to be associated with the appearance of anode spots and an anode glow. Fig. 6.7 shows a sequence of pictures, the first of which shows the normal vacuum arc, with an intense cathode spot and diffuse column. In the next frame a number of streaks are seen coming from the cathode towards the left hand side of the anode. The following frame shows two other streaks directed to the right, and 8 frames later, with no further streaks, the last picture shows a bright region around the anode, together with faint spots.
It was clear that high speed film studies are a useful method of assessing the quality of a vacuum switch, but these studies had to be terminated to allow the microwave measurements to be made.

6.3 Microwave measurements

After the filming, the complete parallel plate system was assembled on the baseplate, and can be seen in fig. 6.9. The left-hand picture shows the lower waveguide plate, with the load material around its edge. In the right-hand picture, the switch and waveguide coupling section are seen mounted on the upper plate, and the special waveguide section which couples down to the waveguide window on the base-plate is also visible. As mentioned in section 4.12, the first check on the complete system was to measure the change in reflection coefficient as the contact was raised by the action of the upper solenoid alone, and the display produced was shown in fig. 4.20. However, when the spiral coil mechanism was triggered, the display shown in fig. 6.10 was obtained. It was found that when the aluminium disc on the switch was thrown upwards by the spiral coil impulse, the force exerted on the upper waveguide plate caused a change in the plate spacing, which in turn produced changes in the overall reflection coefficient. There was not time at this stage to add stiffening webs to the plates to reduce this movement, and so an allowance was made for the mis-match caused by plate vibrations when taking readings from the bridge. However, a second unexpected complication arose when it was found that the vacuum arc reflection was extremely noisy. Figs. 6.11 and 6.12 show the X and Y co-ordinates of the reflection coefficient displayed simultaneously against time, by using the chopped display facility of the oscilloscope. In fig. 6.11 there is no vacuum arcing; the final sweep position, with the contacts fully apart, is represented by the two spots at the left-hand edge of the picture, and it can be seen that at about 0.6 cm from the left-hand edge, the contacts were thrown apart. They achieve
their final open position after about 2 msecs, but the vibration continues for about 80 msecs. Fig. 6.12 shows the same situation when a 23 A d.c. arc was drawn out, lasting about 25 msecs. A mean level can be discerned, but the signal is very obscured by rapid fluctuations.

Three possible sources for the noise might exist: (a) it might be low frequency pick-up caused by different earth potentials around the equipment, despite the measures, including d.c. blocks in the waveguide, which had been taken; (b) it might be microwave frequency emission from the cathode spot: calculations suggest thermal radiation would be negligible, even at 20,000°K, but Froome (59) reported unusual emission of microwaves from the cathode region of a mercury arc; or (c) it might be genuine rapid fluctuations in the arc reflection coefficient. It was proved that in fact (c) is the correct conclusion by setting attenuators $A_2$ and $A_3$ in fig. 4.17 to their maximum value. With the reference signal at its usual level, we have seen that this leaves the bridge sensitive to microwave signals of the order of $10^{10}$ W, which is certainly much less than those which cause the observed effect. When the arc was then drawn out, no noise signal was observed from the microwave bridge. Thus it was concluded that the "noise" was in fact caused by very rapid fluctuations in the microwave reflection coefficient. When the Y channel output alone was displayed with a 20 μsec/cm time-base, the individual 2 μsec. samples could be seen as a series of dots, and there could be large changes in the position of successive spots. Even with the arc velocity as high as 50 m/s, there would be negligible change of phase shift due to arc position in 2 μsecs, and so it must be concluded that within the column itself the structure is changing in times short compared with 2 μsecs.

6.4 Electron velocity in the arc column

Despite the fluctuations, it was possible to deduce from the traces that the modulus of the reflection coefficient of a 30 A d.c. arc column was 1.26
times greater than that for a \( \frac{1}{4} \) in. diam. metal post (the upper electrode).

From fig. 3.2, \( f \) for a \( \frac{1}{4} \) in. metallic post is 0.15, and thus for the value of \( f \) for the arc to be 0.189, \( \varphi \) is seen from fig. 3.5 to lie in the range \( 8.5 \times 10^{12} \) to \( 2 \times 10^{15} \) electrons/m.

