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Author(s): R. P. Heydt and R. H. Eustis

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PERFORMANCE OF ROD ELECTRODES IN SEGMENTED FARADAY GENERATORS

R. P. Heydt and R. H. Eustis
High Temperature Gasdynamics Laboratory
Stanford University
Stanford, California 94305

ABSTRACT

The electrical performance of rod electrodes is being studied. Although previous experimental measurements have shown only moderate increases in insulator breakdown voltages with rod electrodes, rod electrodes may be preferable to conventional flat electrodes because insulator breakdown can be effectively suppressed with very limited additional cooling. Thresholds for plasma-initiated breakdown thus become important in determining axial field limitations in a rod electrode generator. Measurements of applied field plasma breakdown were made on flat and rod electrodes in the Stanford M-2 generator. With zero magnetic field the qualitative behavior of rod and flat breakdown gaps was the same. Applied Faraday current reduced plasma breakdown thresholds by 20% on anode gaps and 50% or more on cathode gaps. The breakdown voltages increased in the presence of magnetic field, probably because of movement by the Lorenz force of the axial arc on the electrode surface. With applied Faraday current and magnetic field, both rod and flat cathode gaps showed a strong decrease in axial interelectrode resistance with increasing applied fields, although no clear breakdowns were observed. Anode plasma breakdowns were observed, with rod breakdown voltages 20% and 50% higher than flat at two axial locations. An analytical study of steady-state rod electrical performance has been undertaken. Predictions of rod current distribution correspond reasonably well with experimental measurements. Preliminary calculations of large channel plasma resistance show that flat and rod transverse resistances are approximately the same. More accurate calculations are planned.

INTRODUCTION

Transverse rod electrodes have the potential of improving aspects of the overall performance of linear open cycle MHD generators. Previous experimental measurements [1] have shown that current is distributed more uniformly on a rod electrode (Figure 1) than on a conventional flat electrode flush to the generator wall. This is especially important at high Hall parameters for which current concentrates strongly at flat

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electrode edges. The combined rod electrode characteristics of a more uniform current distribution and the geometric advantage of electrode contact with the interelectrode insulator only along the generator sidewall, should make a rod electrode generator more resistant to (insulator-initiated) Hall field breakdown. The ability to withstand high interelectrode fields without breakdown has important consequences for power output and generator component lifetime. In addition, an increased resistance to axial field breakdown may allow an increase in electrode pitch, and hence a reduction in the complexity of segmented Faraday generator construction and the number of electrical connections.

Insulator-initiated breakdown is the primary breakdown mode except in generators with very narrow (and hence inherently well-cooled) interelectrode insulators [2,3,4]. Reference 1 reports results of breakdown measurements made in the Stanford M-2 channel on both flat and rod electrodes (1.9 cm. length, 3.8 cm. pitch). For both electrode types insulator breakdown threshold voltages were lower than plasma-initiated thresholds by from a few percent to as much as 50%. A post-test channel inspection showed that the rod insulator breakdowns had clearly occurred along the sidewall interelectrode insulator. The applied field breakdown voltages (B=0) with the rod electrodes were in a range from approximately the same to 30% higher than the flat electrode breakdown voltages.

Despite the fact that these experiments showed a relatively small improvement in insulator breakdown with rod electrodes, there is good reason to believe that a rod electrode configuration is a much better choice with regard to Hall field breakdown. Large scale MHD generators must be designed both to prevent interelectrode breakdown and to minimize damage if a breakdown occurs. In a rod electrode channel, if an insulator arc forms it is pushed along the sidewall by the Lorenz force. A flat electrode arc on the anode side of the generator is driven directly into the interelectrode insulator. Both cases can result in insulator damage, but in the experiments run at Stanford the cumulative damage from several breakdown measurements to the flat electrode insulators was much more severe, with some flat insulators almost completely destroyed.

A second and more important reason for considering rod electrodes is related to insulator cooling. It seems likely that flat electrode generators will require cooled interelectrode insulators to withstand the large axial fields (5 to 10 Kv/m across the electrode gaps) associated with high Hall parameters and current densities [4]. These cooled insulators must extend the entire channel width (up to 1 meter). In contrast, if insulator cooling is necessary in a rod channel, it can be limited to only that portion of the sidewall insulator in the immediate vicinity of the rod. This might result in an important simplification of the channel design and reduced heat loss.

