Experimental Investigation of Factors Affecting the Cathode Wall Slag-Layer Resegmentation Frequency

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A series of magnetohydrodynamic (MHD) power-generator experiments was carried out to investigate the functional dependencies of the cathode wall slag-layer resegmentation frequency upon gas-dynamic and generator characteristics. Variations in gas conductivity, magnetic field intensity, Hall parameter, current density, and electric field intensity were investigated to establish which generator parameter(s) affects the cathode slag-shorting patterns. The validity of three proposed models for slag-layer resegmentations are tested by comparisons with measured data. The generator test results, showing that the cathode nonuniformity patterns are only a function of the Hall voltage, suggest that the high-voltage intercathode gaps might be created by axial leakage currents and maintained by arcs. The voltage across the "open" gap is characteristic of an arc voltage.

Introduction

THE cathode wall slag-shorting phenomenon is important to the development of coal-fired MHD power generators because it affects both the performance of the generator and the channel lifetime. Generator experiments have been carried out to investigate the various physical processes involved in the formation of the cathode nonuniformities.[1-3] An understanding of these processes is necessary in order to predict how the cathode shorting effects will scale with generator size. At present, the polarization process that leads to the slag shorting of adjacent electrodes is well understood. However, the mechanism(s) responsible for the resegmentation of the shorted slag layer is still unclear. The exact mechanism that unshorts and maintains the high-voltage working gaps on the cathode wall has not been identified.

The cathode wall slag resegmentation frequency can influence both the MHD generator's performance and lifetime. A very coarse slag segmentation will decrease the channel performance because of increased axial current leakage. Also, coarser segmentation will result in greater localized voltage stresses on the channel walls, which in turn can reduce the lifetime of the generator.

Several possible resegmentation mechanisms have been postulated. These are 1) Faraday current constriction due to the Hall effect, 2) transverse current reversal due to the interactions of the shorted slag layer with the boundary-layer voltage drop, and 3) axial current and arcs. The identification of the actual slag resegmentation mechanism is crucial to understanding how the cathode nonuniformity effects will scale with generator size.

A series of generator experiments was conducted at Avco to investigate the functional dependencies of the cathode wall slag-layer resegmentation frequency upon gas-dynamic and generator characteristics. Variations in plasma conductivity, magnetic field intensity, Hall parameter, current density, and electric field intensity were imposed to establish which generator parameter(s) affects the cathode shorting patterns. The validity of the proposed models for slag-layer resegmentations is tested by comparison with the experimental data.

The shorting characteristics of cathode slag layers as a function of ash composition and carryover rate have been investigated previously.[2] The slag carryover rate for Rosebud (low iron) coal was found to have very little influence on the observed cathode wall nonuniformity patterns, whereas the severity of slag polarization is reduced at the higher carryover rates for eastern U.S. (high iron) coal ash.

Experimental Conditions

A series of diagonal generator tests was conducted in the Mk VI and Mk VII facilities to establish which generator parameters affect the cathode slag-shorting pattern. The values of magnetic field strength, N/O ratio, diagonal connection angle, and diagonal loading were systematically changed during these tests in order to produce variations in those generator parameters that might influence the shorting patterns.

The Mk VI tests were carried out to investigate the effects of magnetic field intensity (and Hall parameter) on the cathode wall shorting. A supersonic channel, having an inlet Mach number of 1.2, was used for the tests. This channel was 2.5 m long, consisting of 140 segmented electrode pairs. The electrodes were constructed of copper with stainless steel or platinum caps brazed to the gas-side surfaces. Interelectrode insulators were made of 2.5-mm-thick boron nitride wafers. The nonconducting sidewalls were constructed of square (15.2 × 15.2 mm) copper pegs separated by 2.5-mm insulators. The plasma source was an ash-injected oil combustor operating with oxygen-enriched air and No. 2 fuel oil. Rosebud fly ash was used to simulate the slag carryover. The generator was diagonally loaded, with external diagonal connections of eight overlapping electrodes (the angle between the diagonal and the vertical plane was approximately 34 deg). Current control devices were used in the diagonal connections. The nominal test conditions are listed below:

Total mass flux, kg/s	=	2.0
Oxidant N/O ratio	=	0.8
Seed fraction, wt. % potassium	=	1.0
Oxygen stoichiometry	=	0.9
Equivalent ash carryover, %	=	30.0

Measurements of the electrical power output, electrode currents, and interelectrode voltages were taken at the various diagonal loadings with magnetic field intensities of 2, 3, and 4 T. The voltage-current (V-I) characteristics of the Mk VI tests are shown in Fig. 1.

