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Abstract

During the final deuterium-tritium phases of the TFTR and JET tokamaks half of the neutral injectors will be used to produce tritium neutral beams to maintain an equal mix of deuterium and tritium in the core plasma, and such requirements may also occur in future devices. This will require that the voltage hold off capabilities of the high voltage insulators in the accelerators be unimpaired by any charge buildups associated with the beta decay of adsorbed layers. We report tests in which we measured the drain currents under high voltage of TFTR and JET accelerator insulators while they were successively exposed to vacuum, deuterium and tritium. There did not appear to be any substantial reduction in hold off capability with tritium, although at some voltages there was a small increase in the leakage current. We also compared the breakdown properties of a plastic tubing filled with deuterium and then tritium at varying pressures, since such tubing has been considered as a high voltage break in the gas feed system for TFTR, and the presence of large numbers of electron-ion pairs might lead to enhanced Paschen breakdown. We found no significant differences in the behaviour for the geometry used.

I. Introduction

In the present generation of large tokamak fusion research devices, two are planned to operate with a deuterium-tritium fuel mixture during their final experimental phases. These two tokamaks are the Tokamak Fusion Test Reactor (TFTR) of the United States and the Joint European Torus (JET) of the European Economic Community. In the case of the JET device about half (15 megawatts) of the plasma heating power is supplied by neutral beam injectors, while in the case of TFTR the neutral beams supply the overwhelming majority (30 megawatts and more) of heating power to the plasma.

Neutral beam lines for tokamaks consist of ion sources (positive ions in present-day devices), electrostatic multi-aperture accelerator structures which extract ion beams, and conductance-limiting ducts which allow a portion of the accelerated ions to be neutralized through charge exchange reactions with gas molecules. These energetic neutrals then proceed down the beam line into the tokamak, while the residual unneutralized ions are magnetically deflected onto water-cooled dumps.

The large area ion sources which have been developed for magnetically confined fusion applications have been operated with the two lighter isotopes of hydrogen -- protium and deuterium, and occasionally with heavier gases such as helium, but never with tritium, which is unstable to beta decay. During the deuterium-tritium operation phases of TFTR and JET, half the beam systems (and their corresponding ion sources) will be run on tritium gas to produce tritium neutral beams. This is in order to maintain an approximately equal mixture of deuterons and tritons in the hot reacting core of the tokamak, where much of the plasma fuelling will arise from the beam themselves.

Inasmuch as there will be little or no opportunity to make significant changes to the beam system once the deuterium-tritium phases on these tokamaks have begun, the performance of the components must be tested in advance. The unknown behaviour during tritium operation of source components gave particular cause for concern. These are the high voltage insulators ,which separate the grids that are used to extract and accelerate ions from the source, and the insulating tube which supplies the gas feedstock to each ion source on TFTR. This tube also serves as the high voltage break between the gas system (which is at ground potential) and the source (which is at the acceleration potential of 120 kV for TFTR). In the case of the accelerator insulators, the loss of electrons from the surfaces of the insulators due to the beta decay of the tritium coating might lead to net positive charge accumulation on the insulators, this might in turn deleteriously affect the high voltage hold-off characteristics of the insulators. During source operation, these insulators will be repeatedly exposed to tritium at pressures of a few millitorr for periods of several seconds.

The concern with respect to the insulating break in the gas feed line was, that the large number of electron-ion pairs produced by ionizations from the beta particles might cause the tritium to breakdown electrically at a much lower voltage gradient than would have been the case with stable deuterium. The tritium pressure inside this insulating break would be about 500 torr during source operation.

We were unable to find any information in the literature on the high voltage behaviour of tritium-coated insulators or of tritium gas columns. Accordingly, we carried out the set of experiments described in this paper at the tritium test facility of the Sandia National Laboratory in Livermore.