This line of reasoning, along with the fact that insulator-initiated breakdown behavior is somewhat channel-specific and insulator property dependent (the insulators for the M-2 experiments were magnesia), has led to a shift in focus from insulator to plasma-initiated breakdown. Plasma breakdown thresholds become important under the assumption that insulator breakdown must be suppressed with any electrode geometry. The relative ease with which this can be done in a rod electrode channel makes plasma breakdown the predominant breakdown mode and the threshold voltages for plasma breakdown become an important characteristic of a rod generator.

This paper presents results of recent plasma breakdown measurements on rod and flat electrodes in the M-2 channel. In addition, some preliminary analytical results on the steady state (i.e. pre-breakdown) current distribution and plasma resistance of a large-scale rod electrode generator will be presented.

PLASMA-INITIATED BREAKDOWN

Experimental Procedure

Applied field breakdown measurements were made in the Stanford M-2 channel on both flat and rod electrodes. The two types of electrodes were mounted on opposite sides of the channel (Figure 2) to allow comparative measurements at the same axial location. Electrode length (in the flow direction) and pitch were the same for both the rod and flat electrodes (1.9 cm. and 3.8 cm., respectively).

The experiments were run at a mass flow rate of m = 0.068 Kg/s, flow velocity u = 180 m/s, and plasma temperature of approximately 2700°K. The core conductivity was 9 mho/m based on equilibrium calculations, with a value of 7.5 mho/m deduced from channel voltage profiles.

Data from the measurements in Reference 1 showed that the initiation time for insulator breakdown in this channel was on the order of one second or more. In order to allow the onset of plasma breakdown only, a computer-controlled relay circuit was used to apply axial voltages across adjacent electrodes for periods of 400 msecs. The plasma breakdowns were observed to have characteristic times of a few milliseconds, and would generally occur within 150 msecs after the voltage was applied.

Breakdown thresholds were measured at two axial locations within the channel for each type of electrode. Two sets of measurements were made. In the first set applied field plasma breakdown behavior was measured with Faraday current augmentation but no magnetic field. During the second set both Faraday current and magnetic field (B=2.5T, β=1.2) were applied. For all the breakdown runs, voltages were applied with the downstream electrode of each pair having positive polarity.

Applied Field Plasma Breakdown Results

Figure 3 shows plasma breakdown thresholds with zero magnetic field for the flat and rod electrodes, for the three cases of zero Faraday current augmentation and Faraday current augmentation with the breakdown electrodes operating as either anodes or cathodes. With no Faraday current the observed breakdown voltages were 258 volts for the flat and 286 volts for the rod gap (200 volts is equivalent to an axial field of 5.25 Kv/m in the generator core or 10.5 Kv/m across the interelectrode insulator). This difference in plasma breakdown thresholds corresponds to the lower end of the range observed in the experiments of Reference 1 in which the rod gaps broke down at voltages from 10% to 40% higher than the flat gaps over a range of run conditions.

The effect of Faraday current on breakdown is qualitatively identical for the two electrode types. In each case the current augmentation (I_f=10 amp, $j_{y,core}$=0.8 amp/cm^2) decreases the axial interelectrode resistance by means of Joule heating in the near-electrode region. The threshold for plasma breakdown decreases as the steady state (i.e. non-breakdown) axial resistance decreases, indicating a probable correlation of breakdown voltage and power dissipation. For both rods and flats, electrodes operating as cathodes showed a very noticeably stronger effect of Faraday current. This may be due to different numbers or a different distribution of Faraday current attachment sites on the electrode surface in the anode and cathode modes. The axial current arc will attach at existing points of Faraday current attachment. If the Faraday current is concentrated at fewer sites on the electrode surface, plasma breakdown will occur at lower interelectrode voltages. It should be noted that the electrode surface temperatures were fairly low: 970°K on the flat and 870°K on the rod. The Faraday current would not likely be diffuse at the electrode surfaces, a factor which would tend to minimize the effect of flat and rod current distribution differences on plasma breakdown.

The results of experiments run with magnetic field are shown in Figure 4. These data, like the previous data, represent breakdown potentials under applied axial fields for a fixed level of Faraday current (again 10 amp). Figure 4 shows data only for the rod breakdown gap. As with the B=0 data, the nonzero B field data for the flat and rod electrodes were qualitatively the same.