Generator tests for parametric variations in the values of N/O, diagonal overlap, and generator loading were carried out in the Mk VII facility. These tests were performed with a 1.0-m-long supersonic (inlet Mach number = 1.2) channel having 56 segmented electrode pairs. The electrode and insulator wall designs were similar to the Mk VI channel. The ash-injected combustor was identical to that used in the Mk VI

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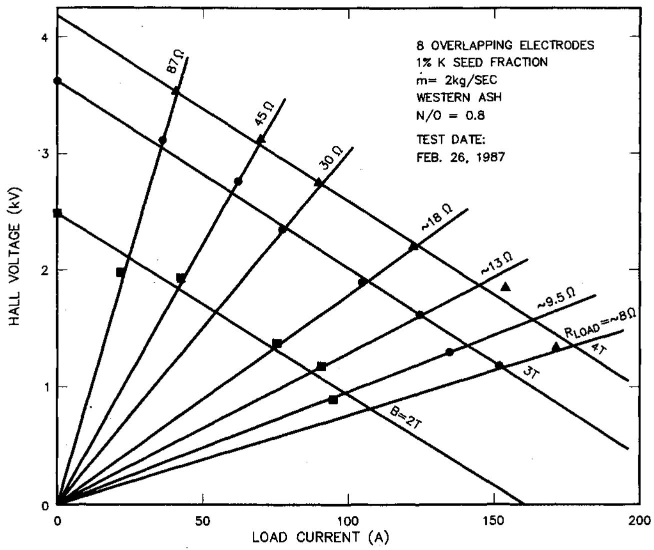

Fig. 1 Voltage-current characteristics of the Avco Mk VI diagonal MHD generator.

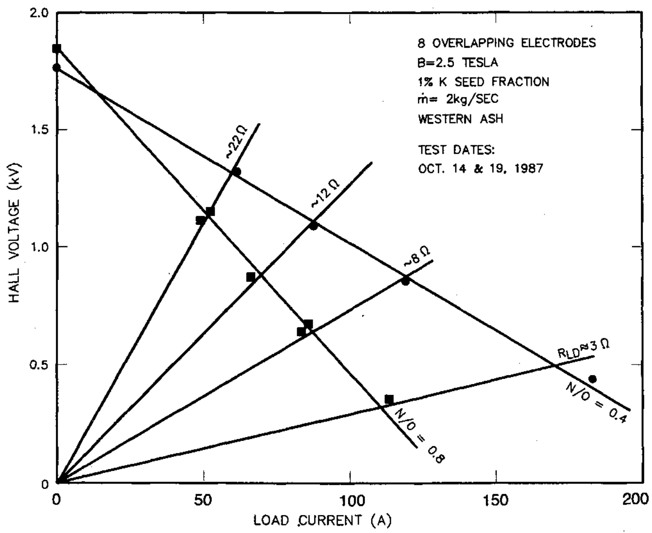

Fig. 2 Voltage-current characteristics of the Avco MK VII diagonal generator for N_{ovlp} = 8.

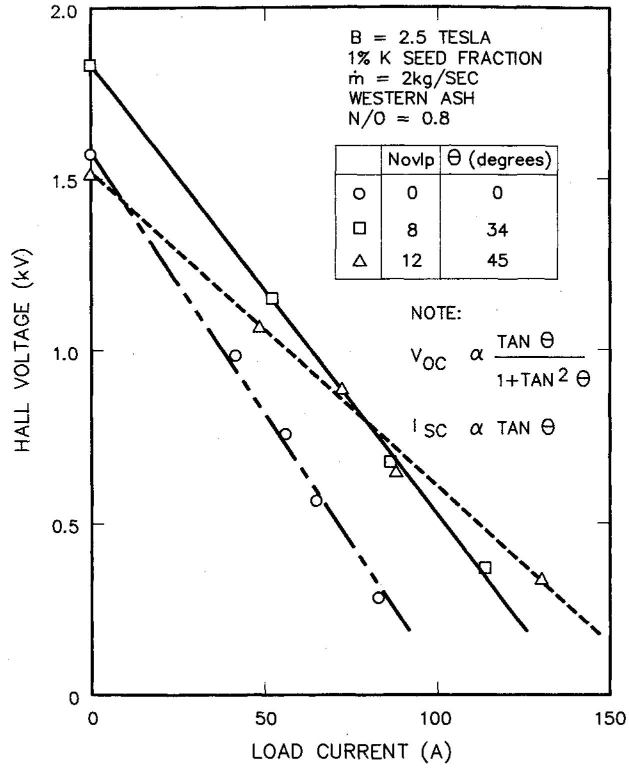

Fig. 3 Voltage-current characteristics of the Avco Mk VII diagonal generator for different external diagonal corrections.

facility. The generator was loaded diagonally and operated with a full complement of electrode current controllers. Interpeg voltage measurements, across the insulator wall, were taken at five different axial locations to provide estimates of boundary-layer voltage drops. Generator operating load lines were obtained at different oxidant N/O ratios (0.4 and 0.8) and diagonal connections (0, 8, and 12 overlapping electrodes). Typical V-I characteristics for the Mk VII tests, operating at a magnetic field strength of 2.5 T, are shown in Figs. 2 and 3. The approximate angles (in degrees) between the external diagonal connections and the vertical plane are also listed in Fig. 3.

Discussion of Cathode Resegmentation Hypotheses

The shorting of adjacent electrodes (or groups of electrodes) on the cathode wall results from the slag-layer polarization. The polarization of the slag is thought to arise from the ionic nature of the current transport across the slag layer, causing the deposition of metallic potassium at the electrode surface.[1,3] These deposits of metal will grow with time and eventually bridge over the interelectrode insulators, leading to the axial shorts. Groups of shorted electrodes on the cathode wall are separated periodically by high-voltage (unshorted) gaps that sustain the Hall voltage of the generator. The formation of these working gaps requires a process to break the metallic bridge between the shorted electrodes. After these open gaps are formed, this same process, or some other process, must also maintain the open gap and prevent the gap from shorting out again. The process must account for or be compatible with the fact that the open gaps do change positions over rather long periods of time—tens of minutes to hours. Several possible mechanisms have been postulated for the formation of these high-voltage gaps. These mechanisms include 1) transverse current concentrations, 2) current reversal, and 3) axial currents and/or arcs. These hypotheses for slag-layer resegmentation are briefly described subsequently. Test results from the Mk VI and Mk VII have been used to investigate the validity of these models.