II. Experimental Setup

The test was carried out inside a chamber which could be evacuated to a pressure of about 2×10^{-5} torr. At constant pressure the voltage across the test piece was increased and the drain current monitored until breakdowns occurred. The pressure was kept constant by feeding a constant flow of the test gas into the chamber. In the case of tritium the gas flow and the pumping speed was reduced in order to economise on the tritium consumption. Due to this reduced pumping speed with tritium, we observed occasionally a considerable increase in pressure during a breakdown and the run had to be terminated. Figure 1 shows the TFTR accelerator insulator structure which was tested. It consists of two epoxy insulators with polished electrodes and corona rings at each end and between the two insulators. On an actual TFTR source, the insulators are longer in the direction parallel to the electrodes. This dimension was reduced for these tests due to size constraints enforced by the test chamber; however, this reduction does not affect the field strengths across the insulator. High voltage could be applied across either the narrower gap (3.4 cm) or the wider gap (11.8 cm).

Figure 2 shows the JET insulator which was tested. It consists of an unglazed ceramic post, fitted with movable high voltage stress shields which allowed adjustment of the gap across which voltage was applied.

The tests of the insulating break for the gas feed system were conducted with a section of Tefcel^{R} tubing (1mm i.d.) which could be evacuated and filled with deuterium or tritium. The piece tested was 58 cm long. This was shorter than the length (about 120 cm) which would be used to feed gas to an actual TFTR source, but the length was chosen to accommodate the constraints imposed by high voltage clearance requirements within the test chamber. The ends of the tubing were terminated with stainless steel fittings, with one being grounded and the other supported by a high voltage insulator.

III. Experimental Results

A. TFTR Narrow Insulator

These tests were carried out by measuring the leakage current as the voltage across the insulator was varied from 0 to 30 kV (corresponding to an average gradient along the insulator of 8.8 kV/cm), and looking for differences when operating with different isotopes. The maximum DC voltage across this insulator during normal source operation is about 15 kV. The insulator was tested in vacuum, in 3 mtorr of deuterium, and in 3 mtorr of tritium. Even at 30 kV, there was no measurable leakage current in any of these cases.

B. TFTR Wide Insulator

The same tests were carried out with the wider TFTR insulator, which under normal source operating conditions has a maximum DC potential of about 105 kV across it. At voltages above roughly 90 kV combined with pressures above about 1.5 mtorr, we found that long path Paschen breakdown took place through the gas from the high voltage electrode to the chamber walls (which were grounded). Consequently, since these breakdowns were unrelated to the insulator, tests were carried out at pressures of 1.4 mtorr and below.

Figure 3 shows the leakage current plotted against applied voltages up to 105 kV with the TFTR long epoxy insulator in vacuum, prior to any hydrogen isotope exposure, and also under exposure to three pressures of deuterium. Figure 4 compares the leakage current as a function of applied voltage depending upon whether the insulator is immersed in 1.4 mtorr of deuterium or tritium. Up to a voltage of about 80 kV there is almost no measureable difference in the magnitude of the leakage current. At higher voltages the current in tritium is seen to be 10-15 microamps higher than in deuterium. This tended to occur as an abrupt increase in the leakage current at a voltage of 80-90 kV, after which the current in tritium continued to increase with voltage at the same rate as occurred with deuterium, but with the additional offset that had been incurred.

Figure 5 compares the leakage current obtained with the insulator immersed in 1 mtorr of deuterium or tritium. The first three voltage scans in tritium have leakage currents only slightly higher (2-3 microamps) than for deuterium at a given voltage. These scans were all taken prior to exposing the insulator to

1.4 mtorr of tritium. The fourth voltage scan in 1 mtorr of tritium was taken after the exposure to 1.4 mtorr of tritium. This fourth scan exhibits a somewhat higher current, almost identical to the scan with the insulator immersed in 1.4 mtorr of tritium.

Figure 6 compares the leakage current obtained in vacuum at the end of the tritium experiments with the leakage current in vacuum before the experiments started. At the end of the experiments the leakage current as a function of voltage in vacuum is essentially the same as it was while the insulator was immersed in tritium. This is presumably because there is still tritium remaining on the insulator.

C. JET Insulator

The voltage hold off of the JET ceramic insulator had been reduced down to 100 kV to match the voltage hold off of the test rig. The pressure in the test rig was limited to a maximum of about 5 mtorr by long path Paschen breakdown from the insulator to the vacuum box.

