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Erosion Measurements on Quasisteady Magnetoplasmadynamic Thrusters

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Erosion of the boron nitride chamber insulator of a high power quasisteady magnetoplasmadynamic thruster has been measured directly using a quartz crystal microbalance (QCM) method. A 1-μ-thick layer of boron nitride is sputtered on the QCM, after which it is mounted flush in the boron nitride backplate insulator, and monitored for change in resonant frequency following thruster operation. The measurements confirm the concept of an "onset" arc current, above which severe erosion occurs, but below which long-term thruster operation at interesting performance levels appears promising.

Introduction

MEASUREMENTS of the impulse delivered by a self-field quasisteady magnetoplasmadynamic (MPD) thruster have demonstrated that as arc current increases for a fixed mass flow, the thrust, specific impulse, and efficiency increase.[1] Typical performance figures for an unoptimized research thruster using argon propellant are a specific impulse of 2000 s at a thrust efficiency of 28%. With nitrogen propellant, the performance of this same reference thruster increases to 4000 s at 38% efficiency, and still further improvements in performance are anticipated using different electrode configurations and other propellants.[2] With its performance capability now demonstrated, the MPD thruster becomes a more serious candidate for a variety of near-Earth and interplanetary space missions.

Since the thruster performance is strongly dependent on the arc current, there is a clear motivation to operate these devices at the highest current possible in order to obtain the maximum performance. There is, however, a geometry-dependent limiting current, called the onset current, J^*, beyond which the normally steady terminal voltage develops large megahertz oscillations, and spectroscopic and photographic evidence of thruster electrode and insulator erosion appear.[3] If severe, this erosion could limit the lifetime of the MPD thruster at the higher performance operating conditions.

Few attempts have been made to measure the erosion of a plasma thruster. Since no diagnostic appears to be capable of providing real-time erosion data in the hostile environment of the MPD chamber, the standard approach in the past has been differential weight measurements before and after a series of thrust pulses. In even the most careful of these experiments, the true erosion was masked by the absorption of both residual water vapor and vacuum pump oil vapor during the time required to remove the thruster from the vacuum vessel, disassemble it and weigh it.[4] Attempts to limit the amount of absorbed mass by a capping mechanism which isolated the thruster between firings, or to account for the absorbed mass by comparing the change in thruster weight to that of an identical insulator-electrode assembly which was mounted in the same vacuum tank but not fired, were only partially successful, and the final differential values of eroded mass did not have the desired accuracy.

This paper describes the use of the quartz crystal microbalance (QCM) to obtain an in situ measurement of the erosion of the principal insulator of the MPD thruster. Part of a larger program to measure the erosion of all thruster components, the technique is based on the property of these oscillators of changing their resonant frequency when a small amount of mass is either added or removed from one surface. The application of this technique to the MPD thruster indicates that erosion can be tolerable for currents below the onset value, but increases rapidly for currents above it.

Experimental Facilities

The MPD thruster apparatus used for these QCM erosion measurements is shown in Fig. 1. The thruster itself, termed the benchmark configuration, consists of a 1.9-cm-diam by 10-cm-long thoriated tungsten cathode mounted on the centerline of a 12.7-cm-diam by 5.1-cm-long thrust chamber, the downstream end of which compromises a 18.7-cm-diam by 1-cm-thick aluminum anode with a 10.2-cm-diam orifice. The backplate, or upstream insulator of the arc chamber is boron nitride, and the chamber sidewalls are pyrex. Argon propellant is injected via a high speed solenoid valve so that 63% flows through an annulus at the base of the cathode and 37% is equally divided among 12 holes in the backplate at a radius of 3.8 cm. Arc current is provided from a 3000-μF capacitor bank arranged to produce single, constant current pulses of up to 24 kA for 1 ms, or up to 48 kA for 0.5 ms. The

