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THE INFLUENCE OF MECHANICAL STRENGTH OF ELECTRODE MATERIAL
ON VACUUM ELECTRICAL BREAKDOWN

A Thesis Presented for
the Degree of Doctor of Philosophy

by

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ABSTRACT

This thesis gives an account of the effect of the mechanical strength of electrode materials on high voltage vacuum breakdown. For mechanical strength of the electrode material to be important, breakdown initiation must primarily occur by the detachment of particles from the electrode surfaces. On this basis a simple theory is developed which takes into account the possibility of detachment of electrode material under electric stress, when the ultimate tensile strength is reduced due to local heating produced by the pre-breakdown field emission current. Methods for estimating local electrode temperatures have been discussed.

Breakdown tests have been carried out for D.C. voltages with plane parallel electrodes of molybdenum, nickel and copper in various combinations, for a fixed gap of one millimeter and in a vacuum better than 10^{-8} Torr. Results are presented in the form of Fowler-Nordheim plots of the voltage-current data. The breakdown results interpreted in the light of above theory, suggest that mechanical strength is a significant parameter in vacuum breakdown between electrodes of copper and nickel, but the theory fails for molybdenum. Breakdown initiation from the anode is indicated as the most common feature.

Supporting evidence has been obtained by examining the electrode surface markings after breakdown, by electron probe x-ray microanalysis, optical and Stereo-Scan microscopy. The

results of this examination have been found to be consistent with the creation and detachment of protrusions from the anode and their impingement on the cathode.

Thus the results of the work described in this thesis generally support those clump theories of vacuum breakdown in which breakdown is thought to be initiated by clumps of anode material striking the cathode.

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CONTENTS

	PAGE
Abstract	2
Acknowledgements	4
Contents	5
Chapter 1 Introduction	8
1.1 General	8
1.1.1. The Prebreakdown Current	10
1.2 Review of Breakdown Theories	11
1.2.1 Field Emission Based Theories	11
1.2.2 Clump Hypothesis	14
1.2.3 Particle Interchange Hypothesis	15
1.3 Discussion	16
1.4 Present Work	20
Chapter 2 Preliminary Considerations	22
2.1 Formula for Breakdown Voltage	22
2.2 The Electric Field Enhancement Factor	23
2.2.1 Field Enhancement for the Cathode	24
2.2.2 Field Enhancement for the Anode	25
2.3 Ultimate Tensile Strength	25
2.4 Temperature at the Electrodes	27
2.4.1 Protrusion Geometry	27
2.4.2 Local Cathode Temperature	28
2.4.3 Local Anode Temperature	31

	PAGE
Chapter 3 Apparatus	34
3.1 Vacuum System	34
3.1.1 Requirements	34
3.1.2 Description	36
3.1.3 Operation	37
3.2 Discharge Tube	39
3.2.1 Initial Tubes	40
3.2.2 Final Tube	43
3.3 Electrodes	48
3.4 Discharge Circuit	49
Chapter 4 Breakdown Tests with Different Electrode Materials	51
4.1 Experimental Procedure.	52
4.1.1 Preparation of Electrode Surfaces	52
4.1.2 Voltage and Current Measurements	52
4.2 Results and Discussion	53
4.2.1 F-N Characteristics	63
4.2.2 Variation of Breakdown Voltage with Electrode Material	65
4.2.3 Local Temperatures	67
4.2.4 Predicting Breakdown Voltages	70
4.2.5 Growth of Projections	75
4.2.6 Effect of Heating on Electrode Surface Protrusions	78
4.3 Summary	83

	PAGE
Chapter 5 Examination of Electrode Surfaces after Breakdown	87
5.1 Direct Visual Observation	87
5.2 Microscopic Examination	89
5.2.1 Optical Micrographs	90
5.2.2 Stereoscan Micrographs.	101
5.2.3 Summary	111
5.2.4 Discussion	112
5.3 Electron Probe X-ray Microanalysis	114
5.3.1 Results	115
5.3.2 Summary	122
5.3.3 Discussion	122
Chapter 6 High Temperature Tests	124
6.1 Procedure	125
6.2 Results and Discussion	126
6.2.1 Rowler-Nordheim Plots	126
6.2.2. Local Electrode Temperatures	136
6.2.3 Variation of Applied Breakdown field, with Electrode Temperatures	144
6.2.4 Summary	148
Chapter 7 Discussion and Conclusions	150
Suggestions for Future Work	156
References	158

CHAPTER I

INTRODUCTION

1.1. General

Interest in the study of electrical breakdown in vacuum is linked with the use of vacuum as an insulating medium in various high voltage devices. Such devices for example include particle accelerators and separators, high power klystrons, electron microscopes and x-ray tubes. Apart from these, vacuum as an insulator is also being utilised in various ways in electric power engineering an example of which is the recent introduction of vacuum circuit breakers. As vacuum is the natural environment in space, space research programmes have generated further interest in the subject. For all these purposes demand to-day is increasing for the insulation of higher voltages and higher field strengths in vacuum. A better understanding of the physical processes which initiate electrical breakdown in vacuum is therefore of considerable practical interest.

The present work is concerned with the study of the influence of electrode material on vacuum electrical breakdown, and especially with examining whether any correlation exists between the breakdown voltage and the mechanical strength of the electrode materials. A previous study of this nature (Rozanova and Granovskii 1957) was made in rather poor vacuum conditions ($\approx 10^{-5}$ torr). A study of the prebreakdown current - voltage characteristics was not made. Significant though this work was in pointing out the influence of

the electrode materials, no reliable conclusions in such experimental conditions could be expected. To-day it is realised that for a reliable interpretation of the experimental results and to indentify the influence of a single parameter, experiments must be performed in good vacuum conditions, so that electrode surfaces may remain relatively clean during the measurements. From these considerations therefore it was considered worthwhile to re-examine the effect of electrode materials on vacuum breakdown, and especially the influence of their mechanical strength.

The term electrical breakdown in vacuum is used to describe the breakdown situation where the pressure in the breakdown tube is so low that the mean free path of electrons is extremely large in comparison to the interelectrode spacing. In this condition the results of breakdown measurements cannot be explained on the basis of Paschen's law. For gaps of less than a centimeter, which are of usual interest, it is usually regarded as corresponding to pressures of less than 10^{-3} Torr.

When the voltage across a pair of metal electrodes in vacuum is raised, a steady current begins to flow at an applied voltage of about 10^5 V/cm. With increase in voltage this current progressively increases until at a critical voltage a sudden jump in current is observed accompanied by luminous sparks across the gap. At this stage, the magnitude of the current is entirely determined by the limiting resistance in the circuit. The situation

in which this power supply limited current begins to flow is generally called vacuum breakdown. In large gaps several short and self quenching discharges are also observed in addition to the steady current and are known as 'microdischarges'. It is believed that the breakdown mechanism for short gaps ($\approx 1\text{mm}$) differs considerably from that in large gaps. The present tests were made at 1mm gap length and therefore in what follows the discussion will usually be confined to phenomena occurring in short gaps.

1.1.1. The Prebreakdown Current

As a result of the work of several investigators, Alpert et al (1964), Little and Whitney (1963), Goldstone (1965), the pre-breakdown current flowing between plane parallel electrodes in vacuum is now identified as the field emission electron current which originates from the tips of microscopic asperities on the cathode surface, where the applied electric field is enhanced. According to the Fowler - Nordheim theory(1928) of field emission, electron emission from clean, smooth metal surfaces becomes significant, when field strength at the cathode surface reaches 10^7 V/cm. To account for the apparent discrepancy between this and the observed field it is assumed that the field at the sharp emitting points is enhanced by a factor of about 100. It has been shown that asperities are created even on a highly polished surface after the application of an electric field(Little and Smith, 1965). Recently Little and Smith(1966) have demonstrated that these asperities on the cathode surface are created

due to the impact of clumps detached from the anode surface. Pre-breakdown current does not come from a single projection but from a number of projections. This has been demonstrated by viewing several luminous patches on a fluorescent screen anode (Little et al 1961, Brodie 1964) and by taking x-ray photographs of the anode surface (Singer and Doolittle, 1965). Tomaschke and Alpert (1967) have shown that voltage current plots even for multiple emitters would result in a straight line Fowler-Nordheim plot, the slope of which would give the field enhancement factor for the projection dominant among them.

The general effect of the pre-breakdown current at cathode and anode is to produce local heating. At the cathode the effect is to heat the tip of the emitter by resistive and Nottingham heating. On the anode, electron bombardment produces local heating on a small circular spot.

1.2. Review of Breakdown Theories

1.2.1. Field Emission based Theories

a) Anode Induced

Several workers (Boyle et al 1955, Schmidt 1958, Maitland 1961, etc) have come to the conclusion that for gaps up to 2mm, field emitted electrons bombarding the anode produce local heating, which releases considerable amounts of metal vapour and gas. When these are ionised by field emitted electrons, primary electron emission is increased due to field enhancement caused by the ionic space charge near the tip of a cathode protrusion. Secondary electrons

will also be emitted by ion bombardment of the cathode. These processes amplify the prebreakdown current and culminate in vacuum breakdown.

b) Cathode Induced

Ahearn (1936) concluded that field emission current originating from the asperity of highest field enhancement, would cause the rupture of the asperity when conditions of resistive heating, mechanical force and tensile strength were most favourable. Denholm (1958) suggested a breakdown mechanism for short gaps on similar lines. Dyke et al (1953) after their experiments with pointed tungsten cathodes concluded that breakdown was caused by evaporation of cathode material due to resistive heating of the emitter tip. For plane parallel electrodes Alpert et al (1964) came to the conclusion that a whisker could explode or melt due to resistive heating and so initiate breakdown.

c) Cathode or Anode Induced

Some recent workers (Chatterton 1966, Charbonnier et al 1967, Utsumi 1967) have tried to resolve the dilemma of the type of breakdown (cathode or anode induced) resulting from field emission. A first attempt in this direction was made by Chatterton who examined theoretically the effect of field emission on vacuum breakdown. Assuming the condition for breakdown to be cathode or anode melting he suggested that the field enhancement factor and the shape of the protrusion on the cathode surface are the main parameters which

decide the site(cathode or anode) of instability leading to breakdown. For known values of emitting area, work function and shape of the protrusion, there exists a critical value of field enhancement factor such that for $\beta < \beta_{crit}$ anode melting will initiate the breakdown and for $\beta > \beta_{crit}$ cathode melting will initiate it.

Later Charbonnier et al, derived an expression for the general case of D.C. as well as pulsed voltages. They performed experiments with plane parallel tungsten, molybdenum, copper and aluminium electrodes in ultra high vacuum and found agreement with their theory using Mo and Cu, but disagreement using Al. They came to the conclusion that field emission initiated breakdown occurs when the local heating at the cathode or anode causes excessive evaporation of electrode material into the electron beam. For materials of low yield strength like aluminium they suggested that detachment of material from the electrode surface under enhanced electrostatic stress may be the main cause of breakdown.

Utsumi (1967), from an analysis of his results for plane parallel electrodes of copper and tungsten, came to the conclusion that knowing the physical constants of the material and the shape of a cathode whisker of that material the type of breakdown(cathode or anode induced) can be predicted. For a given whisker and electrode material the type of breakdown depends on electrode

spacing, and there are regions in which a particular type of breakdown is dominant. In case of tungsten for example, for a typical whisker of height 10^{-4} cm and β between 50 and 100, he shows that breakdown for spacings below 5×10^{-3} cm is cathode induced, while between 5×10^{-3} cm and 2×10^{-1} cm both cathode and anode induced breakdown is possible. For separations larger than 2×10^{-1} cm anode induced breakdown is expected. He too assumes the initiation of breakdown to be caused by the local temperature at the cathode or anode rising to the melting point.

1.2.2. Clump Hypothesis

In 1952 Cranberg suggested that the detachment of charged bits of loose material from the electrode surfaces can occur under the electrostatic stress. He argued that when these bits of material ('clumps') hit the opposite electrode, electrical breakdown will occur if the impact energy is enough to vaporise the particle or the material of the electrode at the point of impact. The charge on the clump is proportional to the electric field E , and the breakdown condition is given as,

$$VE \geq C$$

where C is a constant depending on the particular material, its surface condition, and field enhancement at the clump. For a uniform field

$$E = V/d, \text{ and hence,}$$

$$V \geq (Cd)^{\frac{1}{2}}.$$

In support of this relationship Cranberg showed that a double log

plot of breakdown voltage vs gap spacing from data produced by several independent workers was a straight line of slope $\frac{1}{2}$.

Assuming that breakdown must occur in the vapour due to clump evaporation, in accordance with the Paschen condition for the minimum sparking potential, Slivkov (1957) arrived at an expression,

$$V_B = c d^{5/8}$$

and found this to be in agreement with experiment. Boulloud (1962) has suggested that a clump mechanism may not be possible in short gaps as a clump may not have sufficient energy for evaporation, but there is some evidence which strongly opposes this view and demonstrates that if clumps are present, even in short gaps, breakdown can be initiated solely by this mechanism. Rozanova (1962) produced breakdown in a gap as small as 0.4 mm by placing microparticles on one of the electrodes. Little and Smith (1966) showed a similar effect for a 0.25 mm gap.

Direct evidence showing that clumps torn from the electrode surfaces have initiated breakdown has still not been produced. Material transfer between the electrodes has been observed (Goldstone 1965, Browne 1955) but this does not conclusively prove that a clump mechanism has been solely responsible for breakdown. However it can serve as supporting evidence, when other observations already tend to suggest a clump mechanism.

1.2.3. Particle Interchange Hypothesis

According to this hypothesis put forward by Van Atta et

al in 1933, an electron bombarding the anode produces A positive ions and C photons. These then produce on the cathode surface B and D secondary electrons and when $AB + CD$ exceeds unity a runaway condition is reached culminating in breakdown. Evidence of such a process taking place is found only for poor vacuum conditions and contaminated surfaces (Arnal 1955, Mansfield 1960). It has been shown (Pivovarov and Gordienko 1963) that for electrode surfaces in ultrahigh vacuum such a process is not possible.

1.3. Discussion

From the above review it is obvious that two main breakdown theories need be considered in the interpretation of breakdown results for clean outgassed electrodes in ultrahigh vacuum:

- (a) Initiation of breakdown due to excessive evaporation of electrode material into the electron beam (Field Emission based theories)
- (b) Initiation of breakdown when the metal vapour is formed by the clump impact process (Clump Hypothesis).

It is generally agreed that the final breakdown of the gap is the result of an electrical discharge in the dense vapour of electrode material. Therefore these two theories of vacuum breakdown differ essentially in the mechanism which leads to the formation of the vapour. The two theories must be examined in the light of the fact that in small gaps the prebreakdown current is always a field emission current. Either of the two mechanisms of breakdown therefore must

arise as a direct consequence of the heating at local sites on the electrode surfaces by this current.

For the mechanism (a) the effect of this heating must be to raise the vapour pressure of the electrode material. This pressure must be $\approx 10^{-4}$ Torr, as there is no effect of pressure on breakdown voltage below this pressure (Little et al, 1961). From table 1.1 it can be seen that for usual electrode materials, pressures higher than 10^{-4} Torr are reached only close to the melting point (Honig 1962). Therefore for mechanism (a) it becomes essential for the local temperature at the electrodes to reach the melting point or higher.

TABLE 1.1.

Material	M.P. (°C)	Vap. Pressure (Torr)	0.8 x M.P. (°C)	Vap. Pressure (Torr)
Tungsten	3370	3×10^{-2}	2696	4×10^{-5}
Molybdenum	2620	2×10^{-2}	2096	5×10^{-5}
Nickel	1455	3×10^{-3}	1164	1×10^{-6}
Copper	1083	4×10^{-4}	866	1×10^{-6}

TABLE 1.2.

Material	Ultimate Tensile Strength at R.T.	0.5 x M.P. (°C)	Ultimate Tensile Strength at 0.5xM.P.
Tungsten	19×10^9 dynes/cm ²	1685	1.7×10^9 dynes/cm ²
Molybdenum	14	1310	1.8
Nickel	4.2	727	1.2
Copper	2.2	541	0.45

For the mechanism (b) the effect of heating must be to reduce the tensile strength of the electrode material to such a low value that detachment of suitably sized clumps can occur under the action of the enhanced electrostatic stress. Table 1.2 shows how drastically the tensile strength of the electrode material has been reduced at only half the melting temperature. For tungsten and molybdenum the strength (Metalwerk Plansee, 1961) has been reduced to nearly 1/10 and for nickel and copper (see fig. 1.1) to about $\frac{1}{4}$ of the room temperature value. The corresponding vapour pressure for all the materials at this temperature is less than 10^{-11} Torr. For a typical breakdown field observed in practice (6×10^7 V/cm) the electrostatic stress would be 1.7×10^9 dynes/cm², which is close to the tensile stress of tungsten and molybdenum at $\frac{1}{2}$ M.P. If the temperature rises higher the tensile stress falls further and the likelihood of clump formation becomes greater.

This discussion therefore leads to the view that when the prebreakdown field emission current heats the tip of a cathode protrusion and the corresponding anode spot, detachment of clumps is possible if the electrostatic stress at either point exceeds the hot tensile stress. This process may occur at temperatures significantly lower than those at which excessive evaporation of electrode material is expected. Whether these clumps can cause breakdown will depend on whether they are of suitable size and have the energy required to form the needed vapour after impact. We have seen earlier that

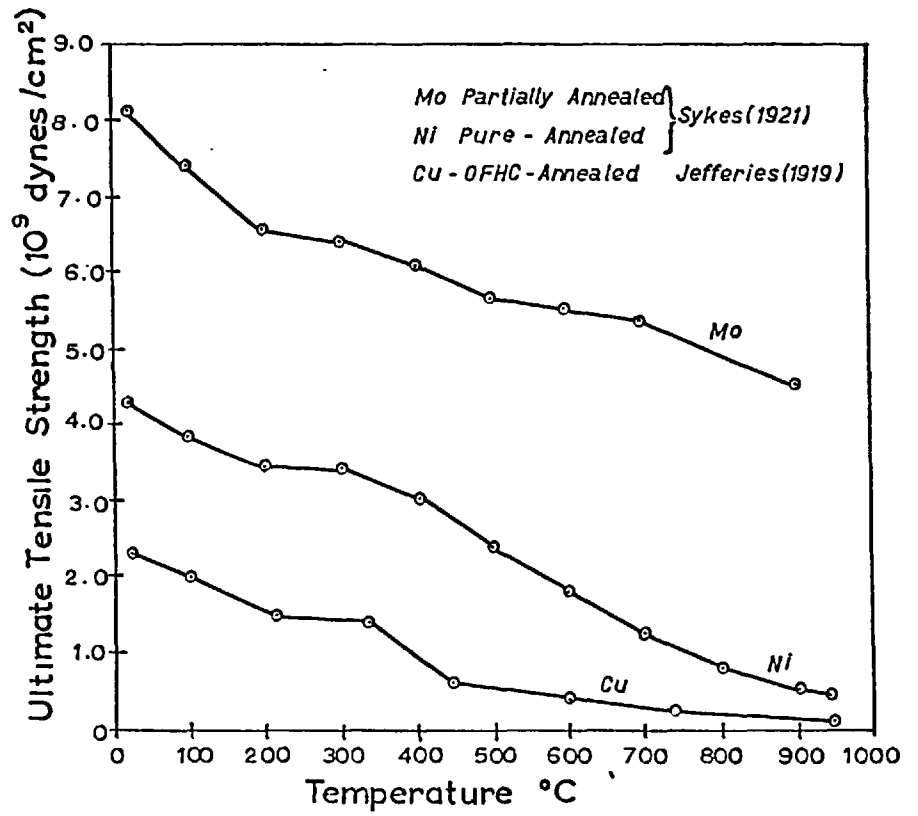


Fig. 1.1. Ultimate tensile strength vs temperature

by placing microparticles on one of the electrodes breakdown can be initiated in gaps as small as 0.25 mm. The possibility of a clump mechanism in short gaps is further supported by the recent work of Davies and Biondi(1968), who find that breakdown between copper electrodes due to a steady evaporation of electrode material is very unlikely. They suggest the detachment of a clump from the hot anode spot as the most likely cause of breakdown.

From these arguments therefore it seems reasonable to think that there is every possibility that clumps of electrode material, even relatively higher strength materials, are detached when the enhanced electric stress exceeds the hot tensile strength at local sites on the electrodes. If breakdown is initiated by this process then the mechanical strength of the electrode material must have a strong influence on the breakdown voltage of the gap.

1.4. Present Work

It was therefore decided to conduct breakdown experiments with the following objectives in view:

- (a) To study the variation in breakdown voltage with electrode material in ultrahigh vacuum conditions.
- (b) To examine whether this variation could be correlated with the mechanical strength of the electrode materials.
- (c) To search for evidence of transfer of material between the electrodes.

Breakdown tests were made using molybdenum, nickel and copper. Plane

parallel electrode geometry was used with a fixed gap length of 1 mm. The need for performing the experiments in clean conditions has already been stressed. Therefore all experiments were performed at pressures better than 2×10^{-8} Torr and most at pressures better than 5×10^{-9} Torr. In each case current and voltage readings were plotted in the form of Fowler-Nordheim curves. Assuming a particular cathode protrusion geometry and knowing other necessary parameters derived from the F-N curves the temperature at the cathode and at the anode have been calculated. Knowing the tensile strength of the material at these temperatures, the breakdown voltage has been predicted and compared with the experimental values.

Since the tensile strength of a material is a function of temperature experiments have also been performed for some materials at elevated electrode temperatures.

To obtain evidence for the detachment of clumps of electrode material, experiments were performed with mixed electrodes. Copper as one of the electrodes was combined with molybdenum and nickel. Areas on the electrode surfaces where the transfer of electrode material is most likely to be expected have been examined using an electron probe micro-analyser.

To aid in forming a physical picture of the breakdown mechanism, the typical markings on the electrode surfaces have been examined under an optical microscope. In one case electrode surfaces were also examined under a Stereo-Scan microscope.

CHAPTER II

PRELIMINARY CONSIDERATIONS

2.1. Formula for Breakdown Voltage

If electrical breakdown in vacuum is initiated by the detachment of material from the electrode surface as a result of the electric stress exceeding the ultimate tensile stress of the electrode material, then the breakdown condition for plane parallel electrodes separated by a distance d cms is simply written as,

$$E^2/8\pi = T_s$$

$$\text{or } \frac{\beta^2 V_B^2 \times 10^{-4}}{72\pi d^2} = T_s \quad (2.1)$$

where $E = \beta V_B/d$ is the enhanced electric field at the tip of the protrusion, β is the electric field enhancement factor, T_s is the ultimate tensile strength in dynes/cm², V_B is the breakdown voltage in volts. For a millimeter gap, (2.1) simplifies to

$$V_B = \frac{150 \times T_s^{\frac{1}{2}}}{\beta} \quad (2.2)$$

From (2.2), it can be seen that T_s and β are the important parameters for predicting the breakdown voltage of the gap. It is therefore necessary to discuss the method for determining the value of β for the two electrode surfaces and the problem of selecting an appropriate value of T_s .

2.2. The Electric Field Enhancement Factor (β)

The field enhancement factor β in eqn. (2.2) applies to any electrode from which material detachment is being considered. It is a parameter which depends on the geometry of the protrusions existing on the electrodes and any process which can alter the shape of a protrusion is likely to change the value of β . β is affected by the degree of polish given to the electrode surface, - the smoother the surface the lower is the value of β and hence the higher the value of V_B (Hawley et al 1965). For the same degree of surface finish β is also dependent on electrode material. Harder surfaces generally have lower values of β e.g. β_k for Mo is typically 100 - 120, where as for Cu it lies between 160 - 200. However for a particular method of polishing and electrode material, β_k is fairly constant unless its value is changed by processes occurring during the prebreakdown conduction stage.

One such process, by which β_k for a field emitting projection can be changed, has been shown by Dyke et al(1960) to be the heating of protrusions in the presence of a strong electric field. Depending on the operating conditions protrusions can become dulled (decreasing the value of β_k) or may begin to grow (increasing the value of β_k). Since local heating occurs both at the cathode and the anode due to the prebreakdown field emission current, it is obvious that while interpreting breakdown results, in accordance with

relation(2.2); the possibility of growth or dulling of protrusions on the electrode surfaces will have to be considered. This point is discussed further in chapter 4.

2.2.1. Field Enhancement for the Cathode (β_k)

The pre-breakdown current for short gaps in vacuum between clean outgassed plane parallel electrodes is the field emission current arising from the microscopic asperities on the cathode surface, and is in accordance with the Fowler-Nordheim equation

$$J = \frac{1.54 \times 10^{-6} E^2}{\phi t^2(y)} \exp \frac{-6.83 \times 10^7 \phi^{3/2}}{E v(y)} \quad (2.3)$$

(Fowler and Nordheim, 1928) where J is the current density in amp/cm², E the electric field in volts/cm at the cathode surface, and ϕ the work function of the cathode material. v and t are slowly varying functions of the variable

$$y = \frac{3.79 \times 10^{-4} E^{3/2}}{\phi}$$

and are nearly unity for the range of the electric field of interest. In a more convenient form (2.3) can be expressed as

$$I = \frac{1.54 \times 10^{-6} A_E \beta_k^2 V^2}{\phi d^2} \exp \frac{-6.83 \times 10^7 \phi^{3/2} d}{\beta_k V} \quad (2.4)$$

where I is the total current in amperes, A_E is the emitting area in sq cm, V is the applied voltage in volts, d is the electrode spacing in cms, and β_k is the field enhancement factor at the tip of the

emitting protrusion. From (2.4) a plot of $\log_{10} \frac{Id^2}{V^2}$ vs $\frac{d}{V}$ will give a straight line of slope

$$m = \frac{-6.83 \times 10^7 \phi^{3/2}}{2.3 \beta_k} \quad (2.5)$$

From (2.5) it can be seen that, knowing the work function ϕ of the cathode material, β_k can be found.

2.2.2. Field Enhancement for the Anode (β_A)

This parameter can not be directly determined from experiment. The best approach seems to be to assume that $\beta_A = \beta_k$ on the ground that electrodes of the same material polished in the same way are likely to be in similar condition. The value of β_A may subsequently be affected by local anode heating in the presence of any electric field, but it is impossible at this stage to describe the effect quantitatively.

2.3. Ultimate Tensile Strength (T_s)

Data on the ultimate tensile strength of materials available in the hand books is of two types a) for work hardened material and b) for annealed materials. Therefore for use in the breakdown formula(2.2), T_s must be selected on the basis of the amount of work hardening given to the material and the extent of subsequent heat treatment. Parameters strongly affecting the ultimate tensile strength of a material are, a) the diameter of the

specimen and b) its temperature. We therefore now consider the effects of these two on T_s and their implications for the Breakdown voltage formula (2.2).

a) Effect of Diameter

Data for the variation of ultimate tensile strength with diameter is given in table 2.1 for tungsten and molybdenum. Data for other materials was not available but these two examples will serve the purpose of giving an idea of the extent to which the ultimate tensile strength for the surface asperities of an electrode material may be affected.

Table 2.1

	Drawn Wire		Annealed Wire	
Tungsten	1.0 mm dia	140 kg/mm ²	0.15 mm dia	175 kg/mm ²
	0.015	470	0.02	400
Molybdenum	1.0	99 - 140	1.0	80 - 99
	0.05	218 - 248	0.03	80 - 119

Data for Tungsten - Kohl(1951).

Molybdenum - Metalwerk Plansee(1961)

It can be seen from table 2.1 that the ultimate tensile strength of 1 mm drawn tungsten wire increases by a factor of 3 when the diameter is reduced to 15 μ , whereas for annealed wire the rise is only a factor of 2. For drawn molybdenum wire the ultimate tensile strength increases by a factor of 2 when the diameter is reduced to 50 μ ,

whereas for annealed 30 μ wire the rise is only 20%. Extending this effect of change in ultimate tensile strength with diameter to protrusions of $\approx 1 \mu$ diameter it seems reasonable to assume that the ultimate tensile strength may be raised by a factor of 2 at most. Under this assumption (2.2) can be then written as,

$$V_B = \frac{150(2T_s)^{\frac{1}{2}}}{\beta} \quad (2.6)$$

where T_s is the handbook value of ultimate tensile strength at the appropriate temperature.

b) Effect of Temperature

The tensile strength of most materials is considerably reduced by an increase in temperature. The areas of interest on the electrode surfaces are the tips of a cathode protrusion and the corresponding anode spot both of which can get considerably heated by the prebreakdown field emission current. Therefore before the correct value of T_s can be used in (2.6) it is essential to know the temperature at these points.

2.4. Temperature at the Electrodes

2.4.1. Protrusion Geometry

An extended cathode surface can contain a large number of protrusions of different shapes and sizes which can become emitters simultaneously. However, the pre-breakdown current is a very rapidly rising function of $\beta_k V$, and it is generally accepted therefore that one emitter dominates and is responsible for breakdown. A F-N plot

effectively gives the enhancement factor for this protrusion (Tomaschke and Alpert, 1967) whose detailed shape is not known.

In practice a shape is assumed for calculations of temperature, and field enhancement factors for several protrusion shapes have been calculated; e.g. cylinder with a rounded tip (Vibrans, 1964), Spheroid (Race, 1940), truncated cone (Chatterton, 1966). A cylinder has the highest value of β_k . It roughly resembles a whisker in shape and it is often assumed for temperature calculations. However this does not seem to be fully justified, since temperature calculations are strongly dependent on the shape of the protrusion and misleading conclusions may result from assuming an incorrect geometry. A better way seems under the circumstances to be to consider at least two protrusions of different shape but similar β which are likely to have widely differing temperatures at the tip. In this way limits can be set on the effect of protrusion geometry and it would be difficult to proceed further unless the shape of the emitting protrusion could be established by direct observation.

2.4.2. Local Cathode Temperature $(T_K)_L$

Consider a protrusion on the cathode surface emitting electrons. The temperature at the tip of the protrusion is controlled by the following energy exchange mechanism:

- a) Joule heating due to flow of current at the tip.
- b) Nottingham heating or cooling (Nottingham, 1941, Charbonnier et al, 1966).

c) Cooling by thermal conduction towards the base. Cooling by radiation is neglected in view of the small area involved.

For every metal there exists an inversion temperature T_i such that as long as the tip temperature is below T_i field emission causes heating; above this temperature it causes cooling. T_i is related to the enhanced electric field at the protrusion tip and to the work function of the metal by the equation:

$$T_i = \frac{5.32 \times 10^{-5} E}{\phi^{1/2}} \quad ^\circ K \quad (2.7)$$

(Levine, 1962, Charbonnier et al, 1966). This expression has been verified experimentally(Charbonnier et al, 1966).

In any particular situation therefore one first determines the tip temperature at which thermal instability leading to breakdown is to be expected. If this temperature is less than T_i the contribution due to field emission heating can not be ignored.

The total temperature^{rise} at the field emitting tip may be written as,

$$(\Delta T) = (\Delta T)_R + (\Delta T)_N$$

where subscripts R and N stand for resistive and Nottingham heating respectively. The temperature of the tip is then

$$(T_K)_L = T_K + \Delta T$$

where T_K is the temperature at the base.

The temperature rise at the tip due

to the resistive heating of a cylinder can be written as;

$$(\Delta T)_R = \frac{\rho J^2 h^2}{2K} \quad (2.8)$$

where ρ is the electrical resistivity and K the thermal conductivity of the cathode material, J is the field emission current density and h is the height of the protrusion. The height of the protrusion is derived from the field enhancement factor β_k and the tip radius r_e using the equation

$$\beta_k = \frac{h}{r_e} + 2 \quad (2.9)$$

due to Vibrans (1964).

For a conical protrusion,

$$(\Delta T)_R = \frac{\rho J^2 r_e^2 \left[1 - \frac{\cot \theta}{2(\beta_k - 5)} \right]^2}{4K \left[(1 - \cos \theta)(\cot \theta) \right]^2} \quad (2.10)$$

(Chatterton 1966) where θ is the half angle of the cone. The temperature rise due to field emission heating is given as,

$$(\Delta T)_N = \frac{6.9 \times 10^{-9} J E r_e \beta_k}{2 K \phi^{\frac{1}{2}}} \quad (2.11)$$

for a cylinder, and,

$$(\Delta T)_N = \frac{6.9 \times 10^{-9} E J r_e \left[1 - \frac{\cot \theta}{2(\beta_k - 5)} \right]}{\phi^{\frac{1}{2}} K \tan \theta} \quad (2.12)$$

for a cone (Chatterton 1966). Expressions (2.11) and (2.12) are adequate for calculating $(\Delta T)_N$ without significant error as long

as $T_i / T > 1.1$, T being the temperature at which the breakdown instability is expected. In the present case since the breakdown instability temperatures are expected to be much less than T_i the use of (2.11) and (2.12) seems justified.

2.4.3. Local Anode Temperature $(T_A)_L$

The electrons emitted from the tip of a protrusion on the cathode spread out due to field distortion near the tip and strike the anode surface just opposite the whisker in a circular area of radius r_a (see Fig. 2.1). Due to bombardment the anode spot is raised to a higher temperature than the rest of the surface.

If the anode is considered to be a semi-infinite block of metal with a plane surface receiving uniform power input over a circular area of radius r_a then the temperature at the centre of the anode spot is given as,

$$(T_A)_L = \frac{V_B I_B}{\pi r_a K} + T_0 \quad (2.13)$$

(Carslow and Jaeger 1959), where K is the thermal conductivity of the anode material, T_0 is the temperature of the back surface and r_a is the radius of the anode spot. The anode spot radius is given as,

$$r_a = 2(\beta_k r_e d)^{\frac{1}{2}} \quad (2.14)$$

(Vibrans, 1964). In applying equation (2.13) T_0 cannot be taken as the room temperature since the whole of the anode becomes hot under the effect of electron bombardment. In those cases therefore, where

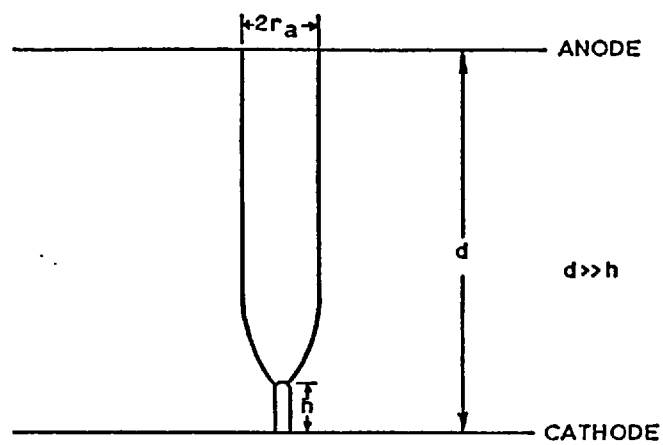


Fig. 2.1.

precautions have not been taken to control the temperature of the back surface, T_o must be determined for the corresponding power input $V_B I_B$ at breakdown (Davies and Biondi, 1968).