Figure 7 shows the drain current as the voltage is raised in vacuum and in deuterium at several pressures. The hold off voltage is about 90 kV (for an average field at the insulator of 60 kV/cm) and shows no significant variation with pressure within this range. Figure 8 shows a similar comparison between the JET insulator in vacuum before exposure to tritium, (we did not obtain a vacuum scan after tritium) and in various pressures of tritium. Figure 9 directly compares the currents with the insulator in similar pressures of deuterium and tritium. The leakage currents with tritium are very similar to those with deuterium, although there is a tendency for the currents to be slightly higher in tritium, as is the case with the TFTR long epoxy insulator. However, within the accuracy of these experiments it is difficult to say with certainty whether this tendency is indicative of a real difference in behaviour with tritium.

D. Gas Feed Insulating Break

The high voltage tests on this gas-filled tubing were limited by the voltage holding capacity of the test setup to potentials of 60 kV and less. The normal operating pressure inside this tubing during tritium source operation would be about 500 torr. Accordingly, we began voltage hold off tests with the tubing filled

with deuterium at that pressure, and we monitored the leakage current as the pressure was reduced in steps of roughly 50 torr until a discharge was initiated within the tubing (the light of which could be seen through the translucent tubing).

Until the point of breakdown, the measured leakage current was low (10 microamps at 60 kV), and was independent of pressure or which isotope was used. It appeared to be related primarily to conduction along the test fixture rather than through the gas column. Thus the most appropriate measure of the relative voltage holding capacity of deuterium and tritium is the one we have used -- the pressure at which a discharge is initiated inside the tubing.

The pressure was reduced to about 53 torr before breakdown occurred (as evidenced by the glow inside the tubing and a jump in the measured leakage current from zero to some value off scale on our meter). Since the step size was approximately 50 torr, this means that the critical pressure for this arrangement was between 53 and 104 torr (the previous step, at which no breakdown occurred).

In the case of tritium the volume filled with tritium had been minimized by removing all non-essential components including the pressure gauge. Starting with an initial filling pressure of 500 torr, the pressure was reduced by repeated expansion of the gas into a calibrated evacuated volume. Each expansion reduced the pressure to 92.9% of the previous value. At a constant pressure the voltage was brought up from 0 to 60 kV to check if a breakdown occurred. It is obvious, that with each expansion cycle the error in determining the pressure is increased due to accumulation of errors. Breakdown finally occurred after 44 expansion cycles corresponding to a pressure of 20 torr. The previous scan without breakdown had been done at 41 torr. Taking into account the uncertainty in determining the pressure we observe no significant difference in the breakdown behaviour of deuterium and tritium at least for tubular configurations of this aspect ratio in which the length of the gas column is much larger (by a factor 230 in this case) than its inner diameter. We estimate that the maximum potential gradient in this test was about 5 kV/cm.

IV Discussion

We have observed no differences which would require design changes for systems depending upon whether they were operating with deuterium or with tritium. This is true both with respect to the voltage holding characteristics of insulators transiently exposed to tritium, and with respect to breakdown in gas filled tubing. We have not studied the unrelated materials degradation problems which might arise from tritium permeation in epoxy if it were subjected to heavy long term exposure. Such operation is not planned for TFTR, and epoxy would not be used in future applications which might involve much greater tritium exposure. There does appear to be a tendency for the leakage current to be slightly higher on an epoxy insulator, and perhaps on a ceramic one as well, after exposure to tritium. However, this may constitute a minor advantage, since mildly leaky insulators distribute a voltage gradient more evenly.

These observations are important for planned tritium operations with the present generation of positive ion sources, and will be equally significant for the next generation of negative ion sources (many of which may be required to produce T^- as a precursor to T^0 for plasma fuelling to maintain peaked density profiles). In addition, these results should be of use to any broader applications involving high voltage in the presence of tritium.

Acknowledgements

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Figure Captions

(1) Diagram of the TFTR accelerator structure which was tested. The insulator material is epoxy.

(2) Diagram of the JET unglazed ceramic post insulator with stress shields.

(3) Measured leakage current of the TFTR long epoxy insulator in vacuum before hydrogen isotope exposure, and under exposure to three pressures of deuterium.

(4) Leakage current of the TFTR long epoxy insulator in 1.4 mtorr of deuterium or tritium.