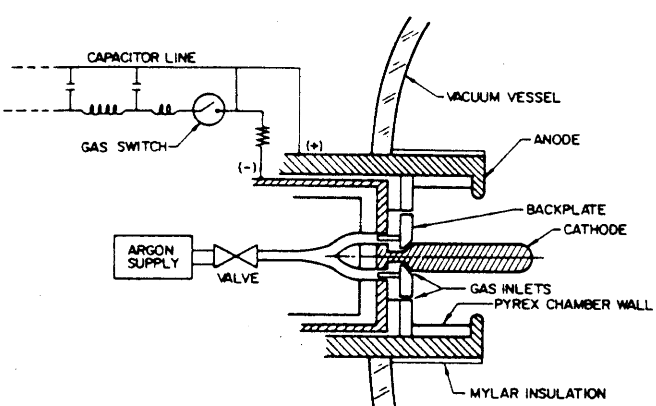

Fig. 1 MPD thruster schematic.

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thruster is mounted in a 1-m-diam by 2-m-long plexiglass vacuum tank which is routinely pumped to 10^{-5} Torr prior to thruster operation.

Previous spectrographic and photographic studies of this thruster have shown that depending on the mass flow division between inner annulus and outer holes, each of the electrodes and insulators erodes to some extent as the onset current is exceeded.[5,6] A more recent extensive spectrographic analysis of the discharge plasma has shown that, with the 63:37 mass division, the principal impurity observed in the discharge as the current is increased to values greater than the onset current is nitrogen from the boron nitride backplate.[7] The apparent concentration of this erosion on the boron nitride backplate has led to the application of the QCM technique, with the goal of estimating the erosion of this thruster component as a function of current.

QCM Instrumentation

The quartz crystal microbalance consists of an electronic oscillator whose frequency is stabilized by the piezoelectric effect of a quartz crystal which essentially couples internal electric polarization with the mechanical strain of the crystalline material.[8] The resulting resonant frequency depends on several properties, but if the oscillator circuit parameters are fixed, the specific mode of crystal vibration depends only on the orientation of the cut crystal plane with respect to the crystal axes.[9]

One of the most widely used cuts and the one that is most important for QCM applications is the AT cut, shown in Fig. 2 along with other commercial cut angles. The x axis in this figure is the electrical axis of the crystal, while the y axis is the mechanical axis; i.e., application of an electric field along the x axis produces an elongation or contraction along the y axis. AT cut crystals oscillate in the thickness vibration mode, a transverse shear of the surfaces, with a resonant frequency of typically 5 MHz.

A property of AT cut crystals is that the resonant frequency varies linearly with both the mass deposited on the surface of the crystal and the temperature:

$$\Delta f = C_M \Delta M + C_T \Delta T \quad (1)$$

where C_M and C_T are the mass and temperature coefficients of the crystal, respectively.[9] In general, C_M and C_T are themselves functions of temperature and crystal cut angle, but careful selection of the cut angle can minimize this complication. Figure 3 shows the angle of cut for which C_T is zero as a function of temperature. This graph shows that for our room temperature experiments, an AT cut angle of 35 deg 10 ft should eliminate the temperature sensitivity. With the added precaution that QCM frequency measurements will only be obtained sufficiently long after thruster operation for thermal variations to be dissipated, the temperature term in Eq. (1) can be neglected. Furthermore, for a considerable range of temperature and cut angle, the mass coefficient does not vary more than 5%, so that the expression

$$\Delta M = 4.4088(10^{-7})\Delta f / F^2 \quad (2)$$

can be used for a sensitive microbalance, where ΔM is the mass added or removed (g/cm^2), Δf the change in frequency (Hz), and F the resonant frequency of the crystal (MHz). Note that for a resonant frequency of 5 MHz and a frequency resolution of 1 Hz, a sensitivity better than $2(10^{-8})$ g/cm^2 is indicated which, for a boron nitride density of 2.25 g/cm^3, gives a depth resolution of approximately 10^{-4} μ or 1 Å.