Considering for approximate calculations that most of the heat from the hot anode is lost by radiation,

$$Q = A e_m \sigma (T_o^4 - T_A^4) \quad \text{watts} \quad (2.15)$$

Where Q is the net quantity of heat radiated per second from the anode surface at temperature T_o , and T_A is the temperature of the anode when no current flows across the gap, A is the total surface area of the anode, e_m is its emissivity and σ is Stefan's constant. The total beam power input to the anode surface is $V_B I_B$ and therefore 2.15 can be written as

$$T_o = \left[\frac{V_B I_B}{5.73 \times 10^{-12} e_m A} + T_A^4 \right]^{\frac{1}{4}} \quad (2.16)$$

Eqn(2.13) then becomes

$$(T_A)_L = \left[\frac{V_B I_B}{2 \pi K (\beta_k r_e d)^{\frac{1}{2}}} \right] + \left[\frac{V_B I_B}{5.73 \times 10^{-12} e_m A} + T_A^4 \right]^{\frac{1}{4}} \text{ } ^\circ K \quad (2.17)$$

One should note that T_A will be room temperature except in those experiments in which the anode is heated externally.

CHAPTER III

APPARATUS

3.1. Vacuum System

3.1.1. Requirements:

One of the chief considerations in the choice of a vacuum system is the ultimate pressure to be attained, and this is governed by the nature of the project undertaken. It has been pointed out earlier that for electrode spacings of about a millimeter, the breakdown voltage of the gap is independent of the residual gas pressure as long as the pressure is kept lower than about 10^{-4} Torr. Though in principle residual gas pressures better than 10^{-4} Torr may seem adequate for this type of study, it is essential that, where information is desired from Fowler-Nordheim plots, experiments should be performed in good vacuum. Fowler-Nordheim plots can be affected in two ways:

(a) From equation(2.5), it can be seen that the slope of the F-N plot is affected by changes in β_K the field enhancement factor and ϕ the work function of the cathode material. Even if ϕ remains constant, an increase in pressure to above 10^{-5} Torr will cause the value of β_K to drop due to blunting of the emitting point by ion bombardment from the residual gas(Alpert et al, 1967). Stable pre-breakdown voltage-current readings can not then be taken because of the surface changes taking place.

(b) For the same emitting point, changes in the slope of the

F-N plot can also occur due to changes in ϕ produced by the chemisorption of the active constituents of the residual gas e.g. oxygen on the cathode surface. While no change in slope occurs on introducing between 10^{-6} Torr and 10^{-7} Torr of Argon, a significant change is observed when oxygen is introduced (Bloomer and Cox, 1968, Goldstone, 1965).

Apart from these considerations even for thoroughly degassed electrodes, at pressures of 10^{-5} Torr an instantaneous pressure rise can occur in the gap due to desorption of adsorbed residual gas layers from the electrode surfaces under electron and ion bombardment. Breakdown can then occur in the residual gas in accordance with Paschen's law (Llewelyn Jones and Owen, 1964) and this can mask the breakdown mechanism due to electrode surface effects.

It is seen therefore that very low pressures are essential. Pressures better than 10^{-10} Torr would be ideal, when monolayer formation time (for nitrogen) is about 6 hours and the number of molecules per litre is only 3.5×10^9 . However pressures $< 10^{-8}$ Torr can be considered adequate for present purposes as no significant variation in β_k with pressure is observed for pressures up to 10^{-7} Torr, if oxygen is not present. Also at 10^{-8} Torr though a monolayer of nitrogen can form in about 4 minutes there are only 3.5×10^{11} molecules/litre present, while the number of molecules per cm^2 required for a monolayer is about 10^{15} .

It has been found that the contamination of electrode

surfaces from pump oil vapour can be deleterious to the performance of a vacuum gap. Insulating patches of cracked oil may form on the electrode surfaces which can affect the breakdown characteristic (Mohr 1961). It was therefore considered essential to use a vacuum system which would be almost free from oil vapour. This obviously meant the choice of a mercury diffusion pump system. But even in this case with lapse of time contamination from rotary pump oil due to back diffusion is to be expected and precautions were necessary to eliminate it.

3.1.2. Description

A vacuum system capable of attaining an ultimate pressure less than 2×10^{-9} Torr was available (Goldstone, 1965). This system consisted of a mercury diffusion pump backed by a rotary pump. Two cold traps were provided in series, between the diffusion pump and the breakdown tube. The high vacuum section lying above bench level could be isolated from the pumps by a bakable metal valve. A flash titanium getter was provided and the pressure was monitored by a Bayard-Alpert ionisation gauge. The whole of the high vacuum section could be baked up to 400°C by lowering an oven over it. Protection circuits were provided to deal with water or power failure, rise in pressure in the system or stopping of the rotary pump.

In the system as found, no precaution was taken for eliminating oil vapour from backing pump. The whole system was therefore stripped down, and all parts were thoroughly cleaned. During

reassembly a zeolite trap was introduced between the diffusion pump and the rotary pump. The zeolite had been previously dehydrated by baking at 350°C for 24 hours. The trap could be detached from the pumping line for periodic degassing of the zeolite pellets. Fig. 3.1 shows a block diagram of the reassembled system. A new Granville Phillips metal valve having a variable conductance from 1L/sec to 10^{-14}L/sec was installed.

3.1.3. Operation

The pumping down procedure was as follows:

- 1) If there were no major leaks a pressure of 2×10^{-6} Torr was usually obtained on initial pumping down of an unbaked system.
- 2) At this stage the metal valve was opened to the maximum and the oven switched on. The temperature was gradually raised to 400°C in about 2 hours. The pressure below the bench was monitored by another Bayard-Alpert gauge.
- 3) After cooling, the oven was lifted and the ionisation gauge was thoroughly outgassed by electron bombardment for about 15 minutes. The electrodes in the breakdown tube were then outgassed at 800°C by radiation heating from the tungsten heating coils mounted behind them until the pressure in the system was better than 2×10^{-6} Torr while the electrodes were hot. This procedure usually took about 8 hours for each electrode. After the metal parts had cooled the pressure fell to better than 2×10^{-7} Torr and the measured system degassing rate at this stage was approximately 4×10^{-8} litre Torr/sec. The

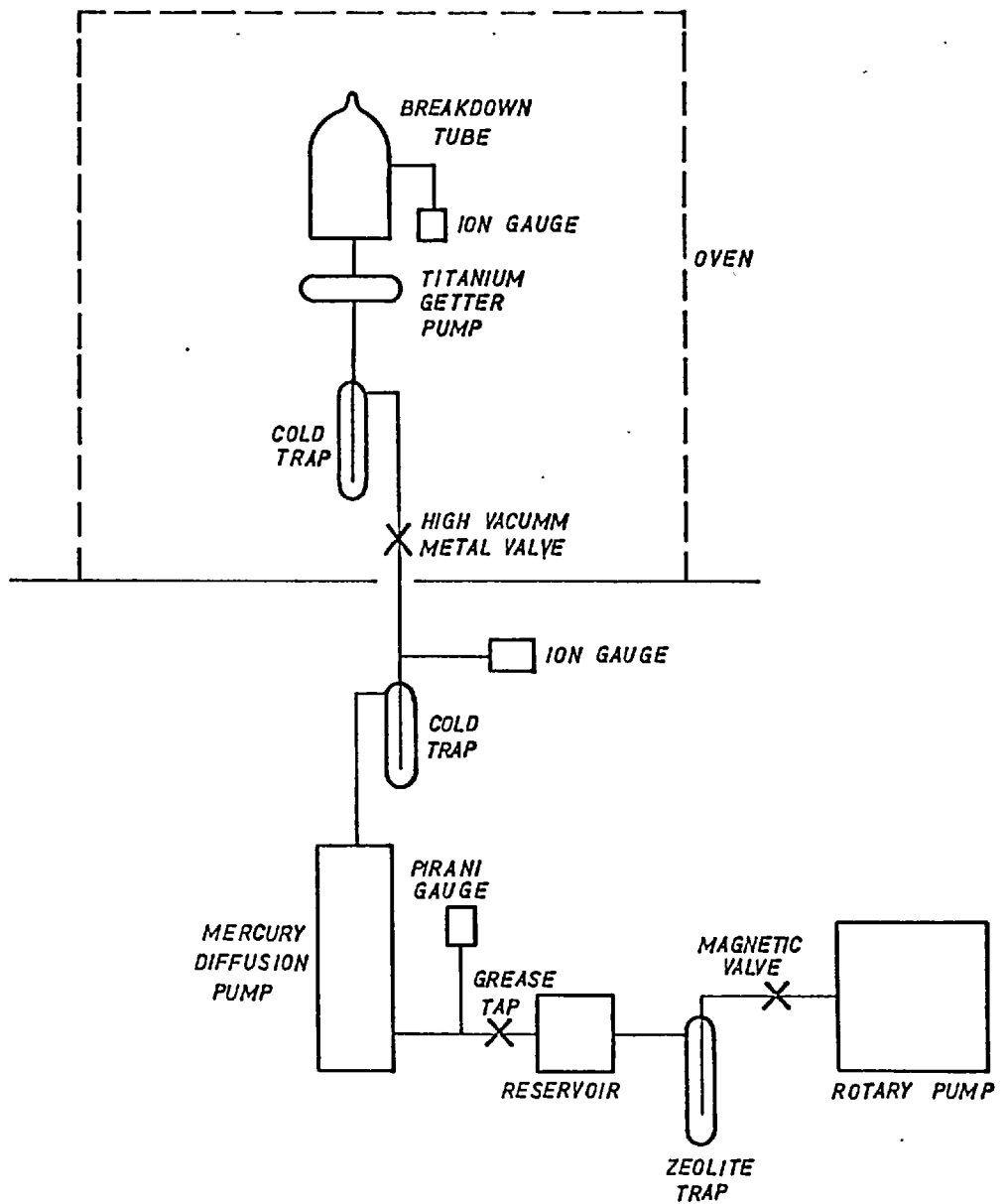


Fig. 3.1. Vacuum System.

system was now baked again at 400°C overnight.

4) In the morning the ion gauge below the bench showed a pressure better than 2×10^{-7} Torr. The system was allowed to cool to about 200°C, after which the oven was partially lifted and a thermosflask with liquid nitrogen was placed round the finger trap.

5) After the system cooled the pressure fell to 6×10^{-9} Torr. A brief degassing of the ion gauge (< 5 mins) and the electrodes ($< \frac{1}{2}$ hour) was then given. At this stage, using the ion gauge at 1mA emission current a pressure less than 2×10^{-9} Torr could be measured. The system degassing rate was measured to be 4×10^{-10} litre Torr/sec. Evaporating titanium was not found to lower the pressure further, but the getter was found useful in keeping the pressure better than 10^{-8} Torr for prolonged periods.

The system was found to function properly, as reported by Goldstone and after being modified as described above, was adequate for the present purpose.

3.2. Discharge Tube

The requirements for the discharge tube were as follows. Electrodes had to be set parallel and at a fixed distance apart. Supporting structures had to be strong enough to withstand the electrostatic forces corresponding to an applied voltage of up to 100kV D.C. An arrangement for heating the electrodes up to 800°C, after pump down was needed both for outgassing and for high temperature experiments. The temperature of the heated electrode had

to be known accurately. The tube envelope had to withstand the dielectric stresses developed by the high voltages applied. The mechanical design had to be such that the electrodes could be easily assembled and disassembled.

A tube fulfilling some of the above requirements, used previously by Goldstone(1965) in this laboratory was available, and after gaining some experience with this tube, a new improved tube was designed as described later. After further experiments had been performed it was realised that considerable loss in time was incurred because glass sealing operations were needed each time the tube had to be taken off the vacuum bench for changing electrodes. Therefore eventually another tube was designed which was demountable but could still be baked up to 400°C for achieving pressures better than 10^{-8} Torr.

3.2.1. Initial Tubes

Preliminary Experience

The tube previously used in this laboratory consisted of a pyrex glass envelope 11 cms in diameter and 30 cms long. The high voltage electrode supports and heater leads entered from the bottom of breakdown tube while the earthy electrode supports and heater leads entered from the side. Two of the supports for each electrode were blind; the third passed through the glass envelope. The high voltage electrode was the upper electrode and all its supports inside the tube were shielded by glass tubing up to the height of the lower earthy electrode. The high voltage feed through was enclosed

externally by a glass tube into which the high voltage lead could be inserted.

The electrode supports were 2 mm tungsten rods. The high voltage supports were sealed directly to the glass whereas for convenience and assembly the low voltage supports were spot welded to 2 mm nickel rods at the base which were in turn welded to 2 mm tungsten rods sealed to the glass envelope. To strengthen the low voltage support structure the tungsten supports were braced by several 2 mm nickel rods.

The high voltage electrode was screwed to a triangular supporting structure made of 2 mm tungsten and nickel rods. This structure could in turn be tightly clamped to the three main tungsten supports by small molybdenum clamps and screws. Heaters made of 0.75 mm tungsten were spot welded to their leads and were aligned to be at a distance of 2mm from the back surface of the electrodes.

After initial experience on this tube it was felt that it lacked two things. Firstly, the 11 cm long high voltage electrode supports were made of 2 mm tungsten rods which lacked rigidity. Prior to breakdown the whole structure began to vibrate, which was undesirable from the point of possible changes in electrode spacing. Secondly, temperature measurements on the heated electrodes could only be made above 600°C using a pyrometer and even this was uncertain due to glare from the tungsten heaters. A thermocouple was therefore needed for accurate temperature measurements.

Modified Tube

A new tube was made with high voltage electrode supports 4 mm in diameter and 14 cm long. The length was increased to accommodate thicker electrodes and larger gap lengths than were possible in the previous tube. A Chromel-Alumel thermocouple was spot welded to additional tungsten feed-throughs provided on the side of the glass envelope. The thermocouple could be attached to one of the molybdenum fixing screws on the earthy electrode, and the junction was held pressed in contact with the body of the electrode by a thin stainless steel washer. The thermocouple leads inside the tube were enclosed separately in quartz tubing and were kept away from the high voltage supports. The temperature was displayed on an indicator/controller having a range 0 - 800°C, with an accuracy of $\pm 8^\circ\text{C}$. The tube operated satisfactorily and the earlier experiments with Mo, Ni and Cu electrodes were performed with it. A difficulty experienced with the earlier tube was the occurrence of corona around the heater leads to the high voltage electrode. This was troublesome above 30 kV. Perspex test tubes containing liquid paraffin placed around the leads had been used and this produced a partial cure. In order to operate reliably above 40 kV it was found necessary to cover the leads with 'Cold Cure Silastomer' (Hopkin and Williams).

At this stage, as mentioned earlier, it was decided to design a demountable tube to facilitate assembly and disassembly of the electrodes. It may be mentioned here that this type of tube has

the inherent advantage, that since no glass sealing operations are required after the electrodes have been put in position, the danger of contamination or the deposition of globules of glass is eliminated, (Rabinowitz and Donaldson, 1963).

3.2.2. Final Tube

In order to make the tube demountable it was decided to use bakeable metal to glass seals. A 4" I.D. knife edge seal, employing an OFHC copper gasket (Vacuum Generators Ltd) was selected.

The use of such a seal made it necessary to redesign details of the breakdown tube and figure 3.2 shows the main features. The basic plan is that of the earlier tubes but the electrode supports are longer for convenience in assembling the electrodes and for facilitating visual observation during the experiments. 4 mm tungsten rods were again considered to be strong and rigid enough for the high voltage electrode supports to avoid any vibrations, and this was justified by experience. The earthy electrode supporting structure was strengthened by a bracing of 2 mm nickel rods, and also by the supporting nickel wires at the base. The length of the high voltage supports was 24.5 cms and that of the earthy electrode 19.5 cms. Fig. 3.3 shows the internal view of the final breakdown tube and fig. 3.4 gives the general view of the system with this tube. Before the two halves of the main seal were joined to the corresponding sections of the tube envelope, the electrode supporting structure, the thermocouple, and the lower heater were aligned and

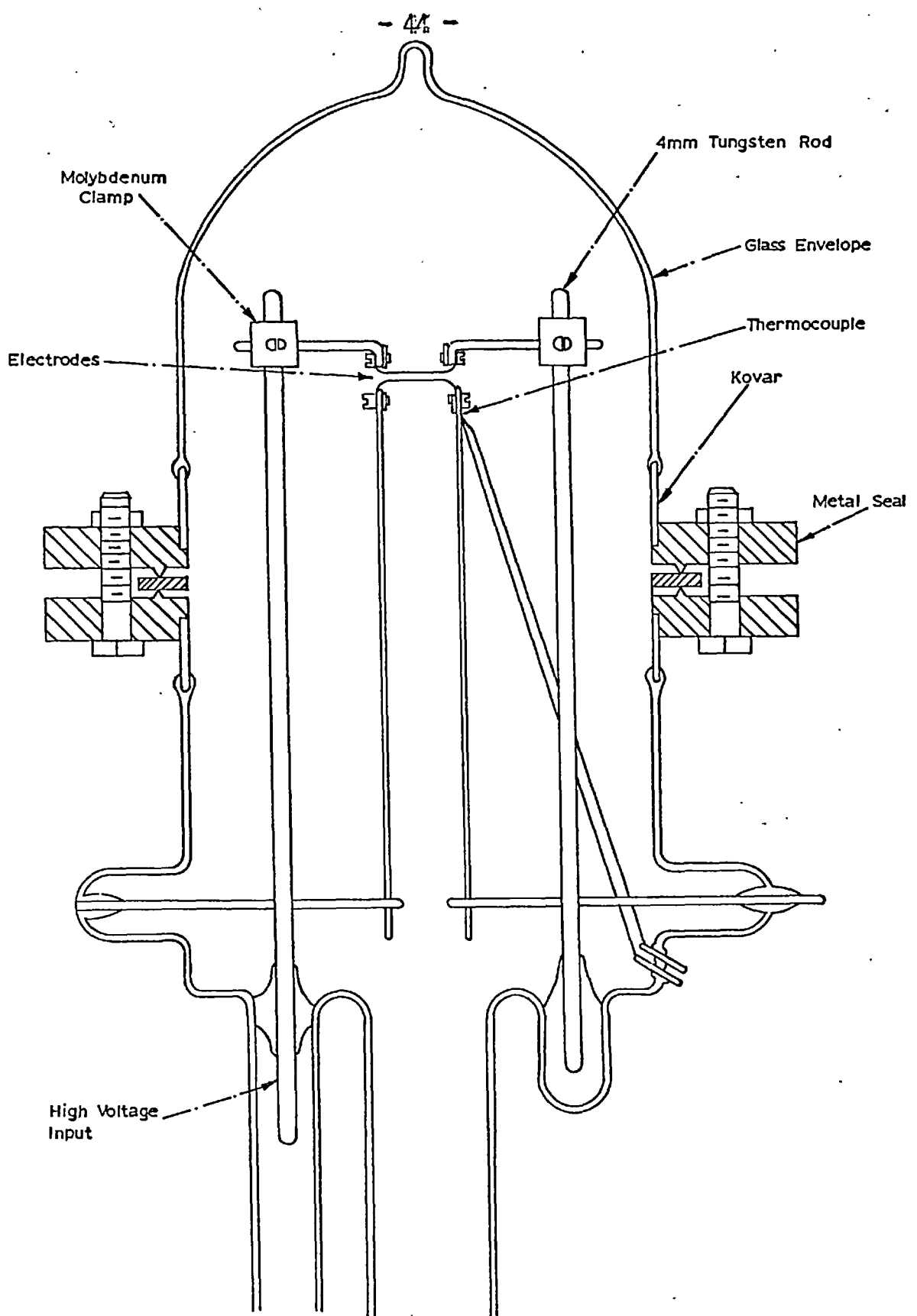


Fig. 3.2. Basic features of the final tube

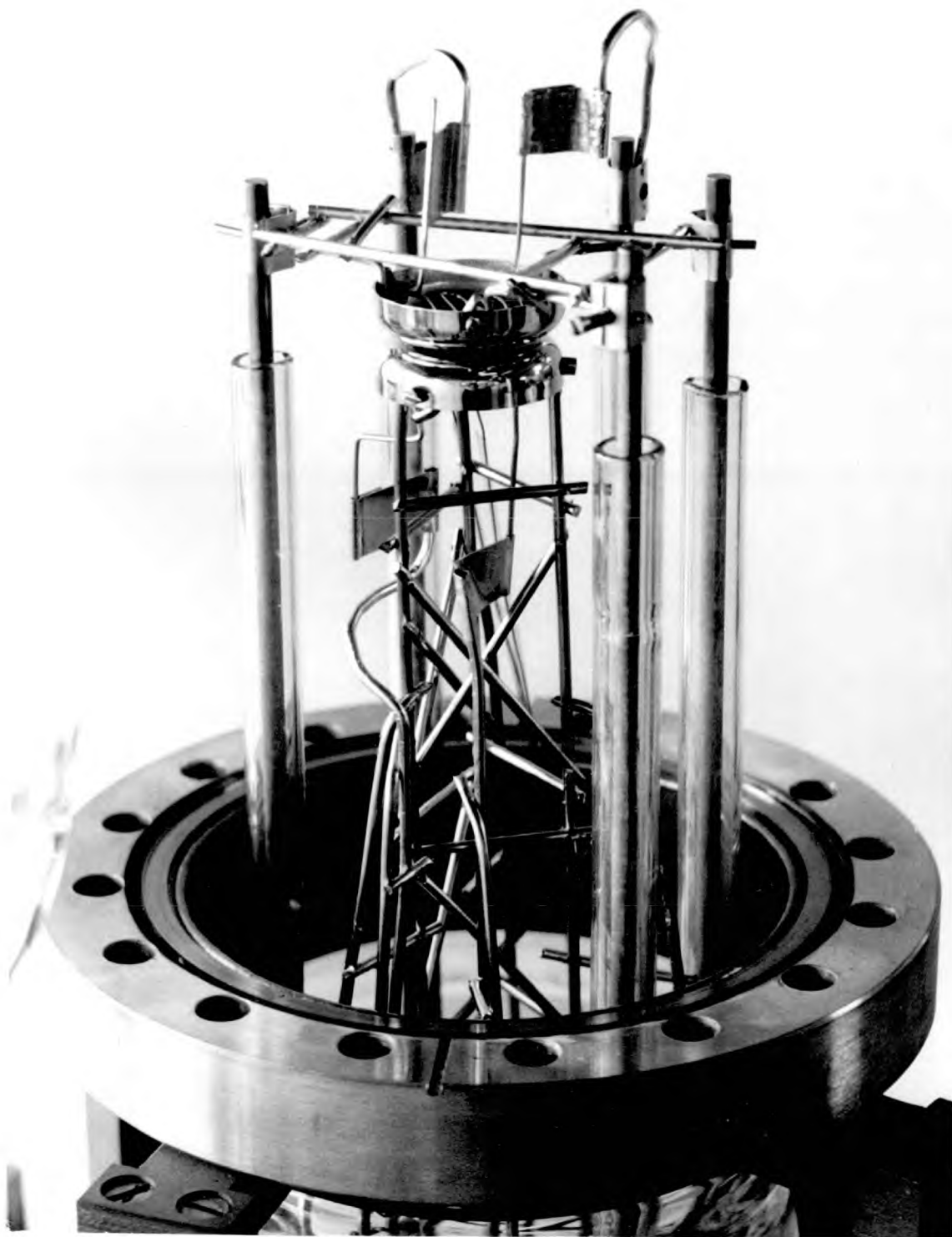


Fig. 3.3 Final tube

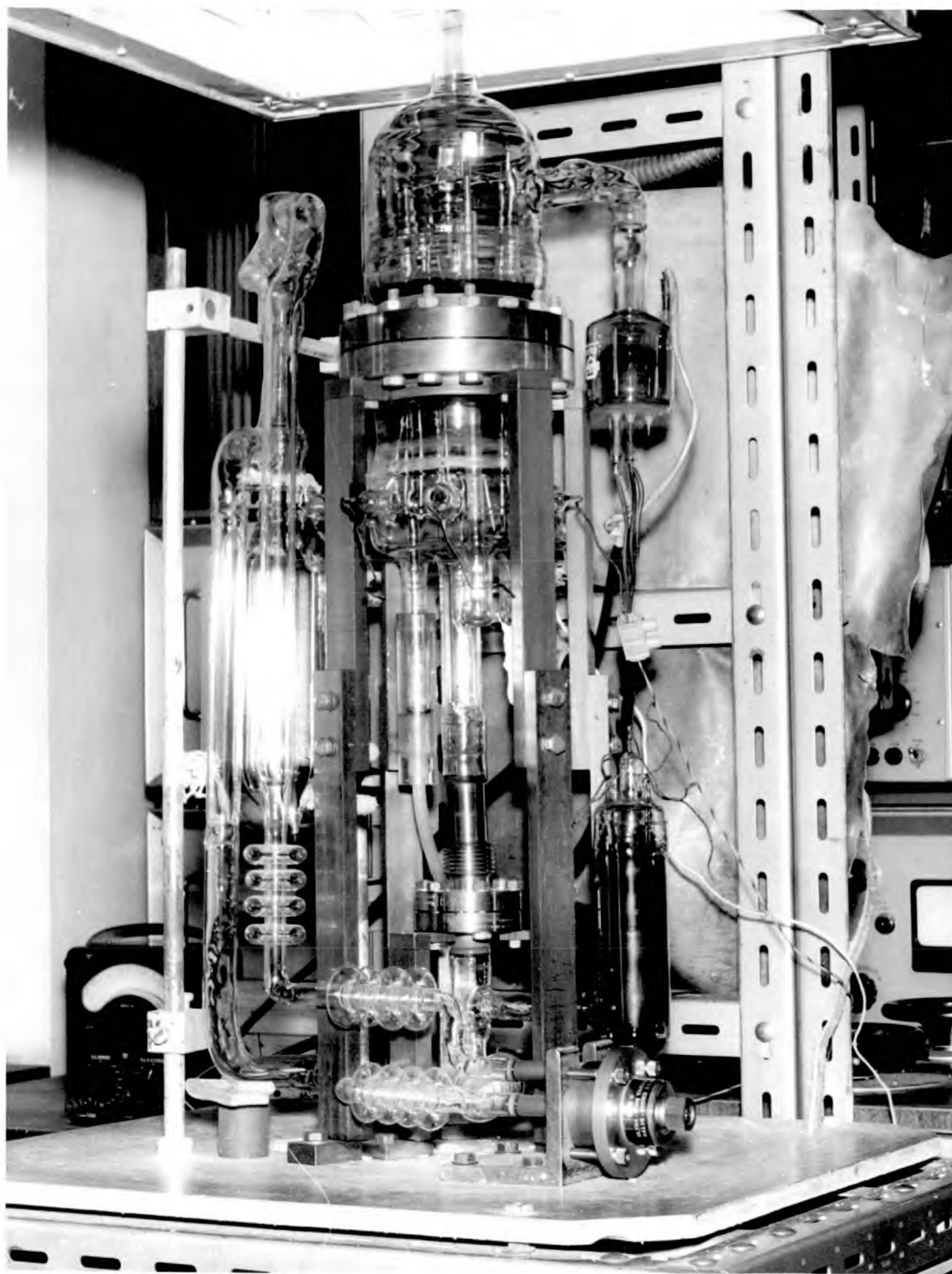


Fig. 3.4 System with final tube

fixed in place. A trial assembly of the electrodes was made. Supporting structures were tested for strength by subjecting them to a 3 lb-weight which corresponds, for 22 mm diameter electrodes, to application of 100 kW across the gap. A movement less than 5% of the electrode spacing was observed and the strength of the structures was regarded as adequate.

After the basic structure had been assembled and tested, the seal was joined to the tube envelope. First, the two halves of the seal were bolted together with a copper gasket between them, the top of the tube envelope consisting of a glass dome of 4" diam. was joined to one half on the lathe. The lower part of the tube containing the electrode supporting structure etc., was then similarly joined to the other half. At this stage a stream of forming gas was passed through the tube, so as to avoid oxidation.

The addition of the metal seal made the breakdown tube much heavier. It was therefore supported by steel brackets fixed to the lower flange of the seal. To make the tube completely demountable from the bench for convenience in changing the electrodes and occasional cleaning of the interior a pair of 1" internal diameter metal seals was used to couple the breakdown tube to the exhaust system. Stainless steel bellows were included to allow for expansion during baking.

During assembly of the tube all handling of the parts was done using clean nylon gloves. After the electrodes were

mounted on their supports, contact surfaces of the seals were wiped clean with lint free cloth soaked in iso-propyl alcohol. The copper gasket was then placed in position and after carefully aligning the flanges, tightening of the bolts was done evenly following a diametrically opposite tightening sequence. Usually about three cycles of tightening made a good enough seal to start the diffusion pump. If the sealing was good, the pressure went on falling and ultimately reached about 2×10^{-6} Torr as in case of earlier tubes. If the pressure did not drop below 10^{-4} Tor tightening was continued until a leak test with a butane jet showed no pressure rise. The pumping down procedure was the same as described earlier and usually a pressure better than 2×10^{-8} Torr was achieved. Pressures below 5×10^{-9} Torr were not obtained despite extensive baking and degassing.

However this was considered adequate for the experiments.

3.3. Electrodes

The electrodes were made of molybdenum, nickel or OFHC copper. All electrodes were made of high purity (99.9 %) poly-crystalline material. They were discs 30 mm. in diameter and 1mm. thick, but the effective electrode area was 22 mm. Edges were curved in accordance with Rogowski's criterion (Rogowski and Rengier, 1926) in order to produce a uniform electric field in the gap. Each electrode had three equispaced holes on the side for fastening to the tungsten supports. In later

experiments a special pair of small Ni and Cu electrodes were made to enable Stereo-Scan microscope studies of the electrode surfaces to be carried out after the breakdown experiments. These electrodes had a threaded stud on the back face and could be screwed into the front face of a larger molybdenum electrode.

3.4. Discharge Circuit

It was decided to perform breakdown tests under D.C. conditions. The breakdown circuit previously used in this laboratory (Fig 3.5) was found adequate. High voltage was supplied from a Hursant, 100 kV D.C. regulated power supply at 700 μ A maximum current. The voltage was continuously variable from 0-100 kV. The supply was equipped with an over load cut out which protected the supply at breakdown. A series resistance of 62 M Ω was included to limit the current flowing in the circuit at breakdown. This was necessary in order to prevent the electrode surfaces being severely roughened during breakdown due to passage of a large current. The breakdown current was measured using a Pye Scalamp galvanometer, having a range 5×10^{-9} amp to $.075 \times 10^{-2}$ amp, connected to the earthy electrode. The applied voltage was measured using a chain of 20 high stability 50 M Ω resistors in series with a 0-100 μ A meter which read the applied voltage directly in kV.

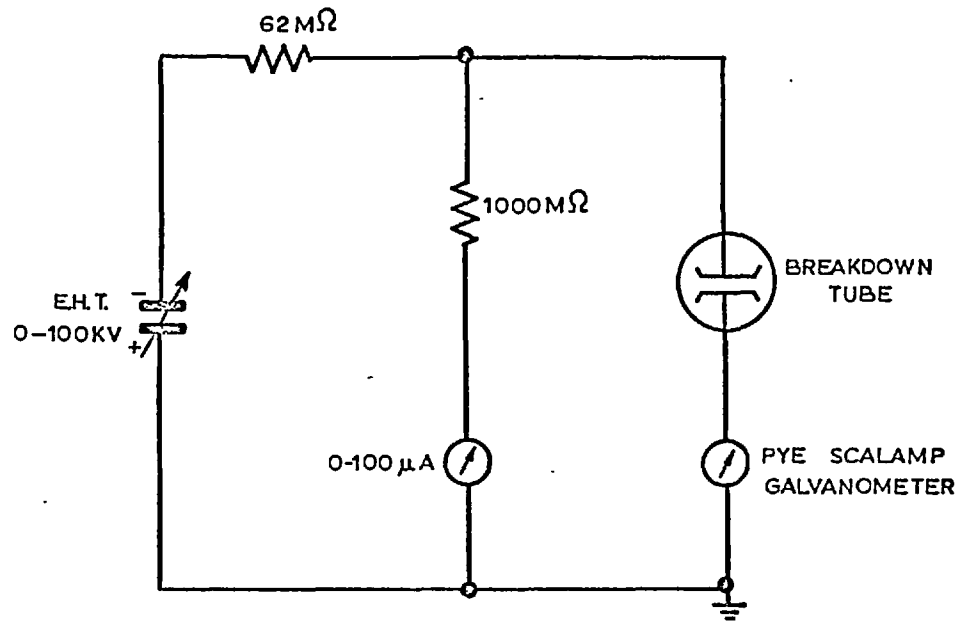


Fig. 3.5. Discharge Circuit.

CHAPTER IV
BREAKDOWN TESTS WITH DIFFERENT
ELECTRODE MATERIALS

Two types of experiments are described in this section:

a) Breakdown Tests with Electrodes of Similar Material.

The materials selected were copper, nickel and molybdenum whose ultimate tensile strengths bridge the gap between low strength materials like aluminium and high strength materials like tungsten. They cover the range of material for which two opposing hypotheses have been suggested namely, Rozanova and Granovskii's (1957) that, for Al, Cu, Fe, Ni and Mo, the breakdown voltage depends on the mechanical strength of the electrode material and Charbonnier's (1967) that it is only for materials of low yield strength like aluminium that the breakdown voltage depends on the mechanical strength.

b) Breakdown Tests with Electrodes of Dissimilar Materials

This class of test was done in order to distinguish the effects of anode and cathode material, and also to establish whether transport of material between the electrodes occurred. Tests were made using copper and molybdenum, and copper and nickel electrodes. After the tests the electrode surfaces were examined under the microscope and using an electron probe x-ray microanalyser, but these results are described separately in chapter V, this chapter being confined to a discussion of the results obtained from Fowler-

Nordheim plots.

4.1. Experimental Procedure

4.1.1. Preparation of Electrode Surfaces

The electrode surfaces were polished mechanically. The machined surfaces, were first ground, using 10 μ diamond paste, on a rotating steel disc. After machining marks had disappeared, grinding was continued using 3 μ diamond paste. A final polish was given using $\frac{1}{4}$ μ paste on selvyt cloth. The electrodes were ultrasonically cleaned in successive baths of detergent solution until after dipping them into distilled water a uniform film of water remained on the surface. This was taken as an indication of a grease free surface (Koontz, 1958). The electrodes were rinsed ultrasonically in distilled water and, after drying and prior to installation in the breakdown tube, they were finally rinsed in trichlorethylene. After the electrodes had been installed in the experimental tube, the pumping down procedure, described in chapter 3 was followed. The maximum temperatures used for electrode degassing were 850°C for molybdenum, 800°C for nickel and 600°C for copper.

