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Report

ARCING AND SURFACE DAMAGE IN DITE

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ABSTRACT

An investigation into the arcing damage on surfaces exposed to plasmas in the DITE tokamak is described. It has been found that arcing occurs on the fixed limiters, on probes inserted into the plasma and on parts of the torus structure. For surfaces parallel to the toroidal field most of the arcs run across the surface orthogonal to the field direction. Observations in the scanning electron microscope show that the arc tracks are formed by a series of melted craters characteristic of cathode arc spots.

The amount of metal removed from the surface is consistent with the concentration of metal observed in the plasma. In plasmas with hydrogen gas puffing during the discharge or with injection of low Z impurities, the arc tracks are observed to be much shallower than in normal low density discharges.

Several types of surface damage other than arc tracks have also been observed on probes. These phenomena occur less frequently than arcing and appear to be associated with abnormal discharge conditions.

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1. INTRODUCTION

Contemporary tokamaks generally have significant impurity concentrations which result in their resistivity being higher than the classical value for hydrogen by factors ranging up to 10. These impurities comprise low Z elements such as oxygen and carbon and metallic impurities representative of the wall and limiter materials. The oxygen and carbon have been shown to result primarily from desorption of adsorbed gases on the walls by charge exchange neutrals(1) and methods of reducing them significantly have been devised. However as low Z impurities decrease the metal impurities appear to increase.

The process whereby metal impurities enter tokamak discharges is not well understood. Possible mechanisms which have been suggested are:

a) Evaporation
b) Sputtering
c) Arcing
d) The production of metallic dust(2,3)

Some of the general features which any mechanism has to explain are the appearance of metals early in the discharge, the large rate of metal deposition on the wall per discharge,(4,5) the fact that metal impurity concentrations have been observed to be similar in hydrogen and helium discharges(6) and the decrease in the absolute metal concentration as the plasma density increases.(4)

In previous investigations in DITE time resolved surface temperature measurements have been made.(7) These indicated that in normal, stable, tokamak discharges the temperature of the wall and the limiter did not exceed 310 K. Large temperature rises do of course occur at times during unstable discharges and in the presence of runaway electrons. However in stable discharges the evidence against evaporation is strong. There is little direct evidence for the production of metallic dust by blistering. As will be discussed later we have found no sign of blistering in our examination of probes exposed to the plasma.

Sputtering of the wall material by the plasma ions is also very difficult to justify in quantitative terms when compared to the rate of deposition of thin metal films at the wall.(5a) Sputtering of metals by themselves or other impurities, (e.g. oxygen) cannot be ruled out, but for self sputtering the metal impurity concentration would be expected to be unstable and for light impurity sputtering a correlation between the oxygen and metal concentration would be expected. In general however neither is found in practice.(8)

We have therefore beeen led to consider arcing as the method by which metal impurities are produced. The type of arc known as the unipolar arc,(9) which occurs between the plasma and a metal surface, was observed many years ago and was proposed as the major source of metals in diffuse pinches. The reason for arcing not being considered in tokamaks seems partly to be due to the argument that cross field plasma diffusion leads to the plasma potential being negative with respect to the wall. However such a condition does not obtain in the region in the shadow of the limiter. We have therefore undertaken an investigation of the presence of arcs in the DITE tokamak. This report presents substantial evidence of arcing occurring on diagnostic probes, on the torus structure and at the limiter in DITE.

2. OBSERVATIONS IN THE TORUS

(i) Diagnostic Probes

Several types of diagnostic probe have been examined for arcing and surface damage. The probes vary in size and shape, since they were designed for various purposes, but they are nevertheless useful in this preliminary survey.

Table 1 gives a brief summary of the exposure of the probes to the plasma. The energy flux probes have been subject to a wide range of conditions, since they were not intended for arcing studies. They have also been subject to considerable rapid pulsed discharge cleaning. The arc test probes have been set at one radial position and where possible, exposed to one value of gas current. Further details are given under the individual probe headings.

(a) Energy Flux Probes

The energy flux probes are shown in Figure 1. These probes were intended for use with the AGA camera(7) to measure the energy flux, to a limiter and to determine the importance of evaporation in the production of plasma impurities as mentioned earlier. Both probes are molybdenum, 38 mm in diameter, with reference and location holes in the probe face. Both probes were inserted into the plasma from a top vertical port and were set at minor radius settings from 27 cm to 18 cm. The Mk I probe however, was only exposed to gas currents of 50-100 kA, compared with 50-200 kA for the Mk II probe. The Mk II probe exhibited two different types of arc (Figure 2), a fern like arc characteristic of the unipolar arcs observed in Zeta,(9) and a linear arc which at first sight resembled a mechanical scratching of the surface. Figure 3 shows a scanning electron microscope enlargement of some linear arc tracks which are further enlarged in Figure 4. The linear arc tracks sometimes have a surface defect such as a crater at one end (Figure 5), and the direction of motion can be determined by assuming a common origin where several tracks meet at such a point. For the fern like arcs, the motion is assumed to be in the direction in which the branches diverge. If these assumptions are made, the two types of arc are found to travel in the same direction, i.e. orthogonal to the B_T magnetic field and towards the centre line of the torus. For electrons flowing from a cathode spot on the surface, this motion is in the opposite direction to that expected from the J x B force.

In addition to the arc tracks, there are numerous craters which can be classified into several varieties; "moon craters", (Figure 5), often associated with arc tracks, "bird's nest craters", (Figure 6), "pebble craters", (Figure 7), and large craters which are probably due to electron beams, since they are observed only in regions facing the electron drift direction, (Figure 8).

Many examples of each type of crater have been observed, and it is probable that each species is produced by a different mechanism or plasma parameters.

The distribution of arcs and craters for the Mk II energy probe is shown schematically in Figure 9, where regions having the highest density of a particular surface phenomenon are shown. The region facing the electron drift direction has been subject to surface melting and it is possible that small surface defects have been obliterated in this zone.

The Mk I probe shows much less surface damage, fewer craters and only a few short linear arcs. In addition, the craters are generally shallow versions of the pebble craters of the Mk II probe. No fern arcs were observed.

(b) The B_p Probe

This probe contained a coil for measurement of the B_p field$^{(10)}$ and was used at minor radius settings of 26 to 16 cm and gas currents of 100 kA. The probe shows a large melted zone on the electron drift side of the probe (Figure 10), numerous craters, some evidence of linear arcs on the sides of cylinder, but no fern arcs. The craters of this probe were situated close to the melted zone and were characterised by having a regular, deep and often circular cross section, containing smaller holes (Figure 11). In addition, a rather curious petal-like effect was observed which may be associated with multiple holes (Figure 12). A few moon craters 10 µm diameter were observed and several large craters 200-500 µm diameter adjacent to the melted region.

(c) Arc Test Probe No 1

This is a molybdenum probe 38 mm diameter, 38 mm long. It was exposed to discharges with currents in the range 50-200 kA at a fixed position of 27 cm. Figure 13 shows the linear arc tracks across the face and down the side of the probe facing radially outward from the torus. The majority of the arc tracks on this side converge towards the probe stem in contrast with the opposite, inner facing side of the probe, where the tracks diverge (Figure 14). This probe clearly shows the general arc pattern which has been observed on all the probes and probe limiters examined so far.

The individual arc tracks are however narrower and less continuous than thosen shown in Figure 3 and Figure 4. Craters are also found within the tracks (Figure 15) and some narrow tracks are formed by a series of separated craters showing a discontinuous motion of the arc root.

(d) Arc Test Probes 2,3, and 4.

These molybdenum probes are 13 mm diameter with conical caps (Figure 16). Probes 3 and 4 were set at a radius of 26 cm and probe 2 at 23 cm. Only linear arcs have been observed on these three probes, but they are very shallow and in the case of probe 4, only a few short arcs were observed. The tracks in fact were so shallow that only poor definition could be obtained in the SEM. They could most clearly be observed in a low power optical microscope with oblique illumination (Figure 17). There was also a considerable variation in the direction of the arc tracks for probe 4 with some of the tracks parallel to B_T. These are the only probes where the gas current and radius remained constant for the period of exposure to the plasma. As noted in Table 1 they were exposed to discharges either with high plasma densities, or with 2% neon added - both conditions which give low metal cocentrations in the plasma.

(ii) Torus Components and Structures

(a) The Probe Limiters

Probe limiters from two positions* have had a preliminary examination which shows linear arcs in a similar orientation to the arcs on the No. 1 arc test probe (Figure 13). No fern arcs have been observed, and the limiters have not been examined for craters in the scanning electron microscope. Figure 18 shows a macroscopic view of the two probe limiters and the arcing on the support tube and the limiter face.

(b) The Fixed Limiters

The fixed limiters show considerable linear arcing and at least one case of severe surface erosion due to runaway electron beams (Figure 19). This damage is unlike the melting observed on probe surfaces, and the multiple craters indicate that it is probably due to individual separate events. Detailed examination of the limiters was not possible due to lack of time and limited access.

(c) Support Ribs

Most of the ribs examined showed signs of linear arcing, Figure 20 shows some typical examples. At least one rib showed signs of surface melting (Figure 21). Figure 22 shows how close the upper faces of the support ribs are to the fixed limiter face. An increase in this separation with a thicker fixed limiter may be necessary to reduce arcing on the torus structure.

(d) Optical Dumps

Two optical dumps have been removed from the torus. The sides of the dump frame, which are positioned orthogonal to the B_T field, show considerable arcing and surface melting, (Figure 23). A casual inspection gives the impression that the position of the dumps relative to the fixed limiters may be responsible for this damage.

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*Vertical top ports between coils 1 and 16, 8 and 9 respectively.