Current Constriction Model for Slag-Layer Resegmentation

This explanation for the formation and maintenance of high-voltage gaps was proposed by Petty[2] and Demirjian et al.[4] It was postulated that, at a high-voltage gap, the transverse Joule dissipation is large enough to partially burn out or thin down the slag layer, leading to an increased axial slag resistance. The localized Joule heating of the slag layer arises from the constriction of Faraday currents near the downstream edge of the shorted electrode group. This current concentration is caused by the relatively long effective pitch of the shorted electrodes, and is strengthened by the Hall effect. A schematic of this current constriction model is shown in Fig. 4. The values of the electrode current in the sketch are typical of a group of shorted electrodes in the Mk VII channel. The current constriction model also provides an explanation for the periodicity of the observed nonuniformity pattern since, for a given level of MHD interaction, a certain number of successively shorted electrodes will be required to yield a Faraday current constriction sufficient to form the "open" gap.

Current Reversal Model

This model, proposed by Solbes,[5] assumes the high-voltage gaps are formed when the slag depolarizes at the upstream end of the shorted electrode group. The depolarization of the slag occurs when the cathode at the leading edge of a shorted electrode group starts to act as an anode, reversing the direction of the local current flow. A schematic diagram of this model is shown in Fig. 5. The criteria for current reversal have been derived in Ref. 5. For N_s cathodes shorted together, the cathode furthest upstream in the shorted group will experience a current reversal when the product of the number of gaps and the "ideal" intercathode voltage exceeds the cathode resistive voltage drop δV_{cath}. The ideal intercathode voltage is the voltage sustained between adjacent cathodes in the absence of slag shortings. Current reversal will occur when the value of N_s is such that

$$N_s\,|E_{xc}|\,p \approx \delta V_{\text{cath}} \tag{1}$$

where $|E_{xc}|$ is the magnitude of the Hall field in the core flow, and p is the electrode pitch. Equation (1) implies that the number of high-voltage gaps on the cathode wall is proportional to the Hall voltage and inversely proportional to the value of δV_{cath}.

Axial Current and Arc Model

In this model, the disturbances in the shorting pattern on the cathode slag layer are due to the destruction of the metallic bridges by axial current. These occur whenever the magnitude of the leakage current in the slag layer, driven by the local Hall field, exceeds the current-carrying capability of the metallic deposits. The high-voltage gaps are formed as the metallic bridges are burned off. The higher the local Hall field, the greater the number of open gaps. As the open gaps are created by the axial current, a different mechanism must take over to maintain the high-voltage gaps and to prevent them from shorting out again. Axial arcs are likely to take over this function. If the gap voltage is sufficiently high to sustain an axial arc across the gap, then the open gap will be maintained since any further deposits of metals will be vaporized by the arc. If the gap voltage is too low to sustain the axial arc, then the Faraday current that has concentrated near the open gap will plate out enough metal to eventually short out the gap again. As the development of the cathode nonuniformity reaches steady state, the number of electrodes within the shorted group is determined by the balance between the Hall voltage spanning the slag short $N_s p|E_{xc}|$ and the axial arc voltage δV_{arc}:

$$N_s\,p\,|E_{xc}| \approx \delta V_{\text{arc}} \tag{2}$$

In this model, the open gap voltage is precisely the arc voltage. As the generator Hall voltage is varied, the number of open gaps adjusts accordingly, while the voltage across each of the open gaps (i.e., the arc voltage) remains fairly constant. A schematic of the axial arc model is shown in Fig. 6.

The preceding three models for slag resegmentation all have different inferences as to how the MHD generator performance is affected by the cathode nonuniformities. The Faraday current constriction model assumes that cathode slag polarization does not result in significant end-to-end current leakage because the cathode slag layer is not physically continuous, but is periodically broken. In this model, the generator-performance reduction by cathode nonuniformities is considered as a finite segmentation loss, resulting from the large effective pitch of the resegmented cathode wall. The axial current/arc model, however, assumes the performance degradation from cathode nonuniformities is the result of end-to-end current leakage. Significant amounts of axial current can leak through the cathode slag layer, along the shorted polarized slag and across the open gaps via arcs. Finally, the current reversal model interprets generator-performance shortfall in the presence of severe cathode nonuniformities as boundary-layer voltage drop losses.

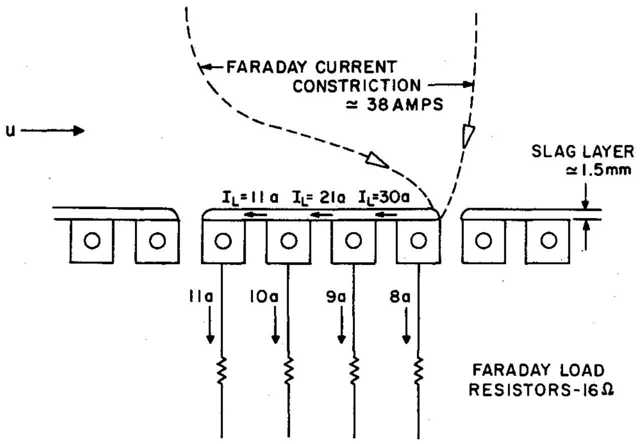

Fig. 4 Schematic of current constriction model for cathode slag-layer resegmentation.