4.1.2. Voltage and Current Measurements

Current and Voltage measurements were made using the circuit described in chapter 3 (Fig 3.5). When fresh electrodes are used, the first few breakdowns occur at low but successively increasing voltage and the pre-breakdown current is very unsteady. Usually after fewer than 5 initial conditioning breakdowns the breakdown

voltage attains a maximum value reproducible within 1 kV. After this conditioning stage the pre-breakdown current becomes steady and is reproducible if breakdown is avoided. In making measurements of the pre-breakdown characteristic of the gap, the voltage is increased slowly. Once a current flow is observed, the voltage is increased in steps of 1 kV and the current is noted until the breakdown voltage is reached. This is indicated by a steep rise in the current, a flash and the switching off of the power supply. Usually for a set of electrodes, ten successive runs of voltage - current, and breakdown voltage measurements were made. It was noted that often, and especially with copper which had the lowest breakdown voltage, the current would begin to rise steeply and the gap voltage would remain constant without there being any obvious spark discharge. The breakdown flash and the switching off of the power supply occurred only after increasing the current to a higher level. This current control is a consequence of using high limiting resistor in the discharge circuit, and proved to be useful when making measurements near the breakdown point.

4.2. Results and Discussion

Results of the breakdown tests are presented in the form of Fowler-Nordheim plots ($\log_{10} Id^2/V^2$ vs d/V) of the voltage and current data. Figures 4.1 to 4.5 show the results of typical runs for molybdenum, nickel and copper electrodes and Figs. 4.6 and 4.7 show results for mixed electrodes. Breakdown voltages and other

derived parameters are given in Table 4.1.

The values of breakdown voltage in the Table are typical of several runs. The experimental scatter in the values of breakdown voltage was small, and generally for successive measurements the breakdown voltage did not differ by more than ± 1 kV, unless some drastic surface change occurred. For the same set of assembled electrodes it was found that even after an interval of a month measurements were often reproducible. The field enhancement factor β_k , calculated from the slope of the F-N plot $\beta_k = \frac{-6.83 \times 10^7 \phi^{3/2}}{2.3 \times \text{slope}}$ was generally reproducible within 10%.

The breakdown current I_B is determined from the intersection of the straight and the steep parts of the F-N plot. It can be seen that the F-N plots become slightly non linear at the high voltage end, the points deviating upwards. The actual breakdown current is therefore somewhat higher than the extrapolated value and this point is discussed further in section 4.2.3. Corresponding to the breakdown field $E_B = \frac{\beta_k V_B}{d}$, the current density at breakdown J_B , is calculated from Tables (Dyke et al, 1953) knowing the work function of the material. From corresponding values of current and current density the emitting area A_E , and tip radius r_e can be found. The local electrode temperatures have been calculated by substituting the appropriate parameters in equations (2.8) to (2.12) for the cathode and equation (2.17) for the anode. Constants used in the calculations are listed in Table 4.2.

Fig.4.1. F-N Plots for Molybdenum electrodes

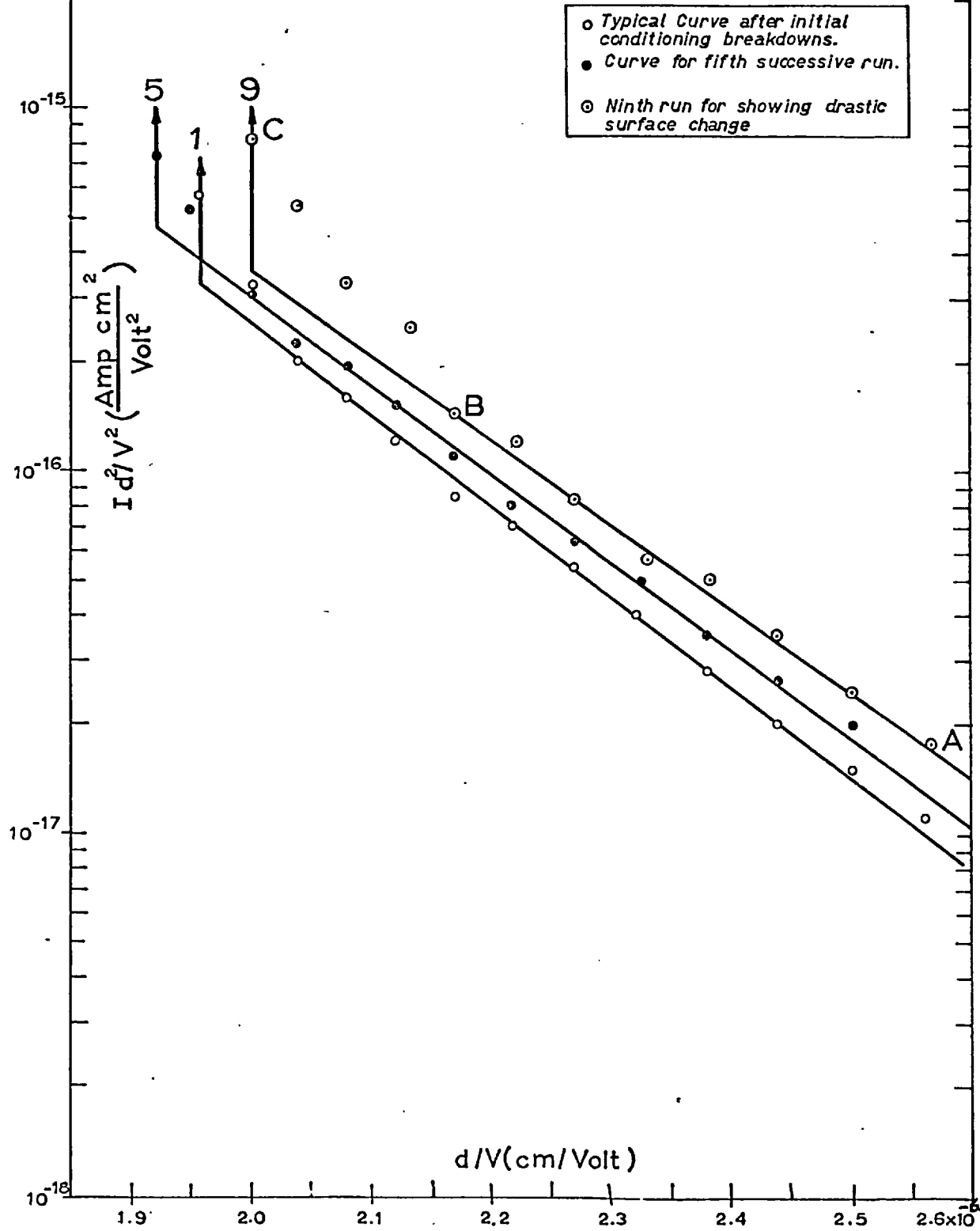


Fig. 4.2. F-N Plots for Molybdenum electrodes avoiding breakdown.

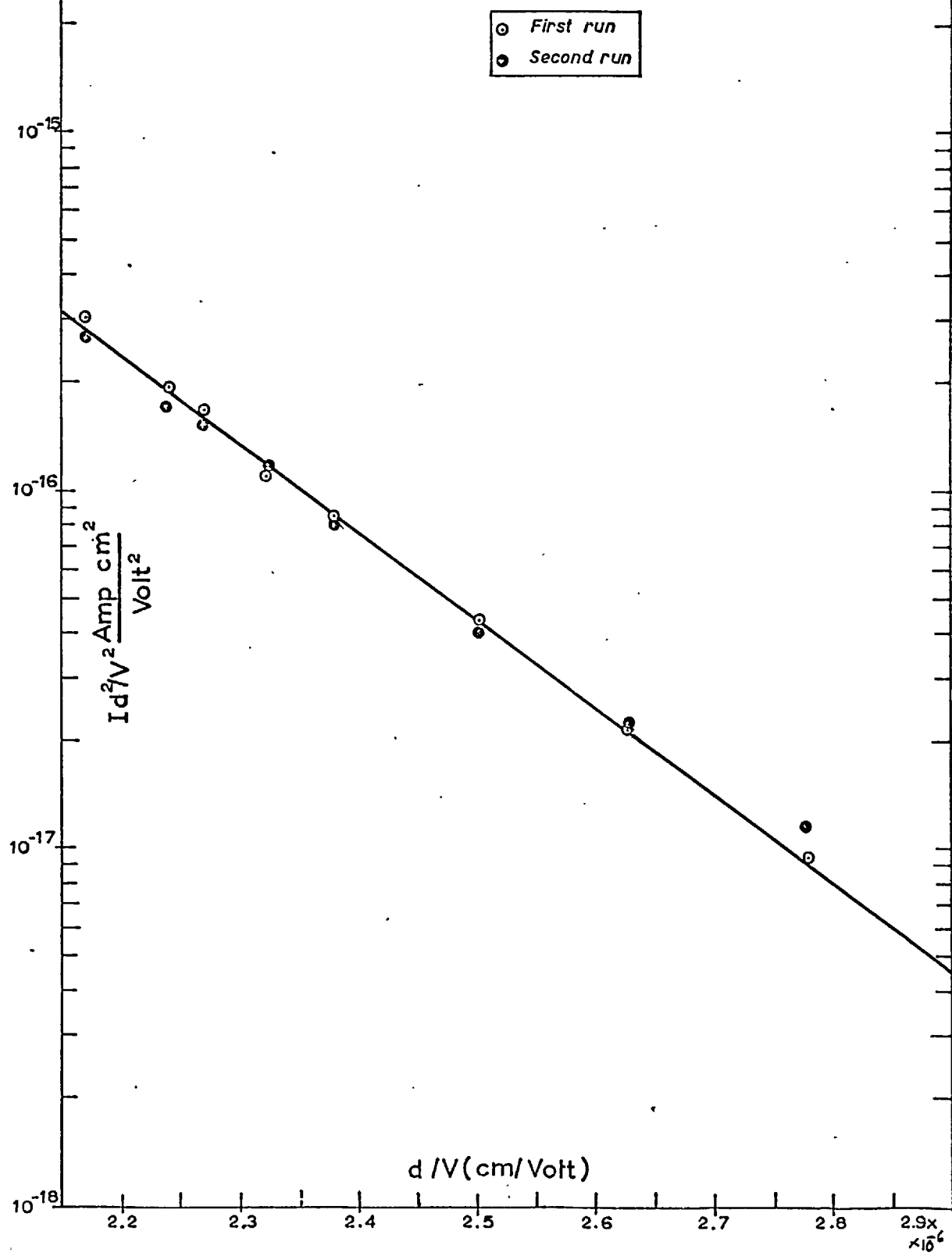


Fig. 4.3. F-N Plot for Molybdenum electrodes after the event at C in Fig. 4.1.

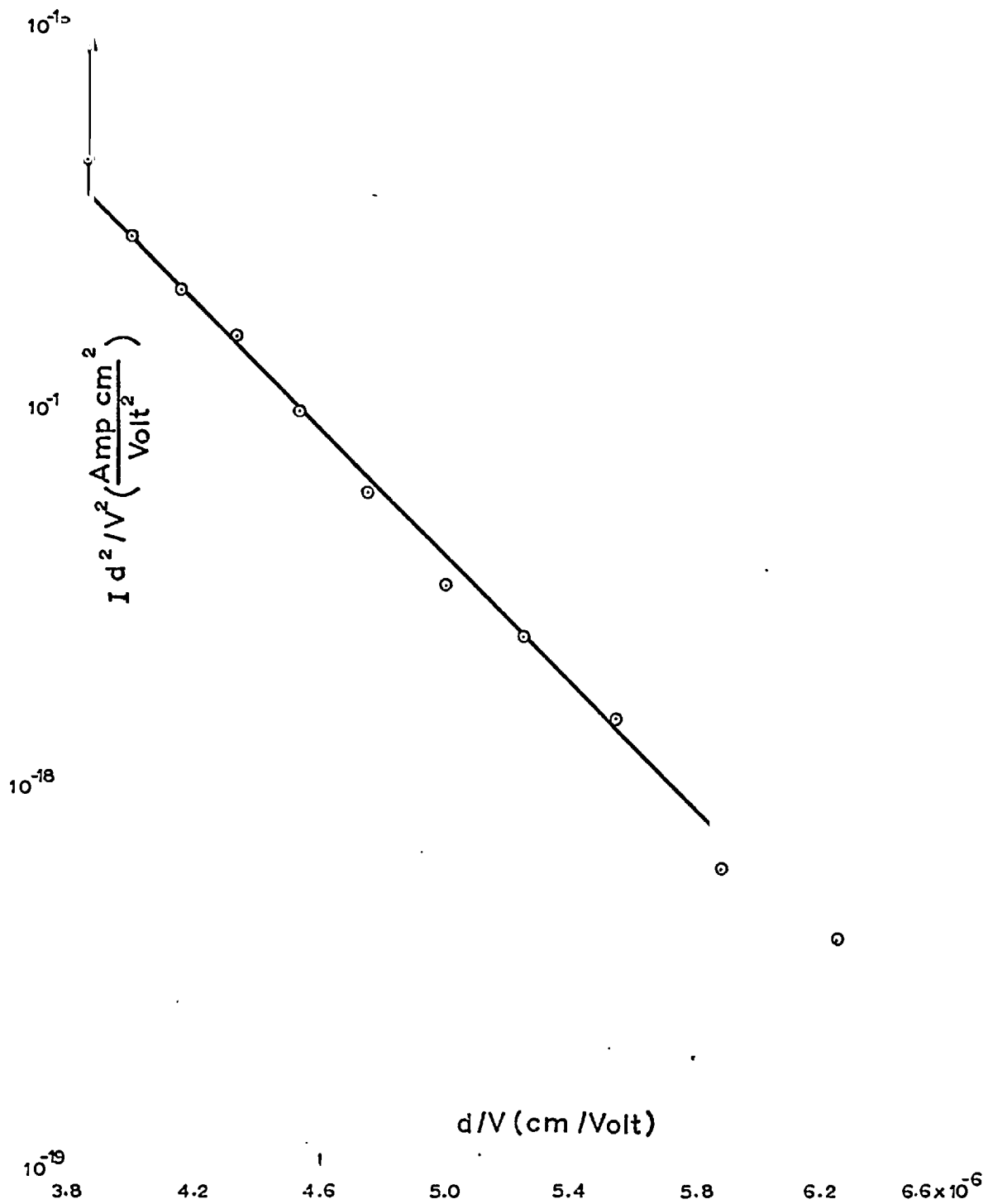


Fig. 4.4. F-N Plots for two successive tests
Nickel electrodes

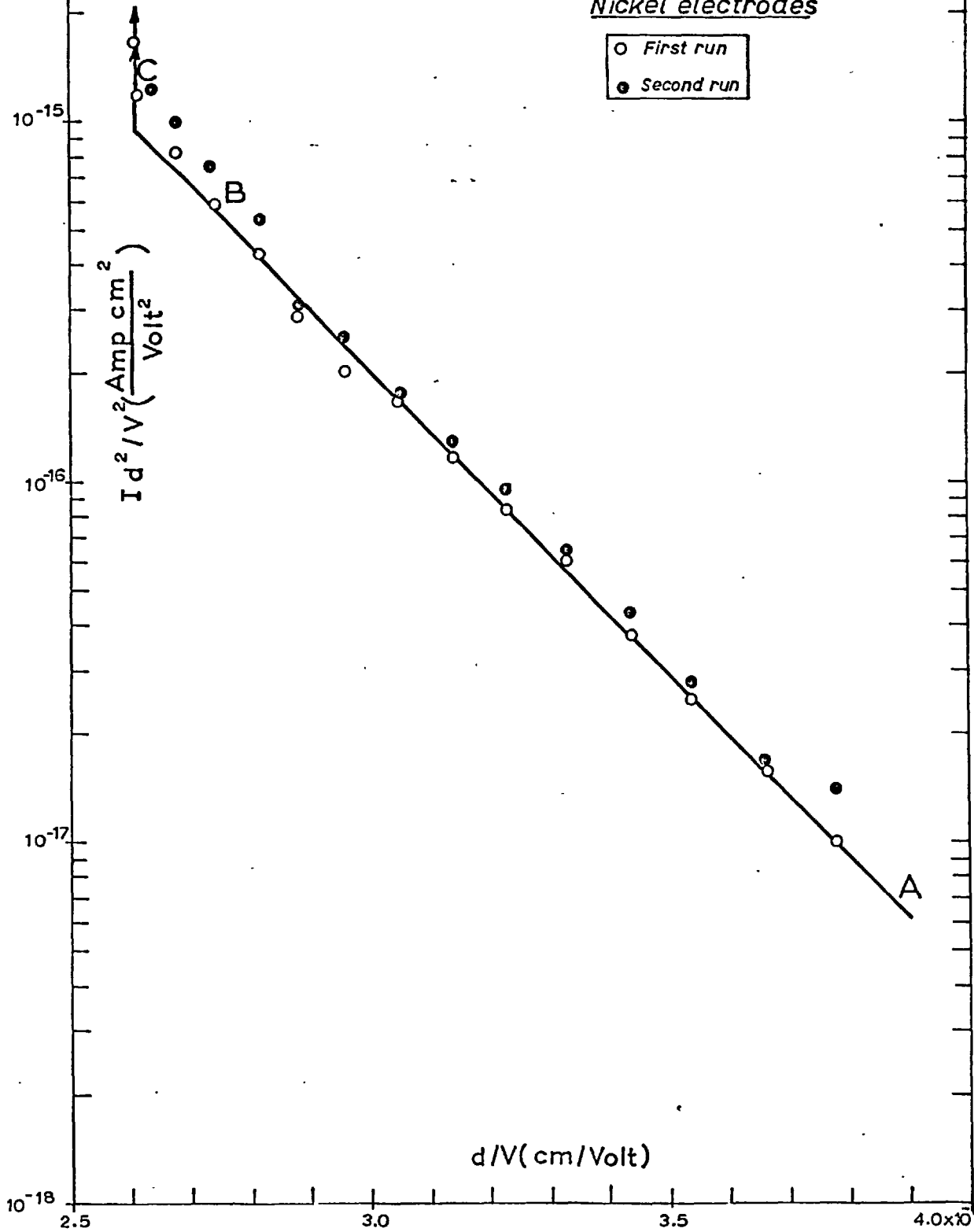


Fig. 4.5. F-N Plots for copper electrodes for successive tests.

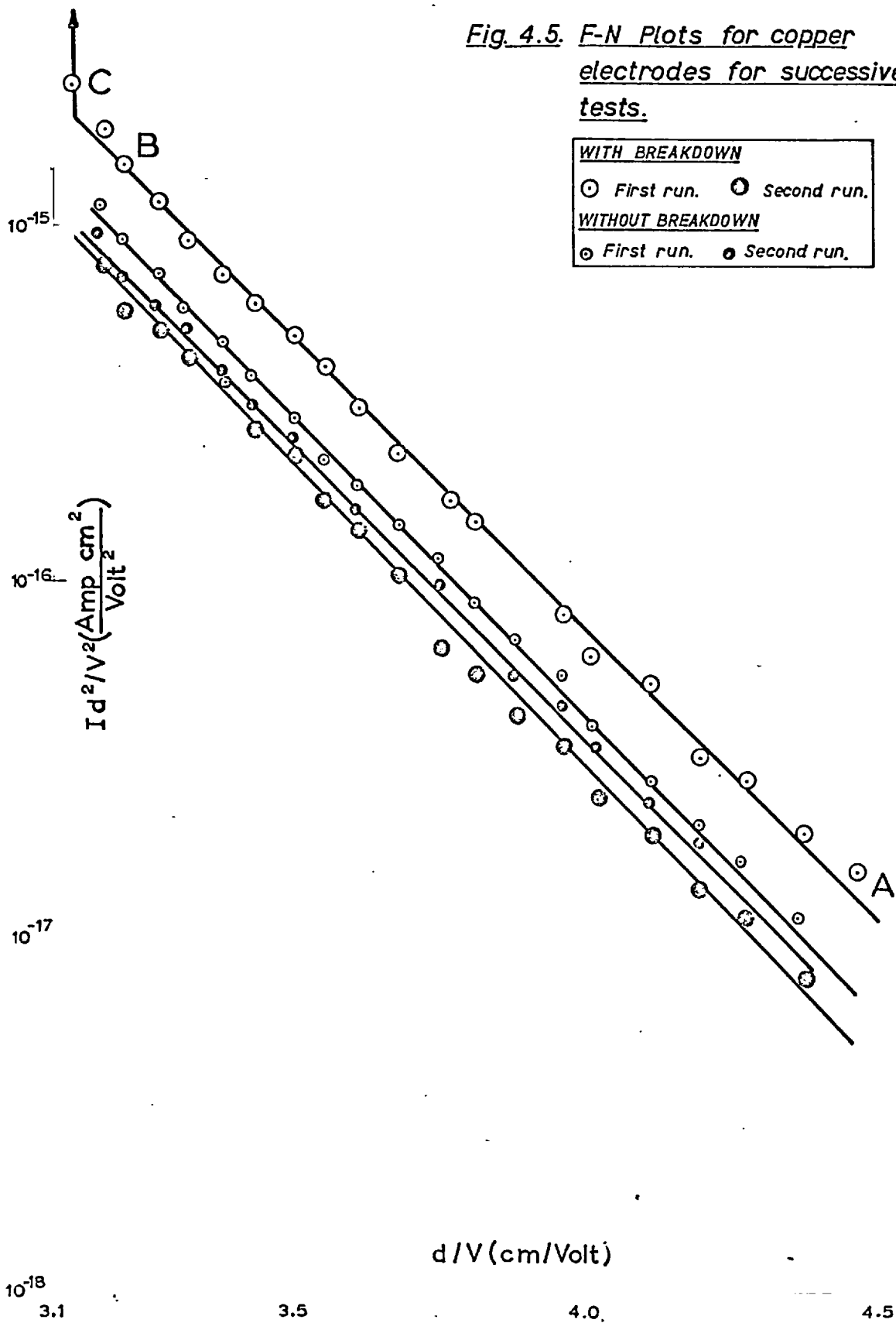


Fig. 4.6. F-N Plots for
Mo/Cu combination.

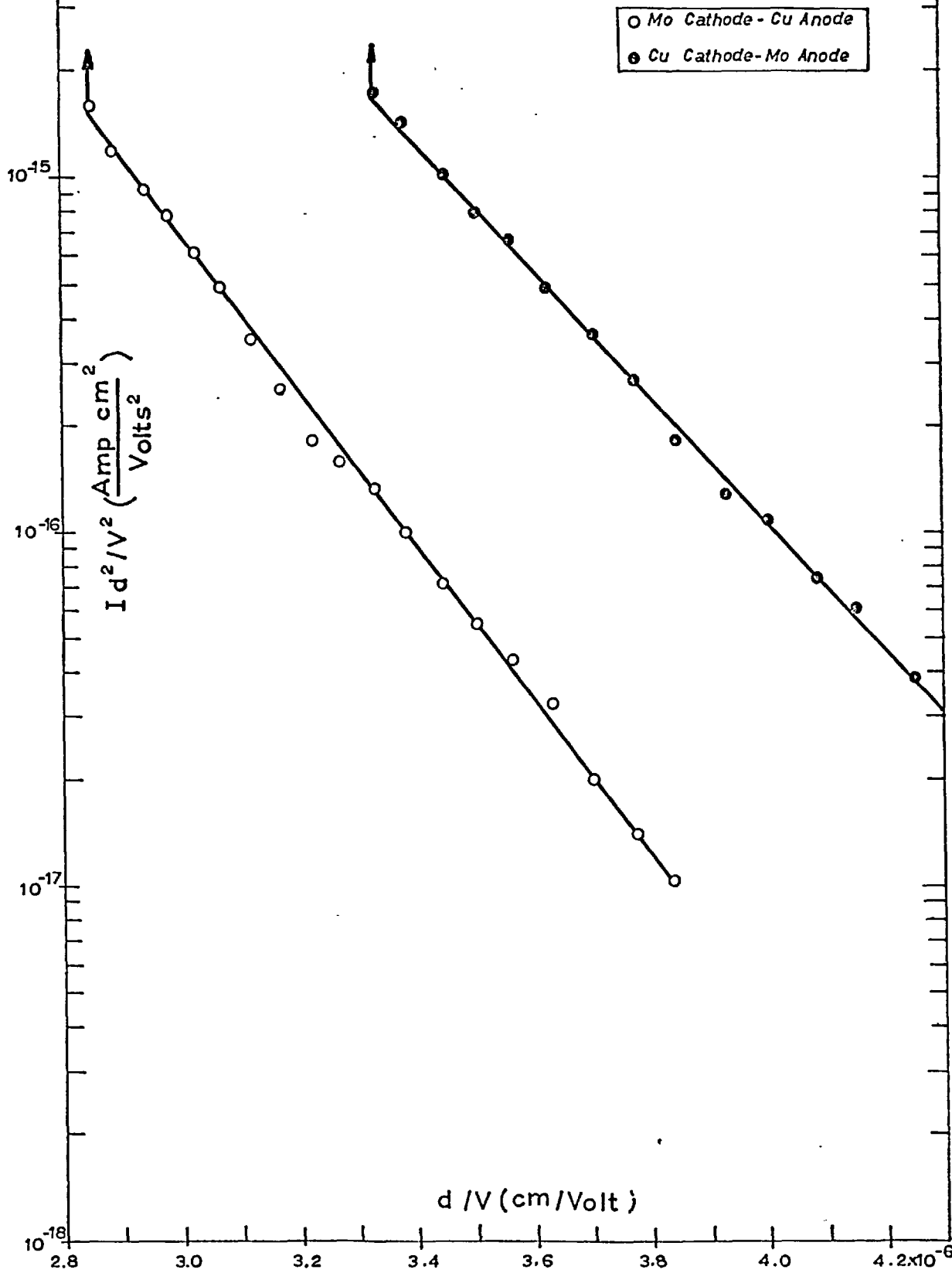


Fig. 4.7. Typical F-N plots for
Ni/Cu combination.

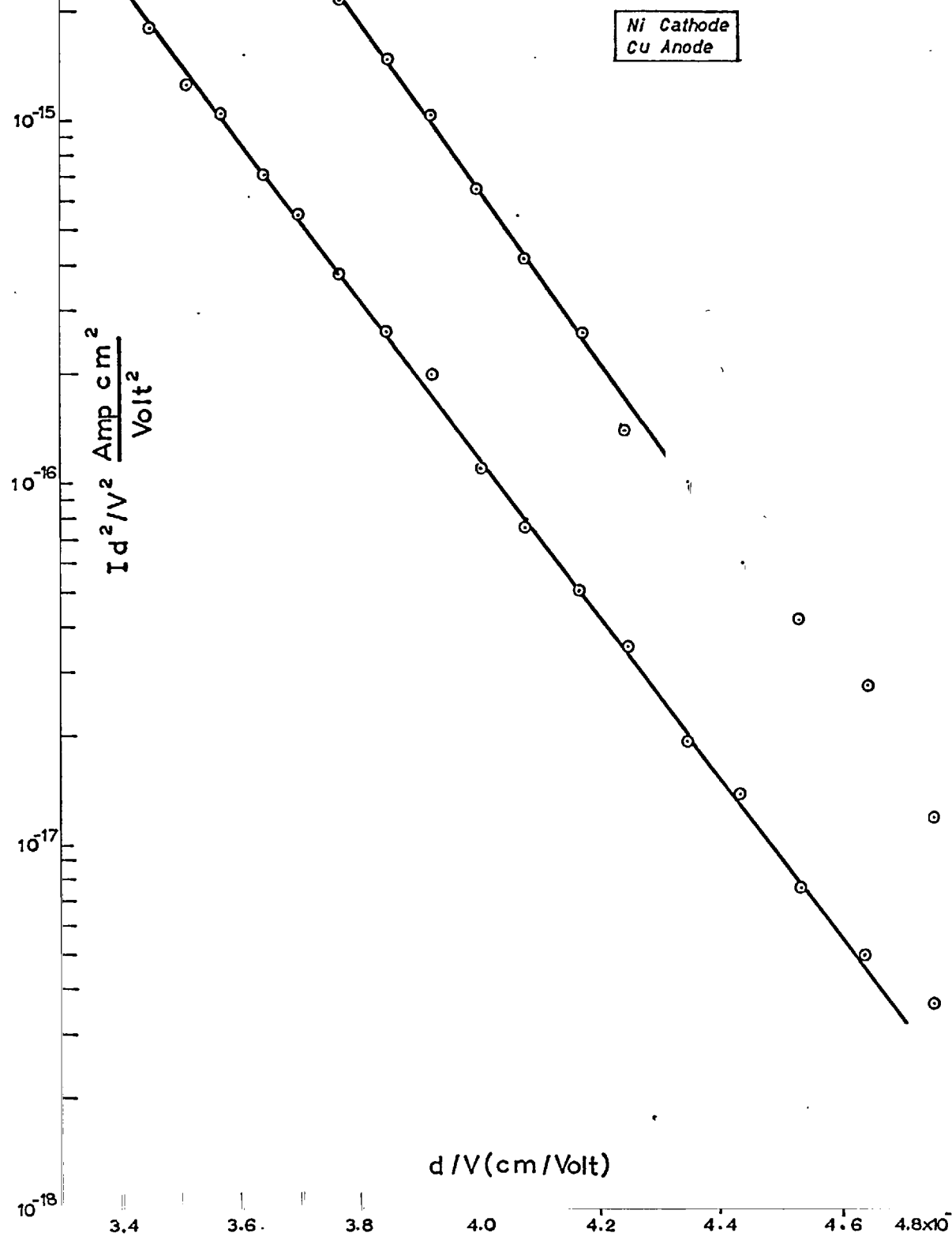


TABLE 4.1

Electrode Material		Gap	V_B	V_B/d	β_k	$\beta_k V_B/d$	I_B	J_B	A_E	r_e	(T_{KL})	$(T_K)_L$	$(T_A)_L$
Anode	Cathode	mm	kV	$\frac{kV}{mm}$		$\frac{10^7 V}{cm}$	μA	$\frac{10^6 Amp}{cm^2}$	$10^{-11} cm^2$	$10^{-6} cm$	$^{\circ}C$ Cone	$^{\circ}C$ Cylinder	$^{\circ}C$
Mo	Mo	1.00	51	51	108	5.5	81	3.2	0.25	12.8	35	110	350
Ni	Ni	1.10	42	38	203	7.75	117	13	0.093	1.7	100	980	420
Cu	Cu	1.05	33.5	32	170	5.4	205	1.3	1.7	7.3	30	70	580
Cu	Mo	1.00	35	35	126	4.4	172	0.14	12.3	19	20	40	570
Mo	Cu	1.00	30	30	178	5.3	144	1.0	0.014	0.67	20	20	430
Cu	Ni	1.00	30	30	150	4.5	306	0.0056	545	132	20	30	640

TABLE 4.2

Material	Mean Thermal Conductivity $W/cm^{\circ}K$	Mean Electrical Resistivity $10^{-6} \Omega cm$	Work Function eV
Mo	1.14	25.8	4.35
Ni	0.81	26.2	5.0
Cu	2.72	5.55	4.5

Temperature range for Conductivity and Resistivity— $0^{\circ}C$ to .8 melting point.

4.2.1. F-N Characteristics

An examination of the Fowler-Nordheim plots shows that in general they exhibit the following features (see Fig. 4.1):

- 1) Over most of the plot the experimental points lie on a straight line which is expected for clean degassed electrodes in good vacuum.
- 2) Plots for successive runs involving breakdown, do not necessarily have the same slope. This is in agreement with the results of other workers (Alpert et al, 1964, Charbonnier, 1967) and is attributable to surface changes on the cathode through destruction and growth of new emitting points during the breakdown process.
- 3) If breakdown is avoided (i.e. if the emitting protrusion is kept the same) experimental points can be reproduced (see Fig. 4.2).
- 4) At the high voltage end the experimental points deviate upwards from the expected straight line. This has been found to be a common feature in almost all the results. It was pronounced for nickel and molybdenum electrodes. This deviation of the points in the upward direction is in agreement with the results of Alpert et al (1964) for tungsten electrodes.

Alpert suggests that the cause might be a sudden change on the cathode surface due to material transfer or to the explosive destruction of the emitting whisker which could reduce the field enhancement factor and so increase the slope of the curve. An interesting event observed during the course of a current - voltage

run with molybdenum electrodes, also points towards this possibility.

In Fig. 4.1 the results of the 8th run were similar to those shown for the first and the fifth runs. When the ninth set of V-I measurements were being made, at the point B instability in the meter readings was observed and at C a strong spark occurred. The current rose abruptly from 200 μ A to 800 μ A and the voltage fell to 26 kV. The next test showed that the threshold value of the applied field for the appearance of 0.5 μ A pre-breakdown current had dropped from $\approx 3 \times 10^5$ V/cm to 1.5×10^5 V/cm and breakdown (indicated only by a steep rise in current) now occurred at 26 kV. The F-N plot for the V-I data after this event is shown in Fig. 4.3. The field enhancement factor as calculated from the slopes of the curves in Fig. 4.1 and 4.3 showed an increase from 121 to 323 and the microscopic breakdown field changed from 6.0×10^7 V/cm to 8.4×10^7 V/cm. An attempt to burn out the protrusion at 800 μ A current did not succeed. Probably the projection could have been burnt by reducing the limiting resistance in the circuit, but instead the polarity of the power supply was reversed. As the voltage was increased, the pre-breakdown current now appeared at 2.5×10^5 V/cm instead of 1.5×10^5 V/cm, indicating the absence of any unusually tall or sharp protrusion on the electrode which was now the cathode. At a field of 2.8×10^5 V/cm a microdischarge was heard without breakdown resulting and this was taken as an indication, that the suspected protrusion on the cathode surface might have been removed.

On reverting to the original polarity and applying the voltage again it was found that the pre-breakdown current now appeared at $2.6 \times 10^5 \text{V/cm}$, which compared well to the original value of $3 \times 10^5 \text{V/cm}$.

