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Prototypic Magnetohydrodynamic Anode Designs and Test Results

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The design description and design rationale for the anode electrodes of the integrated topping cycle (ITC) magnetohydrodynamics (MHD) power generator are reviewed. This generator was part of a 50-MW$_t$ prototypic power train that recently completed proof-of-concept (POC) duration testing at a U.S. government MHD test facility. The conditions of the anode wall after undergoing design verification and POC tests are described. Anode confirmation test results are also reported. These confirmation tests were carried out prior to the actual fabrication of the ITC MHD generator. These tests showed that in addition to the anode design that was selected for the MHD generator, several alternative designs also demonstrated excellent lifetime projections.

Introduction

THE integrated topping cycle (ITC) magnetohydrodynamic (MHD) power generator was part of a 50-MW$_t$ prototypic power train that recently completed proof-of-concept (POC) duration testing at the U.S. Department of Energy's Component Development and Integration Facility (CDIF) in Butte, Montana. Over 500 cumulative hours of duration testing (over 300 h at nominal power conditions) were obtained with the generator hardware before the program funding was terminated. The conditions of the anode wall after 50 power hours of design verification tests (DVT) and after 300 power hours of POC testing are described.

The ITC power generator had to operate at wall stresses commensurate with those projected for future baseload MHD generators, and at the same time, demonstrate a projected lifetime of 2000 hours. In order to meet and exceed this lifetime requirement, lifetime-limiting effects had to be overcome. The two major anode electrode lifetime-limiting mechanisms are 1) surface wear due to electrochemical-induced oxidation and sulfur attack, and 2) damage caused by interanode leakage currents and/or arcs. These effects are illustrated in Fig. 1.

The former mechanism occurs over relatively long periods as a result of material corrosion by oxygen and sulfur ions (O^- and SO_2^-). These ion species can be from several sources. They can originate from the combustion plasma and be driven to the anode surface by the electric field, or they can be released from the slag as a result of arc current transport through the anode slag layer. Judiciously placed protective cappings, using oxidation and sulfidation-resistant materials, are required to mitigate this problem.

The other anode lifetime-limiting mechanism results from interanode leakage currents and arcs. Interanode arcs are dangerous because once initiated, they are pushed by the lorentz force toward the anode wall and can cause severe damage to the internal wall structure. The consequences of interanode arcs can be minimized, first, by limiting the power that can be coupled into such faults; second, by incorporating design features that will quench these arcs; and finally, by employing wall structures that can withstand the effects of these arcs.

Anode design features capable of overcoming these lifetime-limiting effects have been developed and refined in the various subscale test programs conducted over the years. The anode design chosen for the ITC MHD generator was based on the results of these developmental programs in order to assure that the 2000-h lifetime requirement could be met. State-of-the-art metallic anodes were selected for the ITC anode design. To date, only cold metallic electrodes have performed successfully in slagging MHD generators. Ceramic electrodes, while promising for advanced generator designs, have only been tested in generators operating with clean fuels (i.e., natural gas).

Salient features of the prototypic anode design, and the reasons for choosing them, are described in the next section. Anode confirmation test results and the physical condition of the anode wall after 50 power hours of DVT and 300 power hours of POC testing are reported in the subsequent section.

Anode Description and Design Rationale

The prototypic anode design for the POC MHD generator is shown in Figs. 2 and 3. The anode gas-side elements are constructed of a water-cooled copper substrate with brazed-on platinum-on-tungsten caps to provide oxidation and sulfidation resistance. Platinum is the primary surface protection; tungsten serves as a backup protection.

These anode elements are mounted directly onto the interior surface of the anode wallboard (made of composite fiberglass sheets) and separated by strips of interanode insulators. The arrangement of the brass electrical studs and water tubes is also shown in Fig. 2. These parts of the anode electrode protrude through the anode backwall for current extraction and to supply coolant to the electrode from the channel exterior.

Boron nitride (BN) is used as the interanode insulating material. The insulators are recessed at the gas surface in order to provide a foothold for the slag coating during the operation of the generator. Aluminum nitride (AlN) tiles are brazed to the ends of the anode bars in the wall corner joint regions. Their purpose is to provide electrical insulation between the anodes and the sidewall elements.

Features of the ITC anode design were adopted to assure that the overriding requirements for the MHD generator, reliability and lifetime, would be achieved. How the specific anode design features contribute towards achieving these re-

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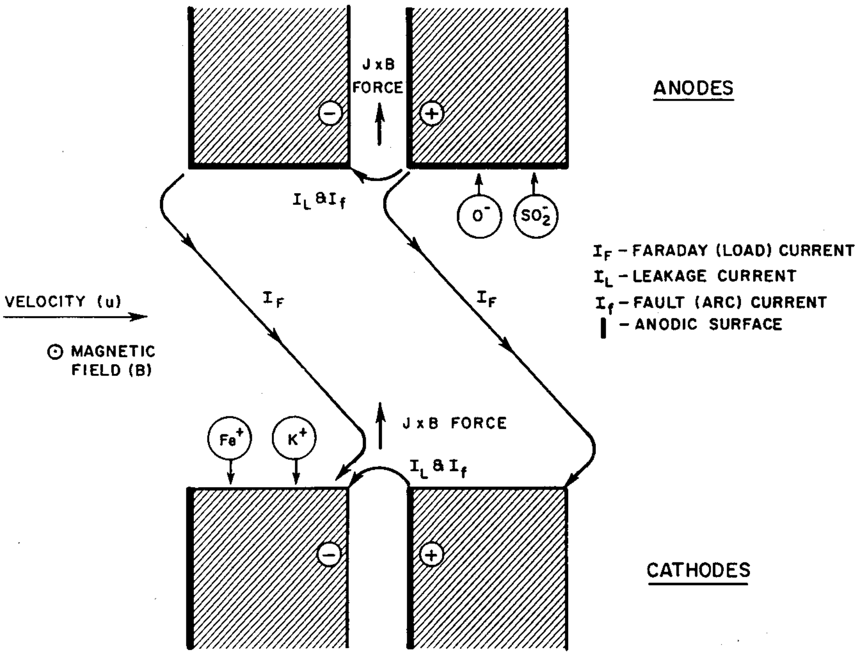