Figure 4 shows the hex inverter circuit used for frequency measurement of the oscillating crystal. It is a variation of a previously developed, variable frequency crystal oscillator circuit employing three of the six inverters contained in a 7404 hex inverter integrated circuit.[10,11] Two of the three inverters form the oscillator and the third is the output buffer. The circuit tunes itself to the crystal resonant frequency, at which the crystal appears to the circuit as a pure resistance of low value. The driving circuit is connected with conducting epoxy to platinum electrodes on the surfaces of the crystal, shown for the typical QCM used in these experiments in Fig. 5. Bench tests with this direct frequency measuring circuit have demonstrated that it can measure the approximately 5-MHz QCM oscillation frequency with a reproducibility of a few hertz.

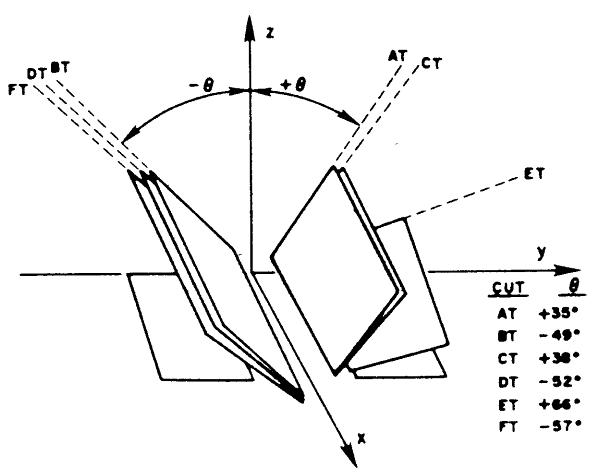

Fig. 2 Principal cuts of quartz crystals.

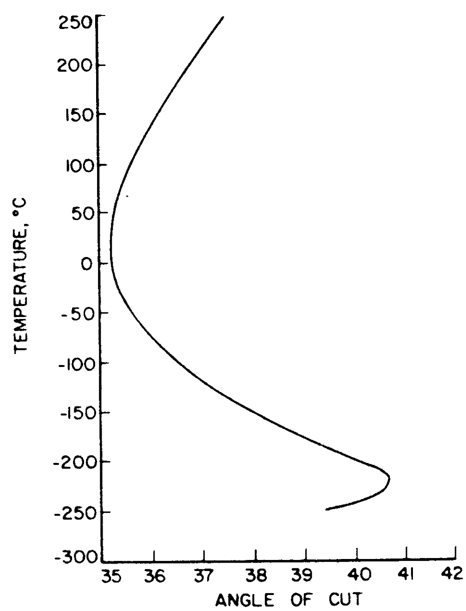

Fig. 3 Temperature for zero temperature coefficient.

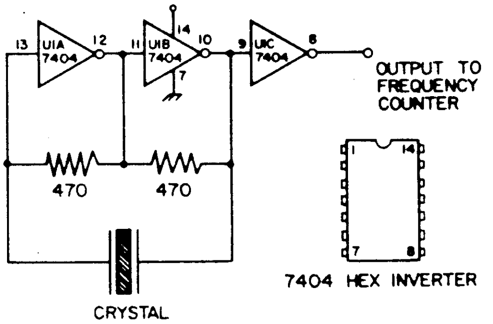

Fig. 4 Hex inverter circuit.

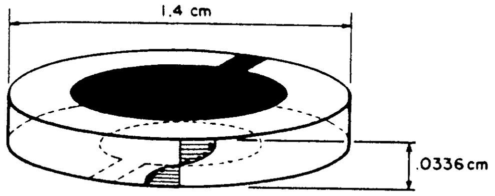

Fig. 5 Quartz crystal.