A certain explanation for these observations can not be given but one can advance the following working hypotheses. At the point B (Fig 4.1) where an instability was observed an event occurred which blunted the emitting tip and so reduced the value of $\beta_k = 121$ for the part AB to 62 for the part BC. One can immediately suggest two descriptions of the event a) detachment of the tip under electric stress when its mechanical strength had fallen owing to resistive heating b) impact of a clump, detached from the hot anode spot just opposite the projection. At the point C when breakdown occurred the emitting point was again modified, this time being left taller or sharper so that β_k was increased. At the cold cathode surface it was bonded strongly enough not to be fractured by electrostatic stress at $2.6 \times 10^5 \text{V/cm}$, but on reversing the polarity the heating of the anode by the prebreakdown current at $2.8 \times 10^5 \text{V/cm}$ could have been enough to weaken the bond and so result in detachment.

Such drastic changes in the slope of the F-N plots as described above were rare but serve the purpose in underlining the possibility that material transfer may occur when the applied voltage approaches the breakdown voltage.

4.2.2. Variation of Breakdown Voltage with Electrode Material

On examining the results in Table 4.1 two points are

worth noting:

1) For experiments with electrodes of the same material, the breakdown voltage increases in the order Cu, Ni and Mo.

2) For dissimilar electrode materials, in which copper formed one electrode, the breakdown voltage for each combination is close to that for copper electrodes.

If deductions are made by simply arranging the breakdown voltages in order of mechanical strength of electrode materials, then

1) leads to the conclusion that $\frac{V_B}{P_K}$ increases with mechanical strength as stated by Rozanova and Granovskii (1957). Result 2) would lead to the belief that for a vacuum gap consisting of dissimilar electrode materials the breakdown voltage is limited by the material having the lower strength. However this simple consideration is an inadequate basis for making quantitative estimates, and an example taken from data given by Denholm (1958) illustrates that these simple rules are not always obeyed.

Electrode Material	Breakdown Voltage (KV)
Aluminium	36.6
Copper	30.3
Steel	38.6

If breakdown voltage were to be simply dependent on mechanical strength then aluminium which has the lowest strength in the group should exhibit the lowest breakdown voltage when, in fact, it has

a breakdown voltage higher than copper and comparable to steel.

Such differences in breakdown voltage can be attributed to possible differences in electrode surface finish, which will cause difference in field enhancement factor β_k and hence in the field emitting characteristic of the cathode. It has been mentioned earlier that breakdown initiation must occur as a consequence of local heating produced at the electrodes by the pre-breakdown field emission current. If breakdown occurs therefore when a critical temperature is always reached at the local sites, it is apparent from eqns (2.8 to 2.12) and 2.17 that for significant changes in β_k , considerable variations in V_B and I_B is expected. Thus anything which changes β_k significantly is likely also to change the breakdown voltage for the same electrode material.

4.2.3. Local Temperatures

Cathode

From Table 4.1 it can be seen that for a conical projection the temperature of the tip is generally negligible. Even with nickel electrodes where the tip temperature for a cylinder is 980°C . for a cone it is only 100°C . For a cylindrical projection the temperature is higher but except for nickel the highest temperature calculated is 110°C for the molybdenum cathode. Thus in the present experiments the cathode local heating is unlikely to be significant. It can also be seen from Table 4.4 that the contribution of Nottingham heating $(\Delta T)_N$ to the total value $(T_K)_L$ is higher than the contribution from resistive heating $(\Delta T)_R$ which is in agreement with the views

TABLE 4.3

Cathode	$(T_K)_L$ °C		β_k	$2T_s$	V_B/d	Anode	$(T_A)_L$ °C		$2T_s$	β_A	V_B/d	V_B/d
Material	Cyl.	Cone	$\theta=5^\circ$	10^8 dynes cm^2	kV/mm Predicted	Material			10^8 dynes cm^2	Assumed	kV/mm Predicted	kV/mm Expt.
Mo	110	40		108	145	Mo	350		124	108	152	51
Ni	980	100		203	8	Ni	420		57	203	56	38
Cu	70	30		170	41	Cu	580		8	170	25	32
Cu	20	20		178	44	Mo	430		120	126	130	30
Mo	40	30		126	156	Cu	570		9	170	27	35
Ni	30	20		150	84	Cu	640		7	170	23	30

108

Values of T_s have been taken from Fig. 1.1.

TABLE 4.4

Cathode	Anode	$(\Delta T)_R$	$(\Delta T)_N$	$(T_K)_L = (\Delta T)_R + (\Delta T)_N + T_o$
Mo	Mo	10°C	80	110
				$T_o = 20^\circ\text{C}$
Ni	Ni	310	650	980
Cu	Cu	0	50	70
Cu	Mo	0	0	20
Mo	Cu	0	20	40
Ni	Mo	0	10	30

of Chatterton(1966) and Charbonnier et al (1967) that in estimating local cathode temperatures, neglecting $(\Delta T)_N$ may result in serious errors.

Anode

From Table 4.3 it can be seen that highest temperature calculated for anode is 640°C for a copper anode and the lowest temperature is 350°C for a molybdenum anode. It was mentioned earlier that actual temperatures at breakdown are expected to be somewhat higher due to slight non-linearity that occurs at the high voltage end of the F-N plots. Examining this non linearity it is found that for molybdenum and nickel electrodes the actual value of I_B was higher by 50% at most, and for copper by not more than 25%. The local cathode and anode temperatures would be raised by not more than 30% for molybdenum and nickel and 20% for copper electrodes. Even taking this correction into account it is seen that the actual temperatures would not have been high enough for there to be any significant evaporation of anode material into the electron beam.

4.2.4. Predicting Breakdown Voltages

Having seen that local heating is not sufficient for evaporation of electrode material to occur we now consider the detachment of material from the electrodes using the relation (2.6).

Cathode Initiated Breakdown

In Table 4.3 the necessary data needed for predicting the breakdown voltages is given together with the predicted values

of V_B for the cathode and anode. V_B for the cathode is calculated for a cylindrical protrusion since this is expected to reach a higher temperature than other types of projection. It can be seen that the calculated cathode breakdown voltages are high except for Ni-Ni electrodes. The lowest of the other values is 54 kV for a copper cathode, which is higher than the highest experimentally observed value of 51 kV for molybdenum electrodes. Therefore on this theory cathode initiated breakdown in all cases except Ni-Ni, seems unlikely.

Ni-Ni Electrodes

The predicted breakdown voltage is 22 kV which is considerably less than the experimental value of 38 kV. This may be a consequence of making calculations based on the extrapolated straight part of the F-N plot, and an attempt can be made to explain the disparity taking account of the non linear portion which was a pronounced feature of the Ni-Ni tests. On examining the F-N plot for first run in Fig. 4.4 which corresponds to the data given in Table 4.3 for Ni-Ni, one sees that a distinct departure from linearity occurs at B in the direction of higher slope i.e. lower β_k . This is also the point where occurrence of sparks is first noticed. They are intermittent between B and C and become frequent at C where the current rises steeply. This observation is typical for nickel and is in agreement with similar observations of previous workers (Goldstone, 1965). Two possibilities for this non linearity

may be a) transport of material to the cathode from the anode spot if equation (2.6) is satisfied at the anode or b) detachment of the field emitting tip if it is satisfied at the cathode.

Since the maximum anode temperature at Breakdown is calculated to be 420°C , the temperature corresponding to point B is expected to be even lower i.e. the voltage needed for material transport from the anode would according to theory, be higher than 57 kV. The cause of the non-linearity must be looked for at the cathode. For the point B the field current $I_L = 80 \times 10^{-6}$ amp., the measured voltage $V = 37$ kV, $\beta_k = 203$, the enhanced electric field is therefore $7.5 \times 10^7 \text{ V/cm}$. Using these figures $(T_K)_L$ is found to be as 620°C . The voltage needed for the detachment of the projection in these conditions is predicted from equation (2.6) as 42.5 kV, which is in good agreement with the measured value of the voltage of 37 kV. This means that material transfer from the cathode may have commenced at fields lower than the breakdown value. Repeated transfer when the applied electric field is increased may then create sufficient nickel vapour, for breakdown to occur. However, the possibility of anode contributing to the formation of metal vapour at breakdown by material transfer can not be ruled out, as the predicted breakdown voltage for the anode, of 57 kV in Table 4.3, is only 50% higher than the experimental value, and in fact this discrepancy will be less if non linearity of the F-N plot is taken into account. Although the details of this explanation are open to doubt we may conclude that for Ni-Ni electrodes the instability

arising from the detachment of cathode material in accordance with eqn (2.6), plays a dominant part in the breakdown initiation.

This discussion demonstrates the need for further investigations into the cause of the non linearity of the F-N plots.

Anode Initiated Breakdown.

Copper Anodes

It may be seen from Table 4.3 that the predicted values of V_B for anode initiated breakdown are in quite good agreement with experiment. The predicted values are lower than the experimental ones but the maximum difference is only 20%. The discrepancy may be explained in the same way as for a nickel cathode by a consideration of the non linear part of the F-N plot. The anode temperature at breakdown for copper electrodes was calculated using linear extrapolated values to be 580°C . At the point B in Fig 4.5 where the F-N curve becomes non linear $I = 140 \mu\text{A}$, $V = 32.5 \text{ kV}$, $\beta_k = 170$, and the effective field is $5.3 \times 10^7 \text{ V/cm}$. Using these values, $(T_A)_L$ the local anode temperature is found to be 470°C . The voltage needed for the detachment of a projection is then given from eqn(2.6) as 31 kV/mm , which is in numerical agreement with the voltage at the point B.

Molybdenum Anodes

For a molybdenum anode the anode temperature is calculated to be 350°C when a Mo cathode is used and the corresponding calculated breakdown voltage is 152 kV . With a Mo anode and Cu

cathode the calculated anode temperature is 430°C and the corresponding breakdown voltage is 120 kV. These predicted values are higher than the experimental values by more than a factor of three.

Even if actual temperature near breakdown had been higher by $\approx 30\%$ the temperatures would not exceed $\approx 450^{\circ}\text{C}$ and $\approx 550^{\circ}\text{C}$ respectively and corresponding breakdown voltages would still be too high by a factor of two. Thus local heating produced by the field emission current does not seem to be sufficient to allow material transfer to occur in accordance with eqn (2.6).

However subsequent electron probe x-ray analysis(Ch.5) of the copper cathode used opposite to a Mo anode does indicate unmistakably the presence of spots of molybdenum on the cathode. On re-examining eqn.(2.6) one sees that for transfer of molybdenum to occur at voltages used in these experiments either the tensile strength (T_s) must be sharply reduced or the field enhancement factor (β_A) must be considerably increased. Taking the case of the copper cathode - molybdenum anode, for $\beta_A = 120$ and $V_B = 30$ kV, the local anode temperature $(T_A)_L$ for the necessary reduction of T_s must be $\approx 2000^{\circ}\text{C}$. It is difficult to see how this temperature could be produced. Alternatively, a value of $\beta_A \approx 500$ would be required, and though the assumed value of $\beta_A \sim 120$ may be in error a value of 500 arising from surface roughness left behind after polishing seems improbable. Possibly it arises during the local heating of the anode by the pre-breakdown current i.e. sharp pro-

jections might grow during this period and so produce the large value of β_A required. Occurrence of β_K as high as 320 after instabilities observed near breakdown point has already been noted (section 4.2.1). Microscopic examination of the anode spots after the copper cathode-molybdenum anode test showed marks which strongly suggested the presence of projections in these areas. Growth of protrusions on anode surface prior to breakdown has also been reported in the literature (Hawley and Walley, 1961). Thus the growth of projections can not be ruled out as a possible cause of an increase in β_A and hence the transfer of material.

4.2.5. Growth of Projections

Dyke, Charbonnier et al (1960) have already made extensive studies on the stability of heated field emitters. The following results are relevant here. When a field emitting needle is heated to a high temperature in the absence of an electric field the tip is gradually dulled as the tip radius r_e increases owing to surface migration. This effect is more noticeable with sharper tips i.e. the dulling rate is high for tungsten tips of $\sim 10^{-7}$ cm radius, but negligible for tips of 10^{-4} cm radius. For a given temperature, the lower the melting point the higher is the dulling rate. If the heating is continued in the presence of a steady electric field dulling is slowed down but still occurs if $E < E_c$, a critical field. It ceases for $E = E_c$, and needle begins to grow if $E > E_c$. Sharp corners may then result due to formation of facets at the tip

and this results in an increase in β . When this "build up" phenomenon occurs tip may be detached under electric stress.

E_c has a characteristic value for particular cathode material and is given as,

$$E_c = (4.5 \times 10^6 \times S r_c^{-1})^{\frac{1}{2}} \quad \text{V/cm} \quad (4.1)$$

where S is the surface tension of the material in dyne/cm at the particular temperature. It can be seen from this relation that for a given field a critical tip radius exists such that projections having r_c larger than this will grow. Thus dull projections are more likely to develop unstable tips since for them the critical field is smaller.

The minimum surface migration temperature T_{SM} in practice is given as $0.3 T_M^{\circ} \text{K}$ (Gomer, 1961) where T_M is the melting point of the electrode material. Equation (4.1) is useful for intermediate temperatures from $0.3 T_M^{\circ} \text{K}$ to $\approx 0.6 T_M^{\circ} \text{K}$. At higher temperatures volume diffusion is the dominant process. Values of T_{SM} for Mo, Ni and Cu are 580, 250 and 140°C respectively and the range of application of (4.1) are for Mo: $580 - 1740^{\circ}\text{C}$, Ni: $250 - 760^{\circ}\text{C}$, Cu: $140 - 540^{\circ}\text{C}$.

Another important consideration is the rate at which a protrusion tip might be expected to grow. Can significant build up, i.e. increase in β_K , occur during the period of a few minutes that usually elapses while measurements are made near breakdown point. Since data for nickel and copper is lacking estimate given

for the build up time for a tungsten field emitter by Dyke et al (1960) will be taken as a guide. For $r_e \sim 3$ to 6×10^{-5} cm, $T = 1500^\circ\text{C}$ to 1700°C and $E = 6$ to 7×10^7 V/cm they find that build up leading to instability can occur within one minute. Their estimates were found to be correct within an order of magnitude, by experiment.

As the parameters at the cathode are known within the limits of the experimental error, prediction of build up can be taken as reasonably accurate. Substituting the values of E_R for copper and molybdenum cathodes from Table 4.1 in eqn (4.1) the value of r_e is found to be of the same order as that calculated from the emitting area, but as can be seen since the values of $(T_K)_L$ are far below the respective T_{SM} temperatures, the possibility of build up in these cases is remote. For nickel cathode, the value of r_e corresponding to $E = 7.5 \times 10^7$ V/cm at the point B in Fig. 4.4 is found to be $\sim 1.3 \times 10^{-6}$ cm and that from the emitting area is $\sim 1.6 \times 10^{-6}$ cm. The tip temperature calculated at this point was 620°C which is towards the higher limit of the temperature range $245 - 760^\circ\text{C}$ for surface migration for nickel. Therefore at the point B, build up of the tip i.e. increase in β_K was possible. Thus in this case conditions for detachment of the material from the cathode by straight forward process considered earlier as well as by growth due to surface migration were present.

For growth of projections to occur by build up at the

anode all that can be said at this stage is that the temperature requirement is satisfied for copper and possibly for nickel but not for molybdenum.

Because of its obvious importance to theories of breakdown and material transport between electrodes a full study of protrusion growth mechanisms in breakdown conditions would be very valuable.

4.2.6. Effect of Heating on Electrode Surface Protrusions

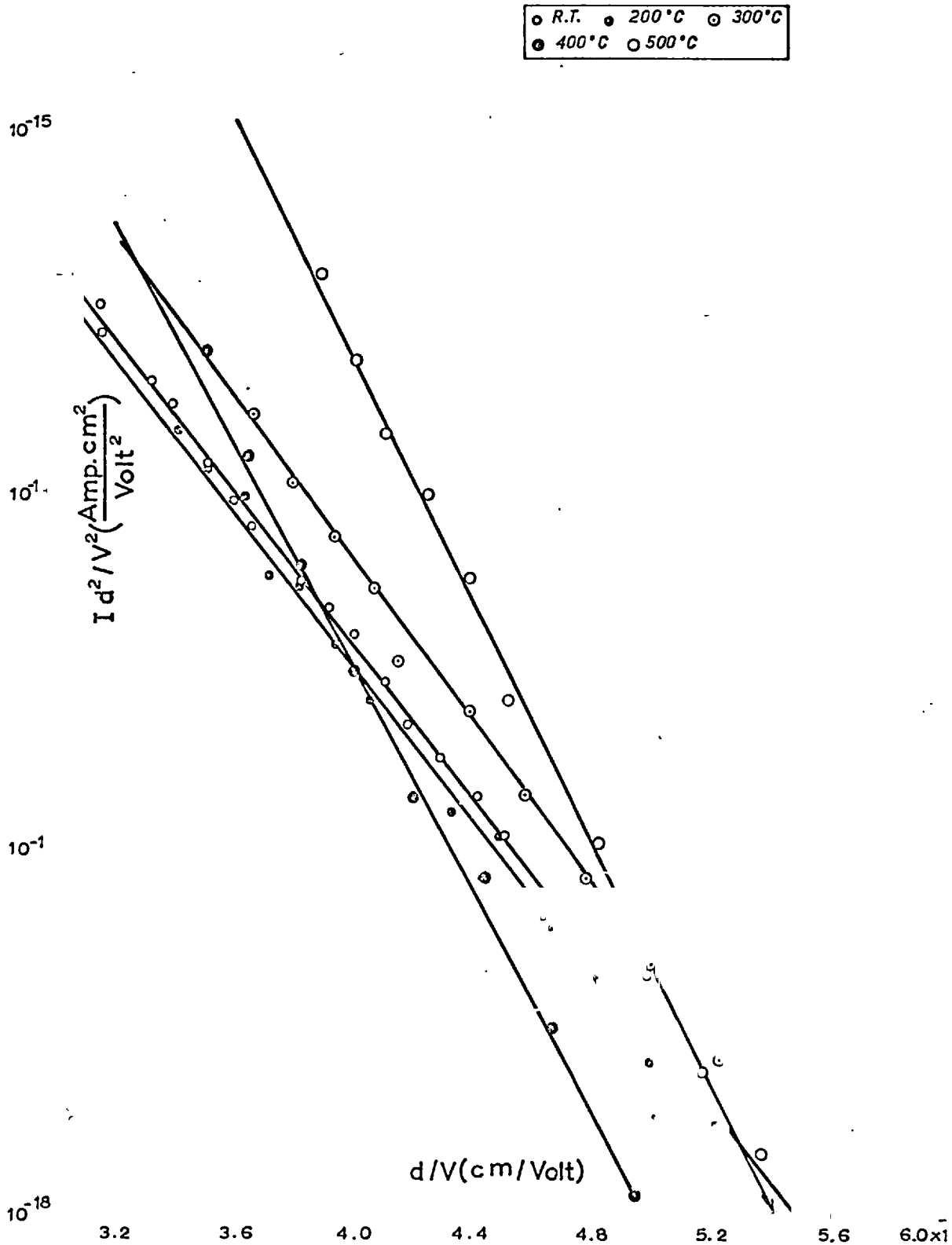
To see whether dulling or growth of electrode surface protrusions can occur on plane parallel electrodes as with the heated field emitters used by Lyke et al(1960) a preliminary experiment was performed with copper electrodes. It was decided to measure β_k from F-N plots for different cathode temperatures, to calculate the current density from the effective electric field. The emitting area and hence the tip radius were then derived from values of β_k , current and current density. An important requirement is that the measurements should be made for the same cathode protrusion. This was ensured by avoiding breakdown by keeping the maximum applied voltage well below the voltage at which non linearity appears on the F-N plot.

Tests were made with thoroughly outgassed electrodes and at pressures better than 10^{-7} Torr at 500°C , and better than 10^{-8} Torr at lower temperatures. Several sets of V - I measurements were taken at each temperature. Typical results are shown in

TABLE 4.5

Cathode	β_k	ρ_k V/d	J	I	A_E	r_e	r_c
Temp. °C		10^7 V/cm	10^7 Amp/cm ²	μ A	10^{-12} cm ²	10^{-7} cm	10^{-6} cm
R.R.T.	266	7.4	5.0	7.5	0.15	2.2	1.0
200	266	7.4	5.0	7.5	0.15	2.2	1.0
300	255	7.1	3.2	14	0.44	3.7	1.2
400	187	5.2	0.071	10	1.14	21	2.1
500	164	4.5	0.01	84	843	160	2.9

Fig.4.8. Heated copper cathode
F-N plots for successive runs
avoiding breakdown.



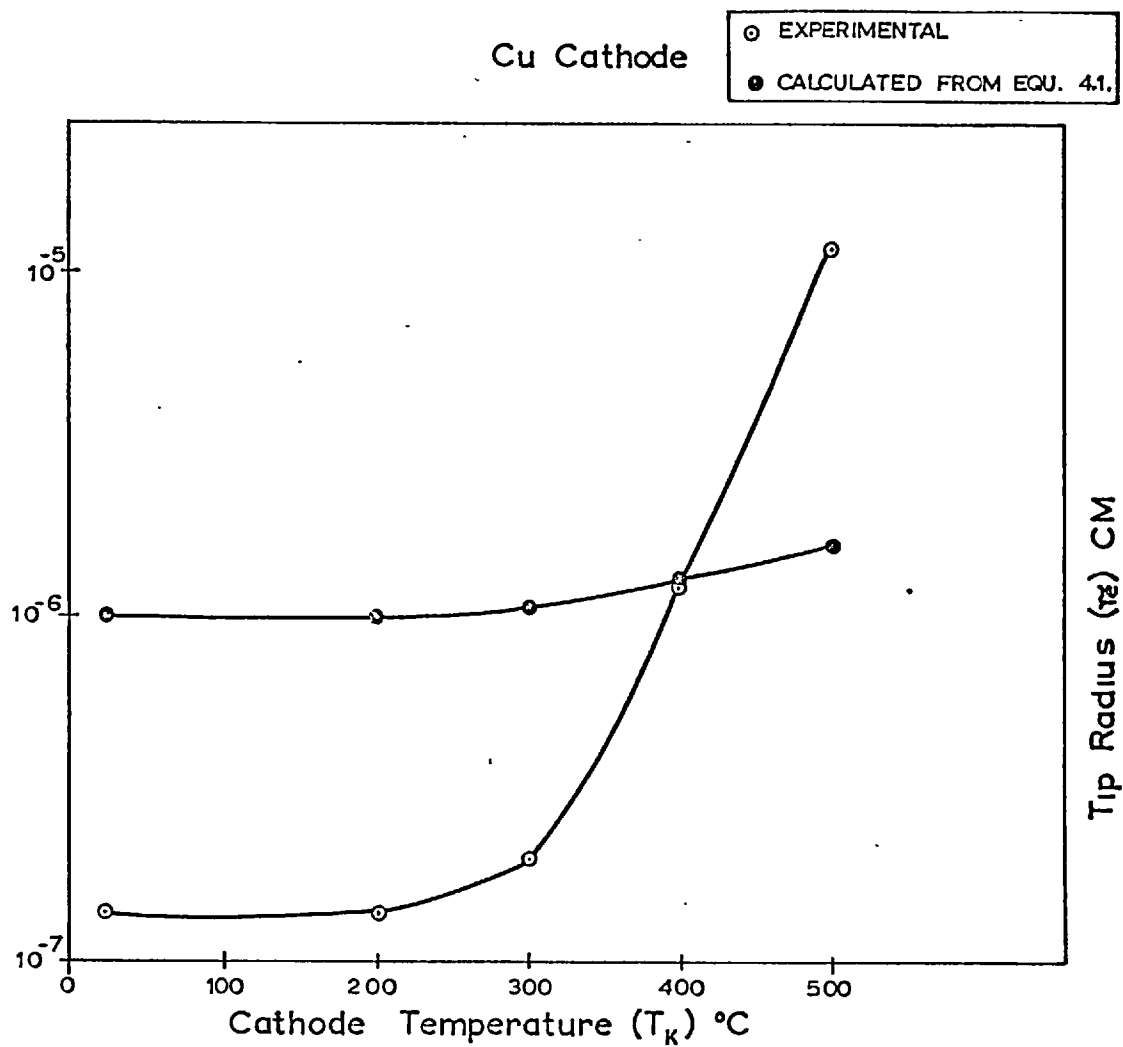


Fig. 4.9. Variation of tip radius with cathode temperature

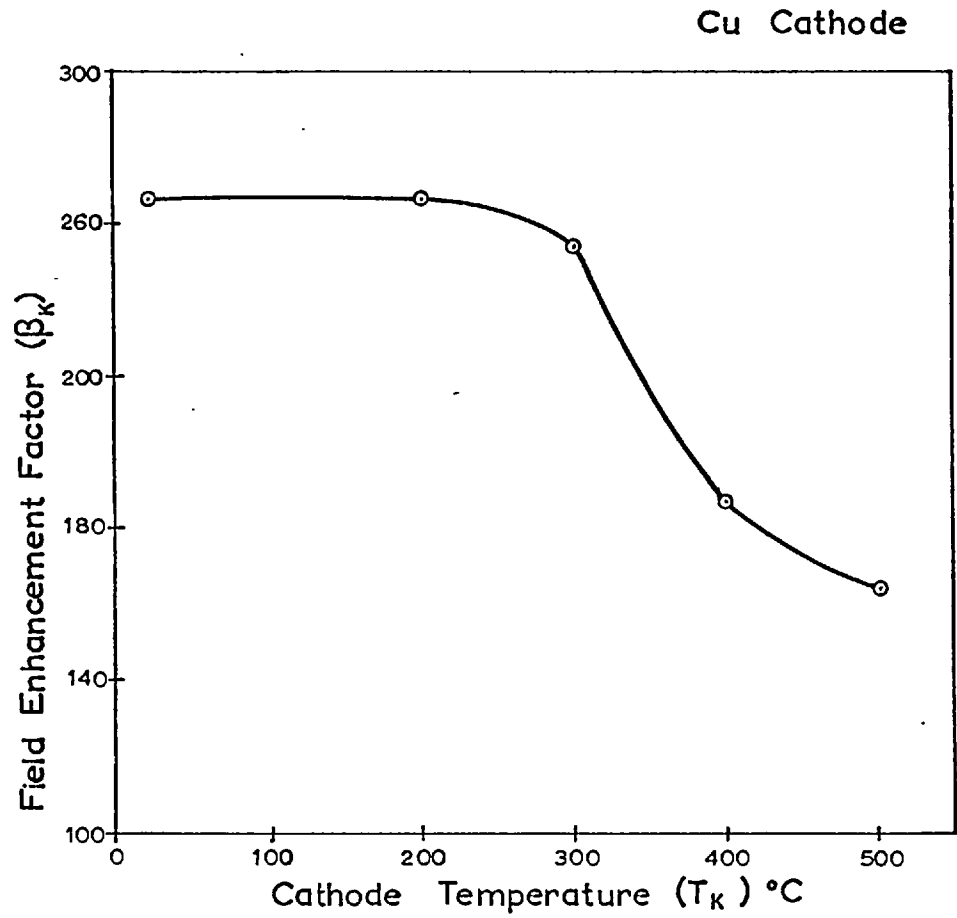


Fig. 4.10. β_K as a function of cathode temperature

Fig. 4.8. The variation of β_k with cathode temperature is shown in Fig. 4.10. For a common value of $d/V = 3.6 \times 10^{-6}$ cm/V the tip radius at each temperature has been calculated, the necessary parameters being given in Table 4.5. In the last column is given the critical tip radius calculated according to eqn 4.1 from the enhanced field E at each temperature. The increase in the tip radius with cathode temperature is quite obvious from Fig. 4.9. It can be seen that up to 300°C , r_e is about an order of magnitude less than the critical tip radius for the build up to occur defined by eqn (4.1), whereas at 500°C , r_e is an order of magnitude higher than r_c . Although detailed conclusions can not be drawn from the result obtained it is apparent that the possibility of growth and dulling exists. Further study of this phenomenon would seem to be essential in future work.

4.3. Summary

1. Breakdown tests were performed with electrodes of copper, nickel and molybdenum and it was found that the breakdown voltage increased in this order. Tests performed with the cathode/anode combinations Cu - Mo, Mo - Cu, Ni - Cu showed that the breakdown voltage always had a value close to that for two copper electrodes. It is suggested that conclusions drawn superficially about the dependence of breakdown voltage on the mechanical strength of the electrode material may be misleading.

2. Fowler-Nordheim plots of the current - voltage data were

found to be linear except at the high voltage end where the curve appeared to diverge in direction of higher slope.

3. From the experimental data local temperatures at the cathode and anode were estimated.

a) With copper and molybdenum, cathode temperatures were in general too low for any thermal instability to arise irrespective of protrusion geometry. With two nickel electrodes the temperature for a cylindrical protrusion was an order of magnitude higher than for a conical one, and might reach 900°C.

b) Anode temperatures were in general higher than cathode temperature though they hardly exceeded half the melting temperatures of the anode material. No significant evaporation of anode material was therefore expected but a drastic reduction in tensile strength was likely.

4. a) The relationship
$$V_B = \frac{150 (2.T_s)^{\frac{1}{2}}}{\beta}$$
 based on the assumption that breakdown is due initially to detachment of material from an electrode, leads to the conclusion that cathode initiated breakdown is unlikely with copper or molybdenum cathodes. For nickel electrodes however breakdown is probably cathode initiated. The predicted value of the breakdown voltage was $\approx 50\%$ lower than the experimental value. Better agreement could be obtained by considering the non linearity of the F-N plot and it seems possible that material transfer begins at the point when the curve becomes non linear.

b) Cu - Anode

- i) Good agreement exists between the predicted and the experimental values of breakdown voltages.
- ii) Anode initiated breakdown is indicated regardless of cathode material.
- iii) Calculations using eqn (2.6) indicate that non-linearity in the F-N plots could well be the result of commencement of material detachment from the anode.

c) Mo - Anode

The theory failed to predict V_B for molybdenum.

d) Ni - Anode

With nickel anode the predicted breakdown voltage was higher by 50% than the experimental value. However, because of non-linearity in the F-N plots the actual temperature at the anode will be higher than the value used in the breakdown calculations. It follows therefore that near breakdown material transfer from anode can not be excluded.

5. Arguments are put forward to suggest that rounding off and build up of projections may occur due to heating in the presence of an electric field.

6. A preliminary experiment conducted with heated copper cathode to see whether phenomenon of dulling or build up, was also applicable to the present case, was successful, as results could be satisfactorily predicted from eqn (4.1). This aspect is of consider-

able interest for understanding the mechanism of material detachment from electrode surfaces and needs further attention.

CHAPTER V

EXAMINATION OF ELECTRODE SURFACES

AFTER BREAKDOWN

Electrical breakdown in vacuum between metal electrodes leaves behind characteristic marks on the electrode surfaces, which can yield information about the physical processes occurring. Thus, if initiation of breakdown is due to the detachment of clumps from the parent metal, a careful examination of the electrode surfaces after breakdown, may show evidence of craters and globules of material.

Results described in this chapter fall under three subdivisions:

- a) Brief account of direct visual observation of the electrode surfaces-- (section 5.1)
- b) Study of surface markings using optical and Stereo-Scan microscopes-- (section 5.2).
- c) Electron probe x-ray microanalysis of surface deposits-- (section 5.3).

5.1. Direct Visual Observation

If the anode surface is viewed with the naked eye, after breakdown, dull spots about 1 mm in diameter can be easily seen scattered over the surface (Fig. 5.1). It is the detailed examination of these spots which is usually of interest.

Any material detached from the anode spot will either

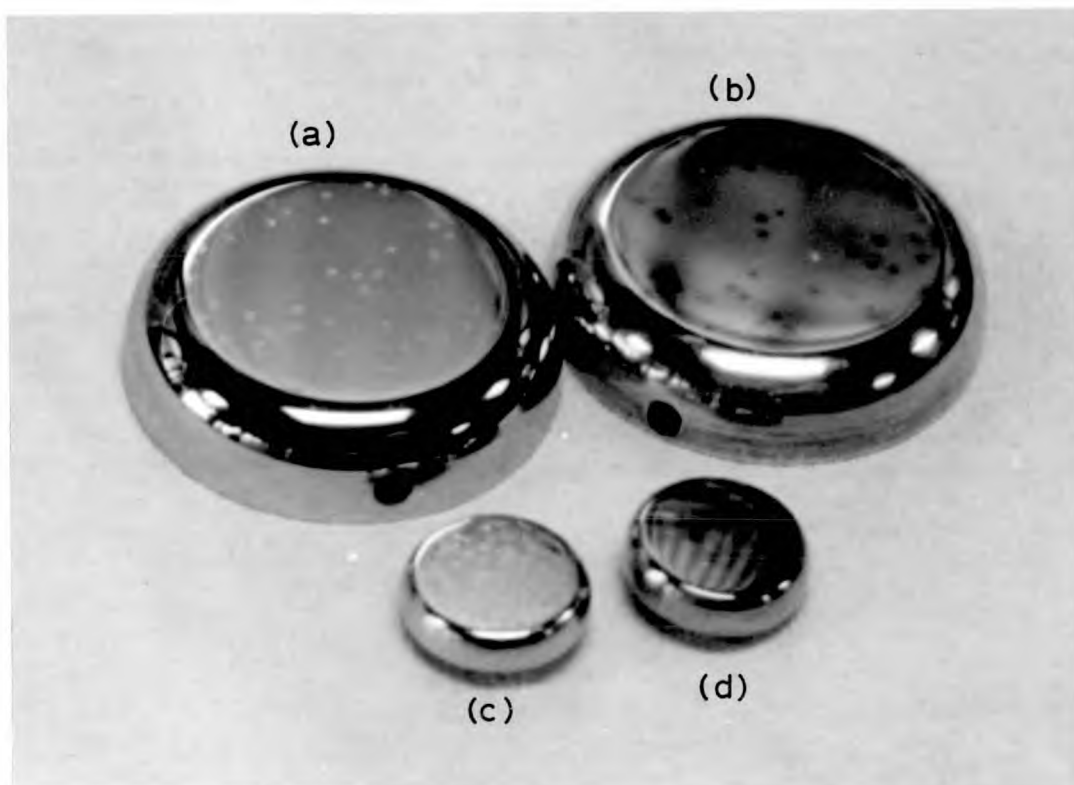


Fig. 5.1 Electrodes after Breakdown.

(a) Mo Anode (b) Cu Cathode

(c) Ni Anode (d) Cu Cathode

get vaporised in the gap by electron bombardment or it is likely to land in the area surrounding the emitting cathode protrusion lying opposite and should leave characteristic traces. Such areas are not so obvious to the naked eye when the electrodes are of similar material but they are often visible as faint circular spots when electrodes of dissimilar materials are used and corresponding marks could be identified on the anode. They have the same colour as the anode material, e.g. red spots are seen on the cathode when a copper anode is used.