Fig. 1 Conceptual diagram of current and ion flows in the MHD generator channel.

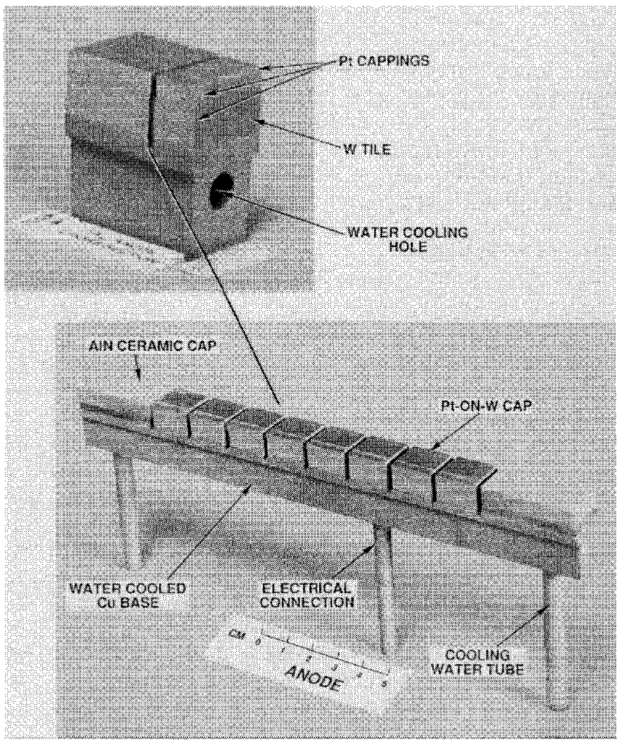

Fig. 2 Prototypic anode design.

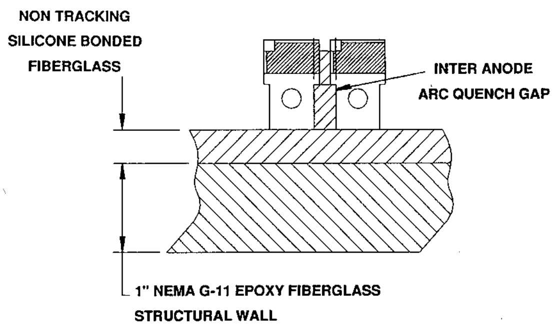

Fig. 3 Prototypic anode, fault protection details.

quirements is listed in Table 1. These are categorized into two groups: 1) features that provide material wear protection and 2) features that minimize interanode leakage current and fault damage.

Protective Cap Design

Platinum and tungsten provide the primary and secondary anode surface protections, respectively. Platinum is used as the primary gas-side protection because of its superior oxidation and sulfidation resistance. The arrangement of the platinum anode caps is shown in Fig. 2. The top surface protection is provided by a 0.8-mm-thick piece of platinum. The upstream corners of the anodes, where Faraday arcs tend to concentrate due to the Hall effect, are reinforced with $3.2 \times 3.2\text{-mm}^2$ strips of platinum. Finally, the leading edges are clad with a 0.8-mm strip of platinum to reduce the anodic wear that occurs there as a result of axial current leakage.

Platinum-capped anodes have demonstrated good wear resistance in MHD generator tests. These anodes were tested for over 1300 h in a 20-MW_t generator channel (Textron's Mk-VII facility), where both ash and sulfur were added in the oil-fired combustor to simulate coal-fired combustor operation, resulting in projected lifetimes of 6000–8000 h.[1] Platinum-capped anodes showed the same superior wear resistance during coal-fired generator tests at the CDIF.

The prototypic anode caps are fabricated from zirconia-grain-stabilized (ZGS) platinum. Electric arc impingement on the platinum capping provides the thermal conditions for grain boundary corrosion. The extent of this attack is proportional to the size of the platinum grains, and so smaller grains are affected least. The addition of a few hundred parts per million of ZrO_2 to the platinum during manufacturing reduces platinum grain growth at elevated temperatures and makes the platinum more resistive to grain boundary attack. Figure 4 shows a comparison of standard and grain-stabilized platinum samples that have undergone similar hours at 1400°C. It has been demonstrated, in Mk-VII and CDIF generator tests, that anodes capped with ZGS material show markedly less arc tracking and grain boundary attack than anodes with non-ZGS platinum.[2]

Although test results indicated that the platinum alone could satisfy the ITC generator lifetime requirement of 2000 h, experience has shown that a backup underlayment is necessary to protect the copper against local loss of platinum from braze

Table 1 Anode features for meeting the ITC lifetime objective

For surface material wear protection
- Pt primary gas-side protection; W secondary protection
- Slagging operation to minimize surface erosion and to decrease size of transverse arcs