3. DISCUSSION

(i) The results of this study are necessarily qualitative because of the nature of the available evidence. In many cases, the surface of the probes examined show the integrated effect of many discharges having a wide range of gas current and probe position with changes in the direction of the current and B_T. Nevertheless information can still be obtained which is valuable for determining the magnitude of the problem and the requirements of a more quantitative investigation.

The probes examined so far show that isolated craters unassociated with arc tracks of the type shown in Figures 6,7,8 and 11 only occur on probes which have currents of 100 kA or more. The craters are also found only on the probe surface facing the electron drift direction and on probes where some of the surface has melted. It seems probable therefore, that the craters are associated with electron beams, and the impact of material from the molten region. Some of the craters do in fact have striking resemblance to the effect produced by the impact of accelerated charged droplets of aluminium onto a cold surface. It is tempting to assume that a similar process may be responsible for the formation of some of the craters on the probe.

A single crater of the type shown in Figure 11 on a molybdenium probe limiter, assuming that the depth is equal to the diameter of 100 μm, would produce 5×10^{16} atoms. Although this would be a serious impurity concentration in the discharge, in practice, craters could be avoided by using the probe limiter at a radius > 18 cm and using high density plasmas to suppress electron beams. Craters should not therefore present a serious source of metallic impurities.

(ii) Unlike craters, arc tracks were found on all the probes examined, with the linear type of arc predominating. An approxiate estimation of the volume of material evaporated by arcs during the metal dominated discharges can be made from the observed tracks on arc test probe No. 1, taking an average number of arcs per discharge ≃ 10 and a track 1 cm long, 1×10^{-3} cm wide. Assuming a depth of $0.2 \times$ track width, the volume of material evaporated is 2×10^{-6} cm^3. This volume produces 10^{17} atoms per discharge or 10^{11} atoms cm^{-3} in the plasma. Considering the ratio of the surface area of torus to probe ∿ 1000:1, this value is more than adequate to account for the thin films which have been observed to cover the torus.$^{(4,5)}$ These films indicate a deposition rate ≃ 3×10^{13} atoms cm^{-2} per discharge or a total rate of 3×10^{18} atoms per discharge.

(iii) The arc tracks seen on probe No. 1, Figure 13, are typical of the arc patterns observed on other probes and probe limiters. A schematic diagram of the No. 1 probe is shown in Figure 24. The probe was at a radius of 27 cm and displaced horizontally 4 cm, from the plasma centre. As previously stated, if the arc current is assumed to be a flow of electrons from a cathode spot on the probe surface, then the arc has a retrograde motion. In the diagram therefore the direction of motion is opposite to that expected from the normal J x B force. An explanation for this anomalous behaviour has been given by Robson and von Engel.(11)

For an arc current into the face of the probe, i.e. into the plane of the paper, the motion of the arc is across the face of the probe towards the centre-line of the machine at an angle determined by the resultant of the B_T and the horizontal component of the B_p field. Since $B_T \gg B_p$, this direction is nearly orthogonal to B_T. For the current J into P (Figure 24) the J x B_T gives a direction of motion into the plane of the paper and J x B_T on the opposite side of the probe gives a motion out of the paper. The horizontal displacement of the tracks on the inner and outer faces of the probe (Figure 25) is consistent with the model proposed by Robson(14) for an arc undergoing retrograde motion where both the arc and an applied magnetic field are inclined to a surface. With the exception of tracks c and c (Figure 25) there is a component $B_{T\perp}$ of B_T perpendicular to probe surface. This together with a component of the arc current parallel to the surface $J_{//}$, which results from the inclination of the arc root to the probe, produces a force $J_{//} \times B_{T\perp}$ displacing the arc tracks in the direction observed.

(iv) Measurements of the flux of metals at the edge of the discharge, using both optical spectroscopy and a probe technique,(12) have indicated that the amount of metal in the DITE discharge is a strong function of the discharge conditions. The presence of light impurities, such as oxygen or neon, or the puffing of hydrogen into the discharge has the effect of suppressing the metal concentration. These results are consistent with those obtained from ST, TFR, Alcator and Pulsator. They also correlate very well with the fact that on probes exposed to such discharges, arc test probes 2, 3 and 4, much less metal appears to have been removed from the surface.

It has been shown experimentally that low Z impurities have the effect of decreasing the electron temperature at the edge.(13) All of these results are consistent with the arcing hypothesis since unipolar arcing is strongly dependent on electron temperature. Arcing can also explain the presence of metals at early times in the discharge since it can theoretically occur with electron temperatures less than 10 eV.

(v) No evidence for cracking, blistering or exfoliation has been observed in any of the probes examined. The magnification used in the scanning electron microscope would have allowed cracks ≤ 1 μm to be seen. There is thus no confirmation of the hypothesis(2) that metal dust from the walls is the cause of metal impurities in the plasma.

4. CONCLUSIONS

The evidence that arcing and other surface erosion phenomena has taken place in DITE is overwhelming. Probes, limiters and torus structure all exhibit surface damage. Of the various features observed, the linear arc running at right angles to the local magnetic field, appears to be dominant. The amount of material removed from the surface by these arcs is quite sufficient to explain the metal films deposited around the wall of the torus and the concentration of metal in the plasma. However as yet we have no time resolved observations of arcing to correlate it with the metal flux entering the plasma. Future investigations will be directed towards obtaining such data, probably with cine photography and narrow band filters.

It has also been demonstrated that arcing is consistent with all the experimental evidence concerning the behaviour of metals in tokamak discharges. Not only the quantity of metal, but also the variation of concentration, as the low Z impurity concentration is changed or as hydrogen is puffed in, are all consistent with arcing. On the other hand, no evidence has been found of the surface cracking expected on the metal dust hypothesis.(2) However, it is clear that much more detailed information about the boundary region between the plasma and the wall as a function of discharge conditions is necessary before arcing can be confirmed as the dominant mechanism causing metal impurities.

The possibility that metal production is by self-sputtering or the sputtering of metals by lighter impurities, still cannot be dismissed. Direct measurement of flux of impurity ions to the wall and the limiter are required to ascertain whether this process is important.

5. ACKNOWLEDGEMENTS

The authors are grateful to the DITE operating and engineering teams for the operation of the machine, to G E Austin for the preparation of many of the probes, and to Dr J W M Paul and our other colleagues in the physics team for valuable discussions.

REFERENCES

1. S A Cohen, MATT 1230, Princeton PPL, March 1976.

2. K J Dietz and F Waelbrook, Proceedings of the Int Symp on Plasma Wall Interaction, Julich 1976, Pergamon Press.

3. T Ohkawa, General Atomic Resport GA A-14232, December 1976.

4. P Staib and G Staudenmaier, J Nucl Mat 63, 37, 1976.

5. G M McCracken, G Dearnaley, S J Fielding, D H J Goodall, J Hugill, J W M Paul, P E Stott, J F Turner and J Vince, Proc 8th European Conf on Controlled Fusion and Plasma Physics, Prague, Sept 1977. CLMP492

5.a G M McCracken and D H J Goodall, to be published.

6. N Bretz, D L Dimock, E Hinnov, E B Meservey, MATT 1052, Princeton, PPL, 1974.

7. D H J Goodall, Proc of the 9th Symp on Fusion Technology, page 523, Pergamon Press, 1976.

8. E Meservey, N Bretz, D Dimoch and E Hinnov, MATT 1175, Princeton, PPL, 1975.

9. J L Craston, R Hancox, A E Robson, S Kaufman, H T Miles, A A Ware and J Wesson, Proc 2nd Int Conf on the Peaceful uses of Atomic Energy, Page 414, Geneva, 1958. Paper P/34.

10. This probe was supplied to us by J Hugill.

11. A E Robson and A von Engel, "Origin of Retrograde Motion of Arc Cathode Spots", Phys Rev 93, 1121, 1954.

12. G Dearnaley, G M McCracken, J F Turner and J Vince, Proc of 3rd Int Conf on Ion Beam Analysis, Washington DC, June 1977, to be published.