From (3.7),

\[
\left( \nu_e - \nu_i \right) = \frac{3 \pi}{\eta} \epsilon
\]

\[
= 2.8 \text{ to } 6.5 \times 10^5 \text{ m/s}
\]

Assuming \( \nu_i = 10^6 \text{ m/s} \), we thus have

\( \nu_e = 2.9 \text{ to } 6.6 \times 10^5 \text{ m/s} \)

This measurement of electron velocity may be used as follows:

From (2.2)

\[
W = \frac{\chi_m m_k}{I}
\]

and from (2.7)

\[
I = \frac{v_e}{v_i} e (\chi_e - \chi_i)
\]

\[
= \frac{v_e}{v_i} e \chi_i \left( \frac{\nu_e}{\nu_i} - 1 \right)
\]

\[
= \frac{v_e}{v_i} e \rho \chi_k \left( \frac{\nu_e}{\nu_i} - 1 \right)
\]

In (6.1)

\[
W = \frac{1.5 m_k}{e \rho \left( \frac{\nu_e}{\nu_i} - 1 \right)}
\]

\[
\therefore \rho \left( \frac{\nu_e}{\nu_i} - 1 \right) = \frac{1.5 m_k}{e W}
\]

i.e.

\[
\rho \left( \frac{\nu_e}{\nu_i} - 1 \right) \approx \frac{10^{-6}}{W} \text{ for copper}
\]

We may use the expression (6.5) to compare previous results with that obtained here:

Tyulina (31) gives a maximum value of 1.5 for \( \nu_e/\nu_i \) using molybdenum and tungsten electrodes, but even with \( \rho = 1.0 \), this implies \( W > 3,000 \mu gm/C \), a most unlikely erosion rate.

Reese (1) assumed \( \rho = 0.1 \) and \( \nu_e/\nu_i = 100 \), giving \( W = 101 \mu gm/C \) for the net
erosion rate, which compares with a measured value for the gross erosion rate of 70\mu g/m/C.

Plyutto (24) measured $p = 0.5$, and $W = 65\mu g/m/C$ for the net erosion rate (his gross erosion rate was 130 \mu g/m/C), and this produces $\frac{v_e}{v_i} = 32$

In this work we measured $(v_e - v_i) = 2.8$ to $6.5 \times 10^5$ m/s; assuming $v_i = 10^4$ m/s, we have $\frac{v_e}{v_i} = 29$ to 66, and assuming $W = 70\mu g/m/C$, this gives $p = 0.22$ to 0.51.

Thus we conclude that the electron velocity measured here is in reasonable agreement with the results of Plyutto, and that the electron velocity figure of $10^6$ m/sec. obtained by Reece from an energy balance is probably rather high. The fluctuations in the reflection coefficient, however, are a limit to the accuracy which can be achieved by a microwave method, although it is probably the only method by which electron density in the column could be measured.
CHAPTER 7

Conclusions

7.1 Summary

A microwave bridge technique was evolved which allowed rapid measurement of a complex reflection coefficient in the range -70 dB to 0 dB. In the course of its design, methods were found using d.c. bias to balance and optimise the detector diodes, and these significantly improved the bridge performance. The X-Y presentation of this on an oscilloscope was particularly convenient during setting up, since the polar display allowed the affects of discontinuities rapidly to be assessed. For time-resolved measurements, however, it was found more convenient to use a dual beam display, to show X and Y components separately against a time-base.

A novel compact coupling system into a parallel-plate transmission line was developed, as were also techniques for the use of quasi-infinite parallel-plates in a high vacuum system. The method of measurement is particularly suited to free arc studies, because the plates may be electrically isolated, and the arc may move around over a fairly wide area without changing the reflection coefficient magnitude appreciably. Experiments showed that the reflection coefficients of metallic and solid dielectric cylinders between the plates agreed well with theory, and this then allowed confidence in applying the analysis to plasma dielectrics.

This analysis was carried out for homogeneous plasma cylinders, and a study then made of a proposed model for the vacuum arc column, to assess expected reflection characteristics. It was shown from this that the technique is suited to the low current vacuum arc, where the assumptions of a constant line density and cylindrical shape may be made. It was also shown that for higher currents, the column becomes equivalent to a very shallow cone, and it was indicated that
the analysis of scattering from this would be formidable.