It was found that the presence of magnetic field always raised the thresholds for applied field breakdown. This can be attributed to movement by the Lorenz force of the axial current arc on the electrode surface. This effect appears to outweigh the effect of Faraday current Joule heating, at least for this level of Faraday current . As before, however, the presence of Faraday current does decrease the axial interelectrode resistance, as evidenced by movement of the load lines to the right of the B=0, Faraday current = 0 load line.

No clear breakdowns were observed in the cathode mode for either the rod or flat gaps at this axial location. As the applied voltage was increased the axial resistance decreased very sharply. In the cathode mode for both electrode types axial arcs are pushed toward the warm plasma core, allowing very large currents to flow before breakdown is initiated in the near electrode region. The interelectrode resistance was stable at approximately 3 ohms at the last data point on the graph.

No further measurements were taken for fear of damage to the channel.

The qualitative behavior of rod and flat anodes was also similar, however the breakdown voltages were higher on the rod side. Figure 5 shows anode data at the upstream and downstream rod and flat electrode gaps. The thresholds for rod plasma breakdown are higher by approximately 20% and 50%, respectively. This may reflect a partial quenching of anode arcs in the relatively cool plasma region between rods as the arcs are driven by the Lorenz force toward the electrode wall.

CURRENT DISTRIBUTION AND PERFORMANCE MODELING

An important concern relating to a rod electrode configuration is its effect on the steady state performance of a large generator. It is clear that a set of rod electrodes raised away from the wall will increase the electrode wall drag. Estimates of the drag were made in Reference 1 and it was reported that the drag increase could be minimized by streamlining the rods.

The effect of rod electrodes on the steady state electrical performance is of equal, if not greater, importance than the effect on the fluid mechanics. Current distribution on the rods will be more uniform than on flat electrodes. It is of interest to study how the improved distribution and the rod geometry will affect the (transverse) plasma resistance. In addition, if rod electrodes can be used to successfully suppress axial field breakdown, it will be important to study the effect on plasma resistance of an increase in electrode spacing. Fewer electrodes are desirable both for simplicity in channel design as well as for a reduction in the number of connections to electrical inverters.

Computer Model

A computer code has been developed to predict the current distribution and plasma resistance in a rod electrode channel. The code solves the MHD electrical equations with the use of a conformal mapping which simplifies handling the rod geometry. The mapping has the advantage of affording analytical and numerical accuracy near the electrode surface. The plasma velocity and temperature fields are specified inputs to the code. Periodicity over one electrode pitch is assumed for all properties and electric fields.

Modeling of M-2 Experimental Current Distribution Results

Rod current distribution measurements obtained in earlier experiments in the Stanford M-2 channel have been modeled in an approximate manner which has yielded satisfactory results. The measurements, which are described in [1], were taken on a special segmented electrode with current flowing on upstream and downstream guard electrodes. The electrode segment surface temperatures were all maintained at approximately 800°K. The total electrode current was approximately 2 amps. and was kept low to minimize the effect of arc-mode current transport on the distribution measurement.

A model plasma temperature field for the current distribution measurements is shown in Figure 6. The field is quite idealized but contains the salient features of the expected temperature field. Within 0.75 cm. of the 1.9 cm. diameter rod, the temperature is assumed to vary according to a 1/7 power law radially inward to the rod surface. While this assumption ignores changes in thermal boundary layer thickness around the rod circumference, it maintains a strong radial temperature variation which is the most important characteristic very near the rod surface. Because of the strong variation of plasma electrical conductivity with temperature, the actual rod surface temperature is not a critical parameter (for current distribution only) as long as it is low enough to give a radial conductivity variation of a few orders of magnitude.

The temperatures at the edge of the assumed radial variation ring are determined by the intersecting isotherms shown in the figure. Below the level of the rod center, the temperature field is symmetric in the horizontal direction and varies (arbitrarily) by a 0.3 power law to the lower wall. While the temperatures in the lower region have some effect on the overall current distribution, in no case has the model shown large amounts of current on the lower half of the electrode (unless, of course, the temperatures in this region are made hotter than those above). Thus these temperatures are not of critical importance.

A thermal boundary of approximately 1 cm. is assumed above the rod. The isotherms above the rod are skewed from horizontal somewhat to simulate the effect of a warm plasma region between the boundary layer stagnation and separation points on the rod surface.