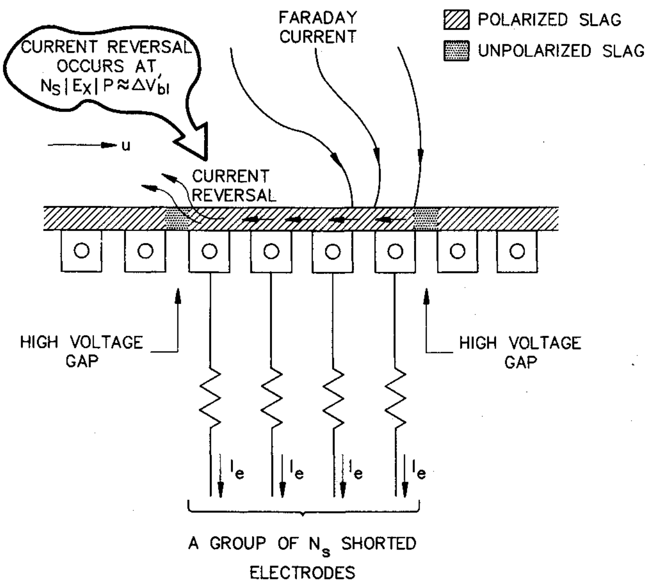

Fig. 5 Schematic of the current reversal model for slag-layer resegmentation.

Test Results

The generator test results showed that the cathode resegmentation frequency is a strong function of the generator Hall voltage. Figures 7 and 8 show the variations of N_{gap} with V_{Hall} from the Mk VI and Mk VII diagonal generator tests, respectively. N_{gap} is the number of insulator gaps on the cathode wall whose interelectrode voltage is greater than 15 V. The data in Figs. 7 and 8 were obtained after the cathode wall slag layer had time to adjust to any changes in the generator operating conditions, usually after 10 or more minutes. Similar trends in the behavior of cathode wall resegmentation were observed in the slagging generator test results from the Component Development and Integration Facility (CDIF).[6]

The Faraday current constriction model of slag-layer resegmentation does not appear to concur with the Mk VI gen-

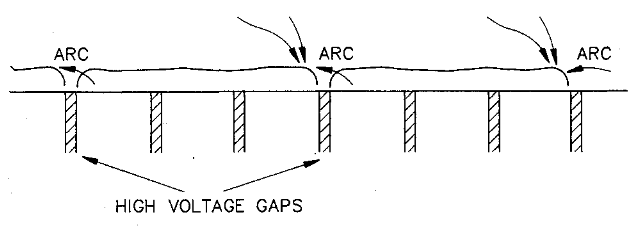

Fig. 6 Schematic of the axial current-arc model for slag-layer resegmentation.

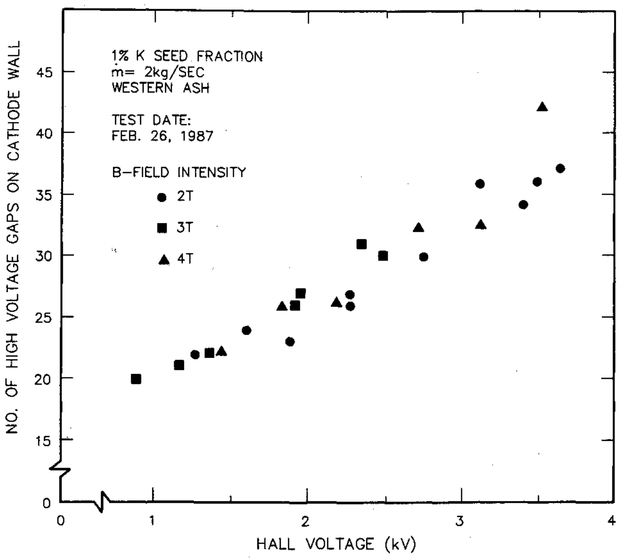

Fig. 7 Variations in the number of cathode wall working gaps with Hall voltage for the Avco Mk VI diagonal generator.

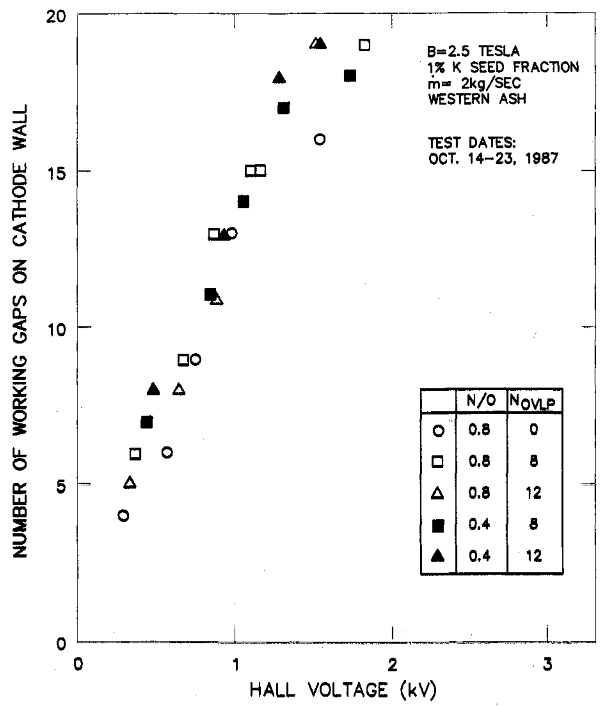

Fig. 8 Variations in the number of working gaps with Hall voltage for the Avco Mk VII diagonal generator.