Quartz crystal microbalances have traditionally been used to measure small amounts of deposited mass, e.g., in a sputtering chamber. More recently, they have beeen employed in the exhaust plumes of solid propellant pulsed plasma accelerators to map the propellant distribution by condensing propellant vapor on the surface of cooled QCM's, although these measurements were complicated by incomplete accommodation of the plasma to the QCM temperature and by backstreaming of propellant in the vacuum tank.[12] The present application of QCM's for erosion measurement is categorically different from such experiments in that it uses the frequency sensitive character of the QCM to measure mass loss rather than mass gain. Briefly, the concept involves coating one surface electrode of the QCM with boron nitride, mounting the QCM flush in the boron nitride backplate, and monitoring its change in frequency as the boron nitride coating is eroded by the MPD discharge. This technique is naturally restricted to insulating surfaces, but since the boron nitride backplate is suspected of having the greatest material loss of any thruster component, the QCM data may provide a reasonable estimate of the magnitude of the erosion problem in these accelerators.

The boron nitride coating of the exposed surface of the QCM must be thick enough to insure the integrity of the crystal and its electrode surface during the discharge, yet thin enough to maintain the crystal oscillation in the thickness vibration mode. Bench tests of this latter restriction using easily removed films showed that the maximum change in frequency which can be generated by mass addition is approximately 40 kHz, which for a boron nitride coating on a 5-MHz crystal translates into a maximum thickness of 3 μ.

After considering a variety of boron nitride coating products, many of which contain impurities necessary for bonding with the substrate,[13] sputter-deposition of boron nitride was chosen. The sputtering was performed using a boron nitride blank as the target material, below which the QCM's to be coated were placed. For the experiments reported here, boron nitride coatings of 1.197 μ thickness were applied to ten QCM's, the coating thickness determined by frequency change using Eq. (2) and the density of boron nitride.

The high purity films that are usually achieved by sputtering, however, can differ stoichiometrically from the initial target material. To investigate this question, Auger analyses were performed on the target material and on the sputtered layer of one of the QCM's. The Auger scans showed that the composition of the sputtered layer agreed to within 1% of the composition of the boron nitride target plate. On this basis, it was concluded that the erosion data obtained for the coated QCM's would be characteristic of the original backplate material.

Prior to mounting the crystals in the thruster backplate, a series of preliminary tests were performed using two coated QCM's mounted on a boron nitride blank and positioned directly in the discharge of the MPD thruster. One of these test QCM's was covered with a thin plexiglass plate which prevented direct contact of the plasma with the QCM without affecting the radiation and electromagnetic environment. While the exposed QCM registered a frequency change which depended on the thruster operating conditions, the covered crystal showed no change in resonant frequency. These tests thus confirmed the concept of erosion measurement using this technique while also indicating the value of a covered reference QCM to ensure the validity of the erosion data.

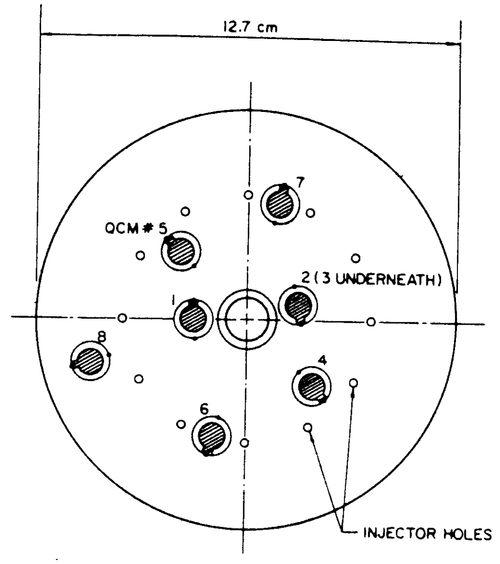

Fig. 6 QCM's on boron nitride backplate.