For minimizing interanode leakage and fault damage
- Current control circuitry to prevent interanode arcing
- Limit magnitude of electrode fault power
- Water-cooled copper base
- Well-cooled BN interanode insulator
- Pt leading-edge capping to prevent wear due to axial leakage current
- Arc-quenching grooves
- Noncharring G-7 backing wall

Others
- Aluminum nitride to increase anode/sidewall electrical resistance

Table 2 Relative current erosion resistance of metals

Impulsive heat load $(T_{mp} - T_B)\sqrt{\lambda \rho c}$	Continuous heat load $(T_{mp} - T_B)\lambda$
Graphite, 7200	Tungsten, 3980
Tungsten, 6800	Graphite, 3600
Iridium, 5550	Copper, 3540
Osmium, 5400	Molybdenum, 3530
Molybdenum, 5250	Iridium, 3300
Rhenium, 4580	Silver, 3180
Rhodium, 4570	Osmium, 3120
Copper, 3750	Gold, 2900
Chromium, 3440	Rhodium, 2620
Tantalum, 3300	Rhenium, 2150
Platinum, 2820	Tantalum, 1450
Gold, 2800	Platinum, 1360
Silver, 2770	Aluminum, 1230
Beryllium, 2740	Beryllium, 1180
Niobium, 2730	Niobium, 1160
Nickel, 2500	Chromium, 1160
Cobalt, 2480	Nickel, 950
Iron, 1970	Cobalt, 835
Aluminum, 1370	Iron, 575

T_{mp} = Melting point; T_B = bulk temperature; λ = thermal conductivity; ρ = specific density; and c = specific heat.

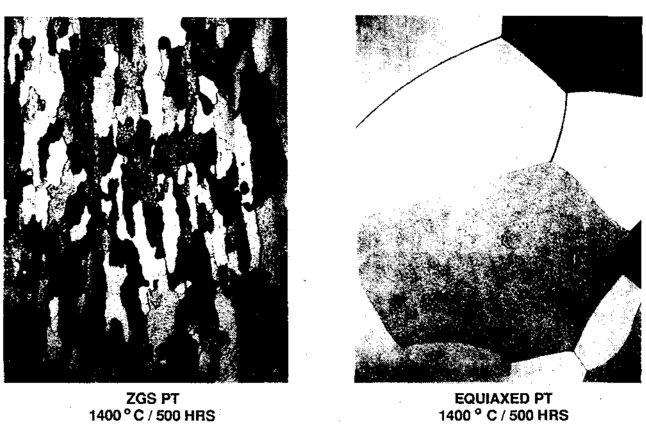

Fig. 4 Comparison of grain structure: platinum vs zirconia grain-stabilized platinum.

defects and/or from strong arcs due to electrical nonuniformities and interelectrode faults. Once the platinum is breached, sulfur attack on exposed copper is rapid. In the event that a platinum anode cap is lost in a utility powerplant MHD generator, this backup protection would allow continued power generation until the next scheduled plant maintenance period.

Tungsten caps are used as a secondary protection under the platinum anode cladding (see Figs. 2 and 3). Tungsten produced excellent results on anodic surfaces in MHD applications due to its high arc resistance, as shown in the relative ranking of metals in Table 2. The reason tungsten works so well is due to a combination of its high thermal conductivity (170 W/m-°C) and high melting temperature (3400°C). Oxidation of tungsten in air or oxygen begins at about 540°C. Fortunately, the partial pressure of oxygen is very low in the MHD channel, and even in the highest heat flux regions of the channel (250 W/cm^2), the temperature differential across the 1-cm-thick tungsten cap is only 120°C with a surface temperature of approximately 260°C, well below the threshold for oxidation.

Tungsten has been extensively tested as an anode gas-side surface material in the Mk-VII and CDIF MHD facilities. Tests were conducted to obtain the wear characteristics of tungsten under conditions that simulate the loss of the platinum primary capping. Wear measurements of test coupons placed at high electrical stress regions of the channel indicated an extrapolated lifetime of over 1400 h for a tungsten anode without a platinum corner.[3]

The slag coating on the electrode surfaces also acts as a protective covering. The slag layer helps to prevent surface erosion and minimizes wear due to transverse arcs. To help obtain a uniform slag covering for the prototypic anodes, the interanode insulators were recessed at the gas surface to provide a foothold for slag attachment. During the assembly of the generator channel, these recessed cavities were filled with castable refractory cement (Dylon-C10), which is subsequently flushed out as the slag layer is established during generator operation. The spacing between the individual platinum/tungsten caplets also aids in slag retention (see Fig. 2). These narrow gaps were left between the caplets to prevent bowing of the electrode bar during postbraze cooling (as a result of the differences in thermal expansion coefficients between tungsten and copper).

Fault Protection Features

In addition to electrochemical corrosion, the anode wall of an MHD channel has the greatest susceptibility to electrical faults. Features of the prototypic channel design that were incorporated specifically to inhibit arcs and to prevent serious wall damage, should any arcs occur, are listed in Table 1.