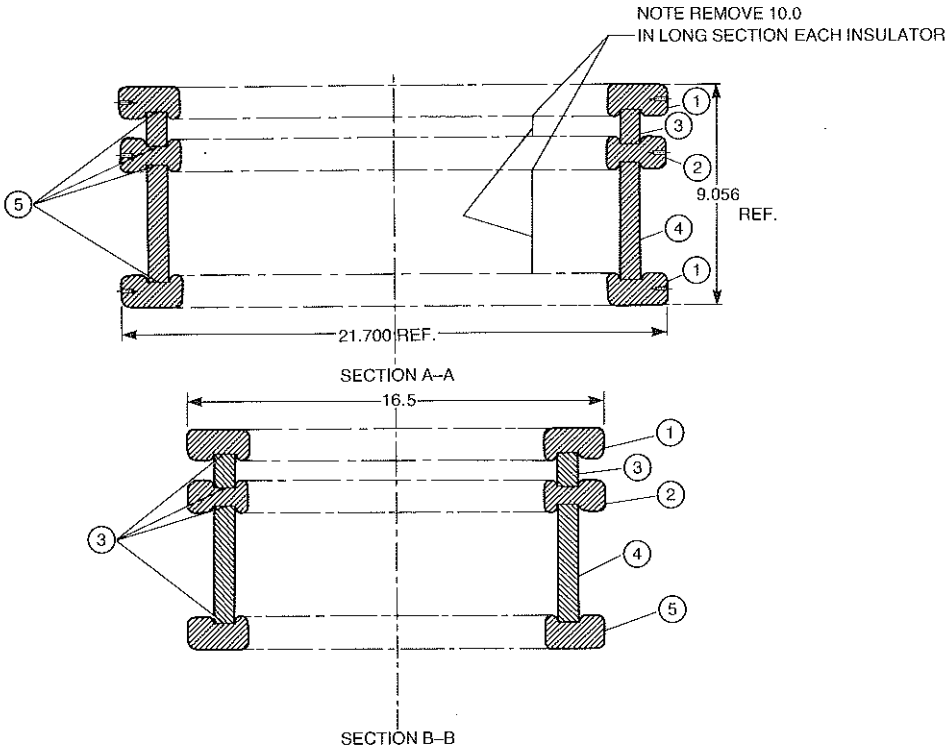
(5) Leakage current of the TFTR long epoxy insulator in 1 mtorr of deuterium or tritium.

(6) Leakage current of the TFTR long epoxy insulator in vacuum before and after exposure to deuterium and tritium.

(7) Leakage current of the JET unglazed ceramic post insulator in vacuum and in several pressures of deuterium.

(8) Leakage current of the JET unglazed ceramic post insulator in vacuum and in several pressures of tritium.

(9) Leakage current of the JET unglazed ceramic post insulator in similar pressures of deuterium or tritium.



