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ENDURANCE TEST OF A 30–CM–DIAMETER ENGINEERING MODEL ION THRUSTER

TASK XII – INVESTIGATION OF THIN–FILM EROSION MONITORS FOR ION THRUSTERS

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16 Abstract

This report describes an investigation of short-term measurement techniques for predicting the wearout of ion thrusters resulting from sputter-erosion damage. The previously established laminar-thin-film technique is shown to provide high-precision erosion-rate data. However, the erosion rates obtained using this technique are generally substantially higher than those obtained during long-term endurance tests (by virtue of the as-deposited nature of the thin-films), so that the results must be interpreted in a relative sense. Absolute measurements can be performed using a new masked-substrate arrangement which was developed during this study. This new technique provides a means for estimating the lifetimes of critical discharge-chamber components based on direct measurements of sputter-erosion depths obtained during short-duration ($\approx 10^1$ hour) tests. The method enables the effects on lifetime of thruster design and operating parameters to be inferred without the investment of the time and capital required to conduct long-term ($\approx 10^3$ hour) endurance tests. Results obtained using the direct-measurement technique are shown to agree with sputter-erosion depths calculated for the plasma conditions of the test and also with lifetest results. The direct-measurement approach is shown to be applicable to both mercury and argon discharge-plasma environments and should be useful in estimating the lifetimes of inert-gas and extended-performance mercury ion thrusters presently under development.

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FOREWORD

The work described in this report was performed under the last of the twelve technical tasks comprising the total contractual effort of Contract NAS 3-18914. Tasks I through XI dealt with endurance testing of a 900-series 30-cm Engineering Model Thruster, and the results obtained under these eleven tasks have been reported in accordance with the contractual requirements. This report deals only with Task XII – Investigation of Thin-Film Erosion Monitors for Ion Thrusters. The work was carried out over a 16-month period at Hughes Research Laboratories. Initially, the program was conducted in the High Voltage Technology Department, managed by Dr. H.J. King. Later, as a result of an organizational change, the program was transferred to the newly formed Plasma Physics Department, managed by Dr. J. Hyman. The contractual work presented was managed by Dr. J.R. Beattie and monitored by Mr. V.K. Rawlin of NASA-Lewis Research Center. Major technical contributions to this effort were made by:

J.R. Beattie	Project manager and principal investigator
H.L. Garvin	Erosion-monitor fabrication, mask-technology development, and interpretation of test results
C.R. Dulgeroff and F.J. Wessel	Erosion-monitor testing
D.R. Deane R.L. Maheux J.A. Tyrrell	Thruster preparation and technical assistance

SUMMARY

The Investigation of Thin-Film Erosion Monitors for Ion Thrusters Task was a study of laminar-thin-film erosion monitors and short-term direct-measurement techniques for assessing the sputter-erosion rates in ion-thruster discharge chambers. The goal of the study was to determine the suitability of laminar-thin-film erosion monitors for use in obtaining accurate predictions of thruster wearout rates based on short-term test results. To achieve this goal, a new direct-measurement technique for assessing sputter-erosion depths was developed. Direct measurements of the baffle wear rate in a 30-cm-diameter thruster were conducted using both sputter-deposited and bulk molybdenum and copper samples. Simultaneous measurements were also performed using molybdenum/copper laminar-thin-film erosion monitors. The results of several tests of varying duration indicate that (1) the laminar-thin-film samples and sputter-deposited molybdenum samples erode at the same rate, (2) the molybdenum and copper sputtering rates obtained using the direct-measurement technique agree well with calculated values for these materials, (3) the molybdenum sputtering rate obtained using the direct-measurement technique agrees with long-term-endurance-test results, and (4) the erosion rates determined by the laminar-thin-film technique are about twice as great as those found by direct measurement. The different rates of erosion suggest that the sputter-deposited material which forms the laminar-thin-film monitors has a different physical structure than the bulk material from which it is derived.

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INTRODUCTION

The inherent low-thrust capability of ion thrusters generally dictates long operating times in order to satisfy the Δv requirements typical of most missions. For example, in prime-propulsion applications, mission durations on the order of 10^4 hours are required[1]. Because of these long lifetime requirements, only a limited number of ground-based endurance tests[2-5] have been conducted to demonstrate the reliability of ion thrusters in both primary and auxiliary propulsion applications. As a result of these tests, erosion of the cathode-potential surfaces within the discharge chamber has been identified as a mechanism which can both degrade performance and limit lifetime. The problem arises not only from the wearout of critical components such as the baffle and screen grid, but also from the deposition and subsequent flaking of the sputtered materials from surfaces where the ion-arrival rate is too low to prevent layer formation. The process by which the surface erosion occurs has been identified as physical sputtering caused by ion bombardment. Through the use of low-sputter-yield materials, surface treatment to minimize flake size, along with selection of thruster design and operating conditions which reduces the formation of multiply charged ions and the energy at which ions strike the internal surfaces, the lifetime of the state-of-the-art 30-cm J-series thruster is thought to have been increased beyond its design goal of 15,000 hr. However, as the operating ranges of both the 30-cm and 8-cm thrusters are extended to higher power levels, the effects of sputter erosion must be carefully considered. Likewise, internal erosion is a critical consideration in the development of the next generation of high-power ion thrusters which utilize inert-gas propellants.