5.2. Microscopic Examination

Most of the examination was done using a Vickers Projection Microscope. Considerable amount of information could be obtained about such features as craters and projections on the anode surface at a magnification of up to 1000 x. Limited information could also be obtained about small markings on the cathode, but for a detailed investigation of these the use of an electron microscope seemed essential. To distinguish between protrusions and craters which may look alike under normal incident light, inclined illumination was used. Stereo - Scan electron microscopy would have been ideally suited to this type of work since specimens can be viewed directly, as in a light microscope, with the additional advantages of good depth of focus and a wide range of available magnification. When this facility became available towards the end of this investigation, a few supplementary breakdown tests with specially made electrodes

of nickel and copper were performed so that surface features could be studied in the Stereo-Scan microscope.

5.2.1. Optical Micrographs

The following combination of electrodes which had been used in breakdown tests reported in Chapter 4, were examined:

	Cathode	Anode
a)	Cu	Mo
b)	Mo	Cu
c)	Ni	Cu

The electrode combinations of copper and molybdenum were conditioned and then subjected to ten breakdowns. To get some idea about conditions in the initial stages of breakdown, the nickel/copper combination was treated differently. After the initial conditioning breakdowns the gap voltage was raised to the value at which the steep rise in current just commenced, but complete breakdown was deliberately avoided by not increasing the current any further.

Tests with Complete Breakdown

Anode

Figures 5.3 a) and b) give a complete view of typical anode spots on copper and molybdenum. The average diameter of these spots, about 300μ , agrees well with values calculated from eqn (2.14) for the diameter of an electron beam as it strikes the anode. Thus the assumption that each spot is caused by an electron

OPTICAL MICROGRAPHS

Typical Anode Spots

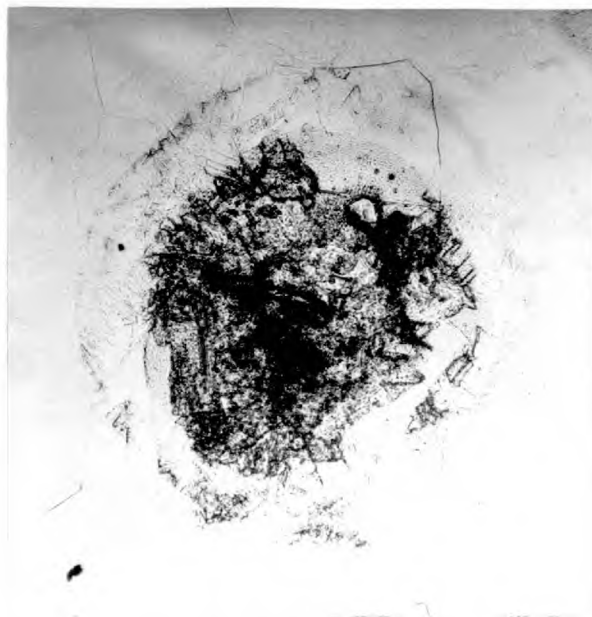


Fig. 5.3(a) Cu - 50x

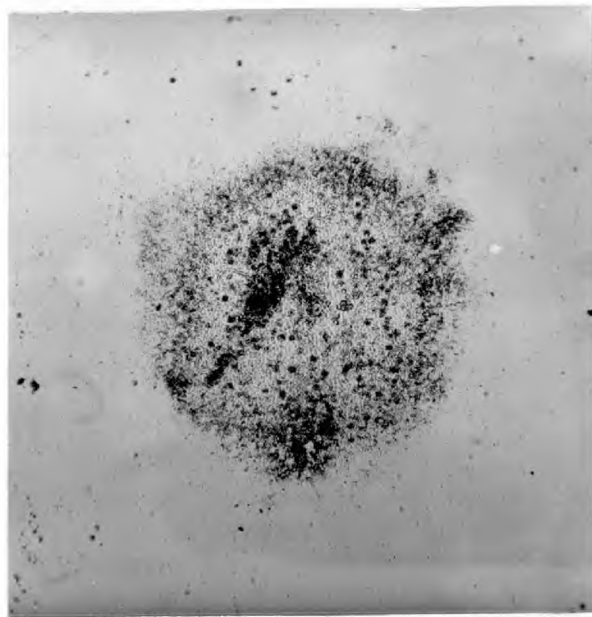


Fig. 5.3(b) Mo - 50x



Fig. 5.3(c) Central area of
(a) 150x

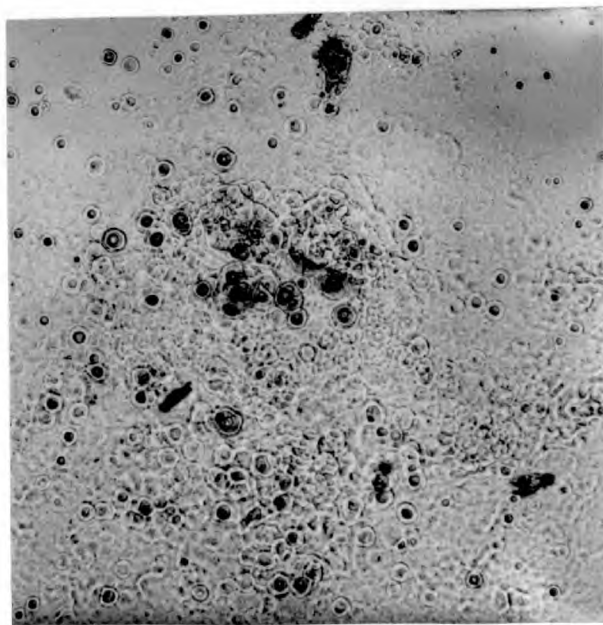


Fig. 5.3(d) Central area of
(b) 150x

COPPER ANODE AFTER BREAKDOWN

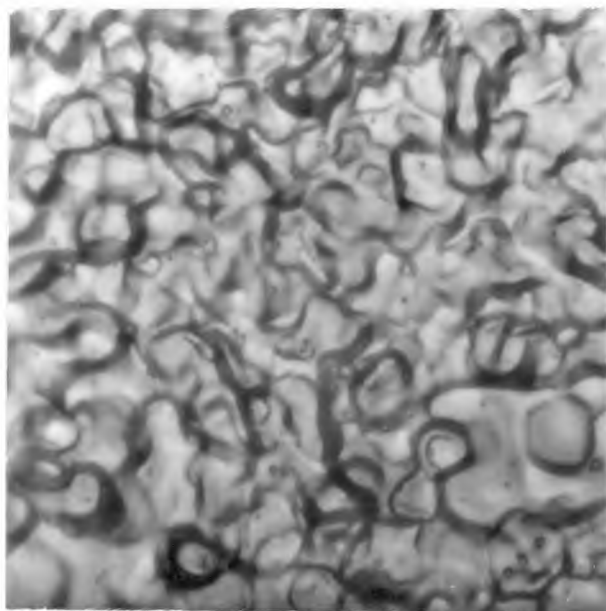


Fig. 5.4(a) Typical disturbed area
600x Normal lighting

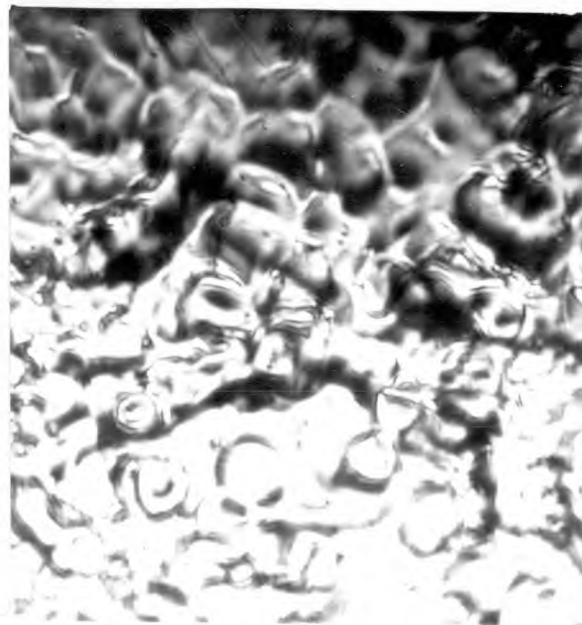


Fig. 5.4(b) Area in 5.4(a)
Oblique lighting 600x

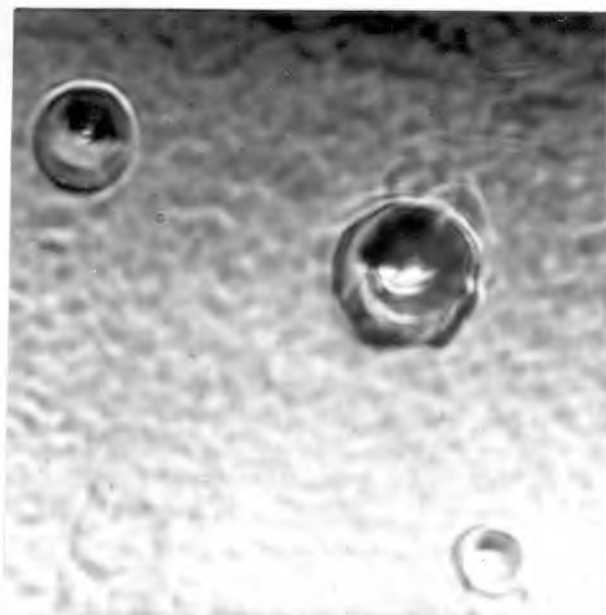


Fig. 5.4(c) Circular depressions
containing protrusions
Oblique lighting 1000x

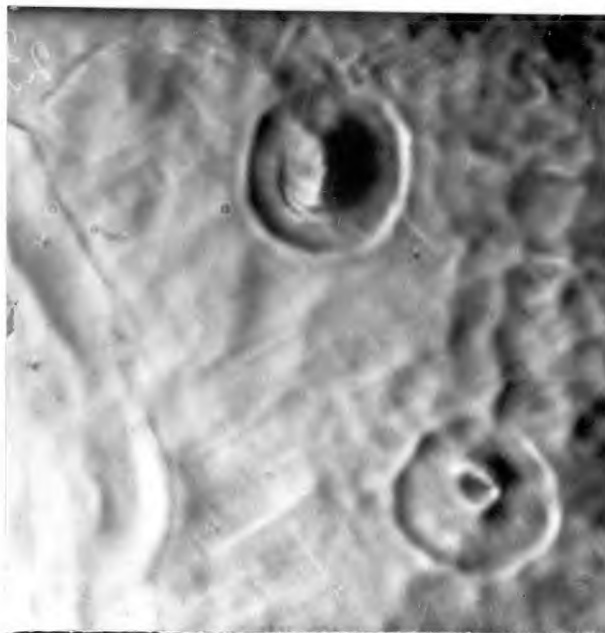


Fig. 5.4(d) Similar area as in 5.4(c)
Oblique lighting 1000x

MOLYBDENUM ANODE AFTER BREAKDOWN

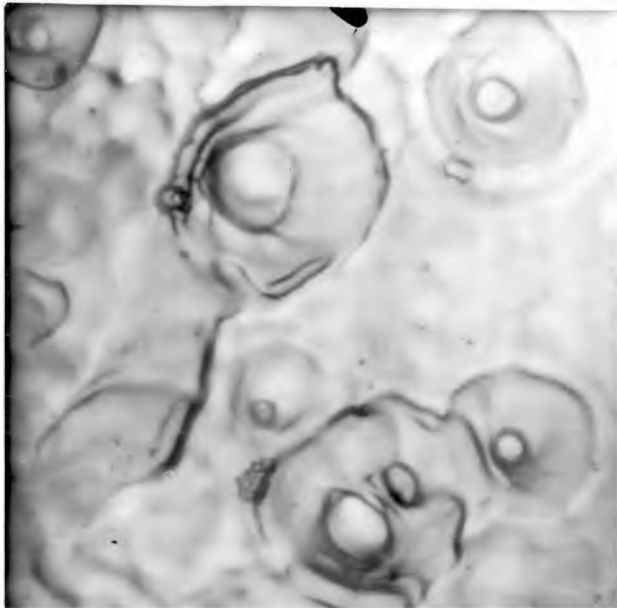


Fig. 5.5(a) Disturbed area
containing protrusions
Normal lighting 1000x



Fig. 5.5(b) Same as in (a) with
Oblique lighting 1000x

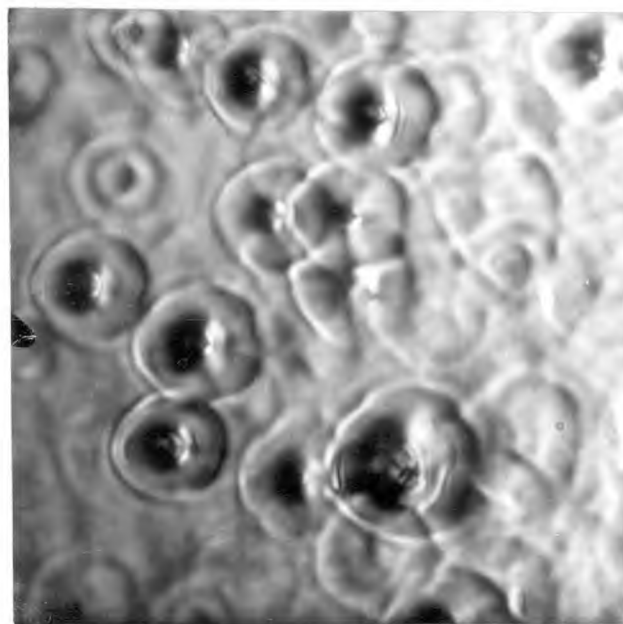


Fig. 5.5(c) Less disturbed area
containing protrusions. Oblique
lighting.1000x

TYPICAL CATHODE MARKINGS AFTER BREAKDOWN



Fig. 5.6(a) Cu - 50x

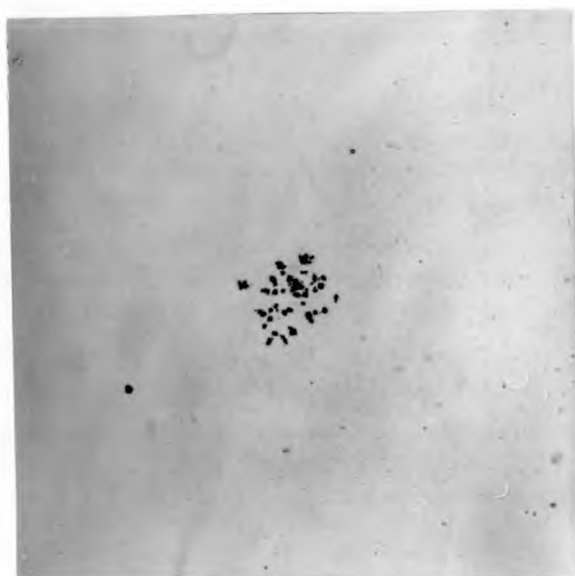


Fig. 5.6(b) Mo - 150x

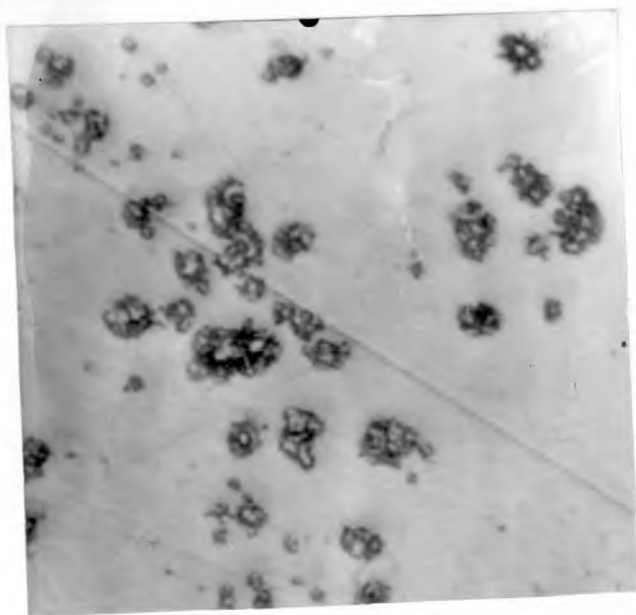


Fig. 5.6(c) Cu - Normal lighting
1000x

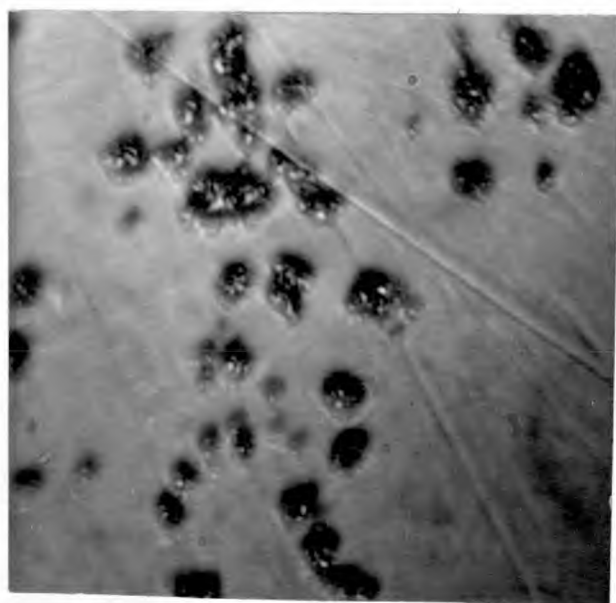


Fig. 5.6(d) Area in (c) with
Oblique lighting 1000x

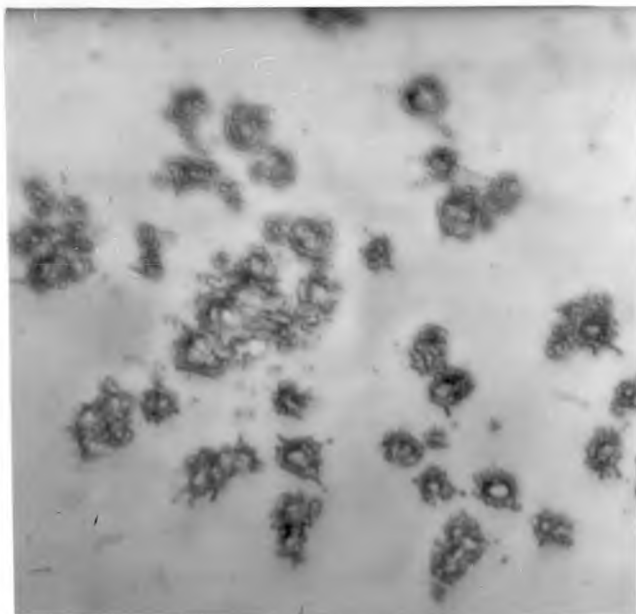


Fig. 5.6(e) Mo-Normal lighting

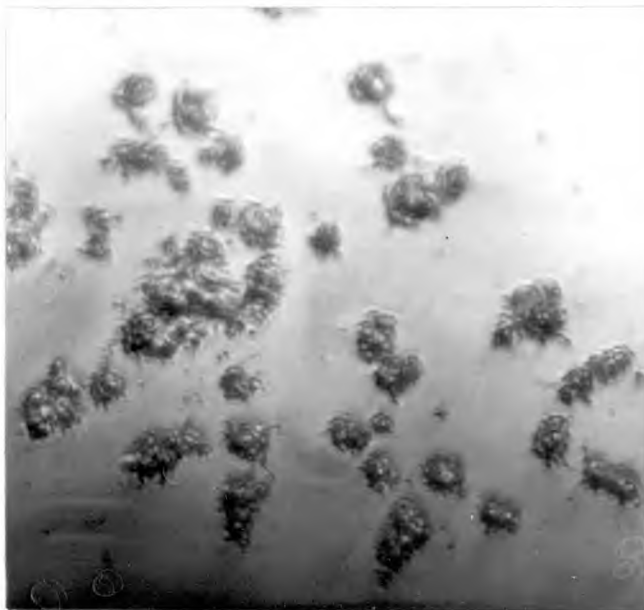


Fig. 5.6(f) Mo-Oblique lighting
1000x

COPPER ANODE AFTER TESTS WITHOUT BREAKDOWN

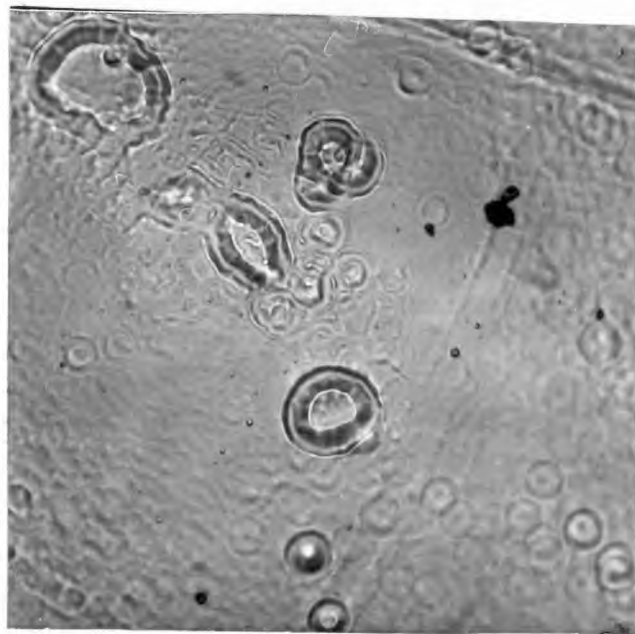


Fig. 5.7(a) Normal lighting 600x

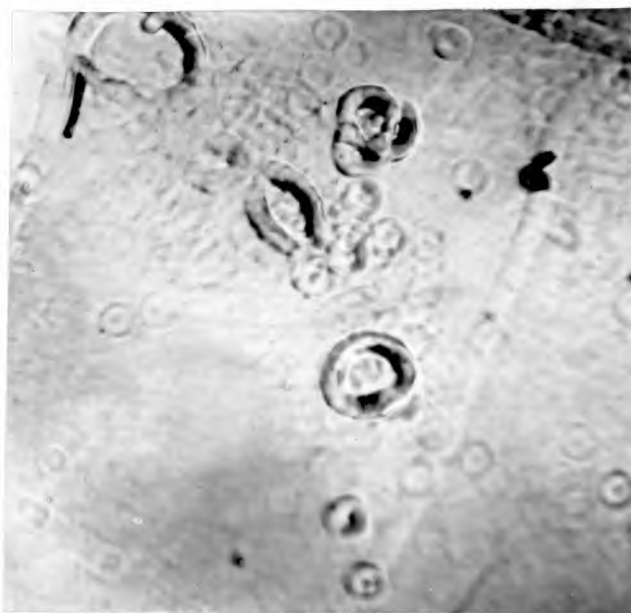


Fig. 5.7(b) Area in (a) with
Oblique lighting 600x

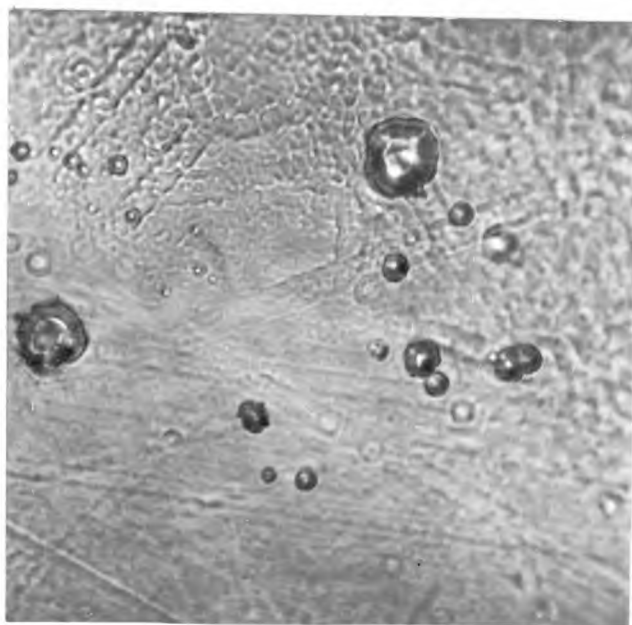


Fig. 5.7(c) Another area
Normal lighting 600x

NICKEL CATHODE AFTER INCOMPLETE BREAKDOWN



Fig. 5.8(a) 600x Normal lighting



Fig. 5.8(b) Another area 600x
Normal lighting

beam originating from the tip of a single cathode protrusion seems reasonable. It may be seen that though the overall appearance of the spots is similar, internal features differ considerably. On copper the grain boundaries are clearly visible and deep markings can be seen. On molybdenum on the other hand the surface is relatively smooth and grain boundaries can hardly be detected. In addition the molybdenum surface is covered with many small circular spots. Figures 5.3 c) and d) show the central region of the anode spots on copper and molybdenum in greater detail.

Copper Anode

Figure 5.4 a) and b) give more highly magnified views of a typical area selected from the dark central patch in Fig. 5.3 c). Figure 5.4 a) was taken under normal lighting and 5.4 b) under oblique lighting. The surface is highly disturbed owing to plastic deformation or surface migration. The area contains many craters which may well be the result of the complete detachment of a protrusion. Fig. 5.4 c) and d) show the appearance of two different portions of the same anode spot under oblique lighting but selected from areas away from the central regions. The circular spots seen in Fig. 5.4 c) are shallow depressions with in their centre a protruding mass. In Fig. 5.4 d) there is a crater in the centre of one shallow depression and a protruding mass in the centre of the other. Examination of several anode spots revealed that circular depressions containing a projection were more common in

the less hot peripheral areas than in the central black patches. This leads to the impression that projections from remain largely intact in the less disturbed cooler areas but are detached in the disturbed hot areas leaving behind craters. This is understandable since the mechanical strength of the anode material could fall to a lower value in the hot central region.

Molybdenum Anode

Highly magnified views of some circular marks selected from the central area of the anode spot in Fig. 5.3 d) are shown in Figures 5.5 a) and b). It may be seen that the surface is less disturbed than that of copper. Seen under oblique light these marks appear again as protrusions standing in the centre of shallow depressions. The diameter of the largest projection in the group is $\approx 10 \mu$ and that of the surrounding depression is $\approx 30 \mu$. Taking 10μ as the typical size for a lump of material detached from the anode one might expect to find traces of comparable size on the cathode surface. Many of the circular depressions overlap and it would be reasonable to expect that material transferred from such close locations should arrive at closely spaced or overlapping regions on the cathode surface. Fig. 5.5 c) gives a view of a portion of the same anode spot (Fig. 5.3 d) taken from the peripheral regions. Here again one can see a number of circular depressions but smaller in size and with central projections almost always intact.

Cathode

On examining the cathode surfaces after breakdown, with the naked eye small faint blue spots were seen on the copper cathode and similar red spots on the molybdenum cathode. Obviously sufficient anode vapour has been formed at some stage to form a visible deposit on the cooler cathode surface. Looked at under the microscope every spot was found to have a central damaged area composed of numerous discrete markings. Figures 5.6 a) and b) show the overall appearance of the markings on copper and molybdenum. Since these marks were situated in the centre of a cathode spot it is likely that they were created by the impact of material transferred from the centre of the anode spot. Production of such markings by ion bombardment is not likely because the surrounding area is smoother.

Figures 5.6 c) to f) show enlarged views of the markings in a) and b). As seen from Figs. 5.6 e) and 5.6 f) their appearance differs from the appearance of the anode markings — they are rougher — the fine detail is not resolved, and the surrounding area shows no sign of deformation. They are rather shallow and it is difficult to tell whether they are pits or blobs of deposited material.

The typical size of these markings varies between $1\ \mu$ to $10\ \mu$ which is somewhat smaller but still comparable with the diameter of typical protrusions observed on the anode. Further

it can be seen that several of the markings overlap just as overlapping markings are found on the anode. The density of damage on the cathode is approximately the same as the density of circular depressions on the anode.

Electrode Surfaces after Incomplete Discharge

Copper Anode

Figures 5.7 a), b), and c) show two adjacent areas selected from the central area of an anode spot. Compared with the surface in Fig. 5.4, this surface is smoother, though projections and craters are again evident.

Nickel Cathode

When seen with the naked eye a striking difference in the appearance of this cathode was the complete absence of any red spots. One may conclude that no significant amount of copper vapour had been formed even though the breakdown voltage had been attained. On examination under the microscope however the unmistakable markings could be easily identified. Figures 5.8 a) and b) show two areas as seen under the normal lighting and the markings are similar to those in Fig. 5.6. Surface details such as grain boundaries and scratches are clearly visible, whereas they were not in Fig. 5.6, confirming the absence of any deposited film.

5.2.2. Stereo-Scan Micrographs

A magnification of 1000 x and the use of oblique illumination in the optical microscope seemed reasonably adequate for

the study of the features within the anode spot, but gave little information about the details of the markings on the cathode.

The advantage of the Cambridge Stereo-Scan Microscope is its wide range of magnification (up to 50,000 x) and large depth of focus. Owing to the small size of the specimen holder, the large electrodes examined earlier under the optical microscope could not be accommodated in this instrument. One centimeter diameter electrodes of copper and nickel were made. Electrodes of dissimilar materials were used, with a view also of detecting material transfer by subsequent electron-probe microanalysis (sec 5.3).

Nickel Anode (Figs. 5.9 a to e)

Fig. 5.9 a) shows the anode surface before breakdown. There is a fine surface structure but no large projections can be seen.

Fig. 5.9 b) gives an over all view of the anode spot selected for study at high magnification.

Fig. 5.9 c) shows a typical crater from which material has probably been extracted. The disturbed general background is similar to that seen in the optical micrographs. An enlarged view of the crater is given in Fig. 5.9 d).

Fig. 5.9 e) shows details of depressions containing protrusions similar to those seen in the optical micrographs, Figs. 5.4 c) and d) and Figs. 5.5 a) to c).

STEREOSCAN MICROGRAPHS

NICKEL ANODE



Fig. 5.9(a) Surface before breakdown tests 12000x



Fig. 5.9(b) Typical anode spots 70x

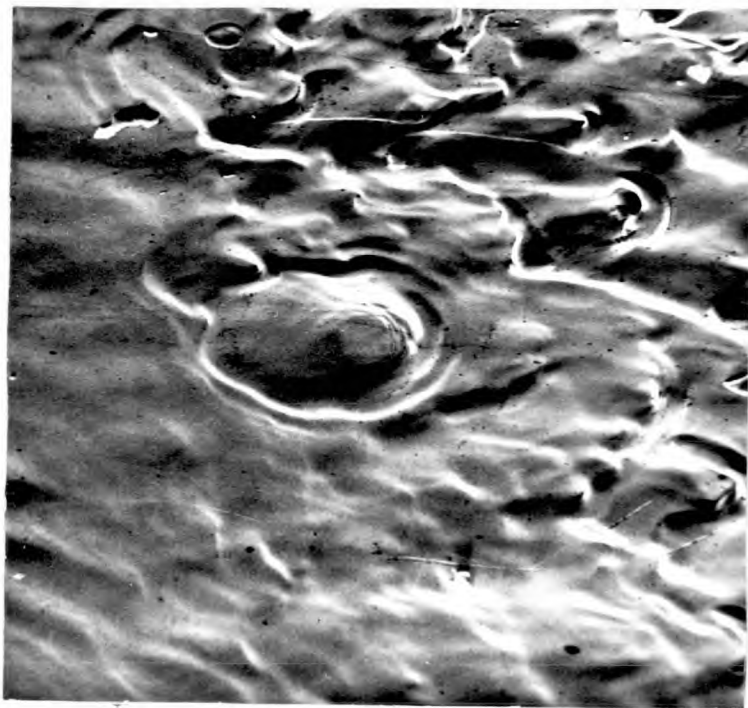


Fig. 5.9(c) Disturbed area with a crater. 650x

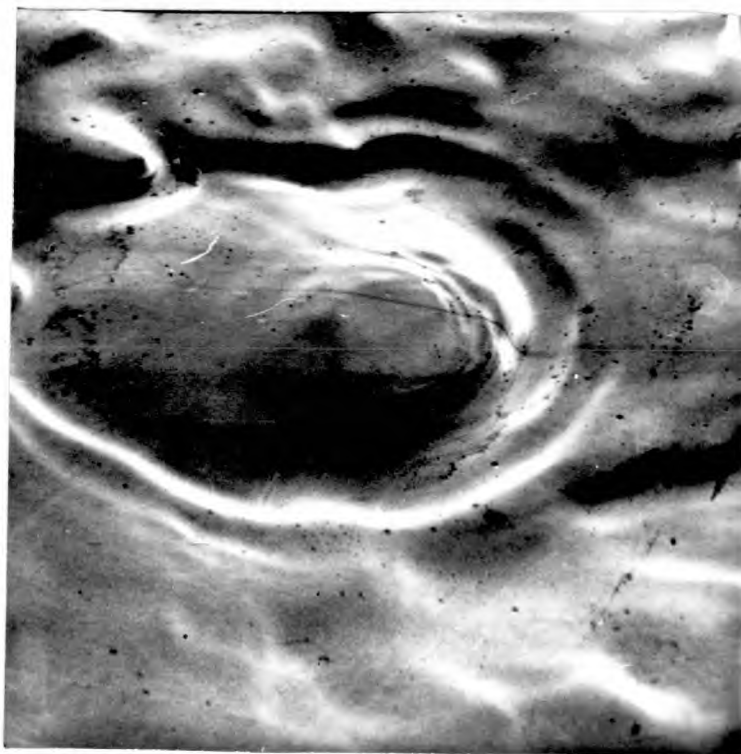


Fig. 5.9(d) Crater in (c) 1325x



Fig.5.9(e) Disturbed area containing protrusions 650x.

COPPER CATHODE

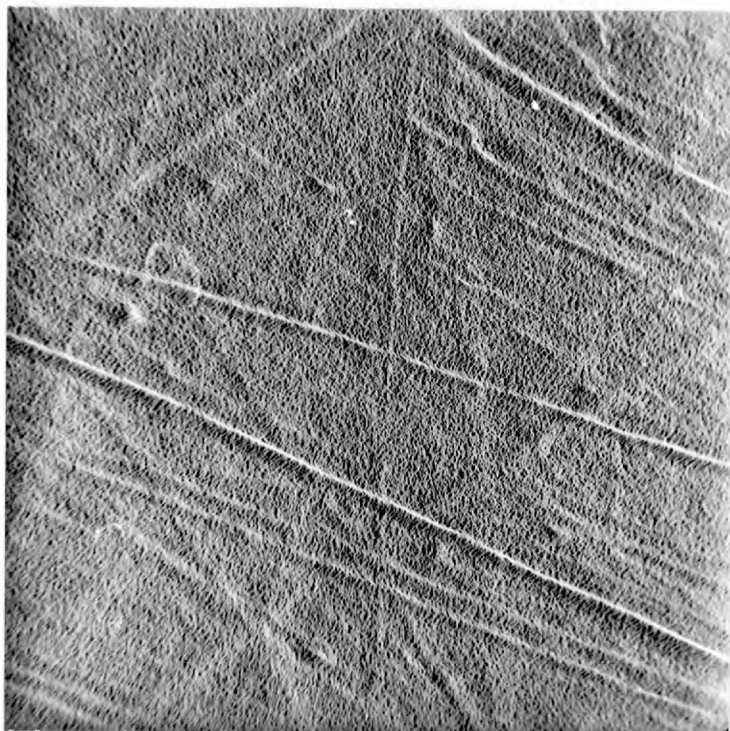


Fig. 5.10(a) Surface before breakdown tests 12000x.