Following other preliminary experiments which demonstrated crystal reliability and integrity over a range of thruster operating conditions, seven coated QCM's were flush-mounted in the boron nitride backplate of the thruster as shown in Fig. 6. The QCM's were arranged to provide information on the radial dependence of erosion, as well as an azimuthal symmetry. In addition, QCM's 1 and 2 were arranged to determine the dependence of the erosion pattern on the injector hole arrangement. An eighth QCM (No. 3) was mounted directly behind QCM 2, on the back side of the 0.64-cm-thick boron nitride plate, to serve as a reference. The leads from all QCM's were brought outside the thruster through two vacuum fittings and were disconnected prior to each thruster firing to prevent an arc discharge to the grounded circuitry.

Results and Discussion

Erosion measurements on the boron nitride backplate were obtained for thruster currents from 4 to 32 kA and an argon mass flow of 5 g/s. Operation at the highest currents was left until last in case it should damage any of the QCM's. For each data point, the initial resonant frequencies of the crystals were measured, the leads disconnected and the thruster fired. Following each shot, the thruster was allowed to sit for several minutes to guarantee that the temperature of the thruster and QCM's had returned to its prefiring value, thereby doubly ensuring that the temperature effect term in Eq. (2) was negligible. Following this period, the QCM's were reconnected and the new resonant frequencies recorded.

The voltage-current characteristic obtained for the thruster at the 5-g/s mass flow is shown in Fig. 7. It is similar to other characteristics obtained with this same thruster, showing a nearly linear dependence on current at low current and a higher order dependence at high current as the electromagnetically generated thrust begins to dominate the propellant acceleration. The onset current, arbitrarily defined as that current where the peak-to-peak voltage fluctuations reach 10% of the mean voltage, is 20 ± 1 kA for this 5-g/s operating condition.

The QCM data are incomplete at the high currents due to failure of two of the crystals. QCM 1 was destroyed at a current of 30 kA early in the high current thruster firing sequence. QCM 2 failed near the end of this sequence, at a current of 31.2 kA. This latter crystal therefore accounted for most of the high current data at the innermost radius.

Figure 8 shows the complete raw data for one of the QCM's, in this case QCM 2. The data are presented in the form of measured frequency increase per shot, and indicate that little or no erosion occurs at this location until a current above the onset value is reached, after which significant mass loss is measured. With reference to Eq. (2), this mass loss reaches as high as $2(10^{-5})$ g/cm^2/shot at this inner radius location.

Data for the other QCM's are similar to that shown in Fig. 8 with the exception that QCM's located farther from the thruster centerline experience less overall mass loss than those closer to the cathode. Within the accuracy of the data, no difference could be detected between the responses of QCM's 1 and 2, 4 and 5, and 6 and 7; i.e., there are no apparent azimuthal asymmetries due either to gross distortion of the current pattern or to mass injection at discrete locations in the backplate. The reference crystal, QCM 3, displayed a resonant frequency which was essentially constant over the complete test range (standard deviation of 6.15 Hz on a resonant frequency of 4.982158 MHz), indicating that the electromagnetic environment had no adverse effect on the QCM data.

The data were combined to produce radial distributions of erosion for those current levels where sufficient data were obtained for a statistically derived error bar to be described. Figure 9 shows this radial distribution of erosion for four currents ranging from well below the onset current to well above it. Since no azimuthal asymmetry was detected, the radial plots include data from all QCM's regardless of azimuthal location. The error bars shown in the figure are typical of these data and represent the one-sigma limit for the QCM's at that radius and current.

Figure 9 shows that at a current of 15 kA, no erosion is detected within the reproducibility of the data. Although data for currents less than 15 kA are not shown in the figure, no significant erosion is measured for those currents as well. As current is increased to approximately the onset value, a small amount of erosion is detected at the innermost radial locations. Increasing the current above the onset value produces a greater degree of erosion over a larger radial extent of the backplate, and above 26 kA, erosion is measured at all radial locations, although by far the greatest fraction of this still occurs close to the cathode. This is consistent with spectroscopic data which show nitrogen from the boron nitride backplate at radii up to 2 cm for currents greater than approximately 1 kA above the onset value.[7]