Although current control circuits are not part of the anode configuration, they are an important part of the overall strategy to prevent fault damage to the anode wall. Experience has shown that the anode wall of a slagging diagonally loaded MHD generator (without current controls) is prone to fault damage. This damage is a consequence of the transfer of cathode voltage nonuniformities to the anode wall through the external diagonal connections of the generator. Unlike the cathode wall, the anode wall cannot tolerate the high interelectrode voltage characteristics of the cathode nonuniformities. Electrical breakdowns at high voltage gaps lead to the creation of faults, which are then driven by the lorentz force into the interanode insulators, resulting in localized channel wall damage (see Fig. 1). The current control devices are installed in each diagonal connection to prevent the high-voltage cathode nonuniformities from reaching the anode wall. Figure 5 shows the current control devices for the ITC power generator installed at the CDIF test facility.

Damage to the anode wall from electrical faults can be controlled by limiting the magnitudes of the electrode current and interanode voltage so that the resulting electrode fault power is below some critical value. This critical fault power is determined experimentally and is defined as the maximum power that the generator may couple into an interelectrode insulator gap.[4] This aspect of the anode design (i.e., limiting the maximum values of the electrode fault power) is taken into account during the geometric design of the generator channel. The fault power criterion also provides a basis for the pitch and length of the anode bars.

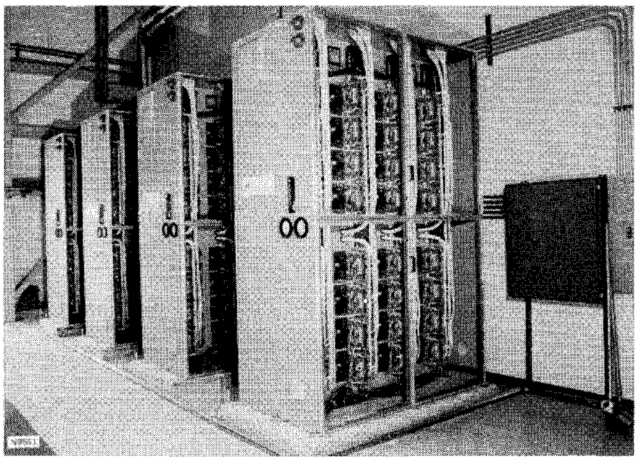

Fig. 5 Current control devices installed at the CDIF.

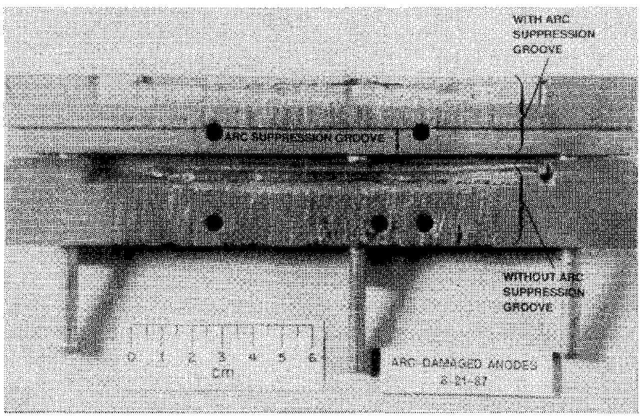

Fig. 6 Posttest photograph of Mk-VII anodes showing the effectiveness of arc-quenching grooves.

The copper anode bases also have a fault prevention function. These well-cooled copper bars serve as massive current leadouts to quench arcs, should they occur, and for dissipating arc energy to prevent potentially damaging faults.

Hot-pressed BN is used for the interanode insulating material. The BN insulators are well cooled to decrease the chances of interanode breakdowns. The insulator strips are installed such that one side is in direct contact with the metal anode in order to provide maximum cooling; the other side of the insulator strip is attached to the anode bar using a thin film of silicone rubber cement.

Another feature incorporated into the anode design is the arc stretching gaps that are machined into the fore and aft sides of the copper base. These gaps more than double the standard gas-side interanode gap from 2.3 to 5.3 mm at the base of the anode (see Fig. 3). The purpose of these gaps is to help quench interanode arcs. The movement of the arcs (as they are pushed by the lorentz force toward the backwall) is arrested at the edge of the cavity. The sudden expansion of the interanode spacing at the edges of the grooves causes the arcs to stretch and consequently extinguish. Tests in the Mk-VII generator channel demonstrated how well these grooves work. Two groups of adjacent anodes were purposely shorted externally to induce a large voltage at the gap between them, and to initiate breakdowns having large values of fault power. Figure 6 is a posttest photograph of these anodes. The upper electrode has arc-extinguishing cavities and the lower one does not. Notice that all the arc tracks terminate at the edge of the arc-extinguishing cavity on the upper electrode, but continue to the base of the anode (and to the channel backwall) on the lower anode.

In the unlikely event that interanode arcs do get to the plastic backwall, a 1-cm-thick sheet of nonarc-tracking G-7 material was installed between the anodes and the G-11 structural wall, as shown earlier in Fig. 3. Without this protection, arc-induced charring of the channel structural wall can create a permanent interanode short. This short would increase the interanode voltage at the gap immediately upstream of the shorted group of anodes, which in turn would lead to additional breakdowns that would continue to cascade upstream. This fault condition would eventually result in a forced shutdown of the power generator.[4] The G-7 material protects the channel backwall from this type of fault. G-7 is a silicone-bonded fiberglass and, therefore, difficult to char. Tests have shown that charring of G-7 occurs only under the most severe conditions, and that the resistivity of this char is at least 30–60 times higher than the char from burnt G-11.

Anode Test Results

Anode test results from the confirmation tests, design verification tests, and POC duration tests are described herein.