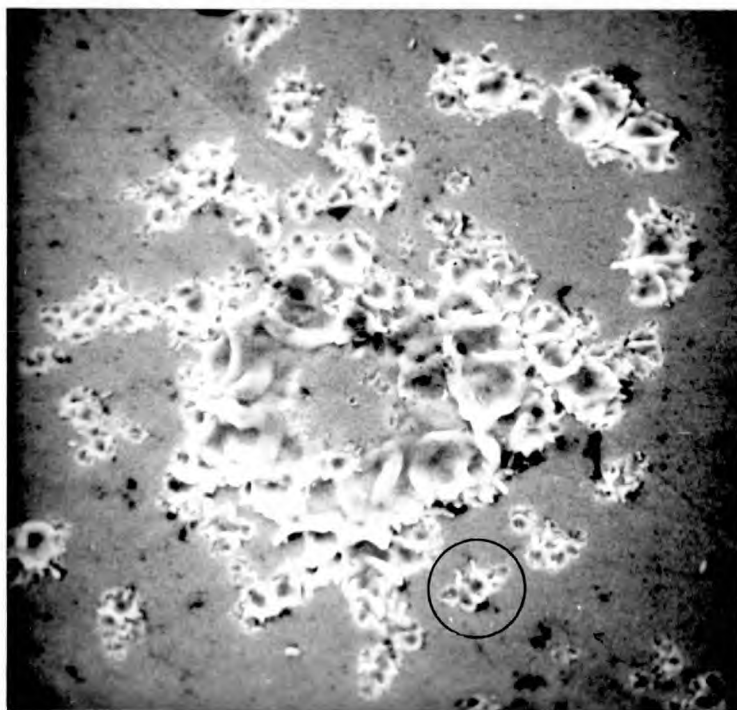


Fig. 5.10(b) Typical markings after breakdown 1200x

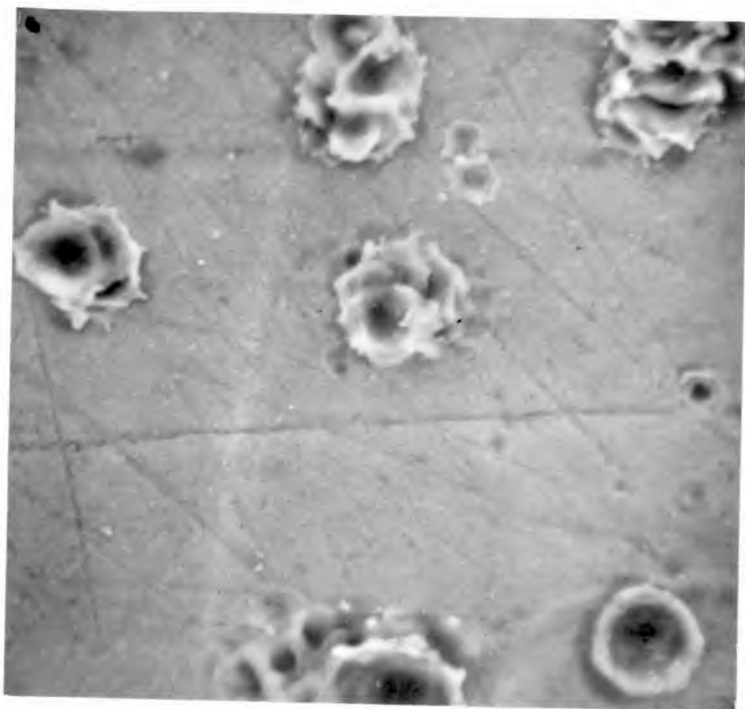


Fig. 5.10(c) 5,800x

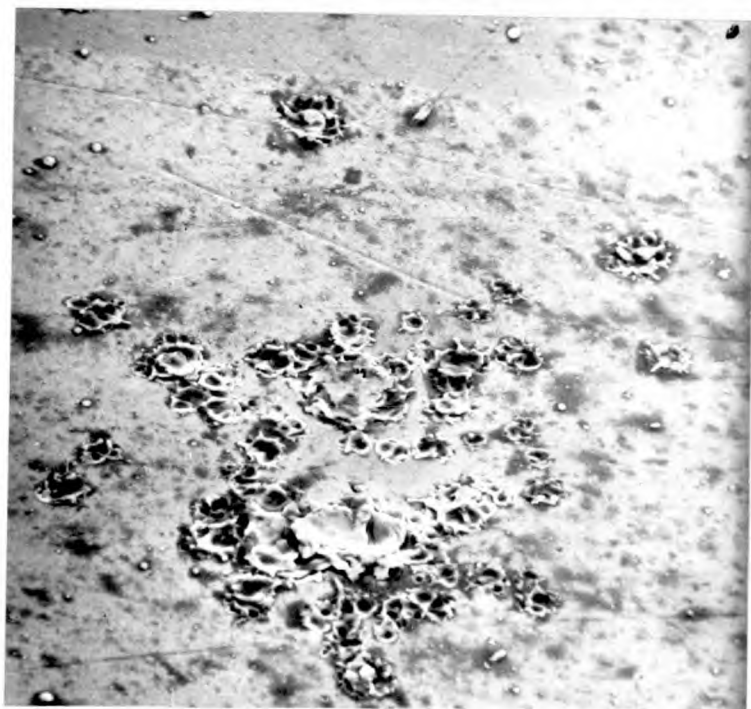


Fig. 5.10(d) 1120x

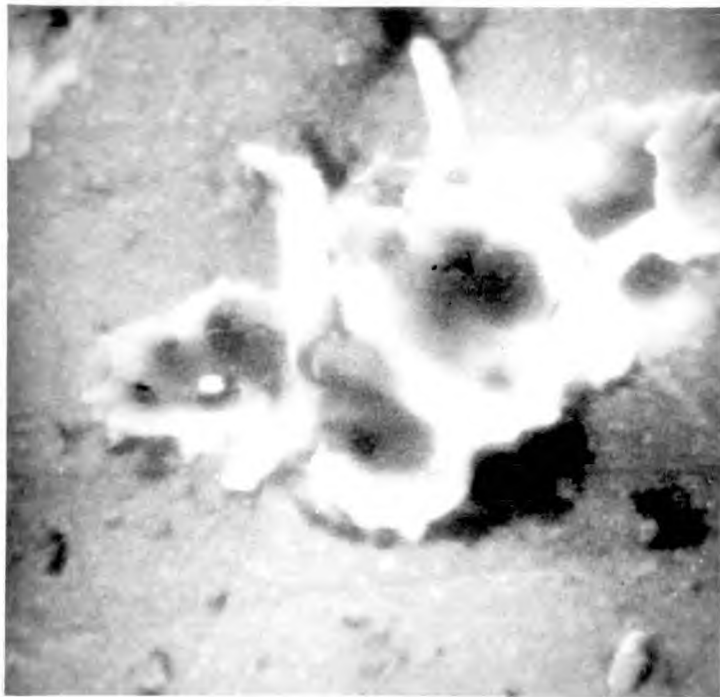


Fig. 5.10(e) Two protrusions 12000x



Fig. 5.10(f) Crater with splashed material 11,200x



Fig. 5.10(g) Craters and overlapping of splashed material. 11,200x

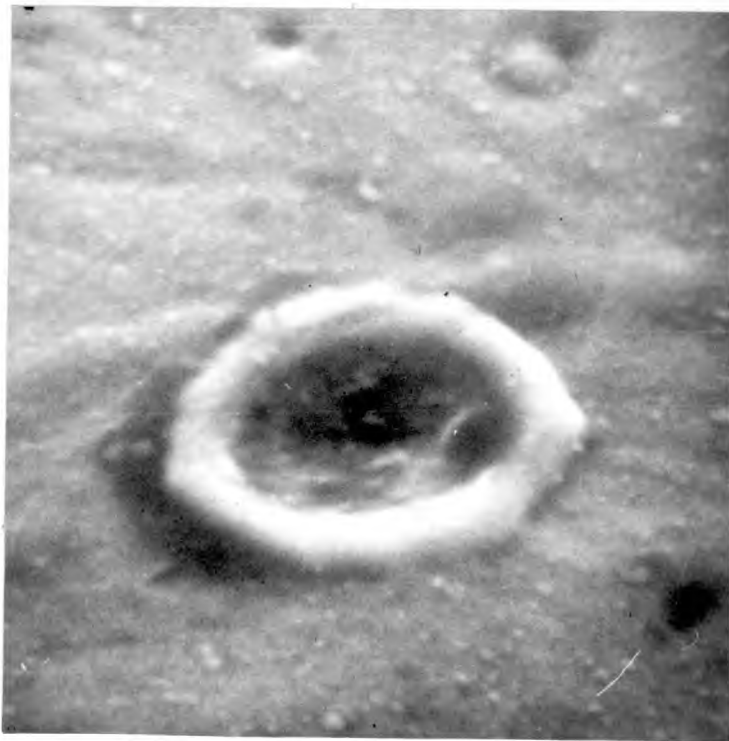


Fig. 5.10(h) Crater 23,000x

Copper Cathode (Figs. 5.10 a to h)

Fig. 5.10 a) shows the appearance of the surface before breakdown. It is slightly rougher than the nickel surface shown in Fig. 5.9 a).

Figures 5.10 b), 5.10 c) and 5.10 d) show typical markings found in the central area of three different cathode spots. The markings are densely spaced and often they overlap. Splashing of material is a common feature. Globules of material which can be seen scattered around these markings may be splashed droplets. Most of the markings are also the sites of sharp protrusions. Later evidence shows that anode material is not present at all these locations though at some places it can be detected. The size of the individual marks lies between 1 to $10\ \mu$ which corresponds to the size of protrusions on the anode estimated earlier.

Fig. 5.10 e) is an enlarged view of the area marked in Fig. 5.10 b). Two whisker like projections can be clearly seen, one of which is standing almost vertical. The radius of the tips is 1×10^{-5} cm and the height of whiskers $\approx 1.2 \times 10^{-4}$ cm. The values agree well with typical values for r_p and h estimated from data in Table 4.1.

Features in Figs. f) g) and h) which have been selected from

the areas in 5.10 b) and 5.10 c) respectively, represent typical shallow craters, $\approx 2 \mu$ in diameter and having splashed material on their borders. Small globules of material are also visible inside and in the vicinity of the craters.

5.2.3. Summary

Cathode

1. With mixed electrodes and complete breakdown, spots of the anode material could be seen on the cathode indicating that considerable quantities of anode material had been vaporized during the discharge.

2. Under the microscope the centre of these spots was seen to contain numerous markings. It is suggested that the markings were made by material coming from the anode spot.

3. When complete breakdown was deliberately avoided, the spots on the cathode were absent but the same markings could again be seen under the microscope, indicating that transfer of material from the centre of the anode spot occurred earlier than complete breakdown and was itself adequate to initiate breakdown.

4. The cathode markings are generally craters of size $\approx 2 \mu$ similar to that estimated for the anode protrusions. Splashing of material around these craters is found to be a common feature. It is concluded that these features resulted due to bombardment of particles from the anode. The cathode markings also included whisker like projections. It is possible that the field emitting

protrusions on the cathode may be due not to inherent surface roughness but to material transfer from the anode.

Anode

1. Spots are seen on the anode surfaces. Their size agrees well with expected values suggesting that each spot is created by a single electron beam originating from the tip of a projection on the cathode.

2. The area within an anode spot is severely disturbed especially in the central area, which is expected to reach maximum temperature. The disturbance is more severe on copper than molybdenum.

3. The anode spot contains shallow depressions, which are usually circular. The depressions have a projection or a small crater at their centre.

4. Numerous grain boundaries are exposed within the anode spots on copper and nickel, and projections and craters are often found near them.

On molybdenum, hardly any grain boundaries were visible indicating that the anode temperature did not exceed the annealing temperature for molybdenum i.e. 1000°C .

5.2.4. Discussion

The appearance of the anode has been found to be consistent with creation and detachment of protrusions. There was plenty of evidence of plastic deformation within the anode spots which is

consistent with the theory advanced in Chapter 4 that the ultimate tensile strength is exceeded.

The appearance of the cathode clearly suggests the arrival of particles from the anode. Since the cathode spot is generally larger consisting of a thin film of anode material, it seems that in addition, the anode vapour spreads over a larger area.

Though these results give a convincing physical picture that the cathode is bombarded by small particles from the anode, there are some questions which remain unresolved. Detachment of $1 - 10 \mu$ particles from the anode has been indicated. It would be interesting to know why such a consistency in this size is maintained. A large number of shallow depressions many of which overlap are seen within anode spot. The reason for the formation of so many spots and their overlapping character is not clear. Is it possible that in addition to the main emitting protrusion, emission from other protrusions in the vicinity also becomes significant near breakdown, which causes additional protrusions to grow? If multiple emission occurs near breakdown then can this be another reason for the F-N plots becoming non-linear at the high voltage end? Since the electrode surfaces examined in this work were subjected to several breakdowns, it is not possible to give satisfactory answers to these questions, and it seems necessary in future investigations to examine the surfaces after tests in which breakdown is avoided or electrodes are subjected to a

single breakdown.

5.3. Electron Probe X-ray Microanalysis

The electron probe x-ray microanalyser has an electron beam spot size $1\ \mu$ and a resolution of $1\ \mu$. The accelerating voltage used was 25 kV. The test electrodes could be placed directly into the vacuum chamber of the machine, after a special holder was made.

The desired area for analysis is selected by viewing through a microscope attached to the machine. When the area of interest is focussed and brought into centre of the field of view, it comes directly under the probing electron beam. The machine is then adjusted for the characteristic x-ray wavelength of the element searched for. A magnified image of the area can be seen on a screen. As a preliminary searching procedure, the electron probe spot is moved using manual controls, over areas of suspected material transfer. When the spot encounters the desired material strong x-ray counts are registered, whereas at other points, the x-ray counts drop to the background level. When such a location has been found the beam is set in the automatic scanning mode along a line passing over this area. A cathode ray trace then registers the x-ray output for this scan giving a peak over the area where the detected material is located. A pattern of the x-ray output from the whole area is also obtained which seems to show any other places where material is present. Ten anode spots, (chosen amongst the

highly disturbed ones) and in this way ten typical areas on the cathode surface were scanned.

5.3.1. Results

Except for the Cu cathode/Ni anode combination used in the Stereo-Scan studies, other electrode combinations examined were the same described in section 4.1 or those used in the optical investigations.

Tests with Complete Breakdown

a) Cu Cathode/Mo Anode

Cu Cathode

As mentioned earlier, under examination with the unaided eye blue spots were apparent. Analysis showed that these spots were composed of films of molybdenum of varying thickness. When the individual markings in the centre of the spots were searched, concentrations of molybdenum were detected in and around some of them. Fig. 5.11 a) shows a typical group of markings together with the x-ray trace along a line passing over one of the suspected points. Fig. 5.11 b) shows the total x-ray pattern for this area. It is only the large dense spots in these pictures that are of significance here. Small dots give some idea of the background, but are not useful for quantitative information, as the number of dots depends also on repeat exposures used to build up picture. The peak in the x-ray trace appears over one of the surface markings and this corresponds to the location of a dense white spot in Fig. . . .

RESULTS OF ELECTRON PROBE ANALYSIS

COPPER CATHODE

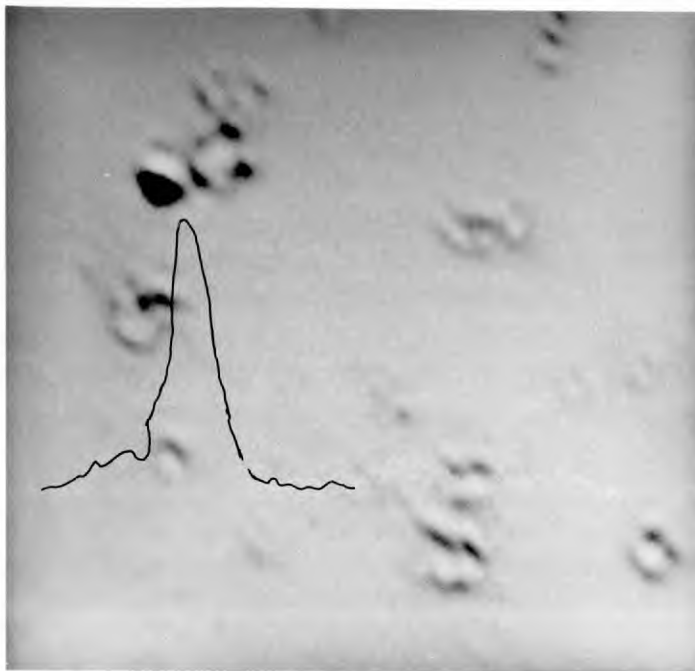


Fig. 5.11(a) X-ray trace of Mo 2400x.



Fig. 5.11(b) X-ray pattern for the area in (a) 2400x

MOLYBDENUM CATHODE

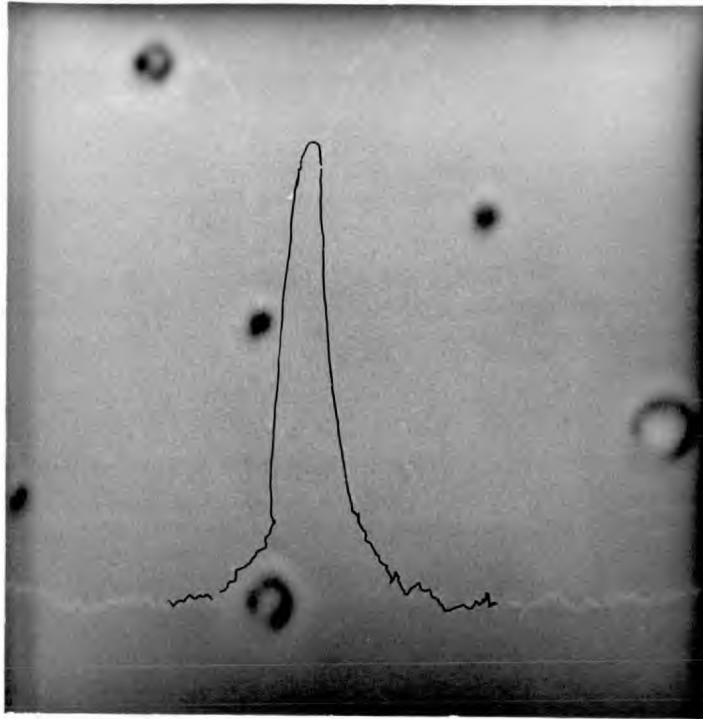


Fig. 5.12(a) X-ray trace for copper 2400x

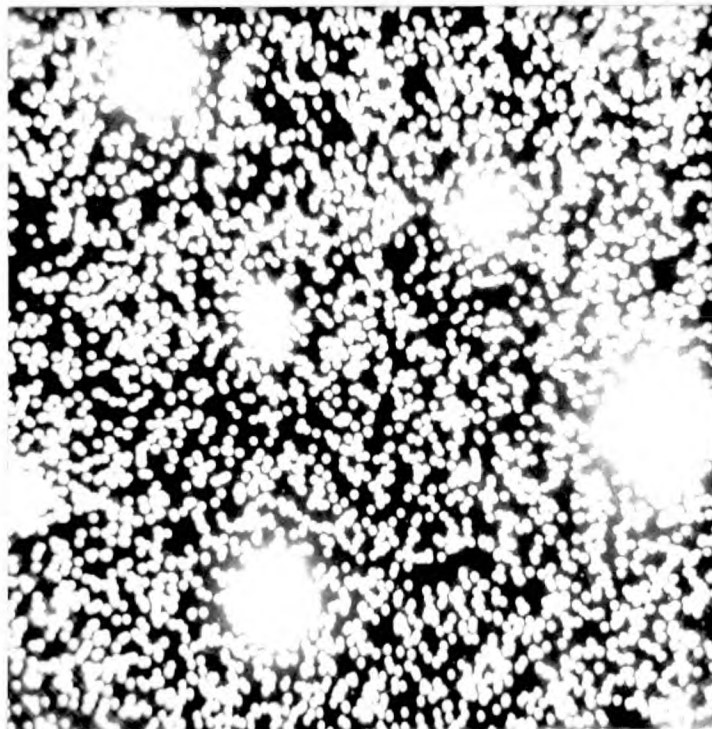


Fig. 5.12(b) X-ray pattern for the area in (a) 2400x

COPPER CATHODE (SMALL)

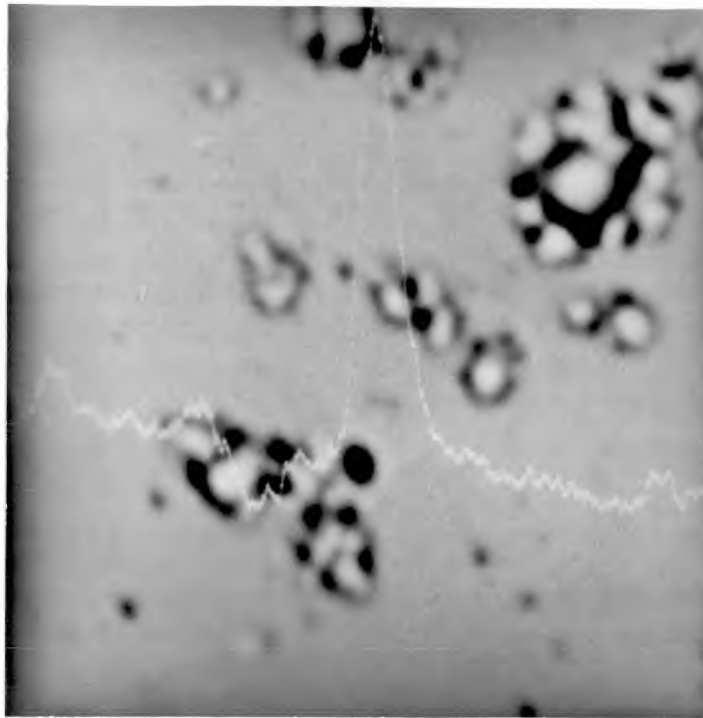


Fig. 5.13(a) Xray trace for nickel 2400x

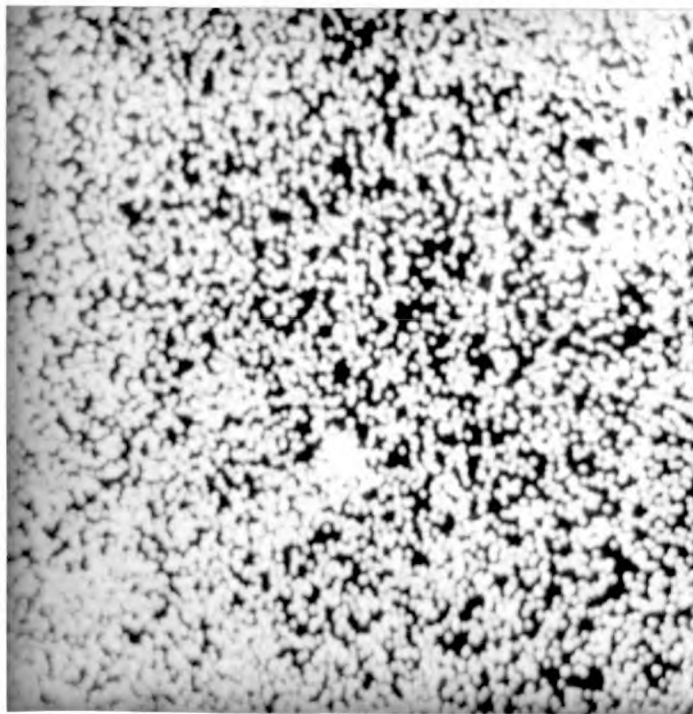


Fig. 5.13(b) X-ray pattern for the area in (a) 2400x

NICKEL CATHODE



Fig. 5.14(a) X-ray trace for copper
1200x

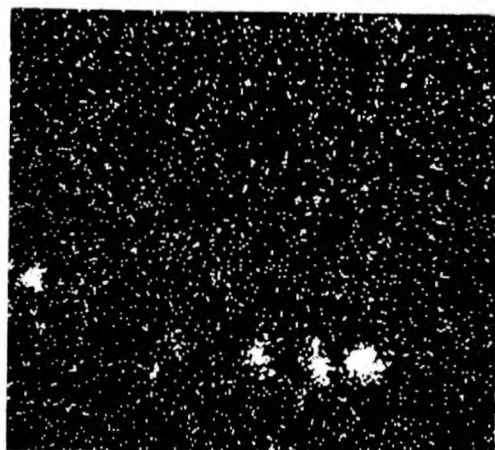


Fig. 5.14(b) X-ray pattern for the area in (a)
1200x

5.11 b). There seems little doubt that the location referred to in 5.11 a) represents a clump or globule of molybdenum embedded on the copper cathode surface. The size of the clump estimated from Fig. 5.11 a) is less than 4μ in dia, which compares well with 2μ craters observed on the copper cathode in the Stereo-Scan investigations (Figs. 5.10 f and g).

Mo Anode

No trace of copper was found within the anode spots.

b) Mo Cathode/Cu Anode

Mo Cathode

The surface had red spots on it and these were identified by analysis as thin films of copper. When the markings in the spots were analysed concentrations of copper in ten of the spots examined was not significant, but at times concentrations of copper away from the markings, but within the cathode spot were detected. Fig. 5.12 a) shows a typical area of this type, together with the x-ray trace. Comparison of Figs. 5.12 a) and 5.12 b) shows that all six spots in a) have high concentrations of copper. The absence of irregular markings and the rounded shape of these spots suggests that these were globules of copper varying in size from ≈ 1 to 4μ , in dia.

Cu Anode

No trace of molybdenum was found within the anode spots.

Cu Cathode/Ni Anode (Small Electrodes)

Cu Cathode

Spots of the colour of mickel were seen on the entire

surface, and were identified as films of nickel. Concentrations of nickel were detected in some of the central markings and 5.13 a) and b) represent typical results. Approximate size of the concentration estimated from Fig. 5.13 a) is $\approx 3 \mu$, and is in agreement with the 2μ dia craters seen on the same surface (Figs. 5.10 f and g).

Ni Anode

No trace of copper was found.

Tests after Incomplete Breakdown

Ni Cathode/Cu Anode

As stated in section (5.2.1), no cathode spots were seen, though the characteristic markings were present. Fig. 5.14 a) shows three x-ray peaks on the edge of a large marking which supported with Fig. 5.14 b) indicates that these are three anode particles which got embedded on the cathode surface after impact. The size of the particles estimated roughly from Figs. 5.14 a) and 5.14 b) is 3μ , which is in agreement with the size of the particles estimated earlier in this section and with the size of craters seen in Figure 5.10 g). The size of the whole marking in which the particles are situated is $\approx 15 \mu$. It may be noted that the density of white dots in background is lower than in previous photographs which is to be expected since red spots of copper were not seen. There were many markings which did not contain any significant concentration of copper.

Cu Anode

No trace of any nickel was found.

5.3.2. Summary

1) The cathode spots, having the colour of the anode material were identified as thin films of anode material.

2) For Ni cathode/Cu anode combination, in which the breakdown voltage was reached but complete breakdown of the gap was avoided, no film of anode material was detected around the cathode markings.

3) Concentrations of anode material at random locations, in and around the cathode markings were found although they were not necessarily present near each cathode marking. The size of a whole marking was greater than that of the concentration detected within it.

4) No cathode material was detected within any anode spot.

5.3.3. Discussion

The detection of anode material in the form of globules at the expected sites on the cathode confirms the picture which had emerged after the microscopic examination of the surfaces. Anode material, transported in clumps reached the cathode, and it is also evident from findings 1) to 3) that atleast with a copper anode, the detachment of clumps can occur earlier than any marked evaporation of anode material. It seems to be sufficient to initiate breakdown.

Regarding the presence of only small concentrations of anode material in a relatively large cathode marking and even complete absence of it in many of the markings, some possible simple explanations are suggested as follows. It is apparent from the highly magnified pictures of the cathode markings (Figs. 5.10 b to d) that a large marking having a typical size between 10 - 20 μ in dia consists of a cluster of small markings, and that single small marking (Figs. 5.10 f and g) has a diameter 3 μ and has a crater of 2 μ dia. This means that a large marking on the cathode is caused by bombardment from numerous anode particles having a typical size of 2 μ in dia. The possibility exists of these impacting particles penetrating deeper into the bulk of the cathode material, in which case they are likely to remain undetected by the electron probe. Even those particles which did not penetrate deeper may easily get covered by cathode material splashed from the adjacent impact sites, and will also escape detection. In addition, the possibility of any loosely settled anode particles being pulled back by the enhanced electric field, as a true Cranberg clump can not be ruled out.

The absence of any cathode material on the anode is in agreement with the prediction made in Chapter 4 that breakdown is anode initiated, and that temperature of the cathode is far too low either for material to be evaporated or for weakened material to be detached under the influence of the electric field.

CHAPTER VI

HIGH TEMPERATURE TESTS

The effect of electrode temperature on breakdown voltage for different electrode materials (Ni, Fe, Cu, Al) was first investigated by Slivkov (1958) for pulsed voltages. He found that cathode heating caused an increase in the breakdown voltage but that anode heating caused a decrease. Goldstone (1965) studied this effect for molybdenum electrodes and D.C. voltages. He found no effect with cathode heating but a steady decrease in breakdown voltage with anode heating. He attributed this to a fall in the tensile strength of the anode material. At that time no other tests on the effect of electrode heating on D.C. voltage breakdown had been reported in the literature and it was felt that a more detailed study on other materials was desirable.

Tests were first conducted with copper electrodes, and contrary to the expectation that the breakdown voltage should decrease with anode temperature it remained practically unaffected. Tests were then made using various combinations of copper, molybdenum and nickel electrode. A variety of behaviour was observed and a simple explanation seems improbable. An attempt has been made to interpret the results, with some success, by considering the variation of the field enhancement factor β and local anode and cathode temperatures. The theoretical basis of the calculations has already been described in Chapter 2 and applied to the results of

room temperature tests in Chapter 4.

6.1. Procedure

The method of electrode preparation and the details of vacuum technique have already been described (section 4.1 and 3.1.3). Tests were made to establish the effect of a) anode heating and b) cathode heating. Voltage - current measurements were made for various electrode temperatures starting from room temperature. The V-I data were plotted as a family of F-N curves and the parameters necessary for estimating local temperatures at the electrode surfaces were derived. During the tests the pressure rose, but even at 900°C it was better than 10^{-6} Torr.

Thermal expansion of the electrode supports caused a reduction in the electrode gap. This was measured at each temperature using a cathetometer and results are expressed in terms of V_B/d . The important parameters which could be affected by the variation in gap width are V_B/d and β_k . The slope of V_B vs. $\ln E$ has been found to be 0.7 (Alpert et al 1964) for a gap width varying from 10^{-3} to 2mm. In the present tests the range of gap is 0.2 mm to 1.1 mm. If this result is accepted V_B/d would vary as $d^{-0.3}$ i.e. a rise in breakdown field strength of up to 70% might be expected as the gap shortened at high temperature. The field enhancement factor β_k has been found to be independent of d for gap widths exceeding 0.1 mm provided the radii of curvature at the edges are sufficiently larger than d (Alpert et al 1964).

These conditions are fulfilled in the present experiments and therefore no variation in β_k is expected as a result of gap changes.