13. E Hinnov, Private Communication.

14. A E Robson, Proc of the 4th Int Conf on Ion Phen in Gases, Uppsala 1959, 2, 346.

TABLE 1

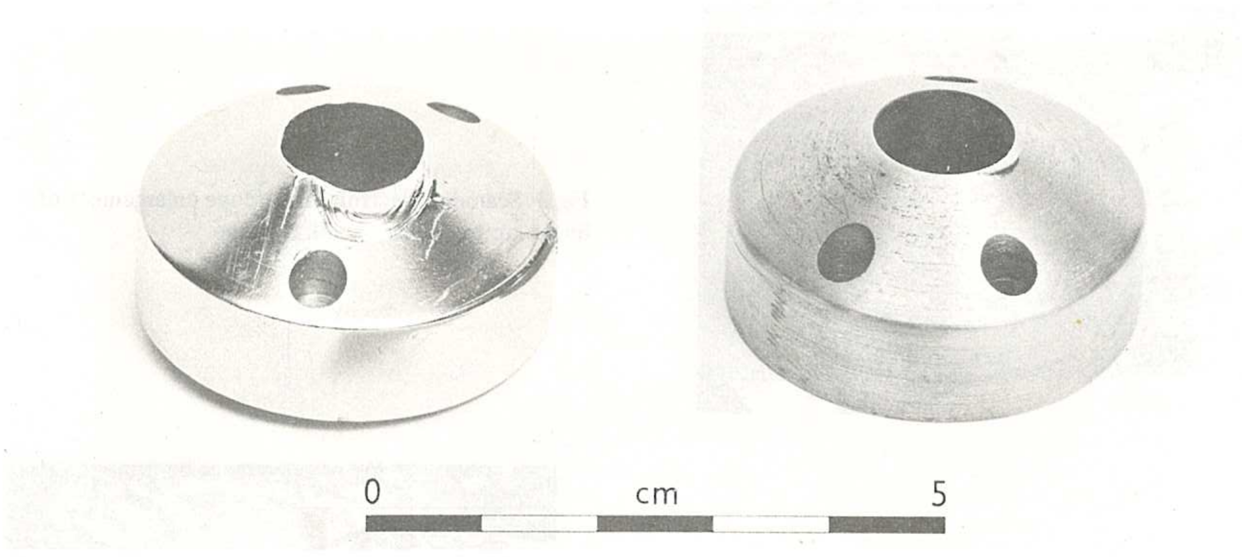
PROBE HISTORY

Probe	++ Position of vertical port (all at R=113cm)	Radial setting	Gas current	Arcs Fern	Arcs Linear	Craters unassociated with arc tracks	Exposure to RPDC	No. shots
Energy flux probe Mk I	13/14	26-18cm	50-100kA	No	Yes	No	Yes	
Energy flux probe Mk II	7/8	26-18cm	50-200kA	Yes	Yes	Yes	Yes	
B_p probe	13/14	26-16cm	100kA	No	Yes	Yes	Yes	
Arc test probe No.1	15/16	27cm	50-250kA	No	Yes	No	No	33 @ 200kA
Arc test No. 2	15/16	23cm	200kA*	No	Yes	No	No	5
Arc test No. 3	15/16	26cm	150kA*	No	Yes	No	No	35
Arc test No. 4	15/16	26cm	200kA$^+$	No	Yes	No	No	7

++ The probe is situated between a pair of the 16 numbered toroidal coils.

$^+D_2$ + 2% Ne

*High density gettered discharges



(a) (b)

Fig.1 The energy flux probes (a) Mk II, (b) Mk. I. The central hole is for a reference cavity and the smaller holes are a location aid.

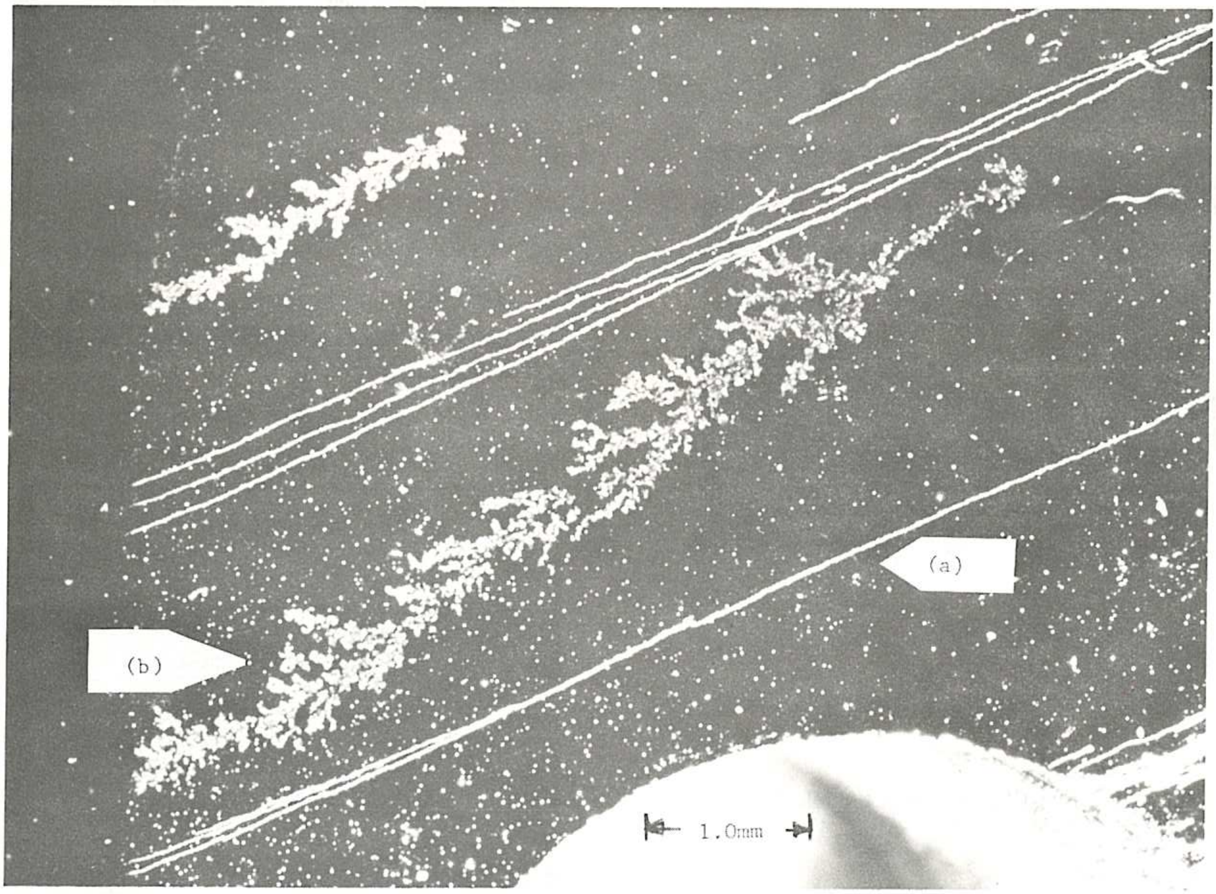


Fig.2 The two types of arc observed on the Mk II energy flux probe (a) "Linear" arc, (b) "Fern" arc. The hole at the bottom of the picture is the right-hand location hole of Fig.1(a).

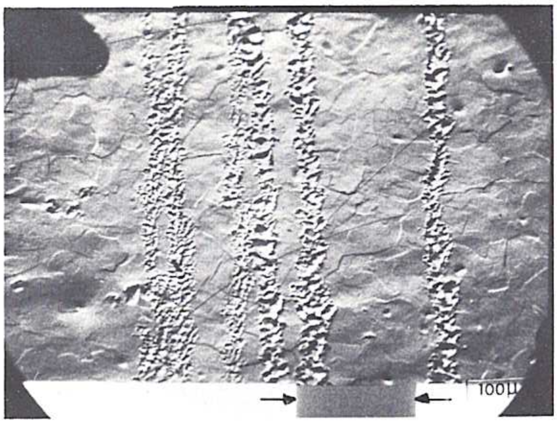


Fig.3 Scanning electron microscope enlargement of linear arc tracks on the Mk II probe.

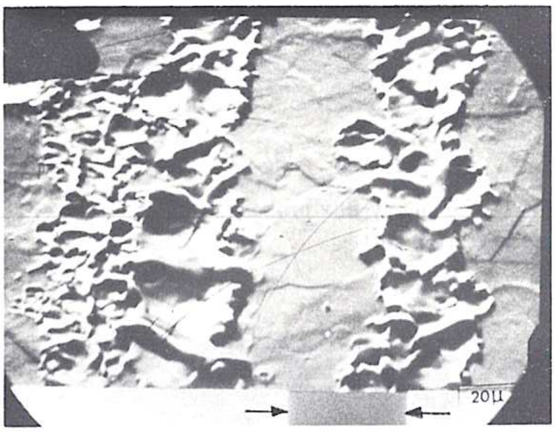


Fig.4 An enlargement of the centre of Fig.3.

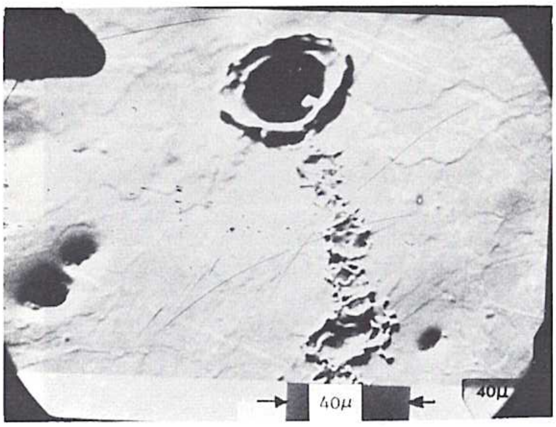


Fig.5 Linear arc tracks and 'moon' crater from the Mk II energy flux probe.

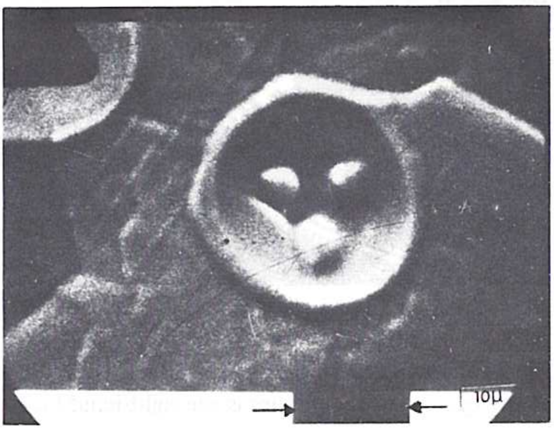


Fig.6 "Bird's nest" crater from the Mk II energy flux probe.

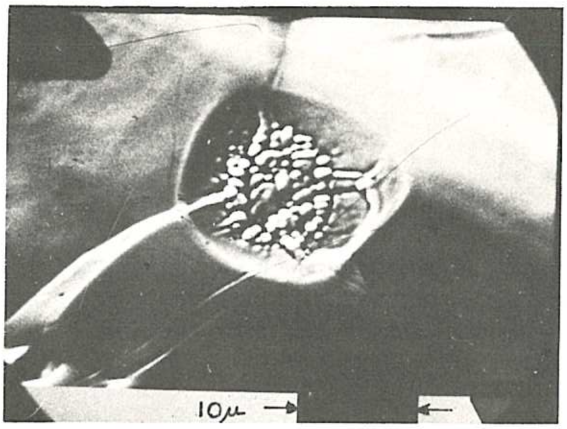


Fig.7 A "pebble" crater from the Mk II energy flux probe.