Confirmation Test Results

Anode confirmation tests were carried out between 1991–1992 prior to the fabrication of the ITC MHD generator. The purpose of these tests was to confirm the anode design features selected for the ITC generator. Sections of the anode wall on the CDIF workhorse channel were fitted with various anode designs and tested under coal-fired conditions. Similar anode design variations were tested for longer duration in the Mk-VII MHD facility under simulated coal-fired conditions (oil-fired, ash-injection conditions). Test results showing differences in the wear characteristics between slagging and nonslagging anode designs are presented below. Alternative anode designs which could meet the requisite lifetime projections are also described.

The significance of having a uniform slag coverage for anode protection was demonstrated in these confirmation tests. Wear characteristics of platinum-capped slagging and nonslagging anode designs were evaluated in both the Mk-VII generator channel and in the CDIF workhorse channel.[2] The slagging and nonslagging anodes used in these comparison tests (shown in Fig. 7) were similar except for the presence of the recessed interanode insulator for slag retention. The nonslagging anode design is similar to that used in an earlier 1000-h anode test.[1] Initially (i.e., prior to the confirmation tests), this nonslagging anode design was the leading candidate for the ITC MHD generator. There were two factors that favored this design at that time: 1) the successful long-duration (1300^+ hours) anode experience was with a nonslagging design and 2) the resultant increase in boundary-layer voltage drop of the bare anode wall is small (compared to a slagging anode wall) and is predicted to have only a minor negative effect on baseload MHD plant performance.[5,6] How-

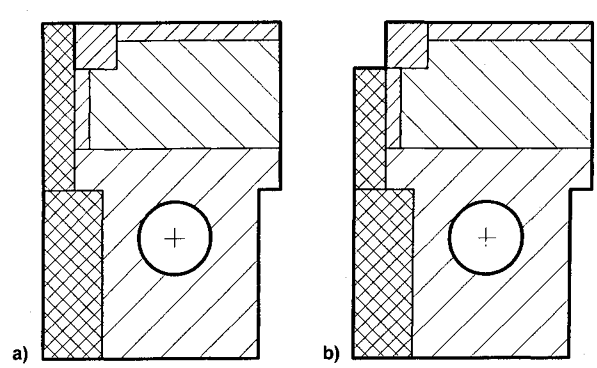

Fig. 7 a) Nonslagging and b) slagging anode designs.

ever, it was noticed during the confirmation tests that the anode wear characteristics can be quite different between the slagging and nonslagging designs. This difference arises mainly from the abilities of these designs to provide a uniform slag surface.

During anode confirmation tests of the nonslagging anodes, local areas of the platinum surfaces had either more pronounced arc tracking, or a marbling (mud cracking) on some of the platinum top caps. This wear characteristic of the nonslagging anode was found in both the Mk-VII and the CDIF generator tests.[2] In both test series, the nonslagging anodes were actually partially slagged. The nonslagging anodes eventually develop a slag coverage as operating time increases. The slag coverage that forms is spotty and uneven, as evidenced by slag pools or slag streamers. These slag covered regions coincided with the anomalous platinum wear, an example of which is shown in Fig. 8. Because of its high surface temperature, a slag covered region of the anode wall provides much lower impedance to charge transfer with the plasma than does a much colder bare metal surface. Slag cover raises the effective wall temperature from less than 700 K to approximately 1800 K. These "hot" spots accentuate current concentrations resulting in regions of localized corrosion. Local current densities may be as much as 7–10 times higher where slag is present on only a small part of the anode. By contrast, the slagging anodes have much more uniform slag coverage, and correspondingly less platinum wear. The slagged anode walls have a higher effective surface temperature, lower boundary-layer voltage drops, and reduced current concentrations, while at the same time maintaining a low metal temperature with little local heating effects. It was for this reason, the need to obtain a more uniform slag coverage, that the slagging anode design was selected for the ITC power generator.

A variety of anode designs were tested during the confirmation tests. In addition to the anode design that was eventually selected and fabricated for the ITC generator, several other designs also demonstrated excellent lifetime projections. Two of these promising slagging anode designs are shown in Fig. 9.

The anode on the left is basically the prototypic ITC anode design, except this design is simpler, lacking the platinum top foil. Initial tests of this design in the Mk-VII generator channel resulted in lifetime projections of 6800 h. This projection was based on wear measurements of test coupons placed towards the rear half of the generator channel where the electrical stresses are lower ($J_y = 0.5$ A/cm^2). In the front of the channel where the current densities are higher ($J_y = 1.0$ A/cm^2), platinum top foil is still needed to get the requisite anode lifetime. Coal-fired operating experience with this anode design at the CDIF is limited to only about 50 power hours on a handful

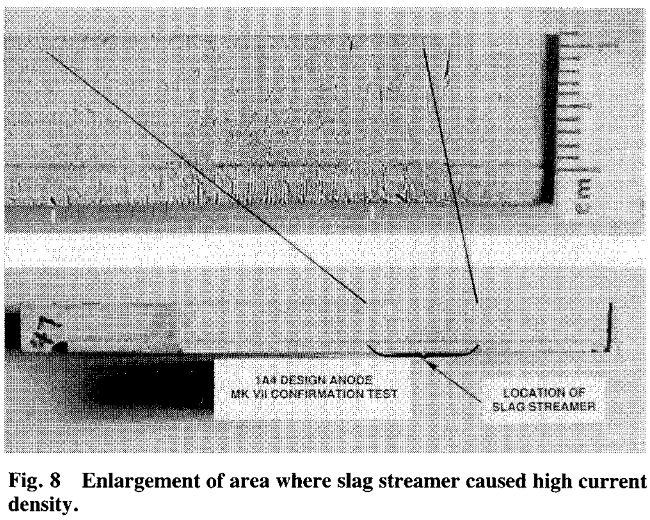

Fig. 8 Enlargement of area where slag streamer caused high current density.