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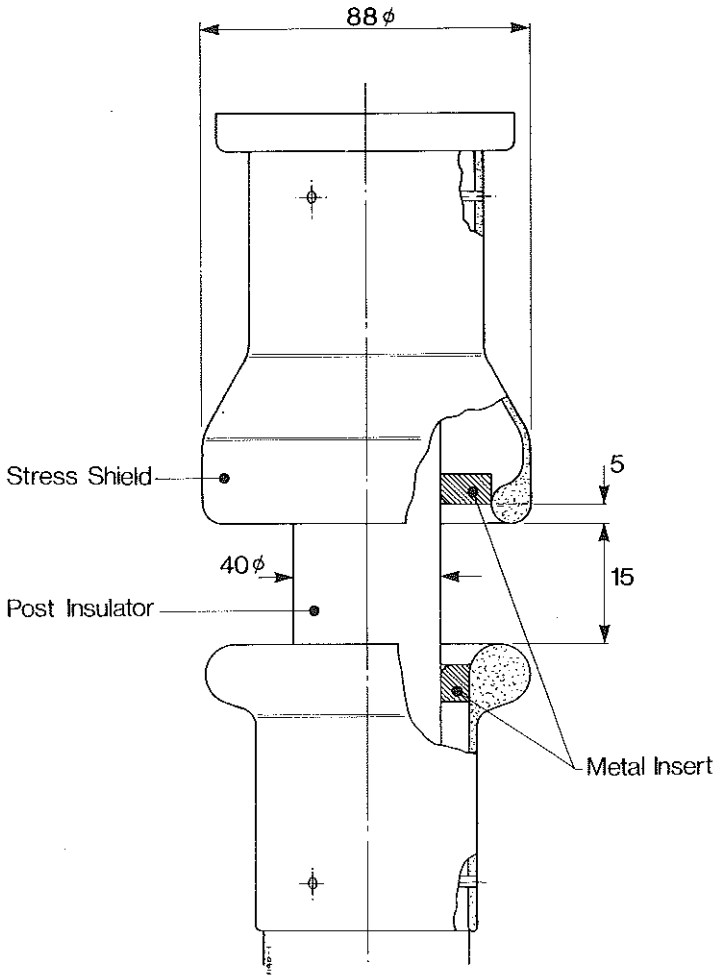
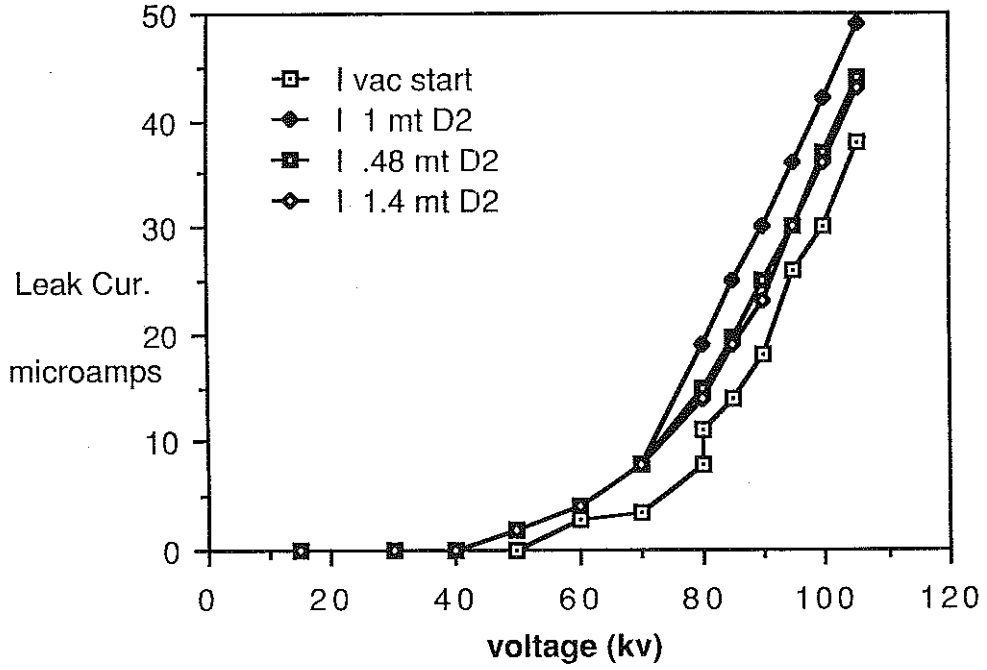
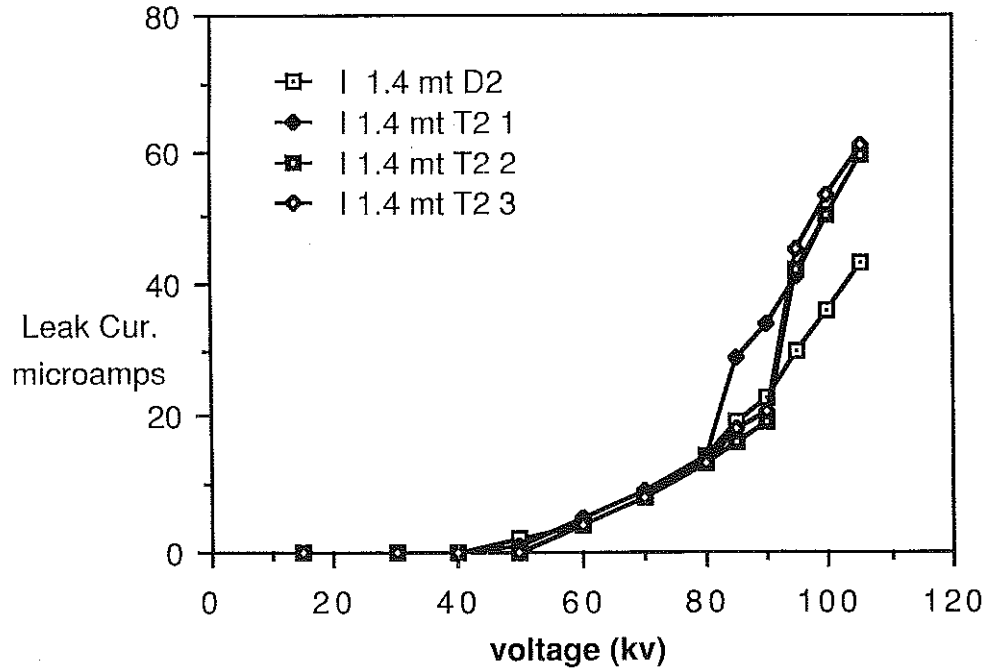