The resultant distributions of current for the model temperature field are shown for cases with and without magnetic field (β=0 and β=1.2) in Figure 7. These are compared with the experimentally measured cathode distributions. Although the temperature field as described has several free parameters, the agreement between model and experiment is encouraging. More current moved to the lower portion of the cathode in the presence of magnetic field than the model shows, but the model correctly shows the fact that the presence of a stagnation region strongly impacts the degree of current shift with magnetic field. In fact, one calculation which assumed a temperature field symmetric about the vertical centerline predicted that 80% of the current would flow to the downstream side of the cathode, far more than the 55% actually observed on the downstream side in the presence of magnetic field. In general, it was found that the B=0 experimental current distribution can be modeled fairly easily with fairly simple temperature assumptions, while modeling accurately both the B=0 and B=2.5T distributions is much more difficult.

Large Channel Performance Calculations

The computer code has been used to give some preliminary results of large channel plasma resistance. A simple comparison was made for a rod and flat electrode at a downstream channel location, the assumption being that in a large channel a rod electrode would be most effective in regions where the Hall parameter is high and the boundary layer already fairly thick.

The calculations assume a core temperature of 2300°K and a "warm" electrode surface temperature of 1600°K. The Hall parameter is 3 and the pressure 1 atm. The channel height is 1 meter, the electrode length 1 cm., and the electrode pitch 2 cm. In the rod channel the bottom of the electrode is 0.4 cm. from the channel wall. The fluid and thermal boundary layers are assumed to be 10 cm. thick (i.e. $\delta_{.99}$ = 10 cm.). In the rod channel the boundary layers are assumed to be 10 cm. above the top of the rods, that is they are in effect simply displaced upward. The rod isotherms are shown in Figure 8. Since this calculation is to serve principally as a reference for comparison, a symmetric temperature profile has been used. The temperature profile from the top centerpoint of the rod and up is identical to the profile above the flat electrode. Beyond one diameter above the top of the rod, the isotherms are horizontal so that there is no difference in the flat and rod temperature fields beyond this point.

The rod and flat transverse plasma resistances are within 5% of each other based on these rather simple temperature assumptions and the assumption of equilibrium electrical conductivity. The freestream conductivity is 3.2 mho/m for the conditions used and the calculated plasma resistance is approximately 55 ohm. More than 80% of the resistance is in the thermal boundary layers for a Hall parameter of 3. The near equality in transverse resistance for the two electrode types shows that the effects of a more uniform rod current distribution and larger effective surface area are balanced (at least for this calculation) by slightly longer current streamlines in the rod channel.

A similar calculation was made for the same electrode length (1 cm.) but with twice the electrode pitch (4 cm.). All conditions and temperature profiles remained unchanged. The plasma resistances for this case are again approximately the same for the two channels and are 25% larger than the 2 cm. pitch resistances.

Effort is now being directed toward making these analytical predictions more meaningful. It is planned to include temperature and flow asymmetries near the rods in at least an approximate way. The effect of the rods on gradients of temperature and velocity in the overall boundary layer needs to be considered also in order to get a valid comparison of the two electrode types. More careful modeling may reveal significant differences in electrical performance with the two electrode types.

CONCLUSIONS

Rod electrodes may improve the electrical performance of segmented Faraday generators. Thresholds for insulator-initiated breakdown are likely to be higher in a rod configuration, and insulator breakdown can be effectively suppressed with a very limited amount of insulator cooling, if necessary. Plasma breakdown therefore becomes important for determining the maximum sustainable axial fields.

Zero B field measurements show very similar plasma breakdown behavior on rod and flat electrodes. Joule heating by Faraday current reduced breakdown voltages by approximately 10% on anodes and 50% or more on cathodes. With magnetic field and Faraday current, rod and flat behavior was again qualitatively similar. Plasma breakdown thresholds were higher than in the B=0 case, however. Also, rod anodes had breakdown voltages 20% to 50% higher than flat anodes. The rod geometry may be an important advantage here.

Analytical calculations show good agreement with experimental measurements of current distribution. A preliminary calculation of transverse plasma resistance gave essentially equal values for flat and rod configurations. Refinements in the model are being made to give more accurate predictions.