erator tests results. For example, consider the four MHD generator data points summarized in Table 1. These selected data points all have approximately the same Hall voltage but the generator was operating at different magnetic field intensities and/or loadings. The observed cathode slag resegmentation frequencies are nearly the same since the Hall voltages are equal. However, the extent of the Faraday current constrictions are quite different for each of these generator operating conditions. In general, the degree of current concentration near the downstream edges of the groups of shorted electrodes increases with increasing Faraday current density and with increasing Hall parameter. For the Mk VI generator tests, the values of the Faraday current density at a given channel location increases with increasing magnetic field intensity and with increasing diagonal load resistance. This can be seen in Fig. 9, where the values of the electrode current measured at the mid-

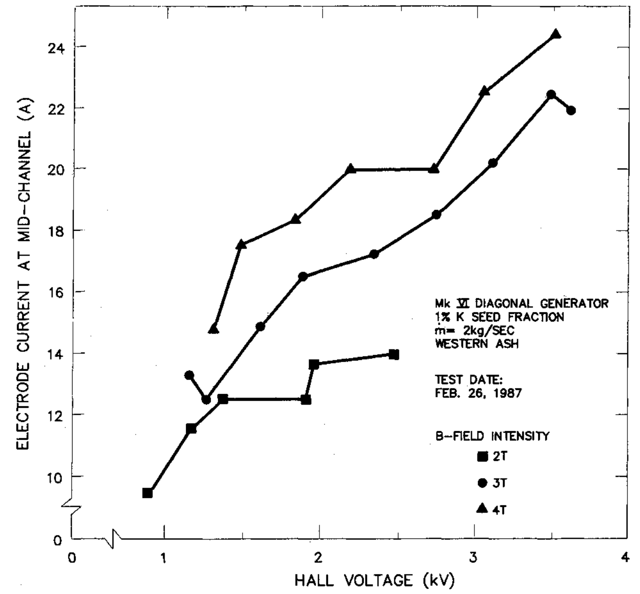

Fig. 9 Electrode current vs Hall voltage at various magnetic field intensities and generator loadings.

Table 1 Typical comparison of data from the MK VI tests having approximately the same values of Hall voltage

Magnetic field strength, T	4	3	2	2
Diagonal load resistance, Ω	12	18	44	89
Hall voltage, kV	1.8	1.9	1.9	2.0
Number of cathode high-voltage gaps	26	24	26	27
Midchannel J_y, A/cm^2	1.53	1.38	1.05	1.15

channel location are presented for various magnetic field strengths and generator loadings. Also, the averaged value of the Hall parameter increases with increasing magnetic field intensity. The values of N_{gap} at the four selected conditions of Table 1 did not increase with increasing values of J_y and β. This suggests that the Faraday current constriction is not a complete explanation for the slag resegmentation process. The trend shown by the results of Table 1 can be further verified by comparing results at other values of Hall voltages.

The boundary-layer voltage drop and cathode nonuniformity measurements from the Mk VII generator experiments have been used to test the validity of the current-reversal model of slag resegmentation. The values of the boundary-layer voltage drop were estimated from the sidewall peg voltage traverses. As shown in Fig. 10, the voltage drop is determined by the difference of the actual electrode voltage and the voltage resulting from the extrapolation of the peg voltage profile to the electrode wall. The values of the cathode voltage drop ascertained in this manner may be affected by the polarized slag shorting. Consider Fig. 11, where typical transverse voltage distributions across the generator are shown for a group of slag-shorted cathodes. Voltage profile N is the sidewall peg voltage traverse at the axial location furthest downstream in the shorted group of cathodes, profile (N-1) is obtained at the axial location corresponding to the first cathode upstream of N, ----, and profile (N-k) is measured at the location of the kth cathode upstream of N. The voltage distributions when the cathodes are not shorted together by the slag are represented by the dashed lines. If the peg voltage traverse occurred amidst a group of shorted cathodes, say at electrode (N-k), then the measured value of the voltage drop will be depressed from the actual value by the amount $kp|E_{xc}|$. For this reason, the appropriate adjustments were made to the Mk VII voltage drop measurements to correct for slag-shorting effects. The resulting corrected cathode wall boundary-layer voltage drops are shown in Fig. 12 as a function of the Faraday current density. The results are time-averaged data (averaged over 1-min intervals).

The values of the cathode wall boundary-layer voltage drop δV_{cath} are compared with $N_s p|E_{xc}|$ in Fig. 13 to test the validity of the current-reversal model of slag resegmentation. The results do not indicate any correlation between the two parameters. It should be noted that the voltage drop δV_{cath} in Eq. (1) is different from the voltage drop δV_{cath} of Fig. 13; δV_{cath} consists of only the resistive voltage drop. The values of δV_{cath} include the transverse arc voltage drop, the boundary-layer velocity defect, as well as the resistive voltage drop. The values of arc voltage have been previously measured[7] to be nearly constant (approximately 60 V) for current density in the range of 0.5–2.0 A/cm^2. Since the Faraday current densities in the Mk VII experiments were of comparable magnitudes (see Fig. 12), one can reasonably assume that all of the results of Fig. 13 have similar arc voltages. Similarly, one can assume the contributions by the boundary-layer velocity deficits are comparable since the measurements were taken at nearly the same axial location (therefore the velocity profiles and boundary-layer thicknesses are comparable). It follows that the resistive drops δV_{cath} are smaller than the total voltage drops δV_{cath} by approximately a constant amount for all of the data points in Fig. 13. The origin of the horizontal axis in Fig. 13 would be shifted by some constant amount if δV_{cath} were plotted instead. The earlier conclusion concerning the invalidity of current-reversal model would still apply.