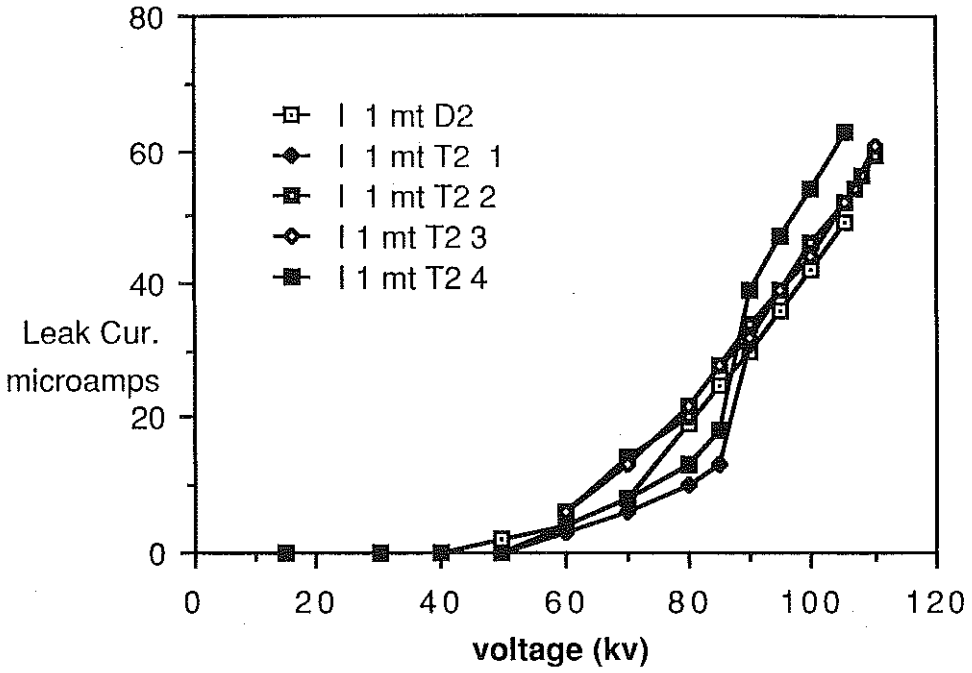
(2) Diagram of the JET unglazed ceramic post insulator with stress shields.



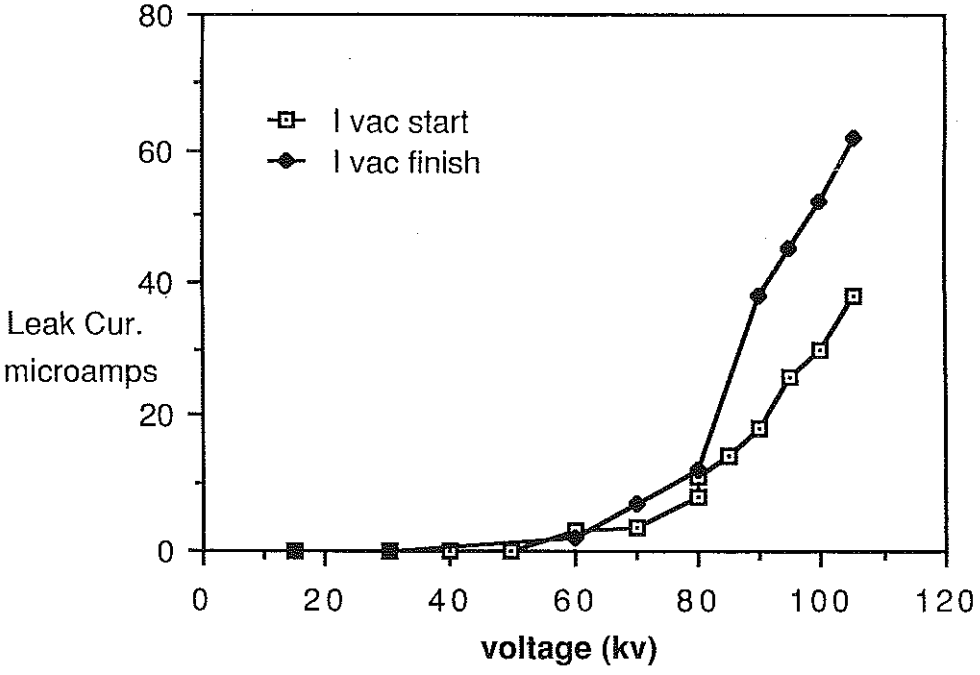
(3) Measured leakage current of the TFTR long epoxy insulator in vacuum before hydrogen isotope exposure, and under exposure to three pressures of deuterium.