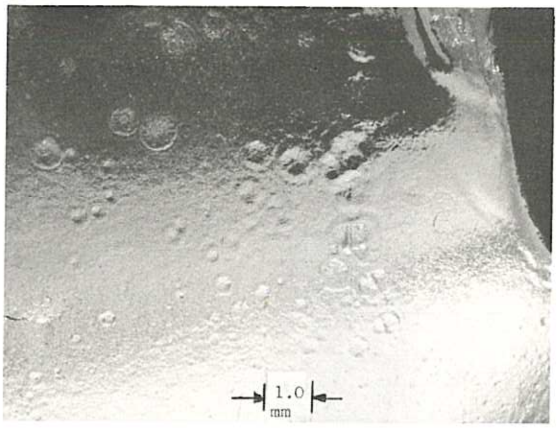


Fig.8 The large craters on the Mk II energy flux probe in the region indicated in Fig.9.

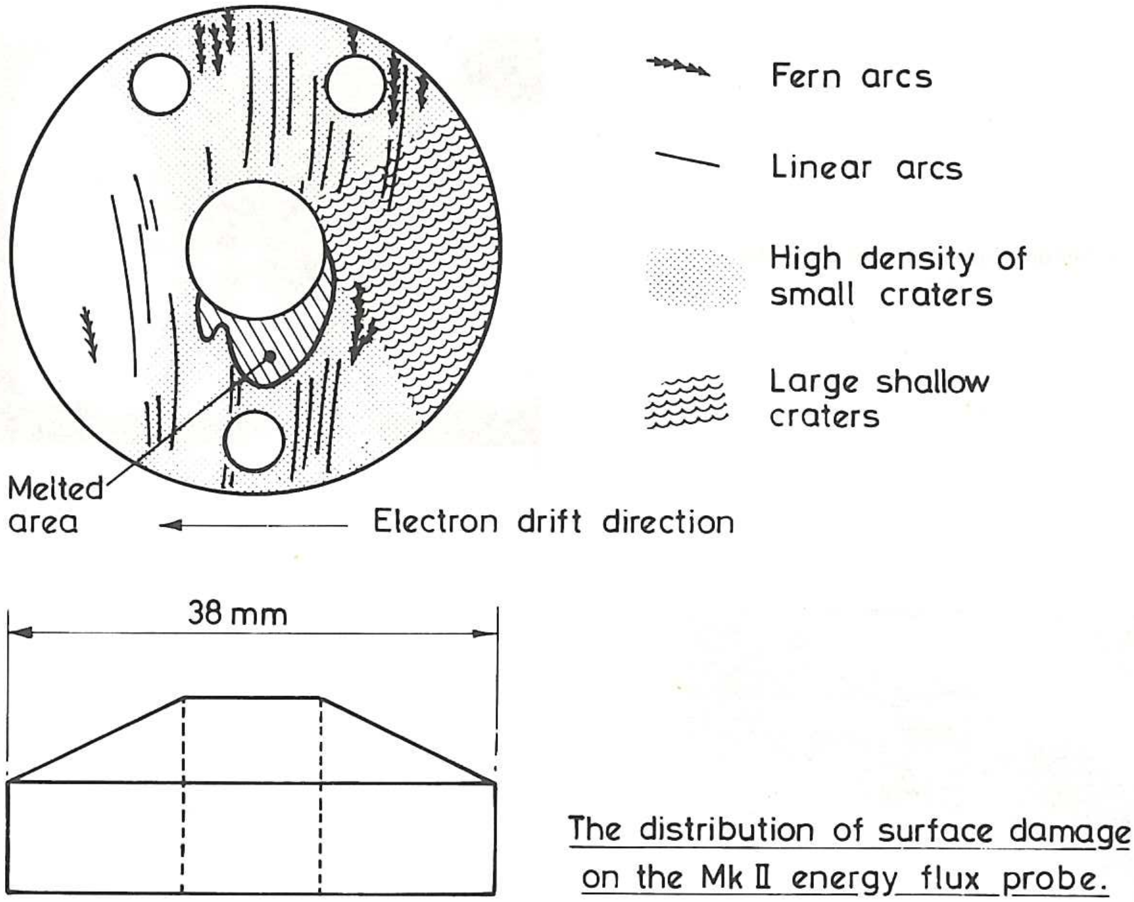


Fig.9 The distribution of surface damage on the Mk II energy flux probe.

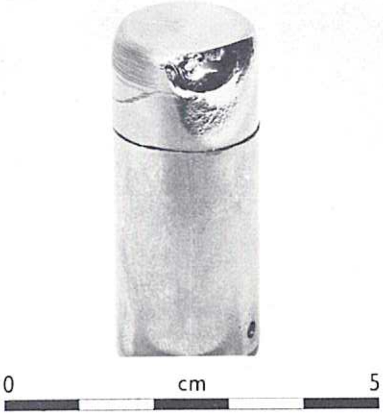
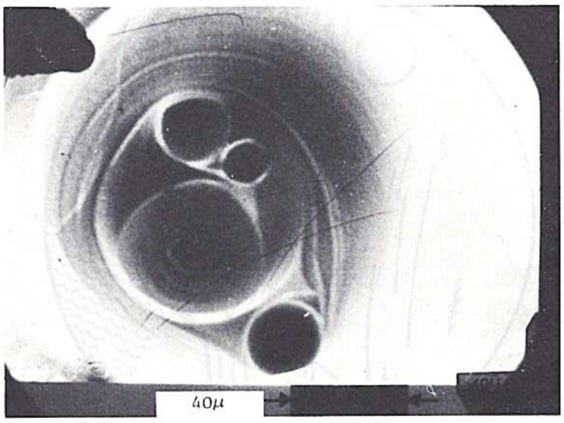


Fig.10 The B_p probe showing the melted region which faced the electron drift. The top of the probe has been separated from the stem for examination purposes.

Fig.11 Multiple holes from the B_p probe.



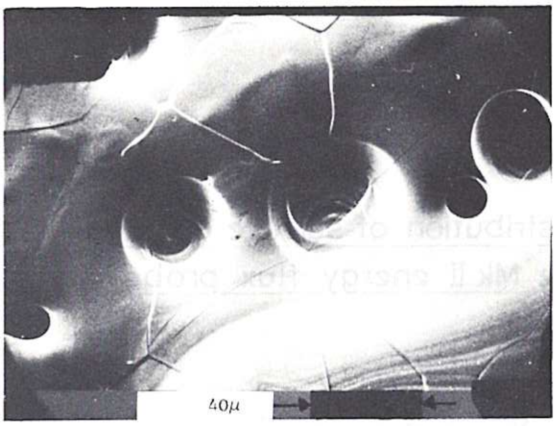


Fig.12 Holes with petal effect from the B_p probe.

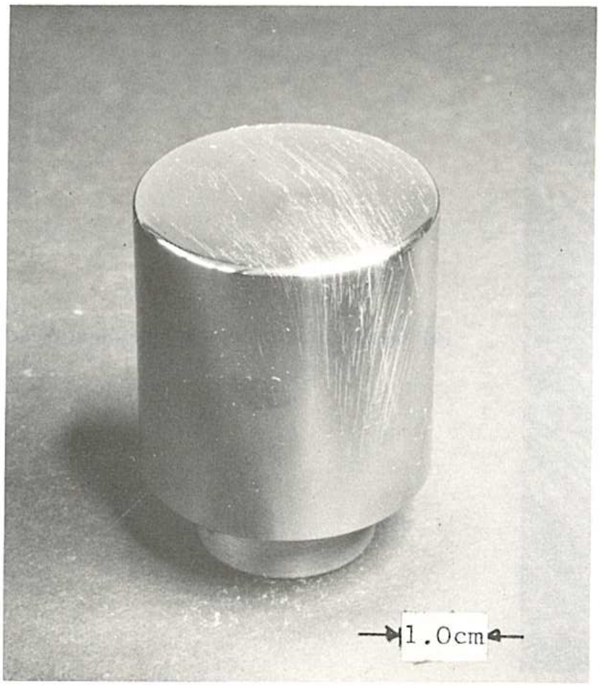


Fig.13 Arc test probe No.1, showing linear arcs on the side facing radially outwards.