High speed make and break mechanisms which allowed operation of vacuum switches inside a vacuum tank without mechanical lead-throughs have been described. These have high initial velocities, switching times of 2-3 msecs, and the jitter is less than 10\(\mu\)secs. The switching time could be reduced even further with a more robust mechanism, and it is suggested that for a given stored energy, a larger voltage is preferable to increased capacity of the capacitor bank.

Observations of the arc in the switch showed minimum arcing voltages around 21 volts, but the waveform was very noisy. The high chopping level of 10-20 A when interrupting alternating current was attributable to the large shunt capacitance across the inductor; for future work it would be preferable to operate with a much smaller inductor of higher voltage rating, and a larger capacitor bank. The gas evolved during arcing was mainly hydrocarbons, and it is expected that these were present because of the limited baking temperature, and inefficient cold trap.

High-speed films of the vacuum arcs showed that relatively slow, luminous macro-particles are emitted from the cathode, and these might be associated with the appearance of anode spots. The absence of these particles from zone-refined electrodes was taken to indicate that they were caused by exploding gas pockets in the material, although this requires further study.

Microwave observations of the arc column were made difficult by plate movement, and by the fluctuating nature of the arc column, but it was shown that the mean radial electron velocity lies in the range 2.9 - 3.5 \(\times 10^5\) m/sec. If the net erosion rate into the column is 70 \(\mu\)gm/C, this corresponds to a degree of ionization of 20-50% for the vapour. The reason for the rapid fluctuations in the microwave reflected signal must be that there are changes in the rate at which plasma is ejected from the high pressure region, associated with the arc
instability at low currents. Since the structure changes radically in 2 \( \mu \)secs, it is expected that an even higher rate of response than is achievable here would be required to follow the changes in reflection coefficient due to the electron density decay at current chop; but this would be very difficult to interpret because of the inhomogeneity of the electron distribution in space.

7.2 Further work

Most theoretical work on the vacuum arc has been concerned with cathode spot phenomena, and these are now fairly well understood. In contrast, little is known with confidence about the high pressure region just above the cathode, and this region could bear much further experimental and theoretical investigation. Studies of the arc column, such as the microwave measurements described here, the mass spectroscopic work currently being carried out by Fransen and Schuy (25, 26), and the several experiments by Plyutto (24), have recently added new data which might help an understanding of the processes in the cathode region. But measurements of gross scattering from the arc column using microwaves can probably not be carried much further, and despite the problems of measurement on a very small and mobile region, it is felt that further study should be directed toward probing the region directly. Optical spectroscopic techniques with high spatial and time resolution could yield valuable new data on the temperature, and this in its turn could help to explain the high velocities of ions and neutral vapour leaving the region.

It should be emphasised that an understanding of this high pressure area, and the manner in which it collapses when the current ceases, would be of first importance in understanding the recovery processes in the vacuum circuit-breaker. It has been found both in theory and experimentally that microwave measurements of these decay processes would offer real difficulty in interpretation of the results, and it is recommended that alternative techniques which offer the
necessary higher spatial resolution be investigated. The scattering of electron or neutral vapour beams at the high density regions by ions and atoms should yield information on how these quantities vary with time, and the electron beam in particular can be focused to very narrow angles. Electron beam probing has been attempted by Lukatskaya (60), but in an axial direction where interpretation of the measurements was difficult.

Another field in which work of interest to the vacuum circuit-breaker designer might be carried out is in further high-speed film studies. Are the macro-particles found here only emitted from gassy electrodes? Are these macro-particles associated with anode spots? The streak film techniques used here were very effective, and applied to a switch which had been designed for convenient photography, could answer these and other questions.

The high-speed switch mechanism was seen to be very effective, and the next step with this would be to build a sealed-off device without bellows based on this principle, and to investigate how this might be used to switch very high fault currents synchronously. High switching speeds with very low jitter have been seen to be possible.
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Finally, the author wishes to thank Mr Eric Lucey of the Animal Genetics Research Film Unit for the skill and ingenuity with which he tackled the problems of the high-speed photography.
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