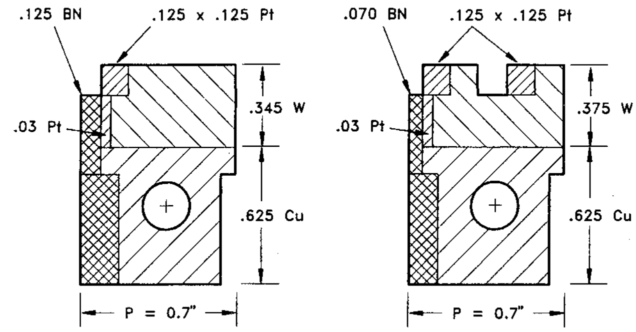

Fig. 9 Alternative slagging anode designs.

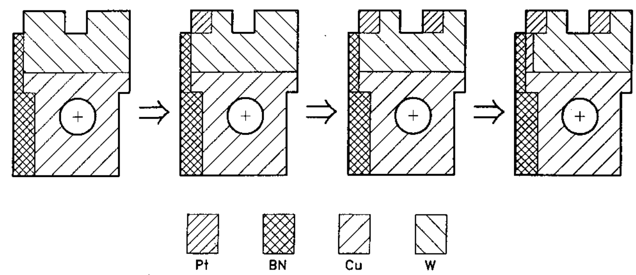

Fig. 10 Evolution of an alternate anode design.

of test coupons. However, the results are very encouraging. The measurements indicated a higher wear rate during the CDIF tests than that measured earlier in the Mk-VII. This trend is not unexpected since the CDIF test coupons were located at a much higher stress region of the channel. Lifetime projections, based on the observed wear rate and normalized to a current density of 0.5 A/cm^2, can still exceed that of the ITC requirement. This lower-cost anode design may prove to be a good candidate for use in large portions of baseload MHD generators where the electrical stresses are low.

Another promising anode design is shown on the right of Fig. 9. This design has an extra slagging groove along the anode surface for better slag attachment. Basically, this design evolved from a cathode bar that was used as an anode wall element. The development of this anode design through its testing stages is shown in Fig. 10. During extensive testing in the Mk-VII, these test coupons slagged well and had a conservatively projected lifetime of 4000–7000 power hours. The surface wear pattern for this design (two slagging grooves per electrode pitch) was found to be different than that observed for designs with a single slag groove. In the two slagging groove anode design, the recession rate of the tungsten material situated immediately behind the upstream platinum corner is significantly reduced. It is conjectured that the presence of the extra slagging groove draws away some fraction of the current that normally concentrates at the leading edge of the anode, thus distributing current more evenly over the pitch of the electrode. Testing of this anode design was also carried out at the CDIF under coal-fired conditions. No observable wear was measured after 22 power hours of operation. Plans to accumulate additional coal-fired test hours on these test coupons in the CDIF workhouse generator channel were abandoned due to funding and schedule limitations.

Design Verification Test Results

Design verification testing was carried out in two 50-h segments between late 1992 and early 1993. The ITC generator channel was unboxed for inspection between the two test segments. Results of the anode wall inspection are described in this section. More detailed discussions on DVT results are reported in Ref. 7.

Most of the early DVT was dedicated to working through "shakedown" problems associated with an extensively modified test facility, establishing combustor operating parameters, and studying the effects of combustor hardware configuration changes. This frequently resulted in off-design operation and harsh operating conditions for the generator channel. Substantial fluctuations were observed in the measured electrical variables during the earlier DVT series. The magnitudes of these fluctuations were considerably higher than those observed during earlier CDIF workhorse generator tests and they caused the ITC generator to operate at electrical stress levels that were much more severe than what are considered to be prototypic. The various sources of these fluctuations were eventually identified and eliminated during the course of power train testing.

The anode fault protection features worked very effectively. The large fluctuations in interanode voltage (both spatial and temporal) were measured throughout DVT, suggesting strong arcing at the anode wall surface. Also, very high interanode voltages (80–140 V) were frequently measured during power tests. At such high gap voltages, arc breakdowns occurred between the anodes. Previous experience during subscale generator testing in the Mk-VII facility has shown that arcing appears at interanode voltages in excess of 60–80 V. In spite of these large interanode voltages, no permanent shorts occurred on the ITC anode wall. This indicates that the fault protection features of the anode design, i.e., arc stretching grooves and noncharring G-7 backwall, worked successfully. Physical evidence of severe interanode arcing was found during post-DVT inspection periods. Arc tracks, and in some cases melted platinum, were found on the leading-edge surface of the anodes. However, all of the arc tracks terminated at the edge of the arc-extinguishing cavity. In no case did the interanode arcs continue to the base of the anode and to the channel backwall.

The use of AlN corner tiles to provide electrical insulation between the anodes and the sidewall elements worked very well. All of these corner tiles were found to be in excellent condition. The two anode/sidewall corner joints were also in excellent shape, with no indication of any electrical breakdowns. These corner regions had been prone to arc damage in the earlier CDIF workhorse generator channel, which did not have this ceramic corner tile feature.