The measured radial distributions of erosion in Fig. 9 can be used to calculate the total eroded mass from the boron nitride backplate as a function of thruster operating conditions. Since data have been acquired at only four radial locations, the calculation is performed as a sum of four distinct erosion zones rather than as a smooth integral; i.e., the data for QCM's 1 and 2 ($r = 2$ cm) were assumed to apply from $r = 1.15$ cm, the edge of the propellant injection annulus, to $r = 2.35$ cm, the midpoint between QCM's 1 and 2 and QCM's 4 and 5; the data at $r = 2.7$ cm were assumed constant from $r = 2.35$ to 3.25 cm; the $r = 3.8$ cm data from $r = 3.25$ to 4.45 cm, and the data for QCM 8 ($r = 5.1$ cm) from $r = 4.45$ cm to the outer chamber wall at $r = 6.35$ cm. This approach tends to underestimate the true erosion at small radii, while overestimating somewhat the contribution of erosion at larger radii.

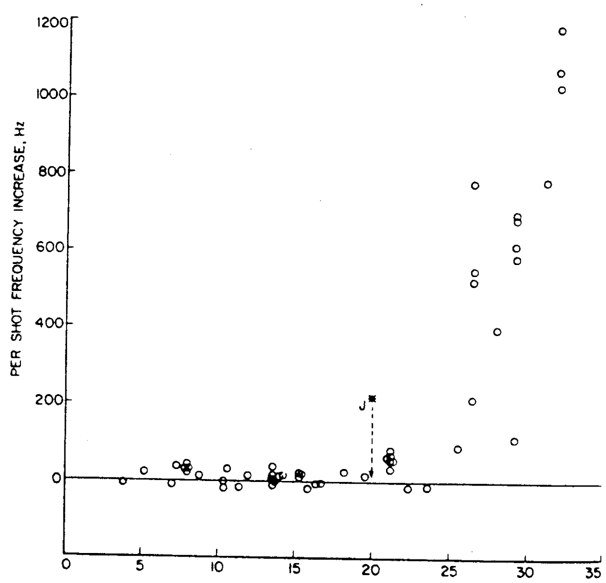

Fig. 8 Raw data, QCM 2.

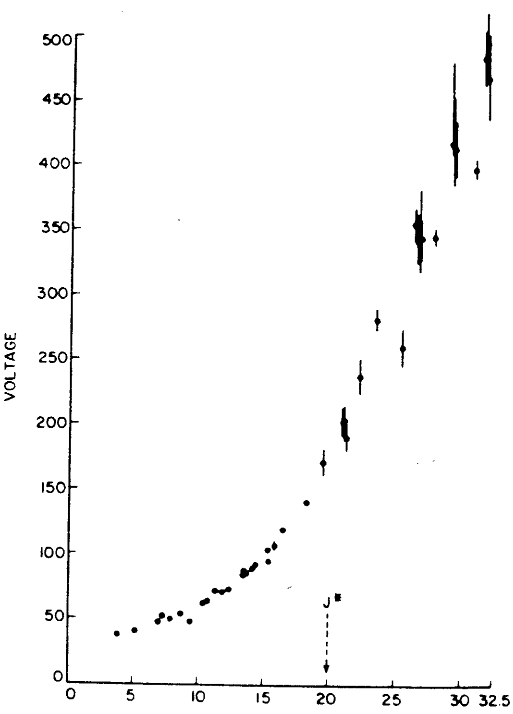

Fig. 7 Voltage-current characteristics; $\dot{m} = 5$ g/s.