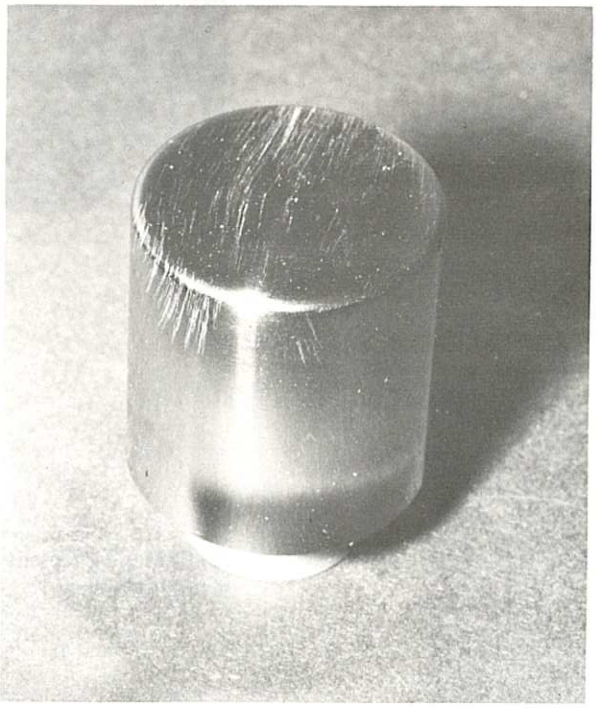
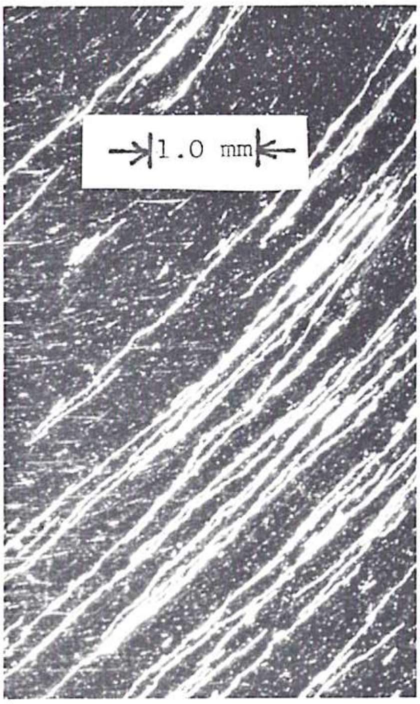
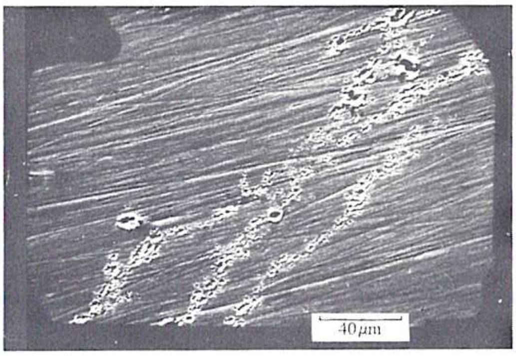


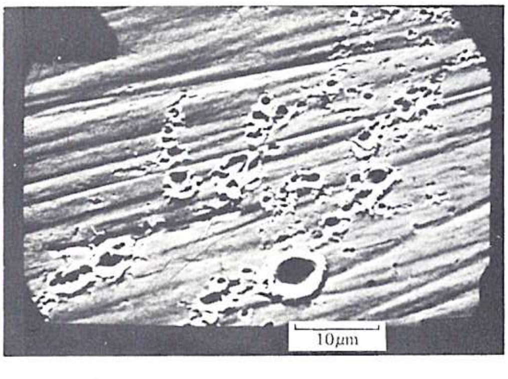
Fig.14 Arc test probe No.1, showing linear arcs on the side facing DITE centre.



(a) Optical microscope enlargement of arc tracks on flat face of probe.

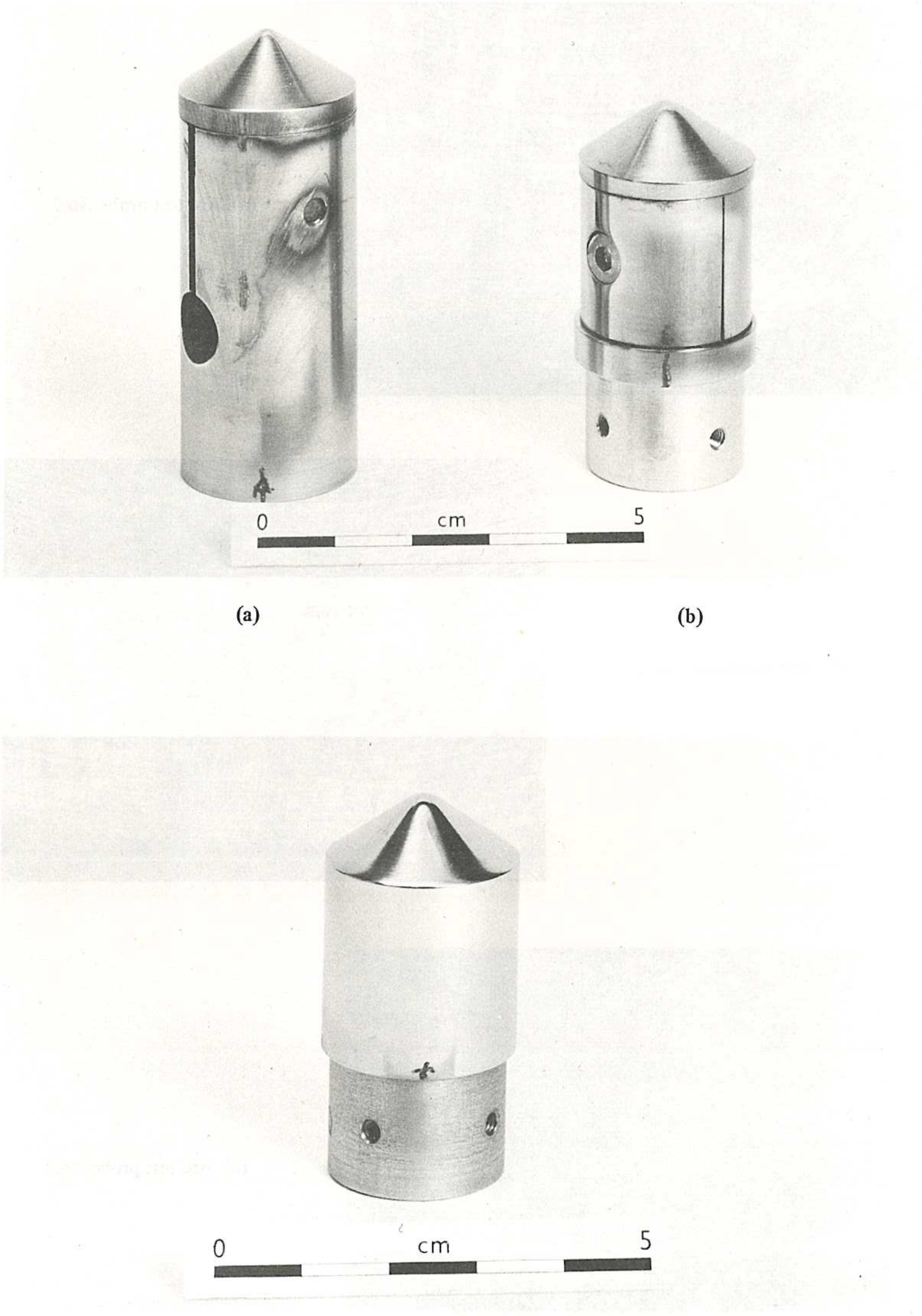
(b) SEM enlargement.





(c) SEM enlargement of the centre of the field of view shown in (b).

Fig.15 Details of the arc tracks observed on arc test probe No.1.

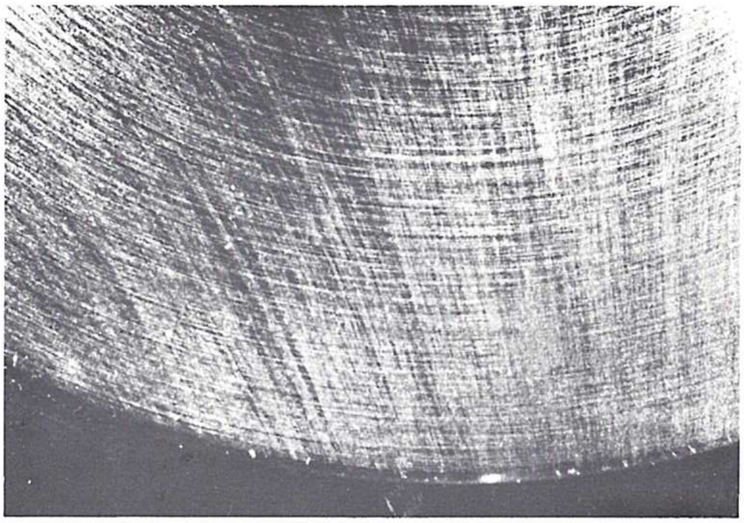


(a)

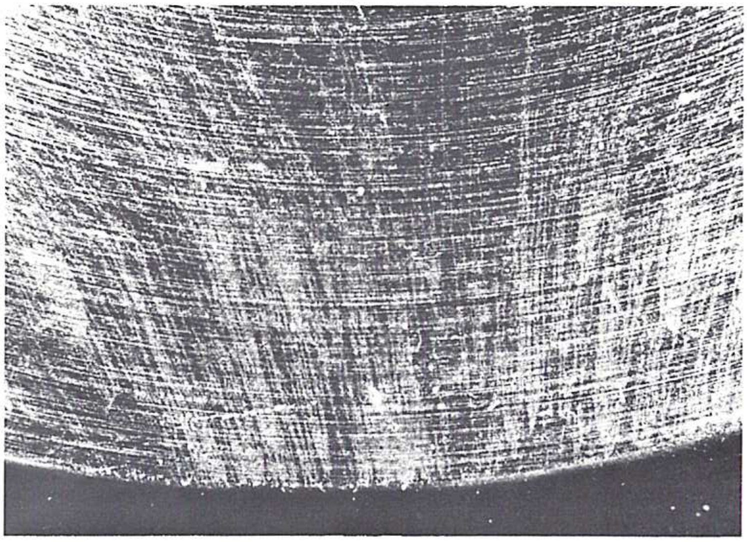
(b)

(c)

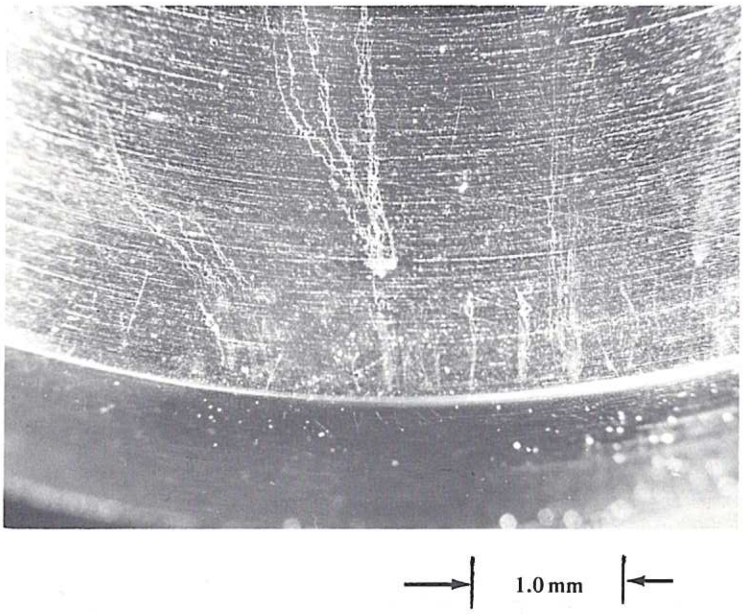
Fig.16 Arc test probes showing the side facing radially outwards, (a) No.2, (b) No.3, (c) No.4.