The inspection technique implemented during the fabrication of the anodes for quality control of the braze joints was found to be inadequate.[8] During the post-DVT generator inspection, it was discovered that the platinum top caps had separated from approximately 5% of the anode caplets (125 out of 2200 total caplets on the anode wall). The loss of the platinum top caps appeared to have been initiated by the failure of the braze joint and the resulting separation of the cap at the trailing edge of the caplets. Records of the anode fabrication and brazing histories were reviewed in an attempt to correlate lifted top caps to specific fabrication techniques and/or oven braze cycles. Nearly 70% of the lifted anode caps were produced in fewer than 10% of the platinum/tungsten caplet subassembly braze cycles. This indicates that a few inadequate braze cycles (about 5 braze cycles) were the root cause of the defective caps. The failure of the ultrasonic inspection procedure to identify all of the faulty brazes suggests it needs to be modified and/or supplemented with other inspection methods.

The loss of platinum anode top caps was not life threatening to the generator tests. At the time of the anode wall inspection, in late 1992, there was no evidence of any wear on the exposed tungsten surfaces where the platinum cap material was missing. The purpose of the back-up tungsten capping is precisely to protect the anodes against the possible loss of the platinum top caps.

POC Test Results

Results from the anode wall inspection, after approximately 300 power hours of POC testing, are presented.

POC tests again confirmed that good slag coverage is a prerequisite for anode lifetime. Unfortunately, slag cover on the anode wall was not uniform during most of the POC test series. When the ITC generator channel was disassembled it was noticed that the slag coverage was irregular. As can be seen in the photograph of Fig. 11, slag coverage was primarily concentrated in a narrow strip down the center of the anode wall. The average width of this strip of slag, over the length of the channel, was approximately 5–8 cm wide. The slag was as thick as 5 mm at some locations. Slag coverage towards the anode/sidewall corner regions of the anode wall was very poor.

The wear on the anode surface was also not uniformly distributed. A higher than normal rate of wear was observed underneath the center strip of slag. The local wear rate in this region of the wall was much higher than what one would expect based on the earlier confirmation test and DVT results. The wear rate over the unslagged regions of the wall was normal. The characteristics of this localized anode wear were similar to those observed earlier, on the nonslagging anode test coupons in the confirmation tests, when the anode slag covering was not uniform. The appearance of melted platinum underneath the slag suggested very high local surface heating due to high Faraday current densities. The condition of the slag coverage also indicated uneven surface heating. The center strip of slag is greenish in color and had a dense glassy consistency, suggesting high temperature and melting. The slag deposits elsewhere were black in color and had a loose porous texture.

A review of generator test data provided an explanation for the nonuniform wall slag coverage during the POC tests. The test data indicated that the accumulation of slag down the center of the anode wall may have been due to secondary flow in the channel, in the form of two counter-rotating vortices as shown in Fig. 12. This flow pattern was caused by the interaction of the magnetic field with a large axial current flowing in the plasma core region of the channel. The cause for this downstream current was due to improper generator loading and large surface current leakage.[7]

The electrode current, which would normally distribute evenly over the width of the anode, concentrated over the slag covered region where the effective surface temperature was higher. The Faraday current density in this localized region could have easily exceeded the maximum design value. In the case of the ITC generator, the slag strip covered only 20% of the anode width, and if one assumes all of the current collected only over the slag-covered region, then the local current density would have been five times higher than normal. Most likely, current constrictions occurred over the narrow slag strips to form arcs. Subsequent to the POC tests, bench-top testing was carried out to explore the hypothesis that excessive currents (or arcs) were the cause of the unusual localized anode wear. A plasma arc-torch test rig was used to establish the electrode arc current damage threshold of the

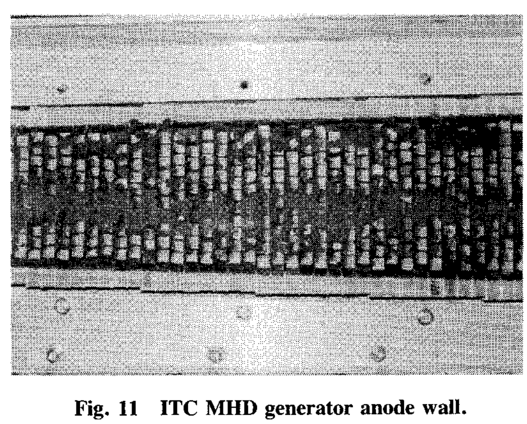

Fig. 11 ITC MHD generator anode wall.

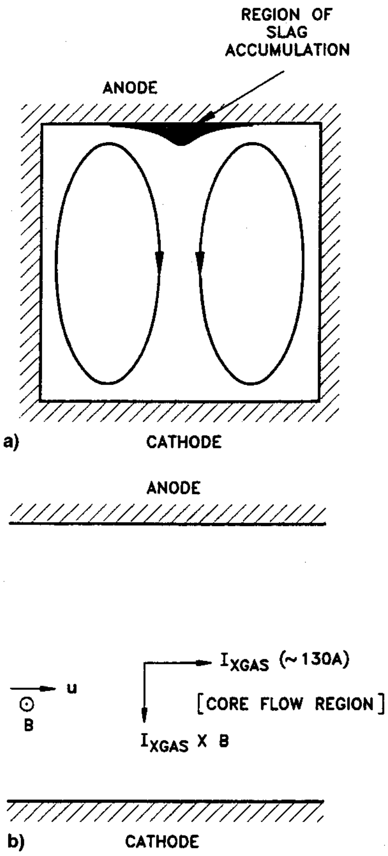

Fig. 12 Relationship between I_x flowing downstream and uneven anode slag accumulation: a) cross-sectional and b) side views.