Another experimental observation that contradicts the current-reversal model involves the variations in the cathode wall slag resegmentation frequency during periods of genera-

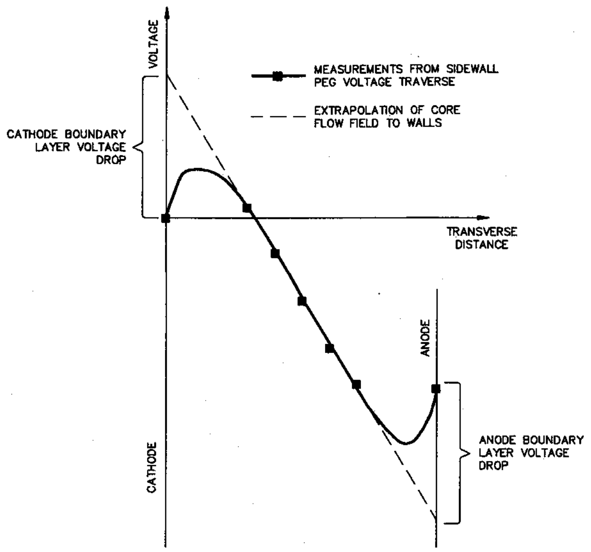

Fig. 10 Boundary-layer voltage drop measurements.

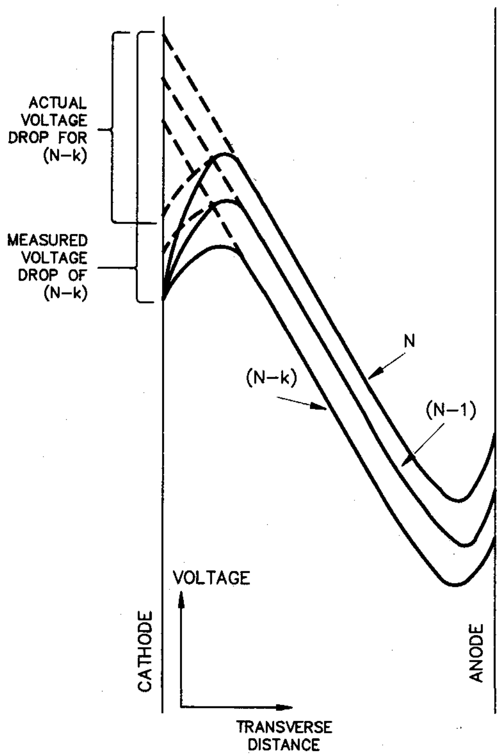

Fig. 11 Effect of cathode slag shorting on the measured boundary-layer voltage drop.

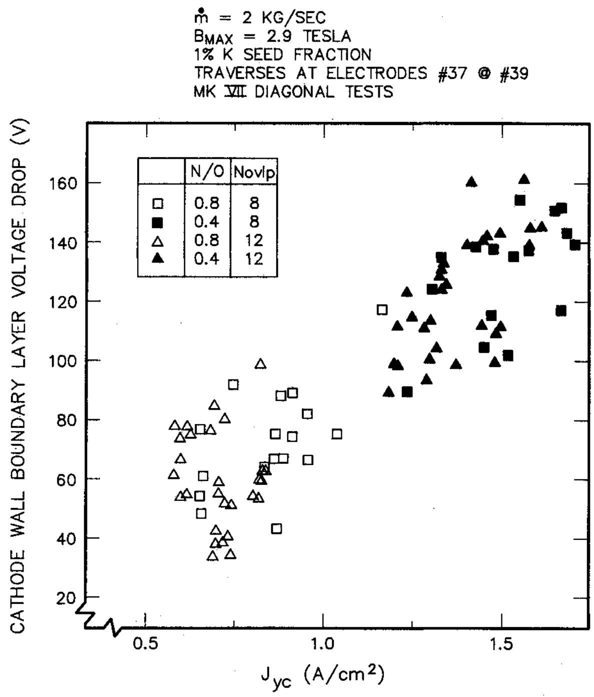

Fig. 12 Cathode wall boundary-layer voltage drop vs Faraday current density.