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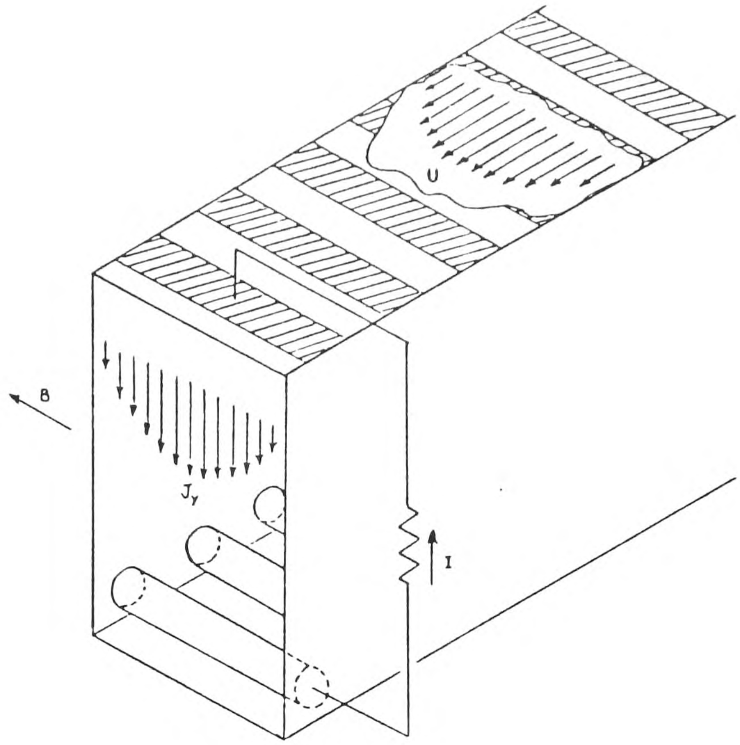

Figure 1. Schematic of segmented Faraday generator with transverse rod electrodes on one side of the channel.

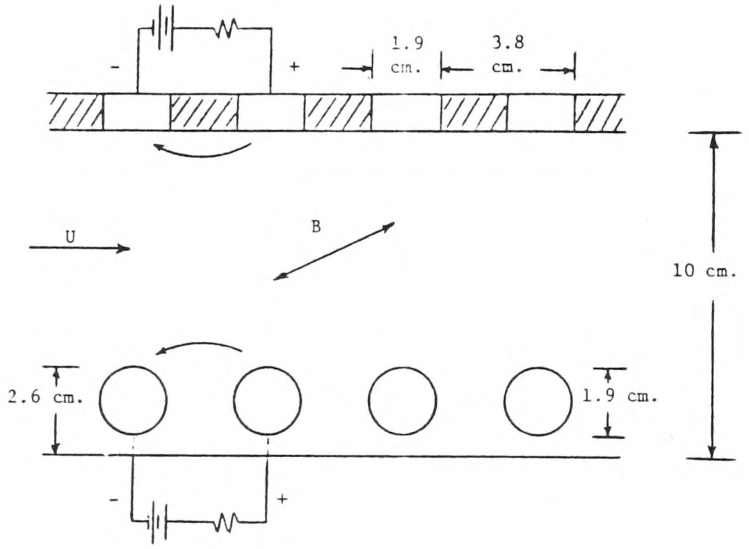

Figure 2. Schematic of M-2 generator as used for measurement of rod and flat Hall field breakdown.