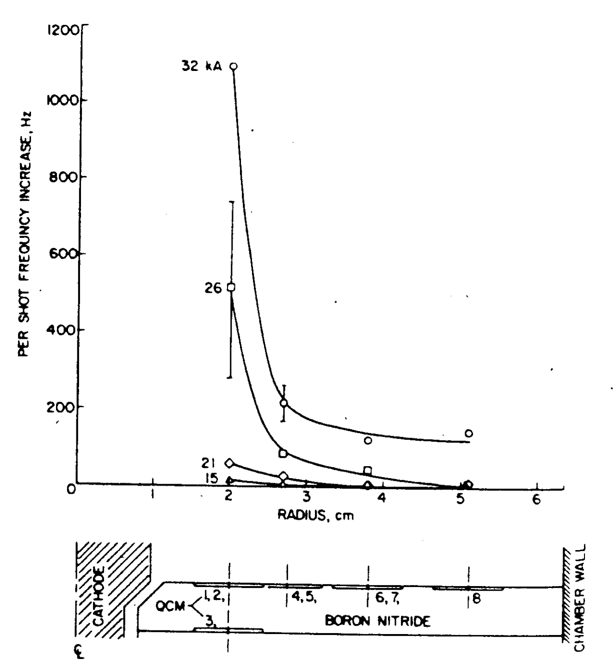

Fig. 9 Radial distribution of erosion.

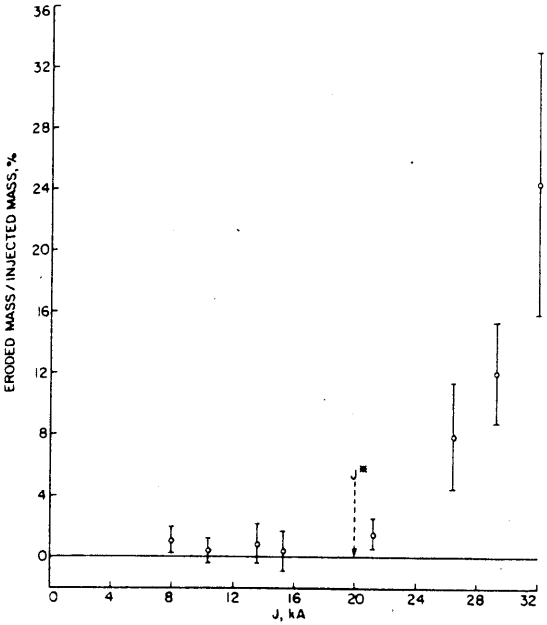

Fig. 10 Eroded mass fraction.

The erosion calculated from this summing procedure is shown in Fig. 10 expressed as a percentage of the propellant mass injected during the 1-ms-long thruster operation. The error bar on each data point represents the square root of the sum of the squares of the individual one-sigma errors in each of the four radial erosion zones. For currents up to approximately the onset current, J^*, the measured erosion is not significant in view of the experimental error bars. At approximately the onset current, the erosion begins to increase rapidly, reaching a value greater than 20% of the injected propellant at 32 kA.

The most important result shown by the data in Fig. 10 is the verification of the onset current concept, i.e., a current below which erosion may be tolerable, but above which it becomes severe. This concept originated from terminal voltage oscillations, which increase rapidly at the onset current, and from spectroscopic data, which show insulator and electrode species in the plasma as the current exceeds the onset value. Thus the QCM erosion data confirm that the terminal voltage oscillations can continue to be used as a guideline for evaluating the performance potential of alternate MPD configurations.

The important question of the total amount of erosion for operation at and below the onset current cannot be answered by this method, which overlooks any erosion from other portions of the accelerator, including the electrodes. A new program of erosion measurement employing radioactive tracer methods is being developed for that purpose.

Summary

The quartz crystal microbalance technique for measuring extremely small mass changes has been adapted for use as an erosion measuring diagnostic on the nitride backplate of an MPD thruster. Erosion of a small portion of an approximately 1-μ-thick boron nitride layer on the surface of the QCM is detected as an increase in the 5-MHz resonant frequency of the crystal. The data show that little or no erosion takes place up to the onset current, but that above this current erosion develops rapidly, especially close to the cathode, eventually reaching a loss rate of 20% or more of the injected propellant. These QCM data represent the first quantitative confirmation of the onset current concept, above which severe erosion occurs, but below which long-term operation at interesting performance levels appears attainable.

Acknowledgment

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