(a) Arc test probe No.2.



(b) Arc test probe No.3.



(c) Arc test probe No.4.

Fig.17 Arc tracks observed on arc test probes No.2–4 using low powered optical microscope. In all cases the region shown is part of the conical cap facing radially outwards from the centre of DITE.

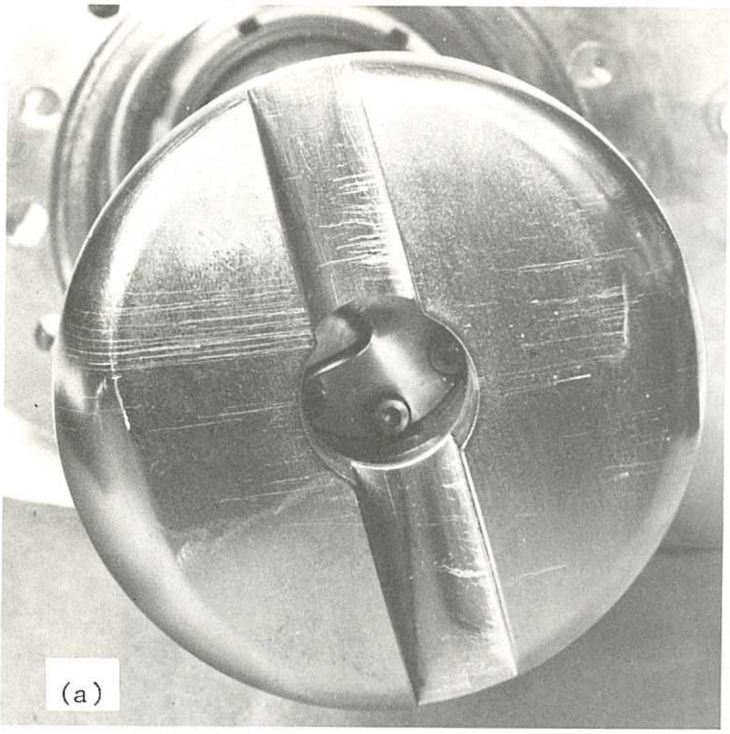
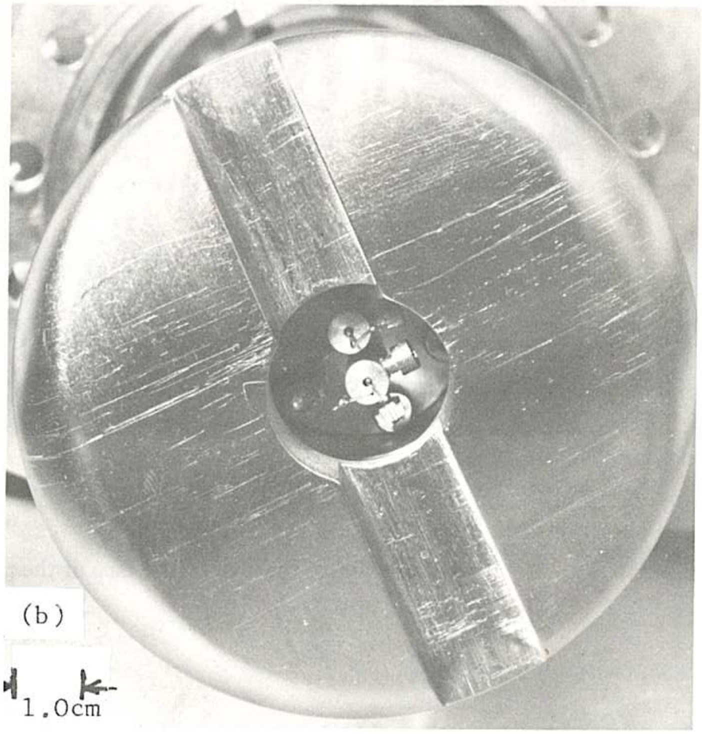


Fig.18a Limiter A from position 8/9.

Fig.18b Limiter B from position 1/16.



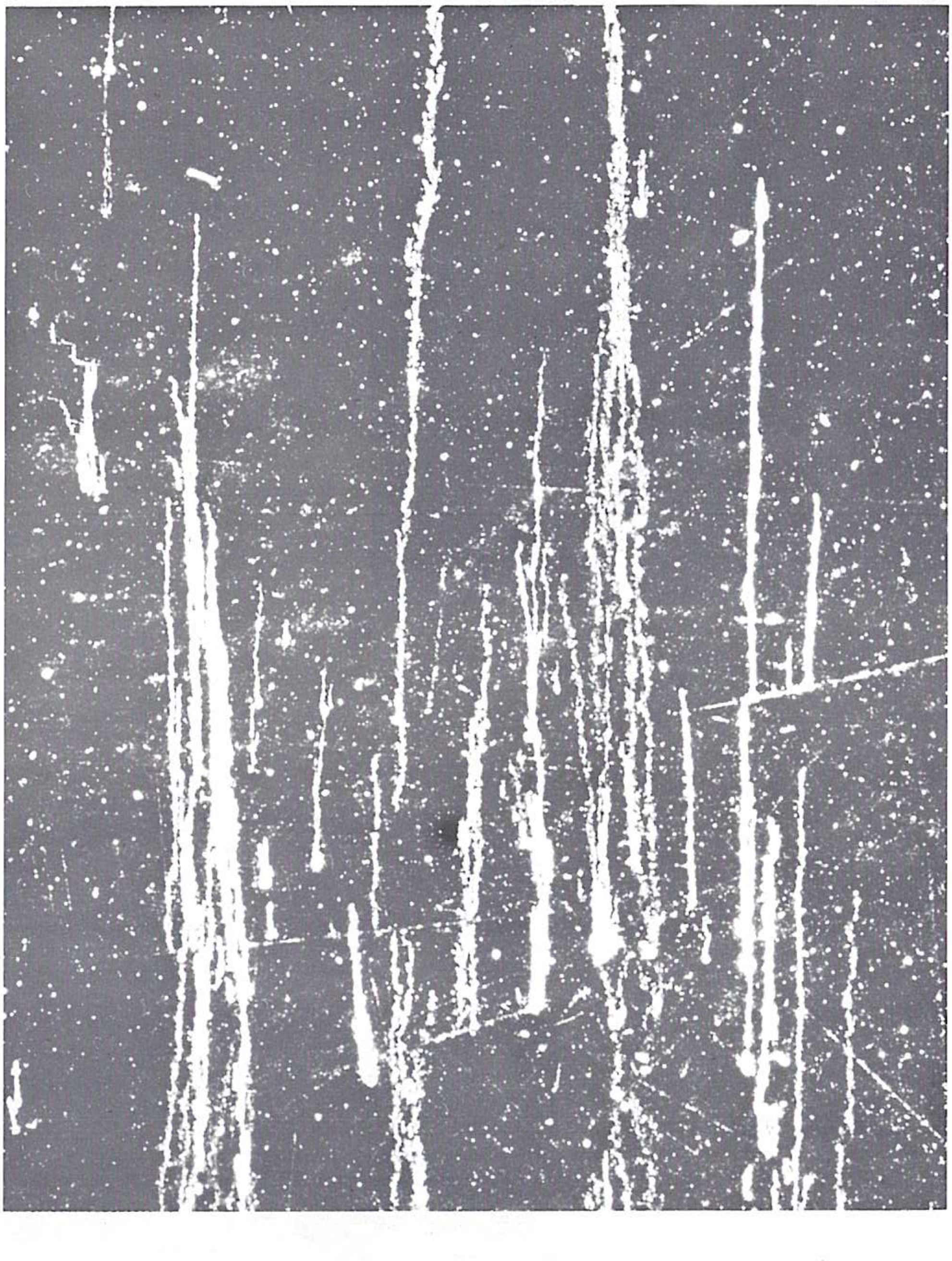


Fig.18c Details of the arcs on the face of the probe limiter shown in Fig.18(b).