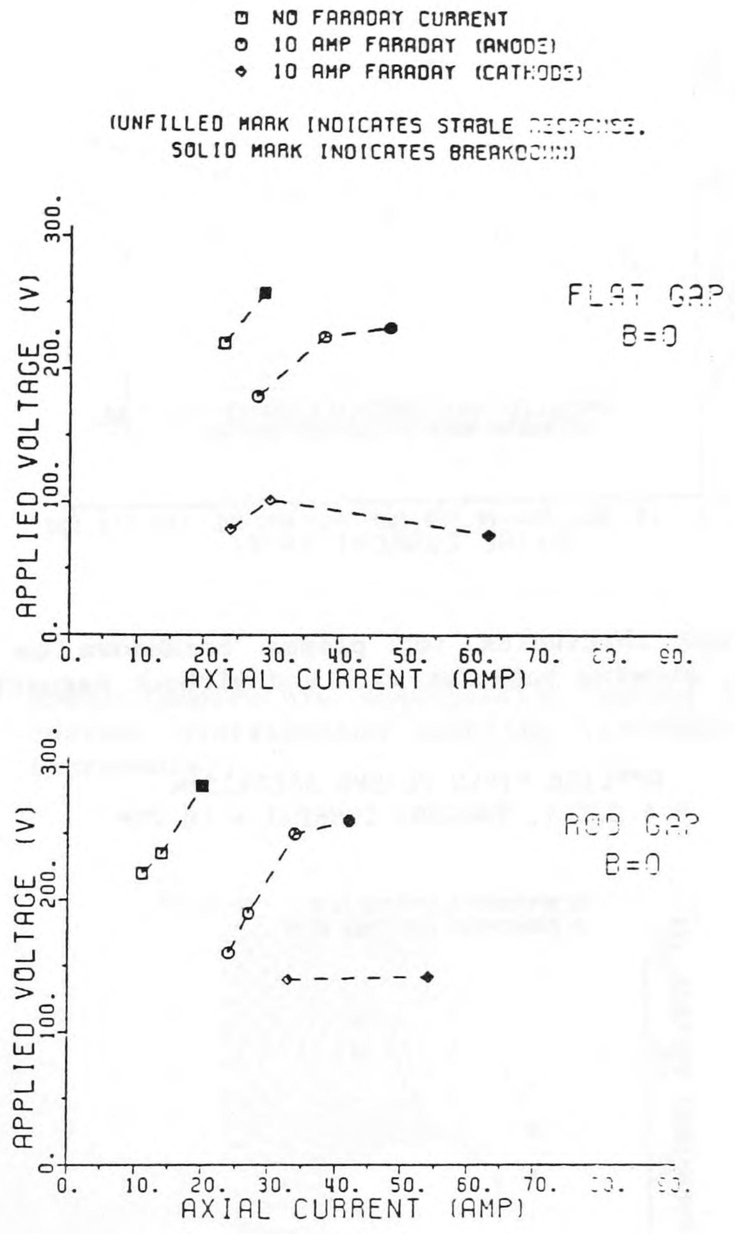

Figure 3. Voltage thresholds for plasma-initiated breakdown without magnetic field on rod and flat electrode gaps.

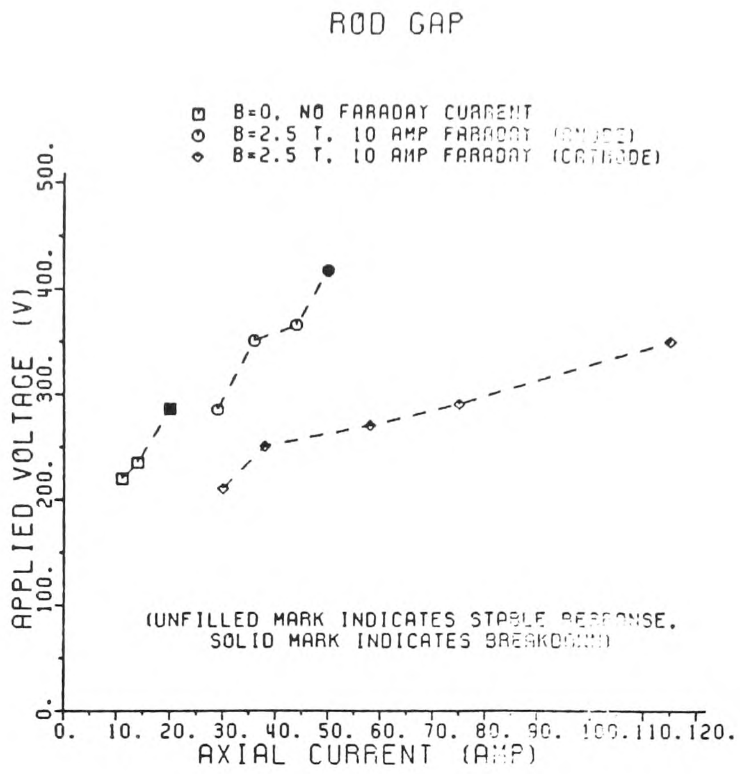

Figure 4. Voltage thresholds for plasma breakdown on rod electrode gaps, showing behavior with and without magnetic field.