6.2. Results and Discussion

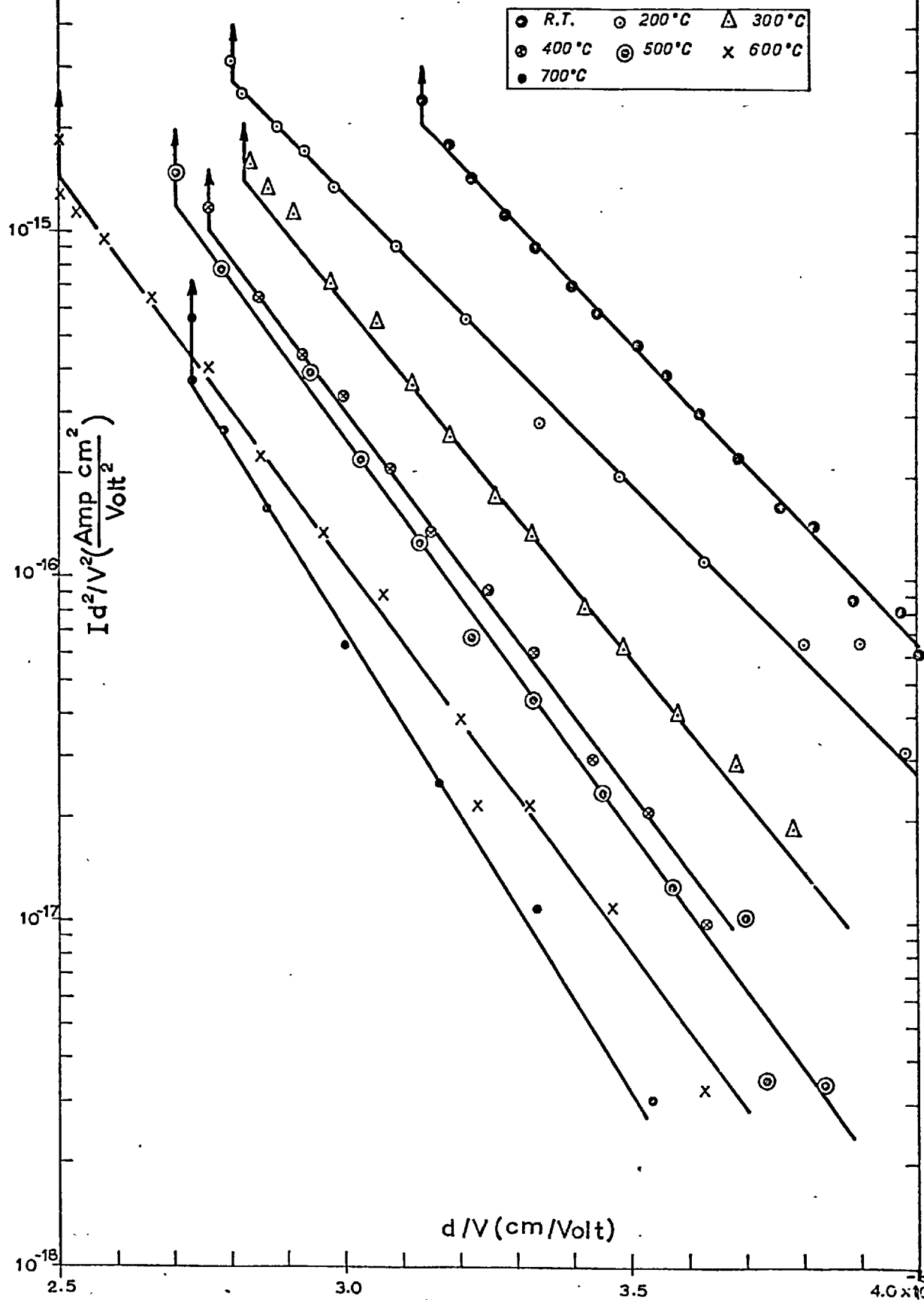
6.2.1. Fowler-Nordheim Plots

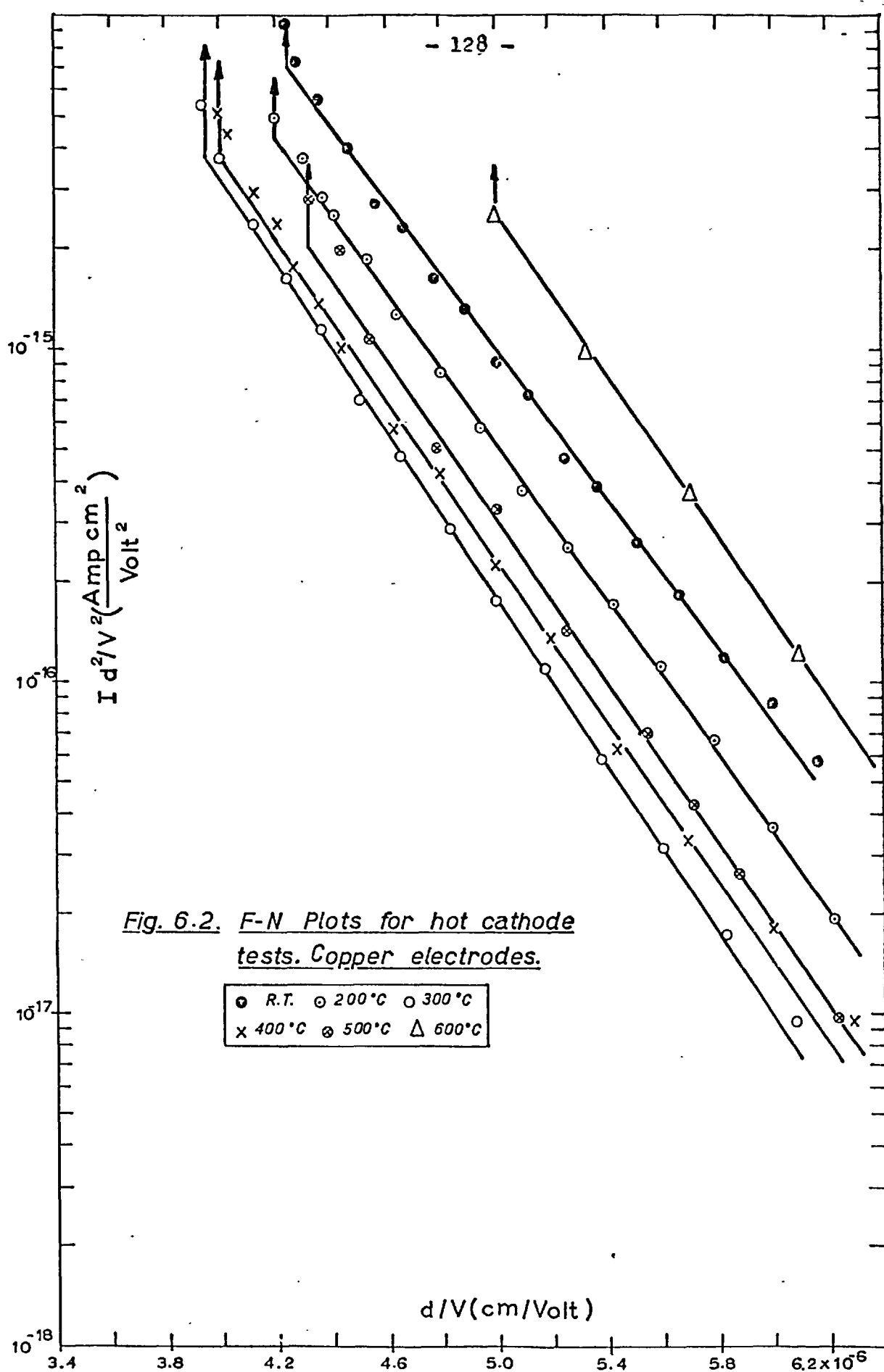
Figures 6.1 to 6.4 show the F-N plots of V-I data for the cathode and anode heating tests for copper electrodes and copper/molybdenum electrodes. Voltage and current readings were reproducible, if breakdown was avoided for anode heating tests up to 700°C but were usually not so consistent above 600°C for the cathode heating tests. Non linearity at the high voltage end is noticeable as before. It is more pronounced for the combination of Cu and Mo electrodes than for two Cu electrodes. The scatter in β_k values at a particular temperature was not usually higher than 10% and often much less.

Results of nickel electrodes (heated anode) were very different, as can be seen from Figs. 6.5 to 6.7. At temperatures of 20°C - 400°C Fowler-Nordheim plots were obtained which exhibit pronounced non - linearity at the high voltage end but are otherwise unremarkable. This pronounced non -linearity seems to be characteristic of nickel electrodes. It was reported in the results of Chapter 4 and could be related to the onset of material transfer.

At temperatures above 400°C plots of completely different

Fig. 6.1. F-N Plots for hot anode tests. Copper electrodes.





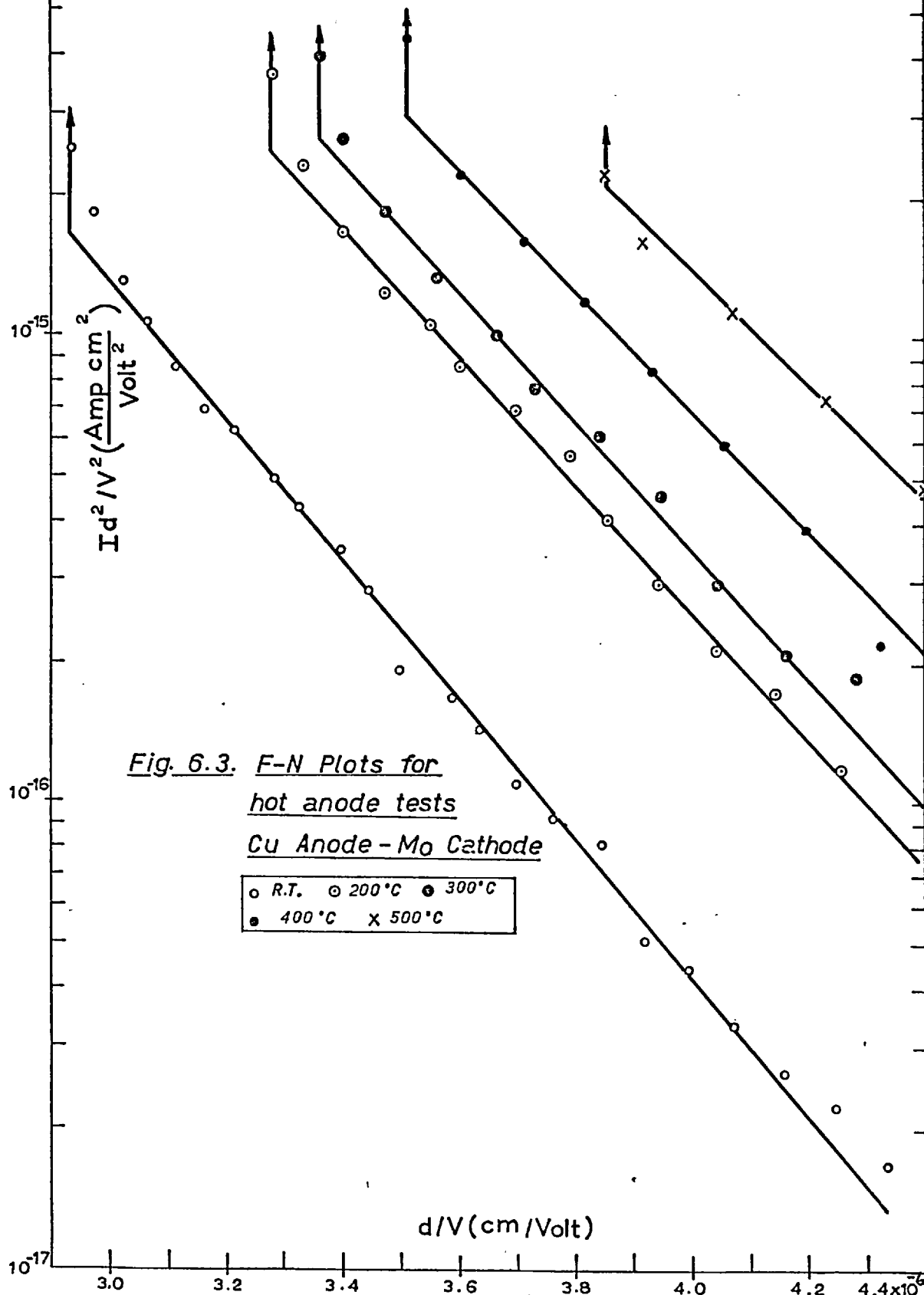


Fig. 6.4. *F-N Plots for hot cathode tests*
Cu Cathode - Mo Anode

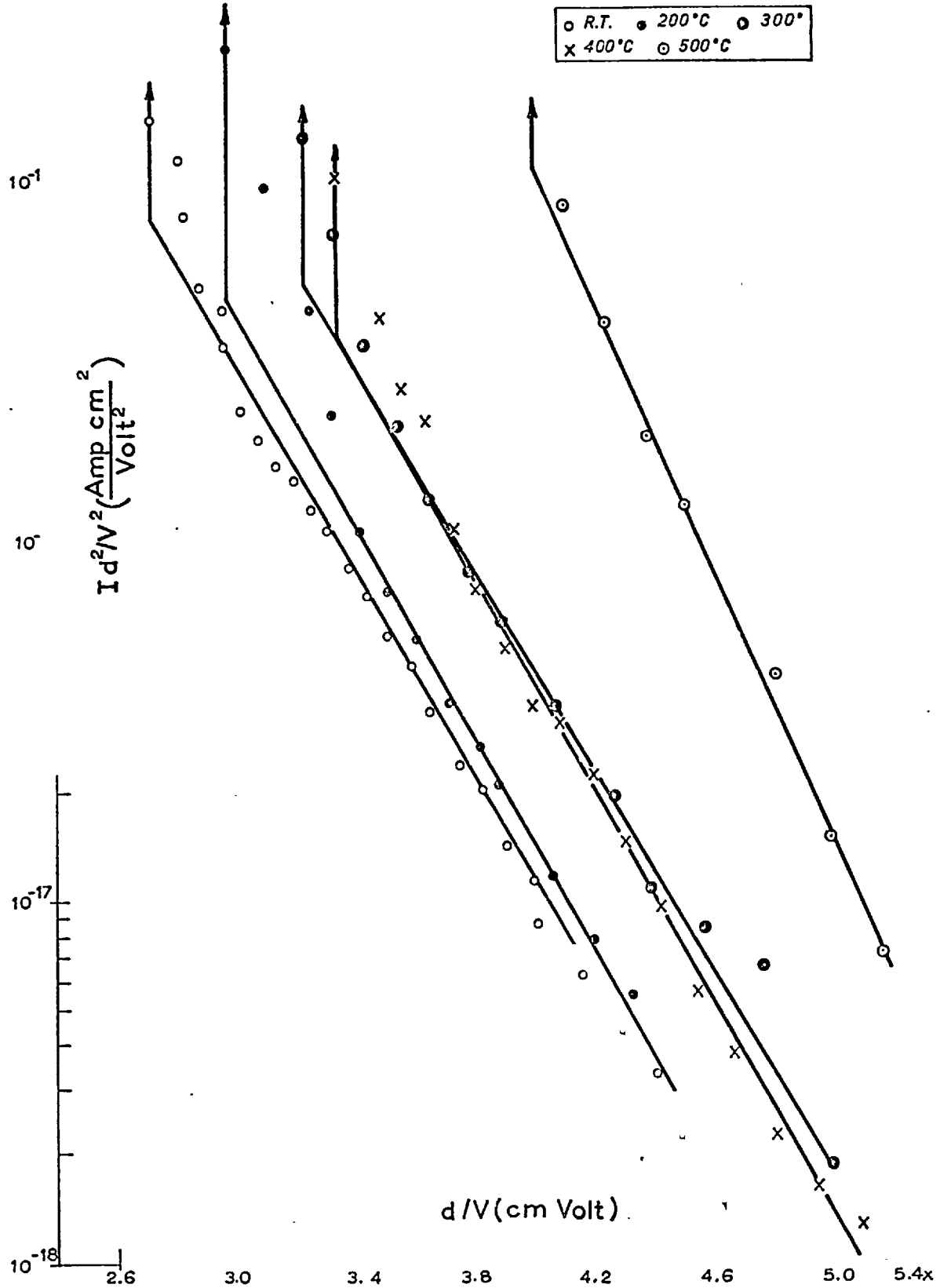


Fig. 6.5. F-N Plots for hot anode tests Nickel electrodes.

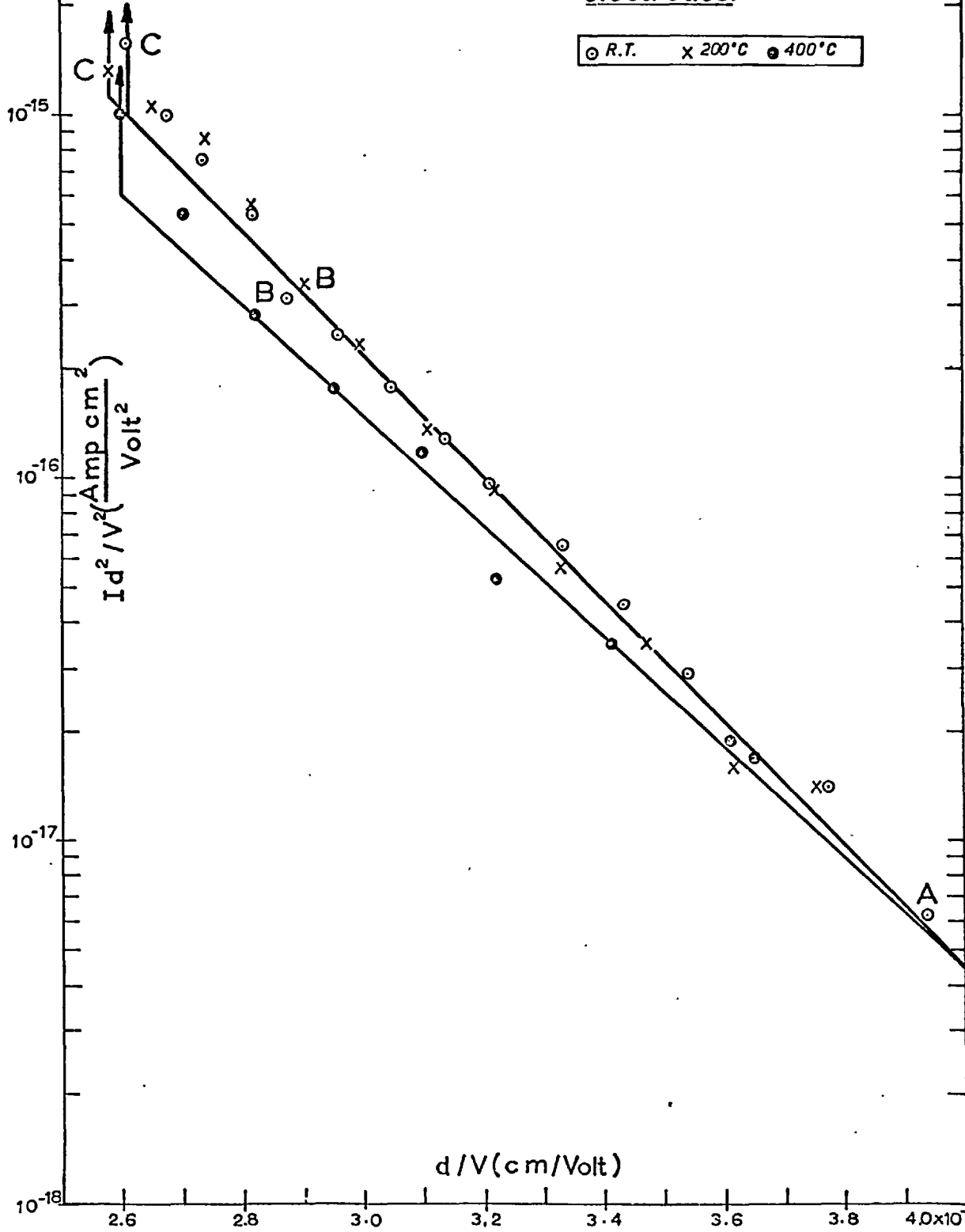
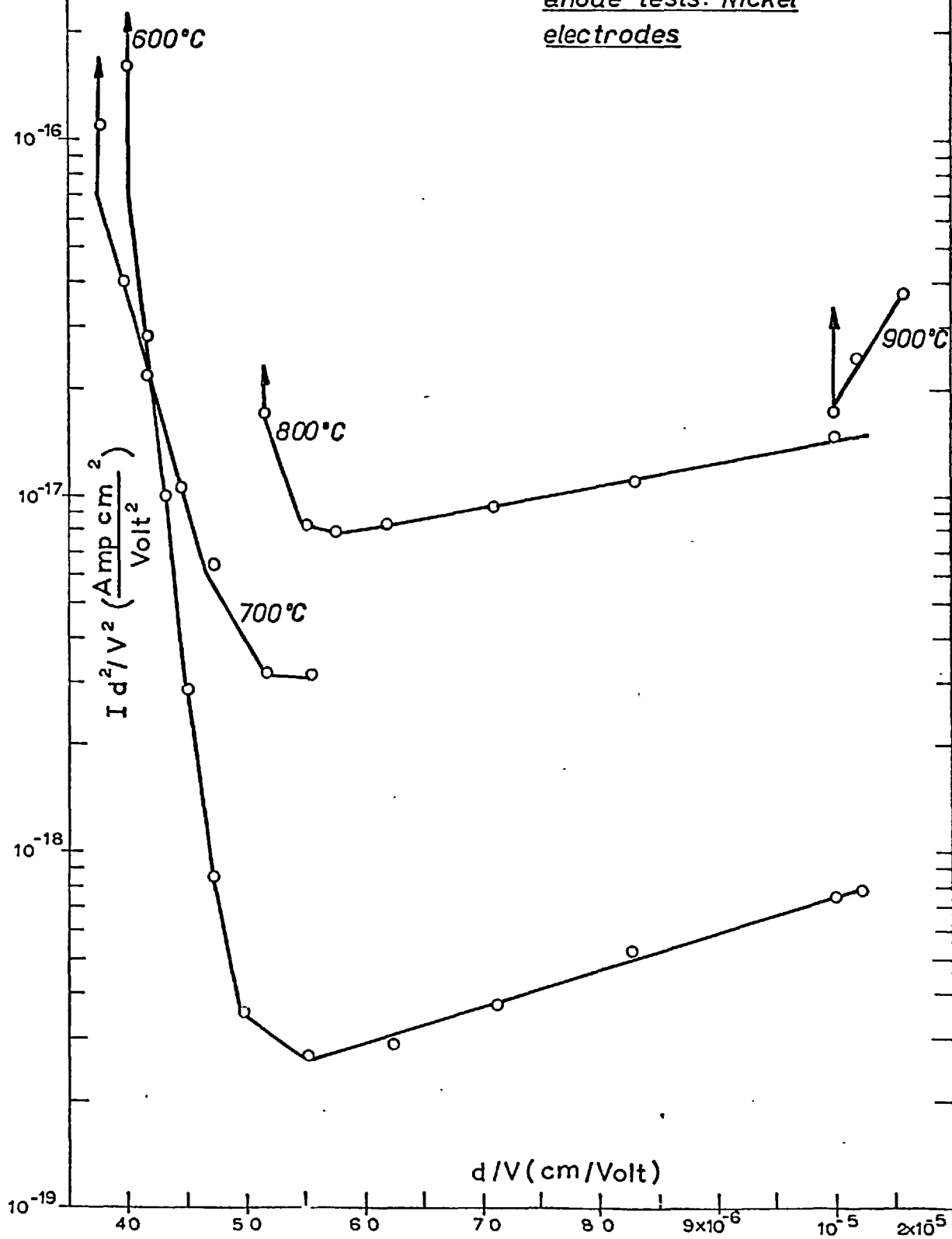
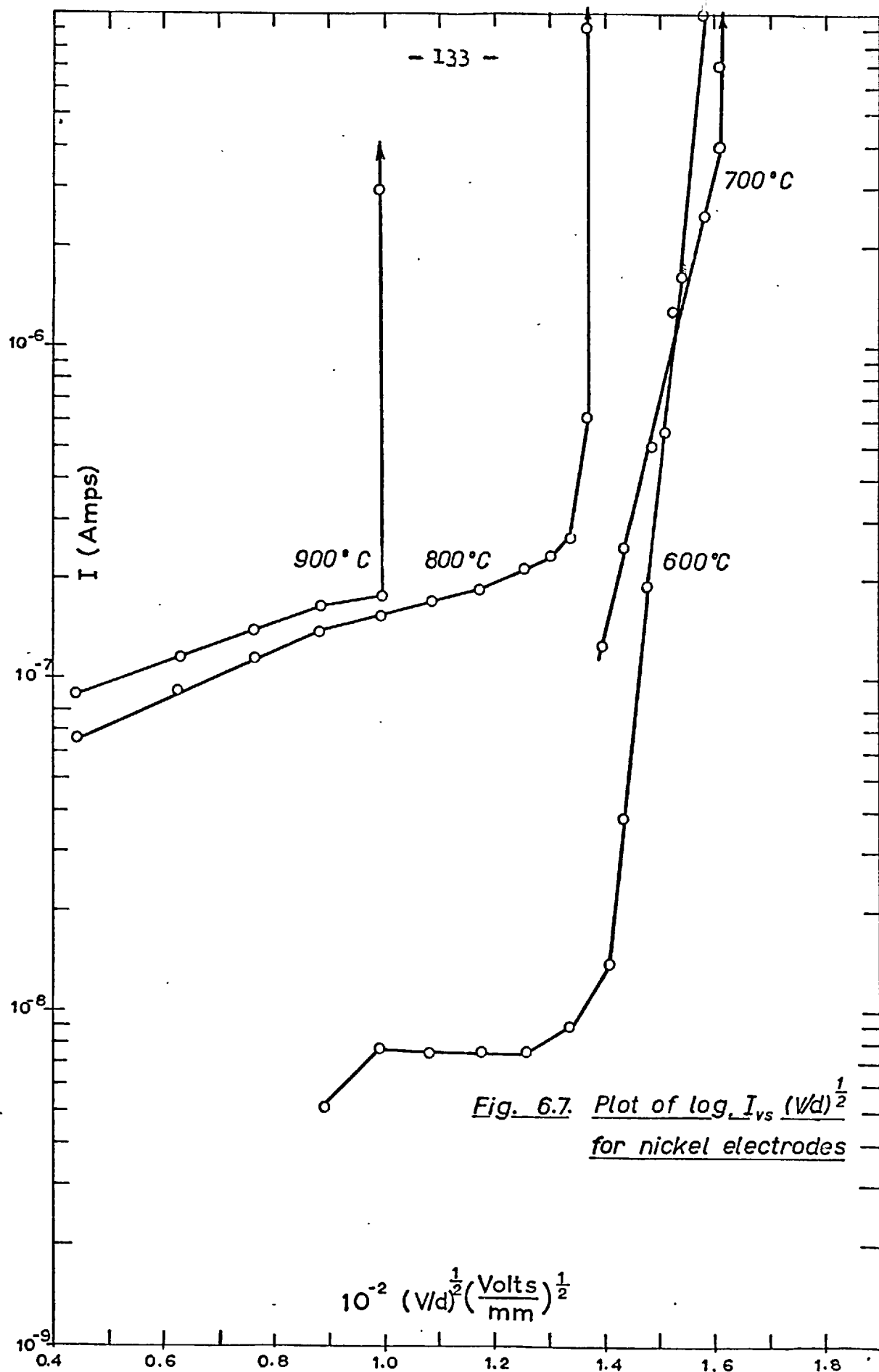


Fig. 6.6. F-N Plots for hot anode tests. Nickel electrodes





shape were obtained. A current of the order of 10^{-8} amp began to flow at an applied field of about 10^4 V/cm which is at least an order of magnitude lower than the fields at which field currents were normally observed. As the applied field was increased the current increased rather slowly until a field strength exceeding 10^5 V/cm was reached. It then rose rapidly and after a further slight increase in the applied field breakdown occurred. The F-N plots of the V-I data can be divided into three regions. At field strengths below 10^5 V/cm the points lie on a straight line having a slope opposite to that for normal F-N plots. Above 10^5 V/cm they lie on a normal F-N line of negative slope. There is a transition region linking the two. The line of negative slope becomes very short at 800°C and disappears for 900°C .

This type of results was found to be reproducible and it is believed to be a real effect. A plot of $\log_{10} I$ against the square root of the applied field $E = V/d$ is shown in Fig. 6.7 and it can be seen that for fields of less than 10^5 kV/cm, the points fall on straight lines. Since the cathode temperature rise due to indirect heating from the hot anode could not have been more than 250°C , Schottky emission from the nickel cathode surface is not expected. However this square root relationship would also be expected if thermionic emission of +ve impurity ions from micro-asperities on the anode surface were occurring in the strong electric field. This has already been suggested by Ionov (1960). Such currents

$\approx 10^{-8}$ amp have also been reported in the literature for molybdenum electrodes (Pivovarov and Gordienko 1963). If ion emission was taking place from the anode then it could have affected electrical breakdown over the range 600 to 900°C. At the gap voltages of 2.5 to 12 kV used in these tests positive ions would have caused cathode sputtering resulting in a roughening of the surface and an increase in the value of β_k . Evidence of an increase in β_k can be found in Fig. 6.6 since the slope of the F-N plots decreased as the temperature rises but one should add that other reasons could be advanced to explain this variation of β_k . The negative slope of the plot for 800°C cannot be accurately determined, but a further check on the increase of β_k can be made by observing that the threshold value of the field at which field emission current appears is decreasing with anode temperature i.e. in Fig. 6.6 the transition region shifts to the right at the higher temperature. Moreover, as seen in Table 6.1 the field required to obtain a typical field emission current of 0.25 μ A decreases at higher temperature.

TABLE 6.1

Anode Temp °C	20	200	400	600	700	800	900
V/d (10 ⁵ Volts/cm) for 0.25 μ A	2.4	2.4	2.6	2.3	2.1	1.7	1.0
β_k	200	180	213	166	268	333	-
I_B (μ A)	147	200	97	10	7	6	3

6.2.2. Local Electrode Temperatures

The local anode temperature $(T_A)_L$ and cathode temperature $(T_K)_L$ were calculated as before for a cylindrical projection using equations (2.8) to (2.12) for the cathode and equation (2.17) for the anode. The variation of local temperature in copper as a function of the bulk anode temperature T_A and the bulk cathode temperature T_K are presented in Figures 6.8 b) and 6.9 b). Similar results for a copper - molybdenum electrode pair are given in Figs. 6.10 b) and 6.11 b), and for nickel electrodes in Fig 6.12 b).

Anode Heating

a) Copper

It can be seen from Fig 6.8 b) that the calculated local anode temperature $(T_A)_L$ is always greater than the local cathode temperature. There is some scatter, but neither varies systematically with the bulk temperature T_A . The average value of local anode temperature is 640°C . The local cathode temperature has a mean calculated value of 100°C , but indirect heating from the hot anode could cause the actual temperature to rise as high as 200°C . These results are in agreement with earlier results for copper electrodes, reported in Chapter 4 (Table 4.1). Due to difference in anode and cathode temperatures the tensile strength at the cathode would be considerably higher than at the anode throughout the test and any mechanical instability initiated breakdown would be expected to occur on the anode.

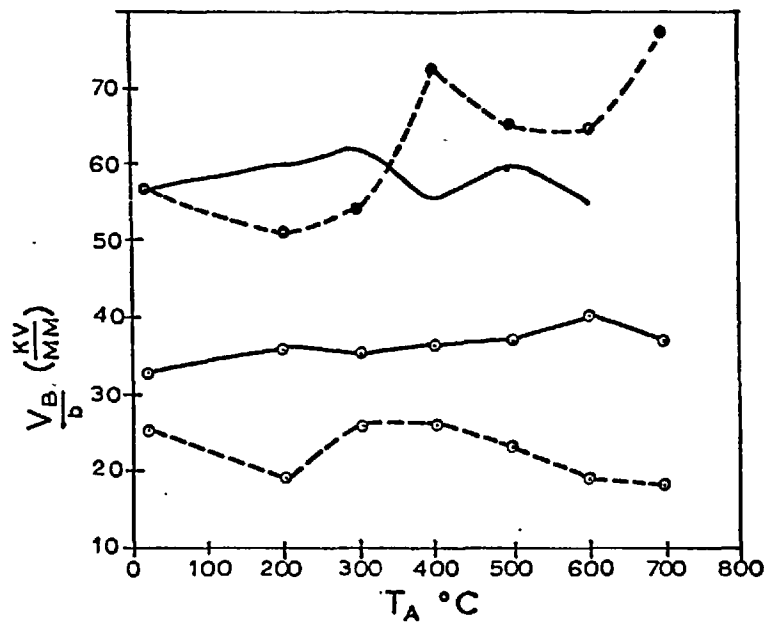


Fig. 6.8. (a)

$V_{B/d}$ vs T_A

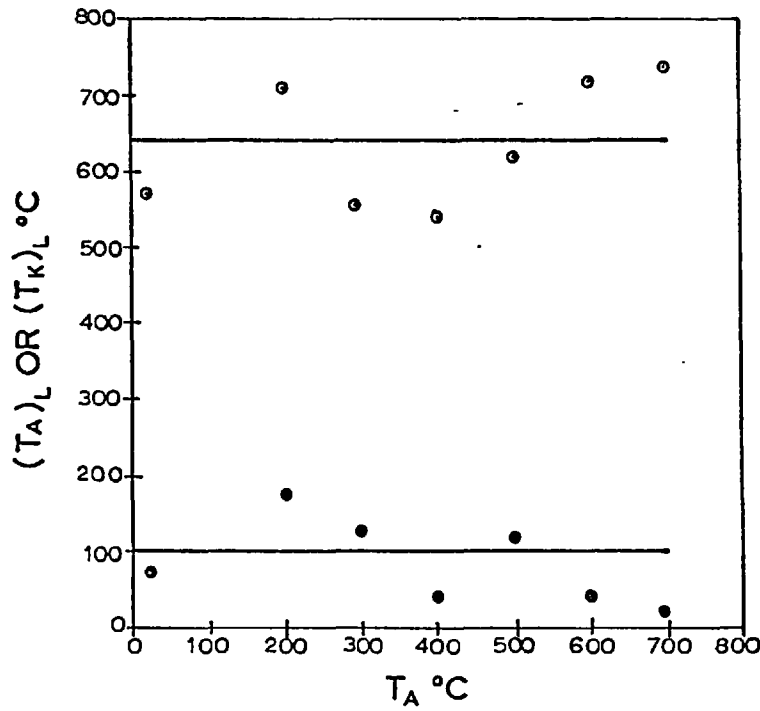
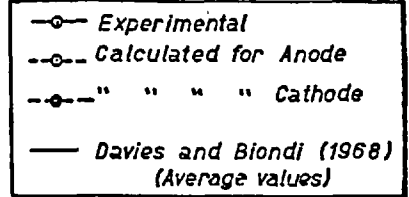


Fig. 6.8. (b)

$(T_A)_L$ OR $(T_K)_L$ vs T_A

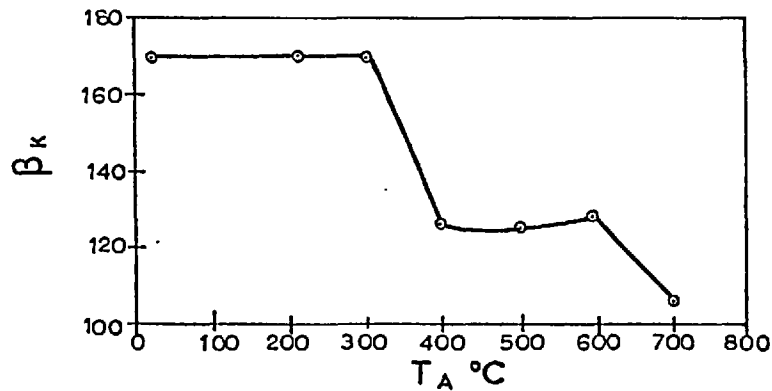
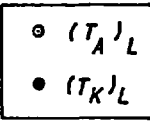


Fig. 6.8. (c)

β_K vs T_A

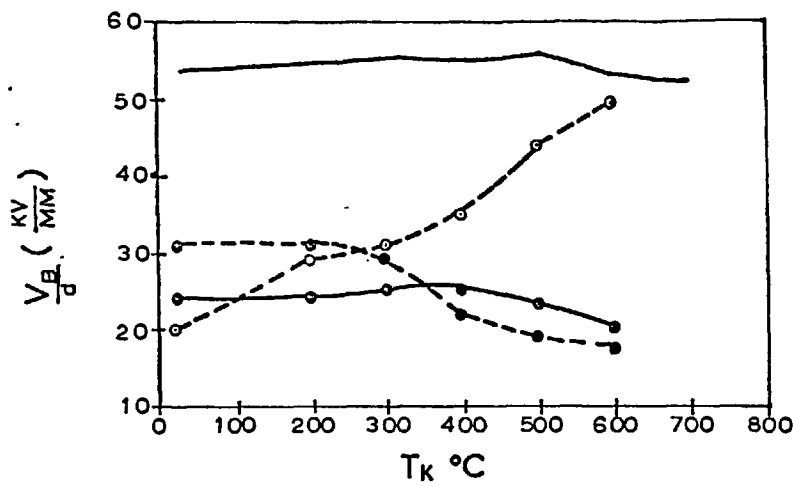


Fig. 6.9(a)

$V_{B/d}$ vs T_K

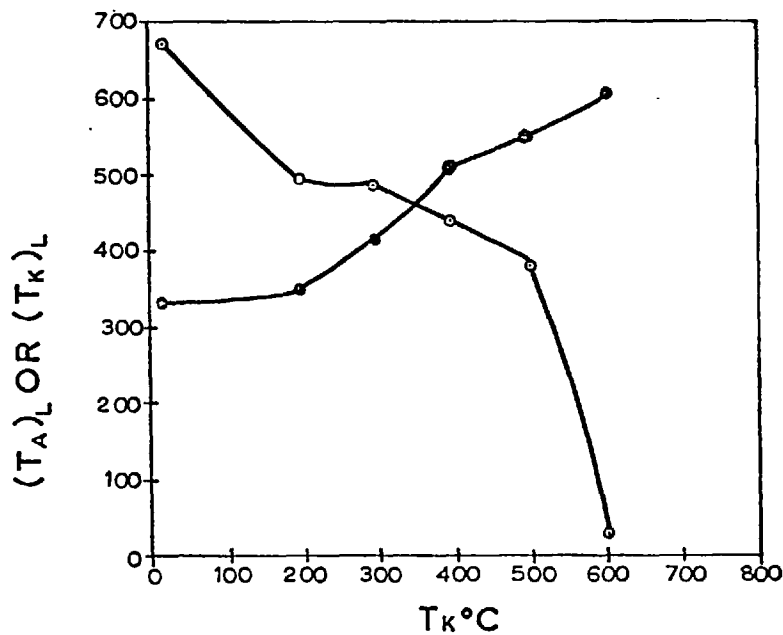
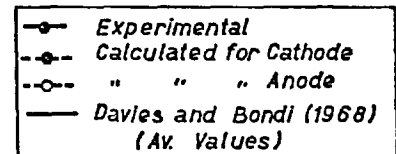


Fig. 6.9. (b)

$(T_A)_L$ OR $(T_K)_L$ vs T_K

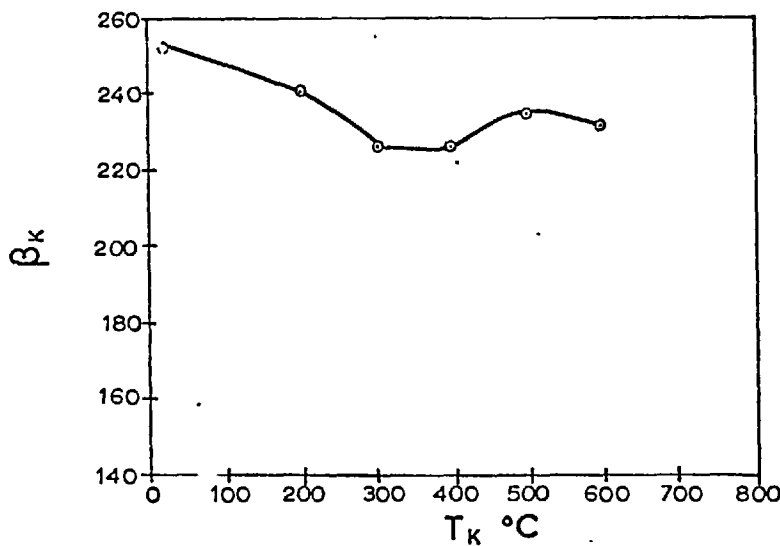
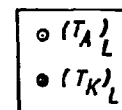


Fig. 6.9. (c)

β_K vs T_K

Hot cathode tests with copper electrodes.