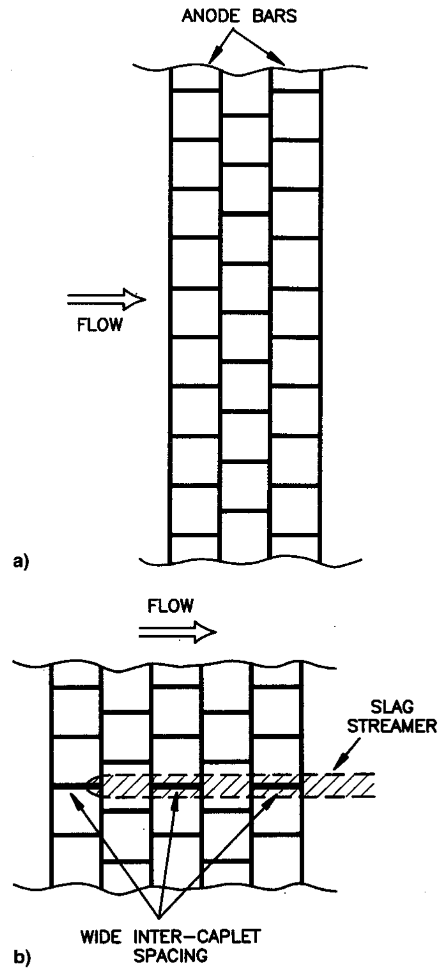

Fig. 13 Arrangement of anode intercaplet spacing.

anode caplets.[9] Arc currents of the order of 12 A were required to duplicate the degree of wear seen on the ITC anodes.

An alternate POC test-operating condition was identified in order to reduce the amount of secondary flow and obtain more uniform slag distribution. This operating condition was tested late in 1993. Test data indicated that generator operation at this new condition resulted in almost the same prototypic wall stress conditions as the original operating conditions, but the magnitude of the axial current in the core flow region and the strength of the secondary swirling flow were both substantially reduced.

During the channel inspection period of June 1993, a group of newly fabricated anode bars was installed in the ITC generator. The intent was for this group of anodes to serve as a control group during the final segment of POC testing to verify that localized wear was indeed eliminated with more uniform slag coverage. Unfortunately, the ITC program funding was terminated soon after. The test times accumulated by the control anodes, approximately 50 power hours, proved to be an insufficient basis for lifetime projections, nor could this test period provide conclusive data on the improvement in wear associated with better slagging due to reduced swirl flow.

From posttest inspections, it was determined that the anode caplets could have been made larger and their spacings tighter. Transverse tile segmentation is needed to prevent bowing of the electrode bar during postbraze cooling, resulting from differences in thermal expansion coefficients of the metals. The tile lengths on the ITC anode bars varied from 1.3 to 1.8 cm long. These corresponded to the dimensions of available tungsten stock from which the tiles were made. However, experience has shown that tiles can be as long as 4 cm before encountering brazing difficulties due to the aforementioned thermal expansion differences. Longer and fewer caps per bar would simplify fabrication of the anodes. Also, the spacing between the caplets should have been narrower and more uniform in gap width. The intercaplet spacings on the ITC anode wall were not constant, but varied from electrode bar to another (gap spacing ranged between 0.09–0.23 cm). This is because the Pt-W caplets were fabricated in specific lengths, and the intercaplet spacing was varied in order to distribute the caplets along the length of the anode bars. The electrode bars are mounted onto the wall so that the caplets are arranged in a staggered pattern (see the sketch in Fig. 13a). During posttest inspections, it was noticed that slag streamers formed preferentially over wall regions where several wider intercaplet gaps lined up in the streamwise direction. This is illustrated in the sketch of Fig. 13b. Higher material wear was observed at the locations of these slag streamers, resulting from current concentrations.

Also, in conjunction with ensuring good slag coverage of the channel walls, future test procedures should incorporate longer slagging periods (thermal operation, but no power) before the start of each power test, especially for those following emergency system shutdowns. Most of the wall surfaces are bare after such emergency shutdowns due to spalling of the slag.

Summary

The design description and design rationale for the prototypic anodes of the ITC MHD generator have been reviewed. The conditions of the ITC channel anode wall, after 50 power hours of DVTs and after 300 power hours of POC testing, are described. Finally, lessons learned from the design and operation of the anode wall are described.

The general state of the anodes after the rough and nonprototypic operations of the DVT series suggests that the fault protection features of the prototypic anodes are very effective.

The latest generator channel inspection indicated that the material wear was not uniform and that local wear rates were higher than the previous confirmation test and DVT results. There were indications to suggest that the localized wear was due to nonuniform slag coverage. The uniformity of the anode wall slag coverage has a large influence on wear rates.

Anode lifetime projections were not made because of inconclusive test data. Localized wear was discovered on the anode wall toward the end of the POC test period. This wear was due to poor slag coverage on the anode wall as a result of improper generator loading. An alternative generator operating condition was selected to correct this situation. However, the ITC test program was terminated before this issue was completely resolved.

Acknowledgments

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