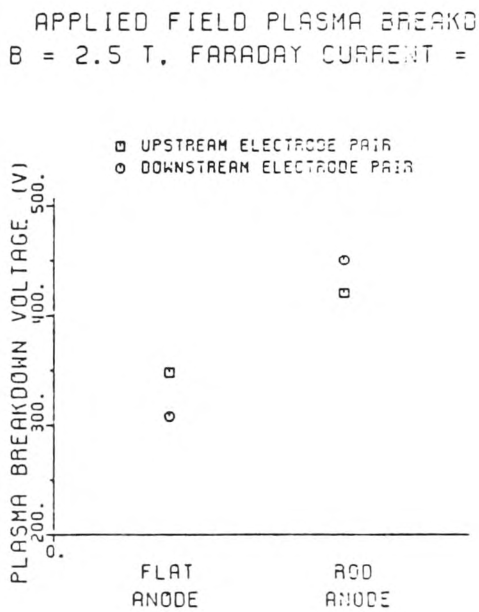

Figure 5. Comparison of rod and flat anode plasma breakdown voltages at two axial locations within the M-2 channel.

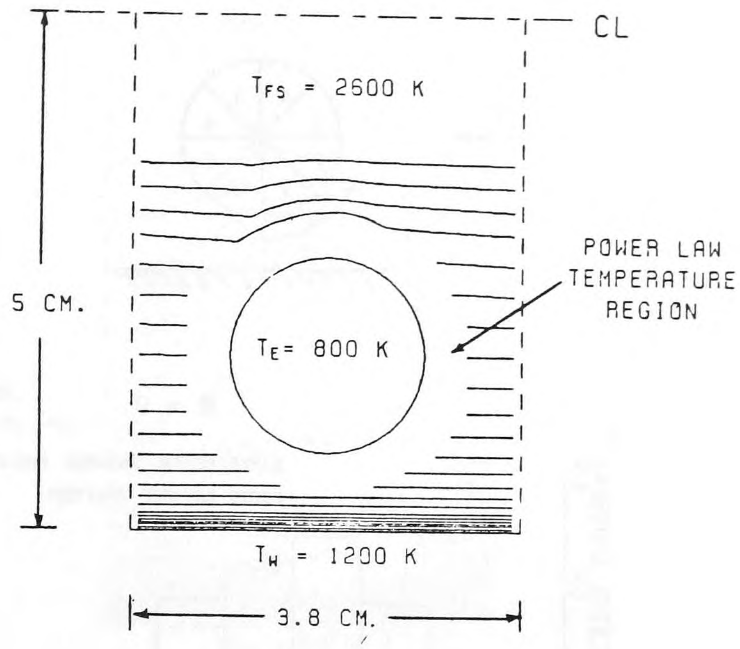

Figure 6(a). Model temperature distribution around rod electrode for current distribution modeling (isotherms represent 50°K increments).

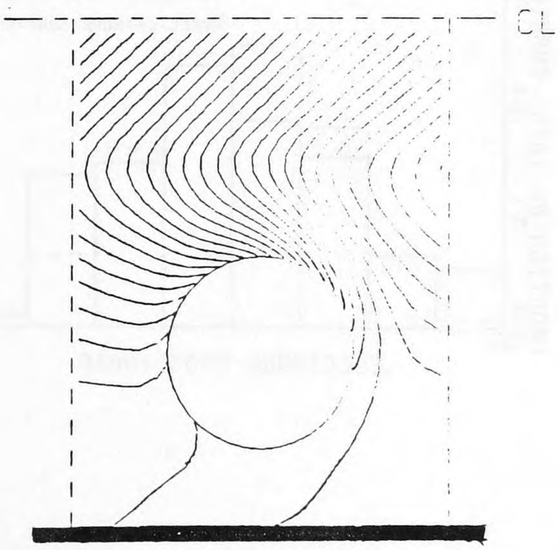

Figure 6(b). Current streamline field for assumed temperature profile. The current field is periodic over one electrode pitch.