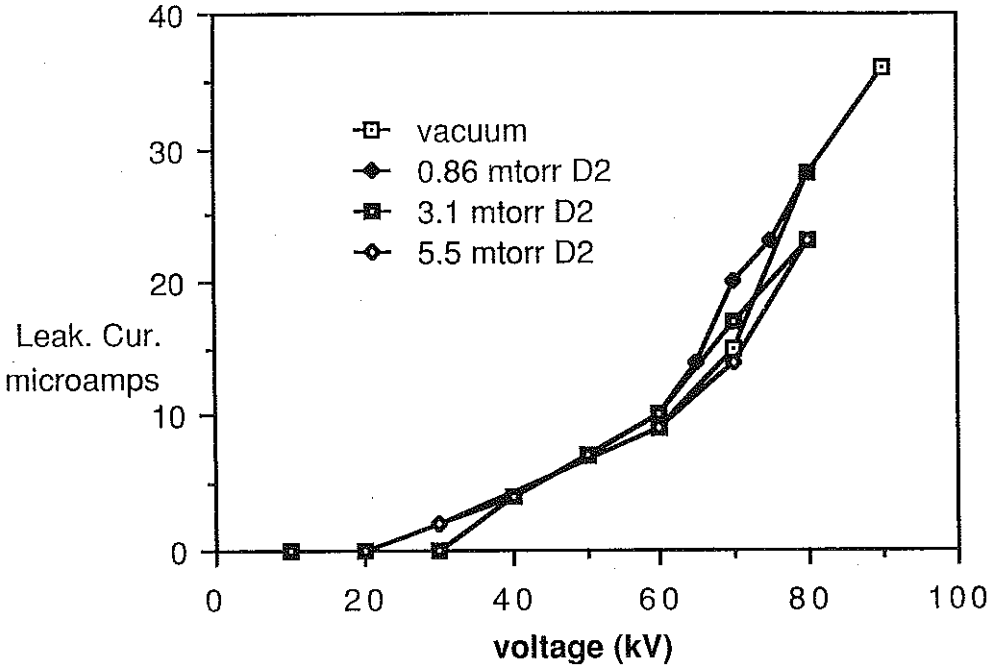
(4) Leakage current of the TFTR long epoxy insulator in 1.4 mtorr of deuterium or tritium.