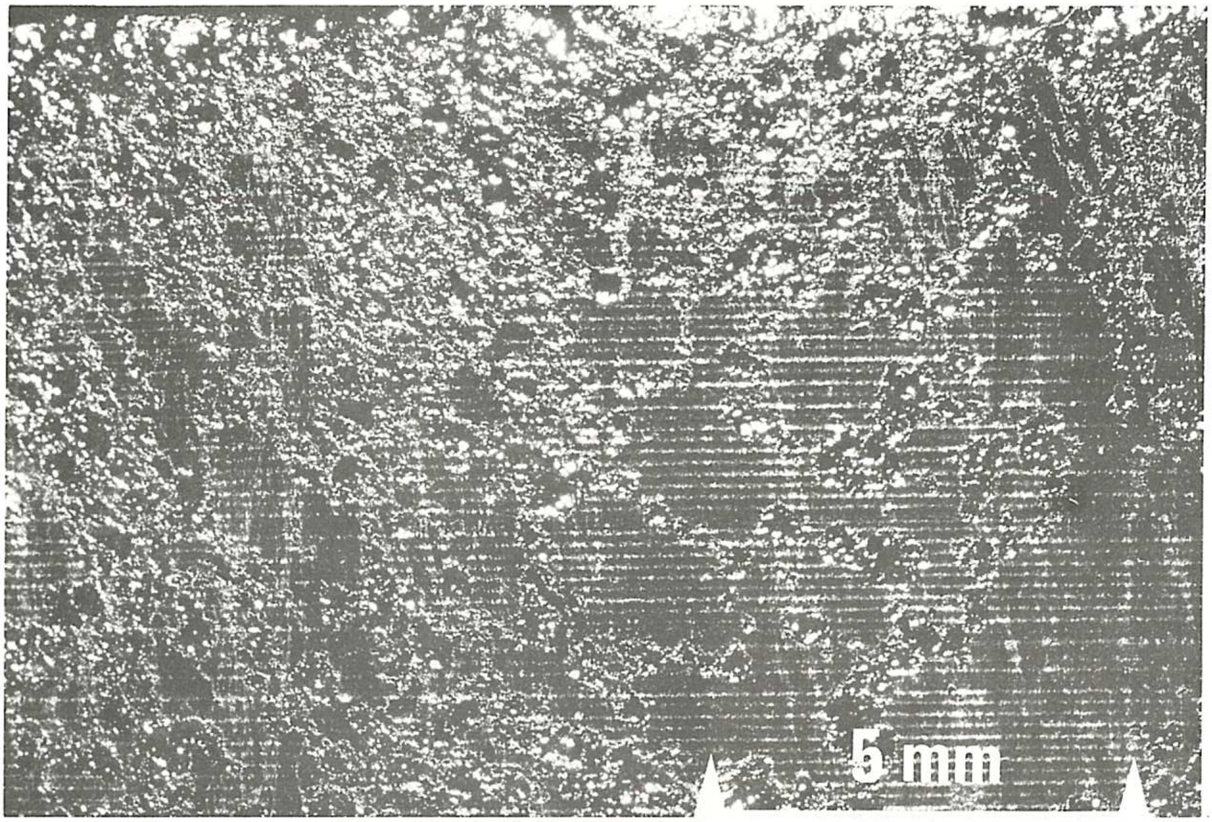
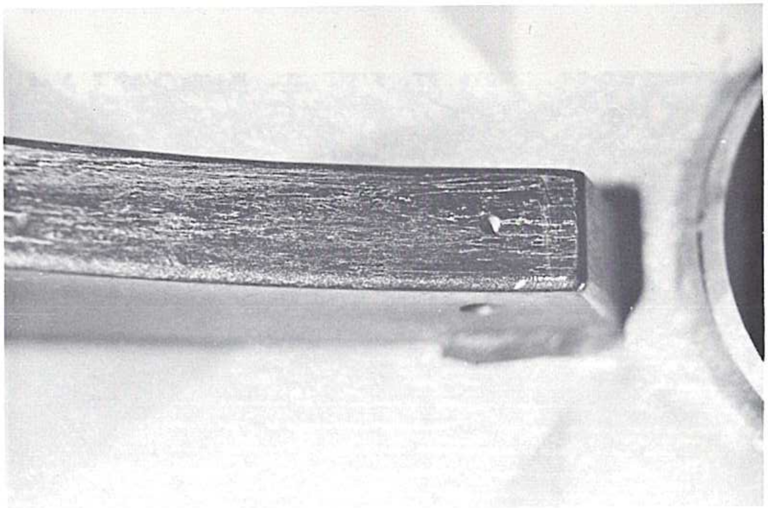


Fig.18d Details of arc damage on the support tube for limiter B.

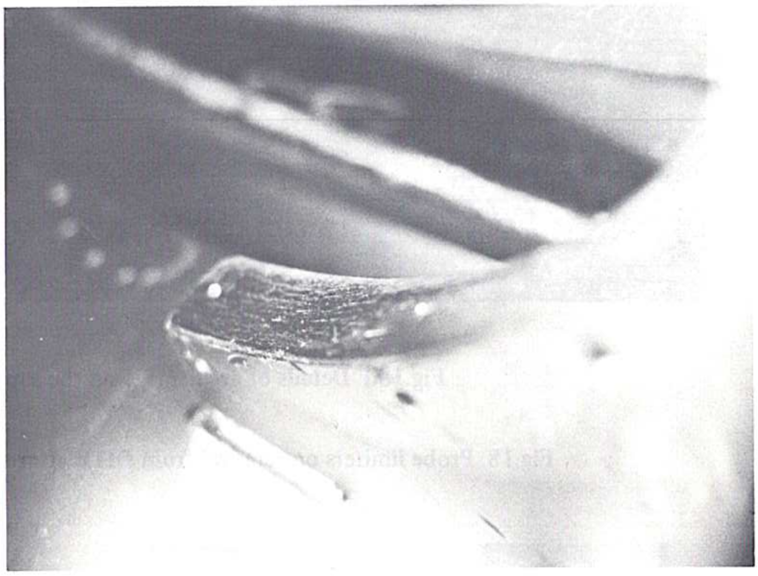
Fig.18 Probe limiters on removal from DITE after the phase 2 shutdown in May 1977.

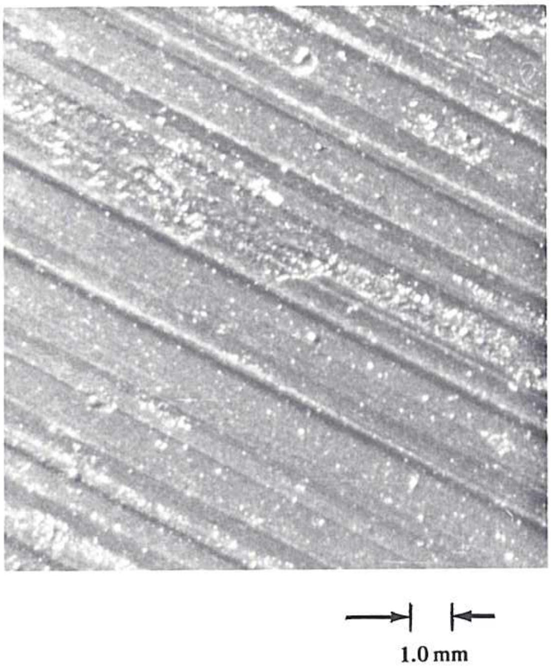
Fig.19 Surface damage to the centre of the outer fixed limiter in position 6/7. See also Fig.22.



(a) Lower inside rib position 8/9.

(b) Lower outside rib position 14/15.





(c) Details of arc tracks on lower outside rib position 3/4.

Fig.20 Surface damage to the support ribs inside the torus.

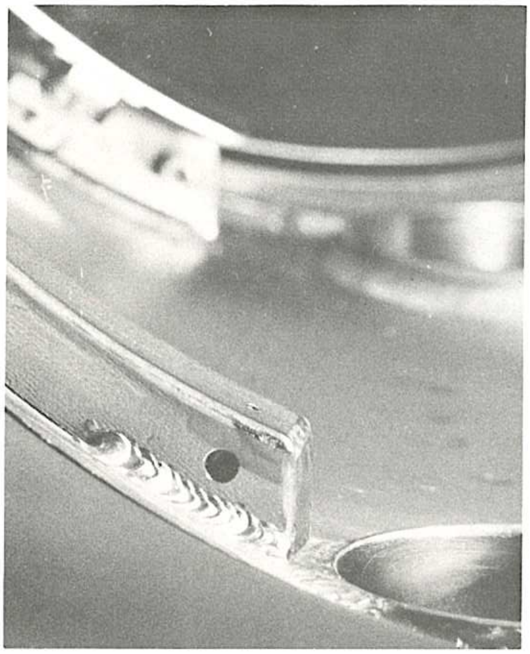


Fig.21 Lower inside rib position 7/8.