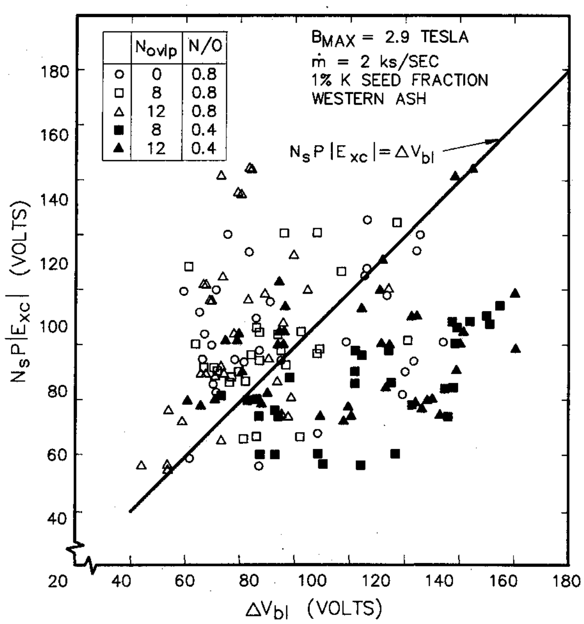

Fig. 13 $N_s P|E_{xc}|$ vs cathode wall ΔV_{bl} from the Mk VII diagonal generator tests.

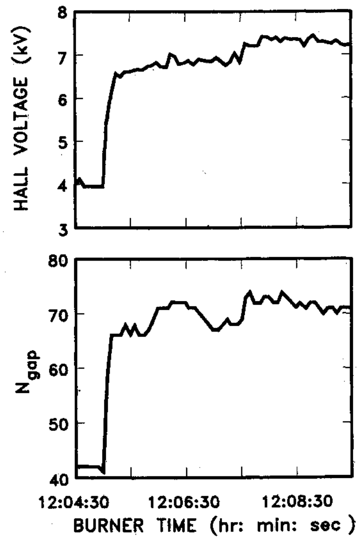

Fig. 14 Transient variations in the Hall voltage and the number of high-voltage cathode gaps during period of increasing Hall voltage.

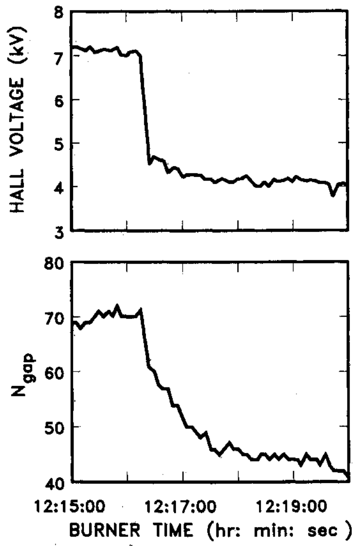

Fig. 15 Transient variations in the Hall voltage and the number of high-voltage cathode gaps during period of decreasing Hall voltage.

tor load transients. The rate at which the cathode wall adjusts its segmentation after a sudden change in the generator loading depends on whether the value of V_{Hall} is being increased or decreased. When the generator Hall voltage is raised suddenly, the slag-layer segmentation readjusts for the change almost instantaneously. A typical example of this can be seen in Fig. 14. The variations in the V_{Hall} and N_{gap} during the 87-SEED-9 test at the CDIF are plotted in Figs. 14a and 14b, respectively. Here N_{gap} is defined as the number of high-voltage cathode gaps whose cumulative voltage adds up to 90% of the generated Hall voltage. At burner time 12:05:00, the generator load voltage increased from 3.9 to 6.5 kV in approximately 15 s. During this same time period, the number of working gaps on the cathode wall increased from 42 to 66. When the generator Hall voltage is reduced, however, it takes a much longer time for the cathode to readjust its segmentation frequency. An example of this from the 87-SEED-9 test is shown in Fig. 15. The Hall voltage was reduced quickly from 7 to 4.2 kV at burner time 12:15:15. Much of the voltage reduction occurred within a period of 15 s. The readjustment of the slag-layer segmentation took much longer, requiring over 1 min to reach its steady-state value.

The rates of change of N_{gap} and V_{Hall} during periods of rapid generator loading change are compared in Fig. 16. These

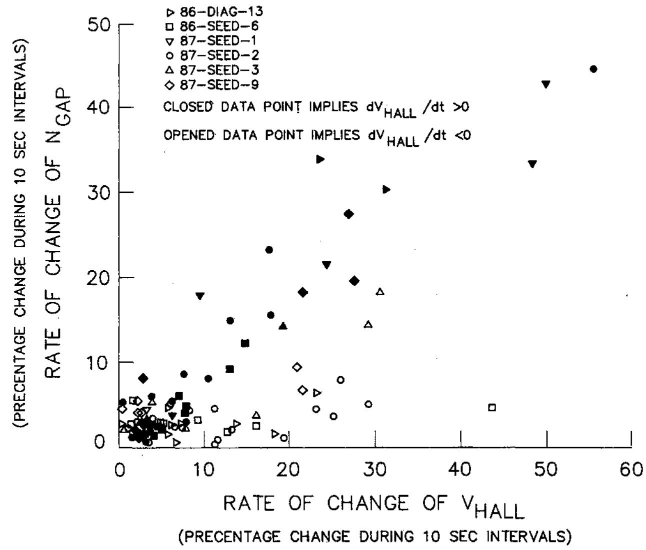

Fig. 16 Rate of change of N_{gap} vs rate of change of V_{Hall} during periods of rapid load change in recent CDIF tests.

data from several recent CDIF tests are presented in terms of percentage change in the magnitudes of N_{gap} and V_{Hall} over 10-s intervals. The closed data points apply to increasing load voltages; the open data points are for decreasing V_{Hall}. The difference in the cathode wall resegmentation rates between increasing and decreasing Hall voltages can be clearly seen.