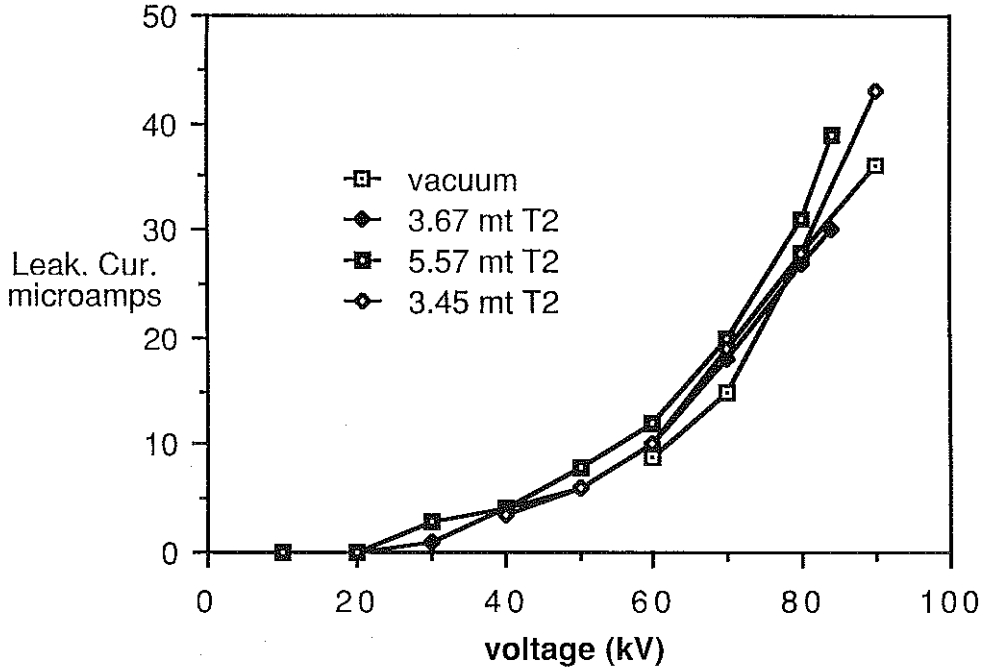
(5) Leakage current of the TFTR long epoxy insulator in 1 mtorr of deuterium or tritium.



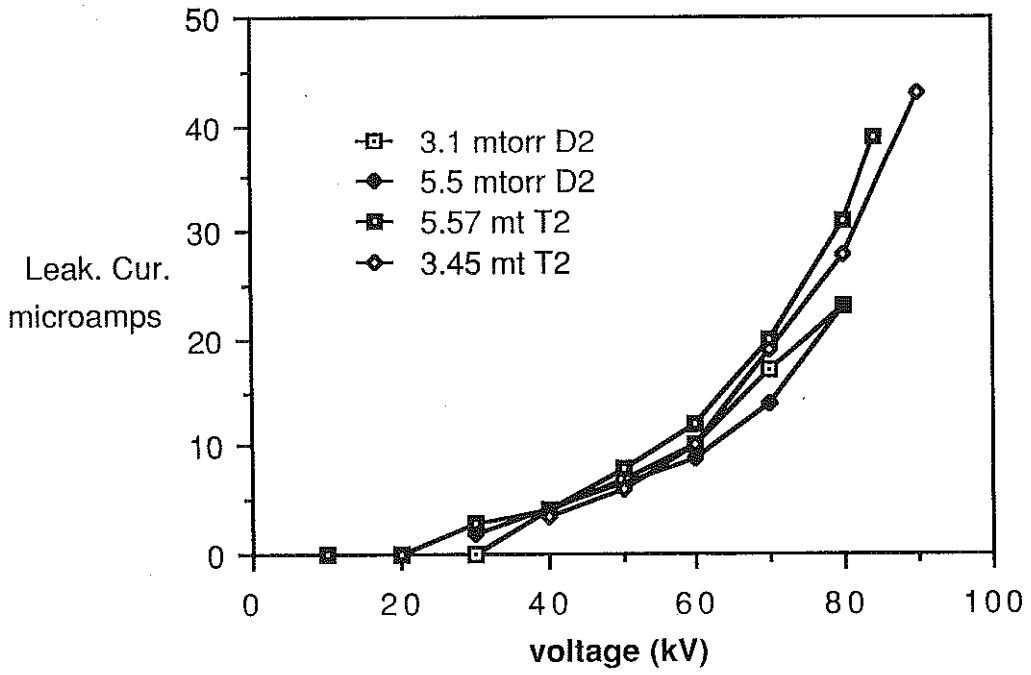
(6) Leakage current of the TFTR long epoxy insulator in vacuum before and after exposure to deuterium and tritium.



(7) Leakage current of the JET unglazed ceramic post insulator in vacuum and in several pressures of deuterium.



(8) Leakage current of the JET unglazed ceramic post insulator in vacuum and in several pressures of tritium.



(9) Leakage current of the JET unglazed ceramic post insulator in similar pressures of deuterium or tritium.

APPENDIX 1.

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