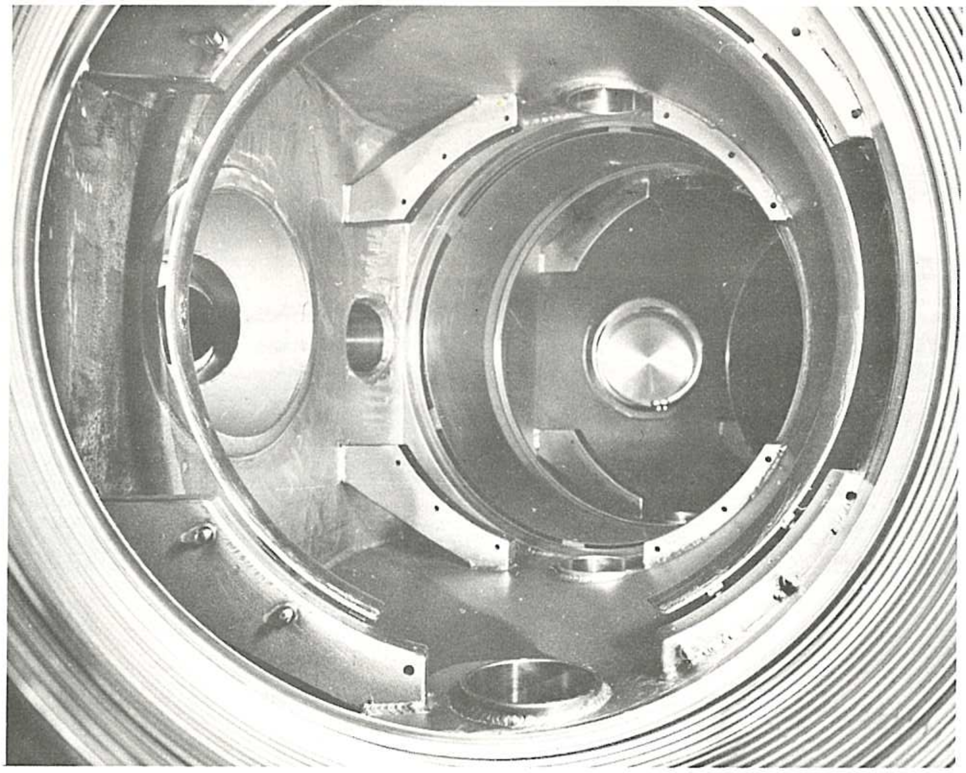
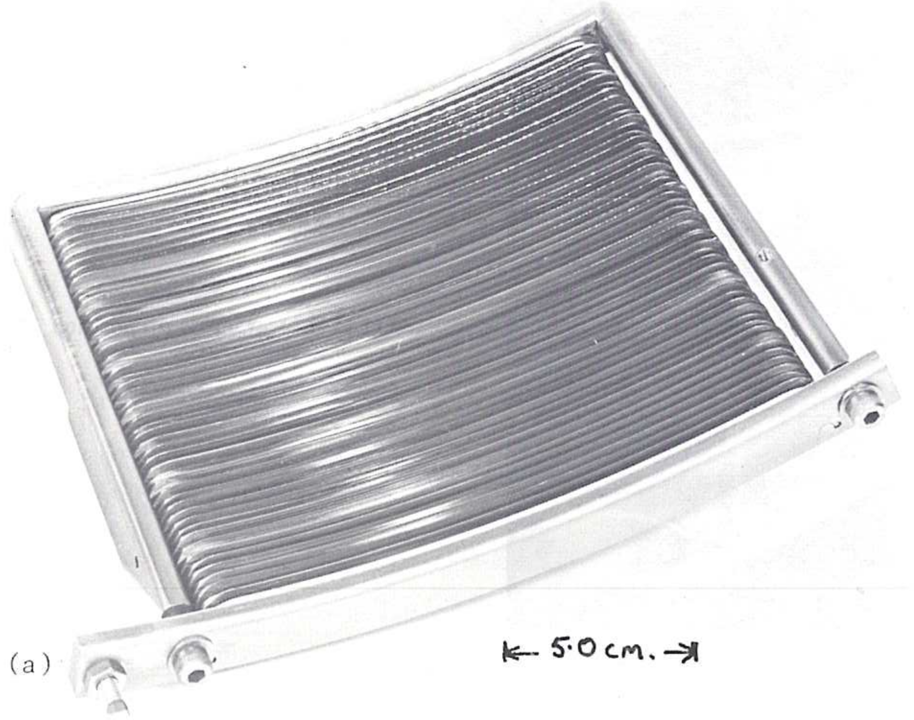
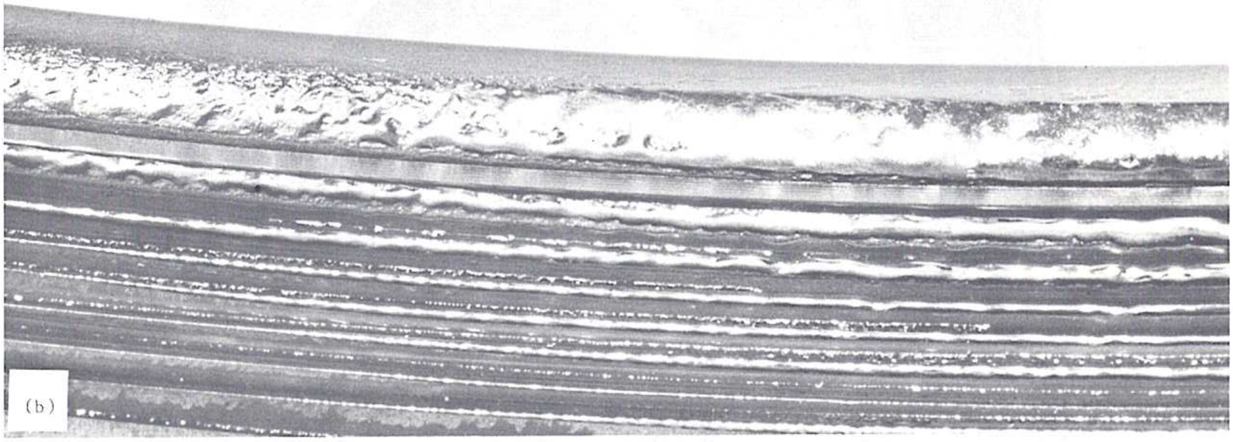


Fig.22 The fixed limiters between coils 6 and 7.



(a) General view of dump.



(b) Detail of the damaged region.

Fig.23 The viewing dump from position 2/3.

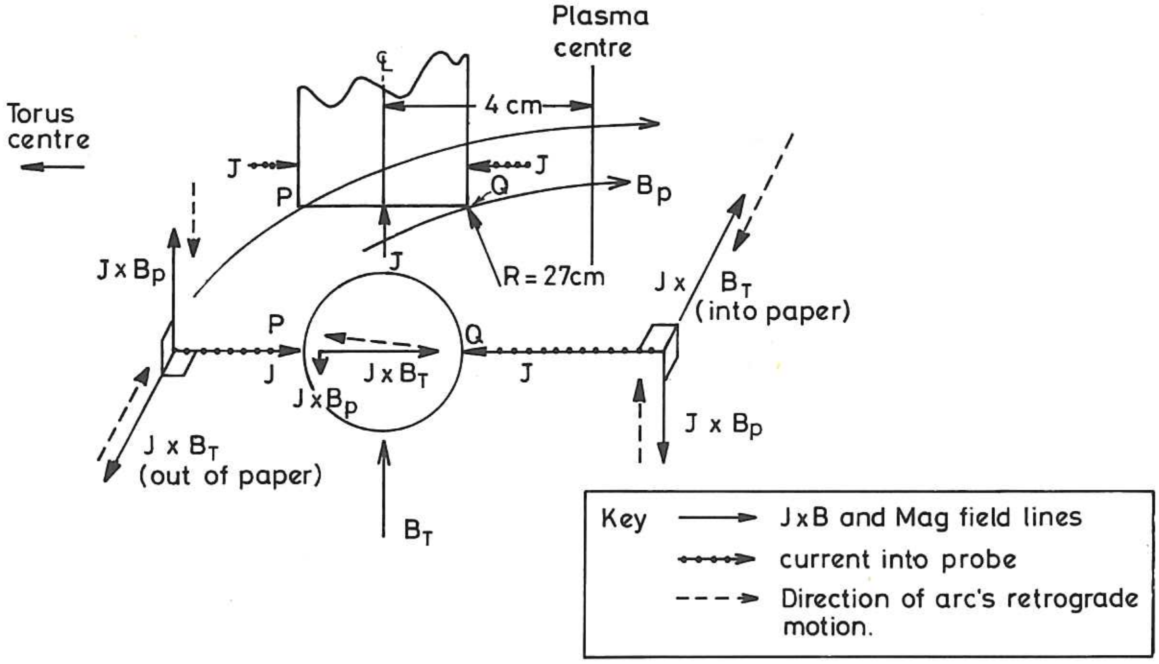


Fig.24 Schematic diagram of an arc test probe and the applied magnetic fields.

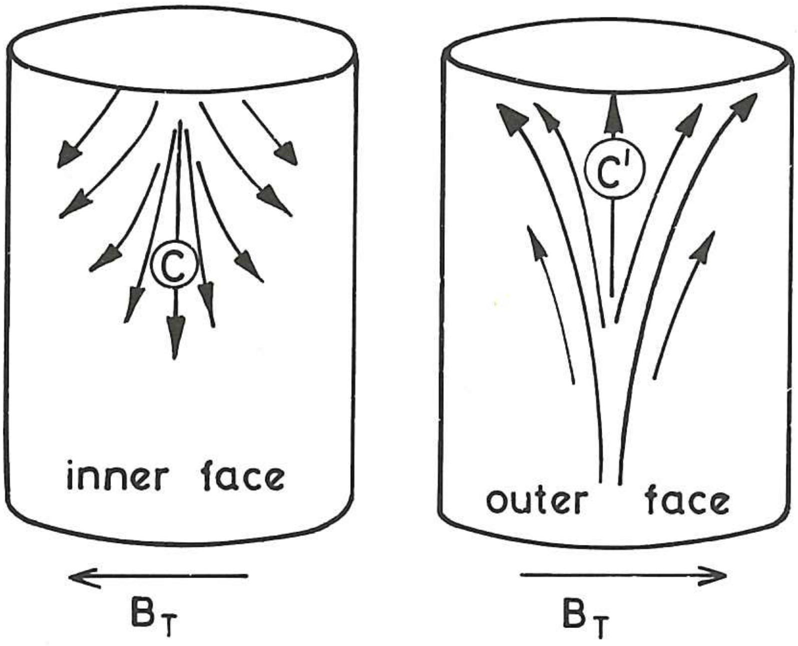


Fig.25 Schematic diagram of the arc tracks observed on the sides of cylindrical probes.

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