The differences in the resegmentation rates of the results of Fig. 16 imply different physical processes are involved in the electrical shorting and unshorting of the cathode slag layer. When the generator Hall voltage is reduced suddenly, the number of open gaps on the cathode wall will decrease as some of the initially open gaps are shorted out. This shorting process is relatively slow, which suggests that it is related to the slow diffusion of iron and potassium cations to the cathode wall and the buildup of a metallic bridge across the insulator. For typical transverse current densities of 0.5–1 A/cm^2, the slag-shorting process and the corresponding adjustment in the segmentation frequency occur on a time scale of minutes. The instantaneous readjustment of N_{gap} when the generator Hall voltage is increased suggests that the process which destroys the metallic bridges between the shorted electrodes must occur instantaneously. The current-reversal model assumes the metallic shorts are removed as a result of slag depolarization due to reversed current flow. This slag depolarization process would presumably occur at a rate comparable to the slag polarization rate, which disagrees with the trends observed in Figs. 14–16.

The results of Figs. 7 and 8, showing that the cathode wall slag resegmentation frequencies are only a function of the Hall voltage, suggest that the high-voltage interelectrode gaps might be created by axial leakage currents and maintained by axial arcs. It is postulated that axial arcs populate each of the high-voltage gaps. These arcs provide the gap with the necessary axial voltage to match the core flow Hall field of the channel. As the generator Hall voltage is varied, the number of open gaps adjusts accordingly, while the voltages of the open gaps are fairly constant (in the range of 70–110 V for the Avco and CDIF conditions). This can be seen in Fig. 17, where the intercathode voltage distributions from a typical test at CDIF are shown for different values of the generator Hall voltage.

High-intensity arcing activities have been observed above the high-voltage cathode insulator gaps during optical measurements in a Mk VII channel.[8] Large and relatively steady arcs were seen over the high-voltage gaps. The arc diameter (or the high-intensity optical region) was between one and three times the intercathode insulator thickness. At the time of the

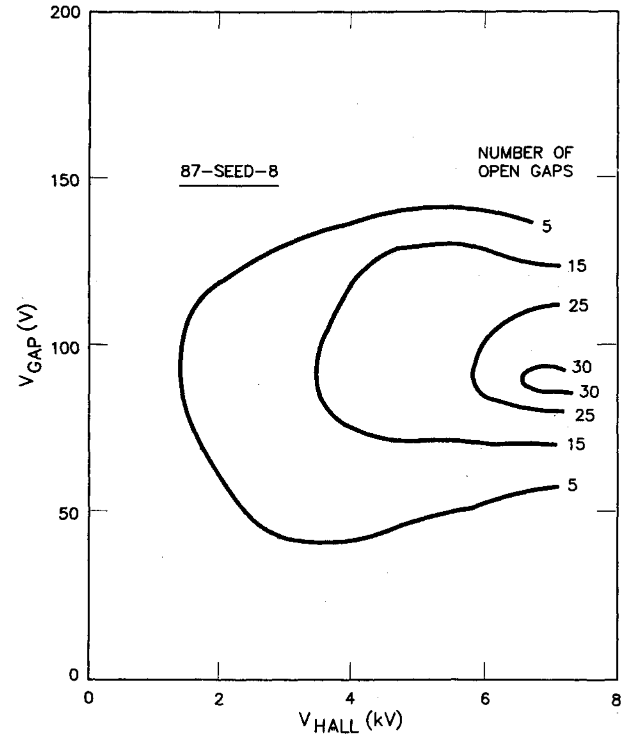

Fig. 17 Number distribution of gap voltages for different Hall voltages.

optical measurements, it was uncertain whether the arcs were transverse and attached to the downstream edge of the group of shorted cathodes, or whether they were axial intercathode arcs. Presently, it is thought that these were the axial arcs that are responsible for maintaining the high-voltage gaps.

The voltage-current characteristic of the high-voltage insulator gaps were extensively measured during subsequent Mk VII generator tests. The results of these measurements are reported in Ref. 9. Plans have also been made to measure the high-frequency properties of the gap current and voltage.

Additional experiments, which were designed especially to identify the mechanism responsible for cathode slag resegmentation, are described in Ref. 10. In these experiments, groups of slag-shorted electrodes were intentionally shorted together externally. When two groups of slag-shorted electrodes are shorted in this manner, a new high-voltage insulator gap usually develops somewhere in the resulting larger group of shorted electrodes. The exact process that forms this new gap can be identified by observing the location and time period required for the new gap to appear. The results from these tests also support the notion that the axial current mechanism is the dominant method for creating high-voltage gaps.

Summary

Cathode slag resegmentation frequency is a strong function of the local Hall field. Parameters such as the magnetic field strength, Hall parameter, transverse current density, and gas conductivity show no correlatable influence on the cathode slag resegmentation process. The effects of these parameters on the cathode nonuniformities are felt only through their effects on the Hall voltage.

Previous investigations[2,11,12] have shown that the cathode slag resegmentation frequency is also dependent on the slag carryover rate, wall temperature, and ash composition.

The results of cathode nonuniformity measurements do not support the current constriction model nor the current-reversal model for slag-layer resegmentation. The test results, showing that the nonuniformity patterns are only a function of the Hall voltage, suggest that the high-voltage intercathode gaps might be created by axial leakage currents and maintained by axial arcs. The voltage across the open gaps is characteristic of the interelectrode arc voltage.

The results of this investigation suggest that the generator-performance degradation from cathode nonuniformities should be modeled as an end-to-end current leakage.

Acknowledgment

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