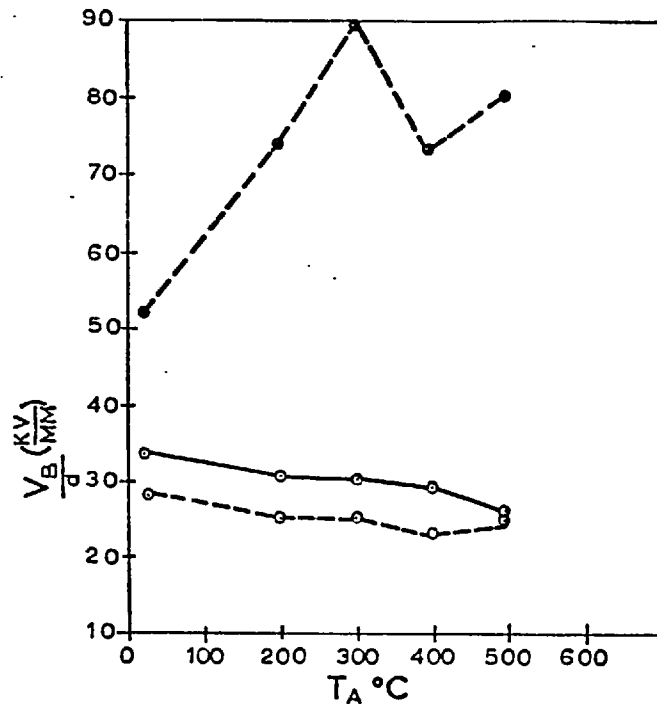


Fig. 6.10.(a)

$V_{B/d}$ vs T_A

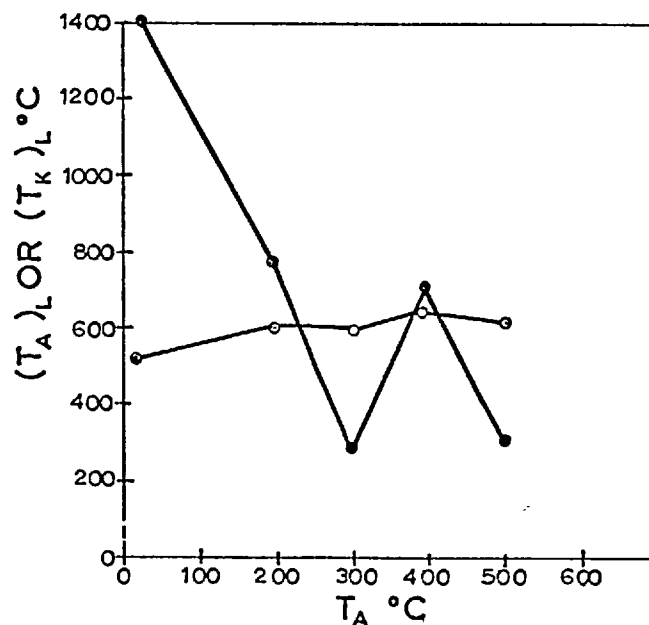
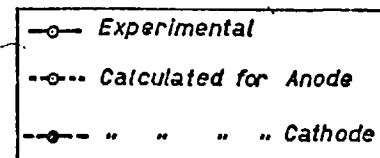


Fig. 6.10.(b)

$(T_A)_L$ OR $(T_K)_L$ vs T_A

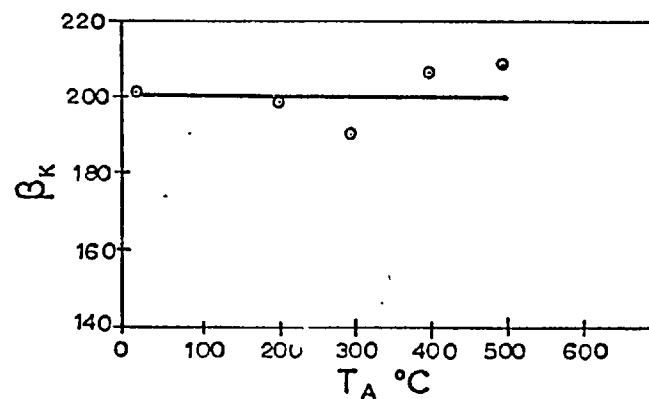
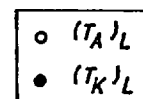


Fig. 6.10.(c)

β_K vs T_A

Hot anode tests with Cu Anode Mo Cathode

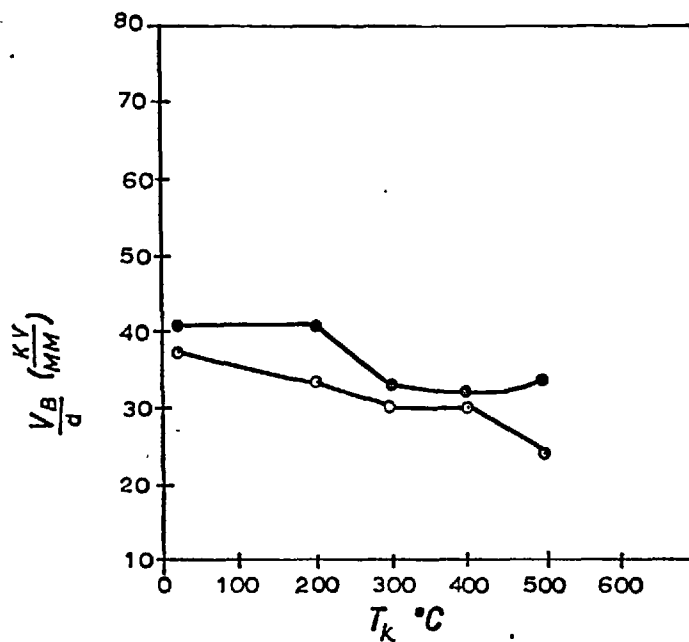


Fig. 6.11. (a)

V_B/d vs T_K

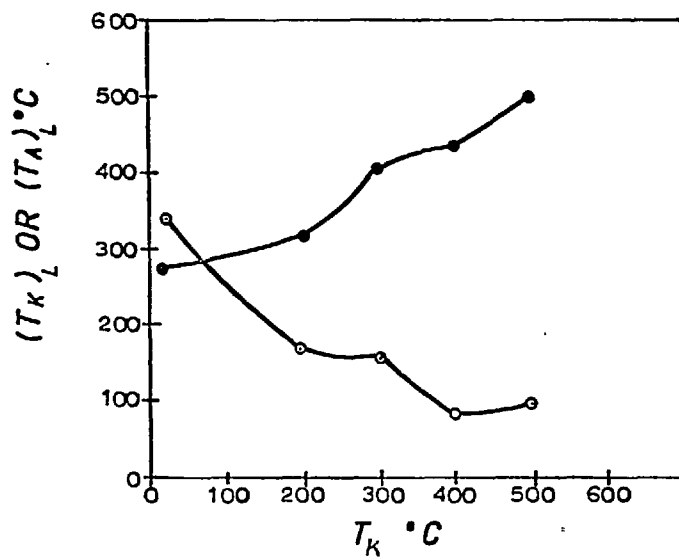
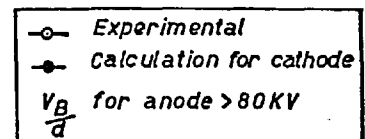


Fig 6 11 (b)

$(T_K)_L$ OR $(T_A)_L$ vs T_K

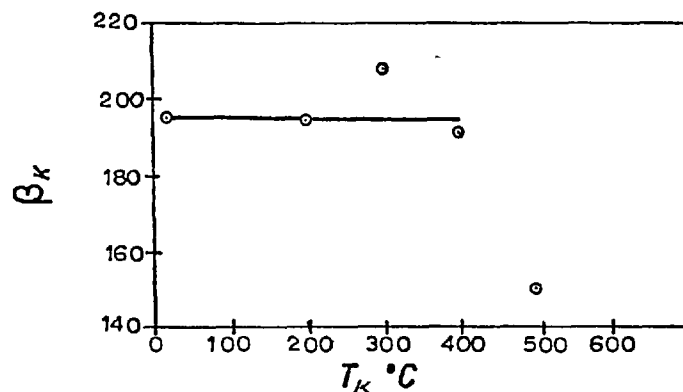
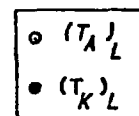


Fig 6 11 (c)

β_K vs T_K

Hot cathode tests with Cu Cathode Mo Anode.

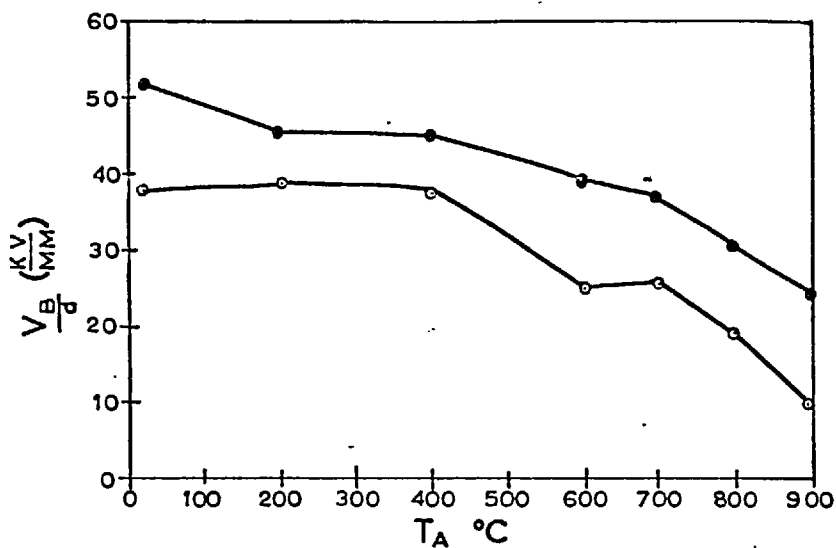


Fig. 6.12.(a)

V_B/d vs T_A

○ Experimental
● Calculated for Anod

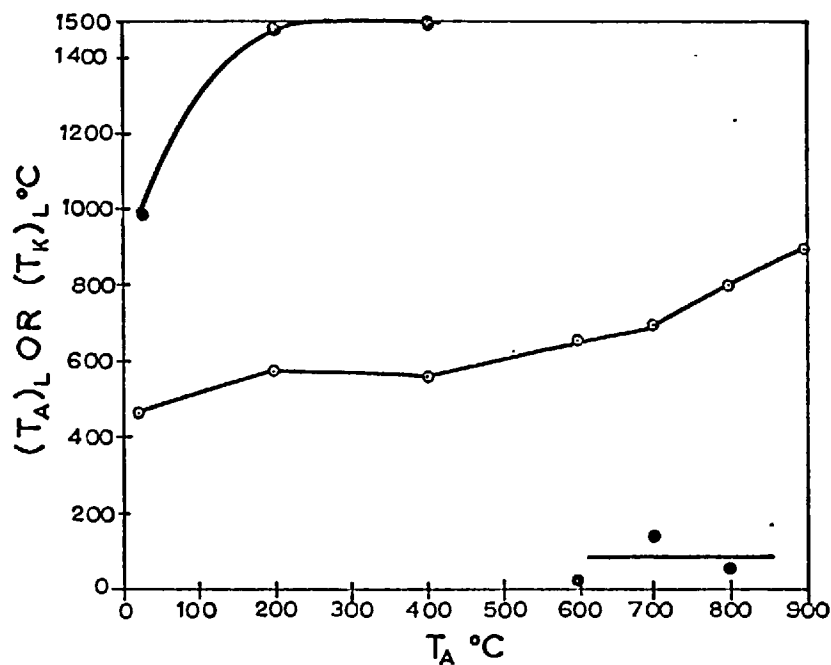


Fig. 6.12.(b)

$(T_A)_L$ OR $(T_K)_L$ vs T_A

○ $(T_A)_L$
● $(T_K)_L$

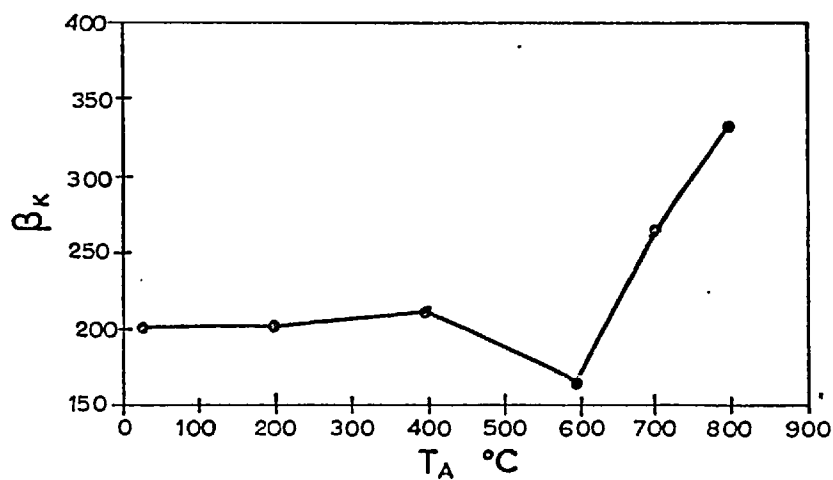


Fig. 6.12.(c)

β_K vs T_A

b) Copper-Molybdenum

The local anode temperature in a copper anode used in conjunction with a molybdenum cathode is also fairly constant (Fig. 6.10b) and has an average value of $(560 \pm 50^{\circ}\text{C})$, which is in agreement with the calculated value of 570°C for a similar combination reported in Chapter 4 (Table 4.1). However the local cathode temperature in the molybdenum can be still higher and it has a maximum value of 1400°C at the room temperature value of T_A . This value is high in comparison to 40°C reported earlier (Table 4.1), but this is accounted by noting that β_K (on which cathode heating is sensitive) in the present case is 200 in comparison to 126 in the previous test (Ch. 4). Though this high value of $(T_K)_L$ is not enough to reduce the tensile strength of molybdenum sufficiently for detachment of material to occur at values of β_K of 200, it is sufficient to permit surface migration. Provided that the conditions of critical field and tip radius are satisfied (section 4.2.5) protrusions could build up in short times, resulting in higher values of β_K .

c) Nickel

With nickel electrodes it is seen in Fig. 6.12b) that the local cathode temperature is initially high. The room temperature value of 990°C agrees with previous result (Table 4.1). However when the anode is heated to 600°C it drops to a low value and then its temperature is mainly due to indirect heating from the anode.

The sudden drop in local cathode temperature must be closely related to the change in emission mechanism inferred from the $F-N$ plots (Fig. 6.6). The cross over in the temperature curves leads to the conclusion that mechanical instability is more likely at the cathode when the anode is unheated, in agreement with conclusions reached in Chapter 4, but will switch to the anode if it is heated above 500°C .

Cathode Heating

Copper and Copper-Molybdenum

It is seen from Figs. 6.9 b) and 6.11 b) that the room temperature value of local cathode temperature for Cu electrodes is 330°C and that for Cu/Mo is 270°C . Both these values are somewhat higher than the earlier values (Table 4.1), but are accountable due to higher values of β_k , (Cu-250 and Cu/Mo-195) observed in these tests in comparison to earlier values of 170 and 180. It is also seen that the local cathode temperature rises with the bulk cathode temperature while the local anode temperature falls towards room temperature. This second conclusion is modified when the indirect heating from the cathode is considered. The actual anode temperature is not likely to drop below $\approx 200^{\circ}\text{C}$. Due to the cross over of the local electrode temperatures in copper, the site of mechanical instability is expected to move from the anode to the cathode as the cathode temperature is increased. There is a similar cross over with the Cu/Mo combination, but at the maximum value of

the local anode temperature the tensile strength of molybdenum is still sufficiently high that instability is likely to be located on the copper cathode.

6.2.3. Variation of Applied Breakdown Field V_B/d with
Electrode Temperature

Anode Heating

Copper and Copper-Molybdenum

Variation of V_B/d with anode temperature is shown in Fig. 6.8 a) for Cu/Cu combination and in Fig. 6.10 a) for the Cu/Mo combination. It is seen that V_B/d for two copper electrodes rises slightly with anode temperature, but only by 25% over the range 20°C to 600°C. Heating of the copper anode in the Cu/Mo combination produces a slight decrease, and at 500°C V_B/d had fallen by 20%. Similar results for copper electrodes obtained by Davies and Biondi(1968) are shown in Fig. 6.8 a) and it is seen that V_B/D varies in similar manner. The difference is only in the magnitude of V_B/d and this is accountable by the fact that β_k is 170 in this work whereas 110 in Davies and Biondi's experiments. When values for effective breakdown field E_B are compared agreement is within 15%.

It appears therefore that when the copper anode is heated V_B/d remains more or less unaffected. It has already been seen (Fig. 6.8 b' and Fig. 6.10 b) that local electrode temperatures do not vary appreciably, so the tensile strength of the material remains

constant. Another reason for no significant fall in V_B/d may probably be related to the earlier expectation that V_B/d may rise due to reduction in gap spacing.

To consider the possibility of material detachment from the electrodes values of V_B/d , the applied field required to produce breakdown, were calculated from eqn.(2.6). Results are shown in Fig. 6.8 a) and 6.10 a). As in room temperature tests reported in Chapter 4 the values of V_B/d calculated for the cathode, in both Cu/Cu and Cu/Mo combinations, are too high and it is very unlikely that breakdown could have occurred by the detachment of the cathode material. The values of V_B/d for the anode are rather lower than the experimental values throughout the temperature range and the detachment of anode material seems likely. Two possible reasons for low values of V_B/d may be considered. Firstly, as discussed in Chapter 4, material detachment may have begun at slightly lower values of V/d at points corresponding to the start of non-linearity in the F-N plots. Second cause could be the smoothening of the anode surface due to the anode heating. The value of β_A of 170 assumed equal to β_k , may have been too high. The determination of β_A is a weak point in the whole of the present work, and unless direct observation of the relevant part of the anode surface can be made considerable uncertainty must remain.

Nickel

With nickel electrodes it can be seen from Fig. 6.12 a)

that V_B/d at room temperature is 38 kV. It remains constant up to 400°C after which it decreases steadily to 10 kV at 900°C. Fig. 6.12 a) also shows calculated values of V_B/d which would be needed for the detachment of material from the anode. In the temperature range 20 - 400°C the estimated local cathode temperatures are very high, and even if they are somewhat in error it is probable that yield stress can be exceeded and material detached from the cathode at voltages below the breakdown voltage. The F-N curves for nickel are markedly non linear and it has already been suggested that material transfer may begin at the point where non-linearity is first observed. Voltages calculated on the basis of local cathode temperatures estimated at the point B (Fig. 6.5) are in close agreement with the experimental values (Fig. 6.12 a). For the tests at and above 600°C the local cathode temperature drops suddenly (Fig. 6.12 b) due to the drop in the field E_B and the current I_B . High values of voltage for cathode initiated breakdown are predicted and in this temperature range breakdown is likely to be initiated at the anode.

Other changes were observed as the temperature rose. In tests below 400°C it was noted that intermittent micro-discharges were observed beginning at the point B (Fig. 6.5) which developed into a burst of sparks at the breakdown field (point C). In tests at 600°C and above the initial micro-discharges were absent. There was only a single burst of sparks at the breakdown voltage and the

current immediately jumped to a high value.

Cathode Heating

Copper

In Fig. 6.9 a) it can be seen that at 20°C V_B/d is 24 kV which is about 30% lower than the value obtained in room temperature tests prior to heating the anode. The corresponding field enhancement factor β_k is 252 which is about 50% higher than in the anode heating tests. These results are understandable when it is pointed out that the cathode surface was not a fresh smooth surface. The tests were done, after the anode heating tests but reversing the electrode polarities. The cathode had therefore already been used as an anode and must have been considerably roughened by material detachment and the growth of projections within the anode spots. Davies and Biondi's results are similar differing only in the absolute magnitude of V_B/d . This is explicable by differences in the value of β_k .

It can be seen from Fig. 6.9 a) that calculated value of V_B/d at the room temperature for the anode is less than the experimental value, indicating anode initiated breakdown which is in agreement with the previous results for copper. However as the cathode is heated V_B/d for the anode becomes higher than the experimental value and steadily rises, whereas V_B/d for the cathode decreases and remains close to the experimental value. Thus it seems when cathode is heated breakdown is cathode initiated.

Copper-Molybdenum.

With the electrode combination, copper cathode/molybdenum anode, in which freshly polished surfaces were used, the values of V_B/d and β_k for the room temperature tests were 32 kV/mm and 195, similar to values found for fresh electrodes in earlier tests (Table 4.1). It is seen in Fig. 6.11 a) that V_B/d falls slowly but steadily with cathode temperature. β_k is constant up to 400°C (Fig. 6.11 c) after which it decreases. Thus the local breakdown field $E_B = \beta_k V_B/d$ up to 400°C is not constant and the decrease is due mainly to the decrease in V_B/d . This fall in V_B/d at constant β_k can be related to a steady decrease in the local tensile strength of the copper cathode caused by the steadily rising local cathode temperature.

Though the local tensile strength was reduced gradually in both cathode tests, its effect on V_B/d is more apparent in the Cu-Mo tests since β_k was then fairly constant up to 400°C.

The effect of tensile strength on breakdown voltage for any material can be shown more clearly if β_k is kept constant by choosing a hard high melting point cathode material. This might be kept in mind in any future investigations.

6.2.4 Summary

1. In anode heating tests with copper electrodes and with a copper anode/molybdenum cathode combination no significant variation in breakdown field was observed. Since the local anode temperature

was calculated to be practically constant this result is not surprising.

2. Although the breakdown field would be influenced by changes in β_k , results were consistent with the hypothesis that breakdown initiation was due to the detachment of anode material due to reduction in tensile strength at local sites.

3. With nickel electrodes breakdown field remained constant up to anode temperatures of 400°C , but decreased steadily at high temperatures. Calculations of local electrode temperature suggest that up to 400°C breakdown would be due to detachment of material from the cathode, but that at higher temperatures breakdown would be initiated at the anode.

4. In cathode heating tests breakdown field between copper electrodes was almost constant. For the combination copper cathode/molybdenum anode a slow decrease in V_B/d with bulk cathode temperature was observed. Since the local cathode temperature gradually increased with bulk cathode temperature the decrease in the breakdown field could be due to the steady decrease in tensile strength at a cathode projection or at higher temperatures to the growth of projections due to surface migration. The site of breakdown initiation, on the protrusion detachment hypothesis, is likely to be on the anode initially, but move to the cathode if its bulk temperature is raised above 300°C .

CHAPTER VII

DISCUSSION AND CONCLUSIONS

In this work the aim has been to conduct breakdown tests with plane parallel electrodes of molybdenum, nickel and copper in high vacuum, in order to determine whether the mechanical strength of the electrode material is a significant parameter affecting the breakdown voltage. Published work did not contain a detailed treatment of the problem, and usually conclusions had been based on simple comparisons of the strength of the electrode material and the breakdown voltage. It was felt that a consideration of the heating produced at local sites on the electrodes due to the pre-breakdown field emission current was necessary.

For the mechanical strength of electrode material to be responsible for limiting the gap voltage, the breakdown mechanism must involve primarily the detachment of electrode material from surface irregularities present at the heated sites, when the mechanical stresses due to the electric field exceed the hot tensile stress of the electrode material. It was pointed out in the introduction that such a process seemed possible for the usual breakdown fields observed in practice, even for high strength materials like molybdenum and tungsten, at local temperatures as low as half the melting point. On the basis of experimental evidence showing that breakdown could, in some circumstances, be initiated by clumps and microparticles, the breakdown condition was assumed to be the

condition for the detachment of clumps of electrode material. The basic approach to the problem was firstly to estimate the local temperature at each electrode, a knowledge of which enabled breakdown voltages based on the above criterion to be predicted and compared with the experimental values. Secondly, to obtain from a study of the electrode surfaces after breakdown tests, convincing evidence that transport of material between the electrodes in the form of clumps had occurred.

The results and discussion contained in previous chapters can now be summarized briefly as follows:

1. Predicted breakdown voltages were in good agreement with the experimental values for copper and nickel electrodes but when two molybdenum electrodes were used the predicted values were too high. It appears, in the present experimental conditions, that for electrode materials such as copper and nickel, and probably for materials of lower strength, the maximum voltage that can be applied is limited by their tensile strengths. The breakdown voltage is also dependent on the electrode surface finish and especially on the value of the cathode field enhancement factor.

2. Though Fowler-Nordheim plots of the V-I data were linear for the most part, non-linearity occurred in the sense of higher slope at fields below the breakdown value. On the basis of estimates of local electrode temperature and applied voltage at the point of non - linearity, it is felt that the onset of material detachment

from heated sites on the electrodes could be responsible for this non-linearity.

3. The calculated temperature rise at the cathode, in all tests except those employing two Ni electrodes was not significant irrespective of the protrusion geometry and despite the fact that the temperature rise due to resistive and Nottingham heating was taken into account. Thus material detachment of hot cathode material was not expected.

4. For two nickel electrodes the cathode temperature for a cylindrical protrusion was calculated to be 980°C an order of magnitude higher than for a conical protrusion. The contribution due to Nottingham heating was greater than that due to resistive heating. We conclude, in agreement with Charbonnier (1967) and Chatterton (1966), that for estimating cathode temperatures for copper nickel and other relatively low melting point metals, Nottingham heating must be taken into account.

5. The maximum heating on the anode was expected to occur with copper electrodes, the calculated temperature being 600°C . Significant evaporation of material from the anode surface into the electron beam is therefore unlikely.

6. In all the tests except when two nickel electrodes were used a consideration of the predicted breakdown voltages and the local anode temperatures indicated anode initiated breakdown. For nickel the breakdown was most likely cathode initiated, though

possibility of material transfer from anode at breakdown can not be excluded.

7. Examination of the electrode surfaces with an electron probe analyser showed that transfer of material occurred, mainly from the anode to the cathode, in the form of clumps as well as evaporated material. However, after a control test with a nickel cathode/copper anode in which the runaway breakdown condition had ^{avoided though V_B had been} been reached, no trace of an evaporated layer could be found, though a number of clumps of anode material were detected at the damaged cathode sites. This result suggested that anode material in vapour form is transported to the cathode only after the runaway condition has been reached, where as material transport in form of clumps can occur before the runaway condition and is sufficient to initiate breakdown. This helps to substantiate the earlier conclusions 1, 3, 5 and 6.

8. A detailed study of the appearance of typical electrode markings after breakdown for the electrodes examined in (7) was made. On the anode, protrusions as well as craters were seen within the anode spots, and these may be the sources of the anode clumps. On the cathode typical shallow craters were seen and in and around them splashed and deposited material was present. The size of these craters matched the size of the anode protrusions. This result supported by the result (7) presents a convincing physical picture for the transfer of anode material in form of clumps to the opposite

cathode surface.

9. An important find on the cathode was the large number of sharp projections at the damaged sites. The tip radii agreed well values expected for field emitting projections in practice. This evidence confirms the suggestion made by Little and Smith (1964) that field emitting projections may be formed by impact of anode material on the cathode.

10. As mentioned in (2) non-linearity in the F-N plots could be due to the onset of material transfer. This means that if the gap voltage is limited primarily by the detaching of protrusions an adequate supply of protrusions must be maintained until the point of complete breakdown is reached. This can only be ensured if the rapid creation of new projections on the electrode surfaces is possible. When the results were examined and compared with the conditions needed for the growth of heated field emitters (Dyke et al 1960) it was found that the possibility for a quick growth of projections existed at the point of non-linearity in the F-N plots.

11. Results of a preliminary test on a heated copper cathode were satisfactorily explained on the conditions for the growth of projections, supporting the view that projections on extended electrode surfaces could grow by the above process.

12. The results of some tests made with heated electrodes were unexpected. Previous work was not confirmed, but there was agree-

ment with the recently published results of Davies and Biobdi(1968). No marked changes in breakdown field were observed with copper or copper/molybdenum electrodes. Nickel was found to behave in a completely different and surprising way.

The results can be interpreted, to a certain extent, using the theoretical ideas developed in Chapter 2, but the variation in behaviour observed with different combination of electrodes is so great that considerably more work would need to be done before hypotheses could be confirmed.

In conclusion therefore we can say that the results of the present work generally support those clump theories of vacuum breakdown in which the clump originates from the anode and strikes the cathode. As mentioned in Chapter 1 such a mechanism for breakdown is supported by the work of Rozanova(1962), Udris (1960), Olendzkaya (1963) and Little and Smith(1966). A recent paper by Hurley and Parnell(1969) further supports this view.

Concerning the origin of anode clumps the results of this work strongly indicate for copper and nickel, that detachment of an anode projection is possible since the enhanced electrical stress can exceed the ultimate tensile strength. Thus for electrodes of these materials and possibly those having similar properties, the mechanical strength of the anode seems to be an important parameter in deciding the maximum voltage that can be insulated in high vacuum between plane parallel electrodes separated by small gaps.

SUGGESTIONS FOR FUTURE WORK

1. The formation of projections and craters on the anode is not well understood. Study of the electrode surfaces by Stereo-Scan microscopy, electron probe analysis and other techniques after applications of voltage corresponding to different points on the F-N plot may give some insight into the circumstances for the growth and detachment of anode projections.

2. The phenomenon of build up is known for heated field emitters (Dyke et al 1960). It would be important to establish whether, under what circumstances, build up occurs on the extended electrodes used in the breakdown tests. Tests might also be made with a heated pointed anode and a cold cathode. The tip geometry of the point could be examined by Stereo-Scan microscopy before and after the application of the electric field. Ideally one would wish to examine it while the test was proceeding.

3. Detection of material transfer in the present tests was done using dissimilar electrodes by examining the surfaces after breakdown by electron probe microanalysis. These tests only indicate indirectly the possibility of material transfer between electrodes of the same material. Experiments may be tried with electrodes of similar material in which one of the electrodes is made from radioactive isotope of the material. A contact radiograph of the ordinary electrode surface after the breakdown test might reveal the locations where the radioactive metal was transferred.

4. Non-linearity in the F-N plots at high voltage end was found to be a consistent feature in the present tests and has also been observed by others. This non-linearity appears only at field strengths a few per cent lower than the breakdown field, and a detailed investigation of this effect may give a better understanding of the physical processes leading to breakdown. Nickel electrodes might be selected at the start since this effect was most pronounced with them.

5. An important test for the clump mechanism is to see whether a double log plot of the breakdown voltage vs the gap spacing yields a straight line of slope half. It would be interesting to study the variation of breakdown voltage with gap spacing, for nickel and copper electrodes. This would mean modification of the tube to include a linear motion drive to which one of the electrodes would be mounted. Such an arrangement would prove useful for other purposes, for example for compensating gap changes due to thermal expansion in high temperature tests.

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