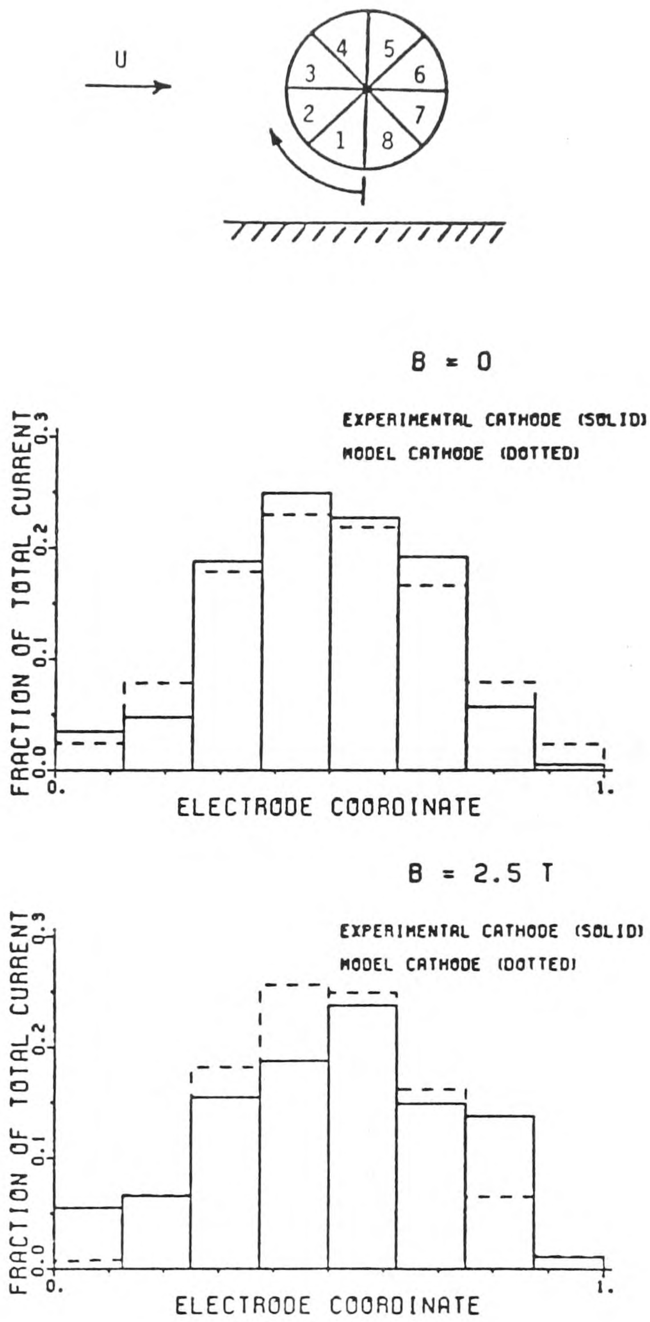

Figure 7. Comparison of model current distributions with experimental cathode distributions.

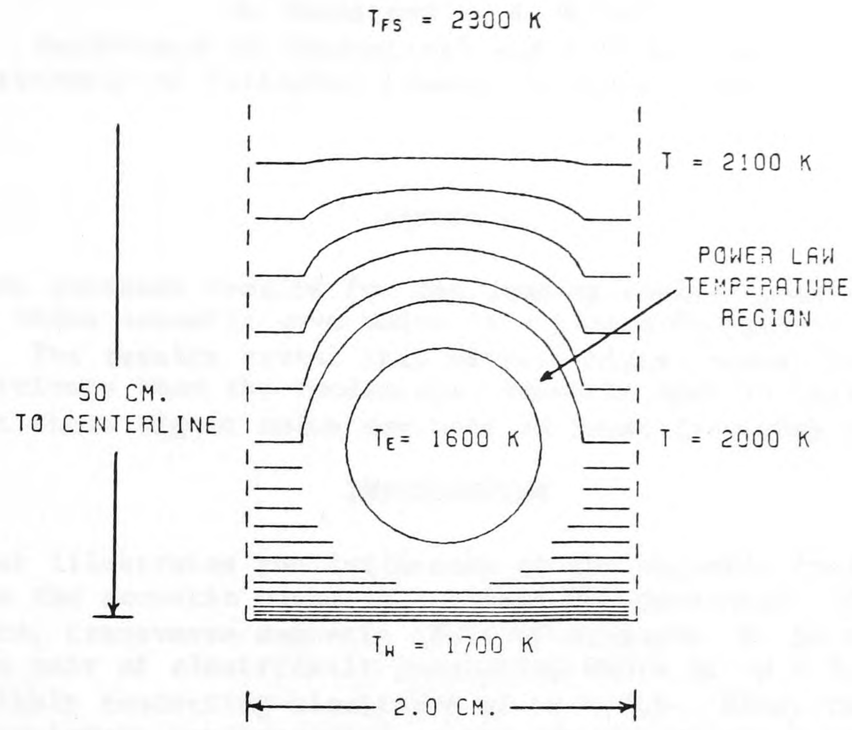

Figure 8. Model temperature profile around rod electrode used for large channel plasma resistance calculations.