The high cost and time required to conduct endurance tests severely restricts the amount of lifetime-verification testing that can be accomplished both with existing and extended-performance thruster designs. To circumvent this, a short-term ($\approx 10^1$ hour) erosion-rate measurement technique has been utilized to enable the effects of thruster design and operating conditions to be assessed within the budgets and the time frames characteristic of ion-propulsion research programs. The technique involves the use of erosion monitors which are fabricated by sputter depositing thin (≈ 600 Å) laminar films or layers of the material of interest onto a substrate. Between each layer is a sputter-deposited layer of copper. When these monitors are exposed to the discharge plasma, they are partially eroded away by ion bombardment. The copper layers erode quickly because of their high sputtering yield, and their bright color facilitates the determination of the number of eroded layers. The technique has been investigated at Comsat Laboratories,[6] Hughes Research Laboratories,[7] and Colorado State University[8] using typical thruster fabrication materials such as tantalum, molybdenum, and titanium. The laminar-thin-film erosion monitors have been prepared in both continuous and perforated configurations, with the latter geometry used to assess the sputter-erosion rates and patterns of screen and accelerator electrodes.

The erosion-monitor technique has been adequate for assessing qualitative effects of design and operating variables on sputter-erosion rates, but the accuracy of the quantitative results obtained from these measurements is questionable; the majority of the measurements do not agree with the results obtained from long-term endurance tests. Recognizing the many variables (such as plasma conditions and test-facility pressure) that could contribute to such a discrepancy, the purpose of the present study was to review the conditions and results of past erosion-monitor tests and compare them with those of the endurance tests. The objective was to assess the accuracy of the thin-film-erosion-monitor technique in determining absolute wear rates in mercury ion thrusters. To accomplish these goals, a short-term direct-measurement technique for obtaining wear rates was developed and demonstrated in an operating 30-cm thruster (S/N 301J).

SECTION 2

LAMINAR-THIN-FILM EROSION MONITORS

Multilayer erosion monitors consist of alternating layers of color-contrasting materials (such as tantalum and copper, or molybdenum and copper) that are sputter-deposited onto a tantalum or stainless-steel substrate, as shown in Figure 1. Layer thickness is carefully controlled during the application process by maintaining the sputtering ion-beam voltage and current constant, and by precisely timing the deposition. The monitors have 8 principal-metal (tantalum or molybdenum) layers and 7 copper layers; the first layer (either tantalum or molybdenum) applied to the substrate has double thickness. Because copper erodes much faster than either molybdenum or tantalum, the copper layers are factored into the analysis as only a portion of an equivalent principal-metal layer.

A small piece of polished material onto which layers are sputter-deposited during preparation of the multilayer monitor material is used for calibrating layer thickness using a surface profilometer. The layer thickness is calibrated by performing measurements on the coated, polished sample, using the following technique. First, a pattern of 25-μm (250,000-Å) lines and spaces is established on the sample surface by optically exposing a photoresist through a suitable mask. The multilayer material is then ion-beam machined away, as shown in Figure 2, to make the layer interfaces readily identifiable. After that step the photoresist mask is chemically removed. Then by guiding the profilometer stylus along the readily identified interface between layers, the interface depth can be determined for each interface, thereby determining the layer thickness. For the usual deposition-control conditions, the layer thickness of samples analyzed in this manner is approximately 600 ±6 Å.

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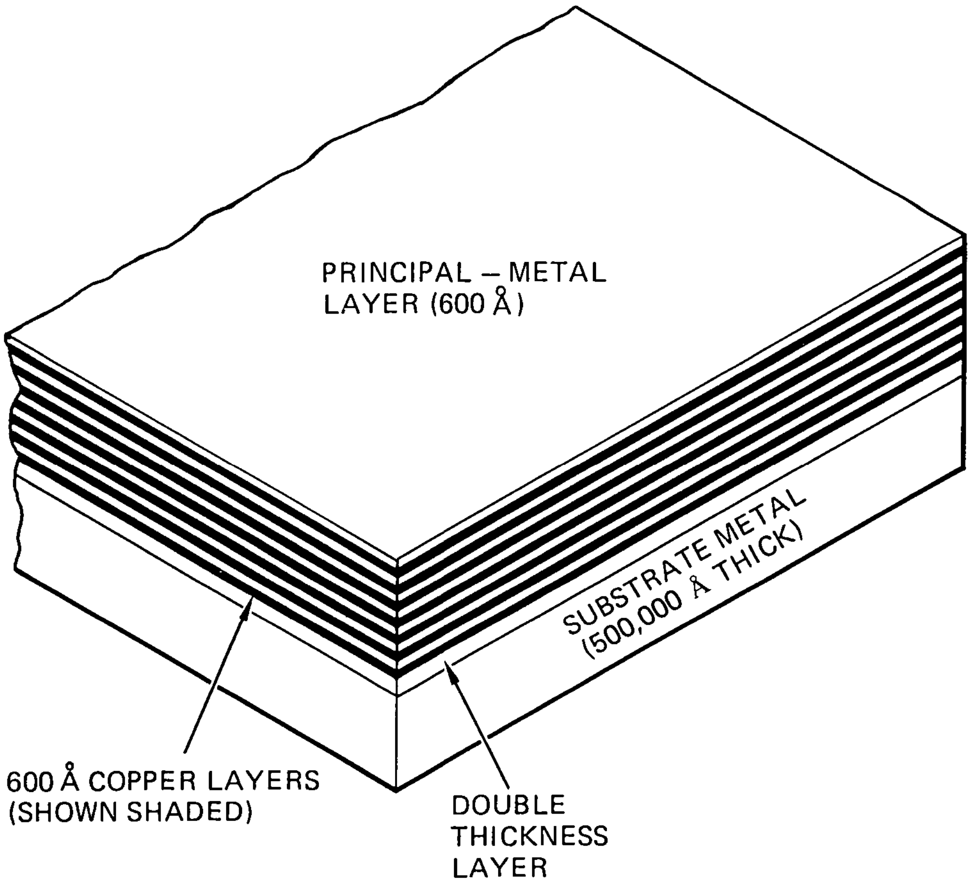

Figure 1. Arrangement of a laminar-thin-film erosion monitor.

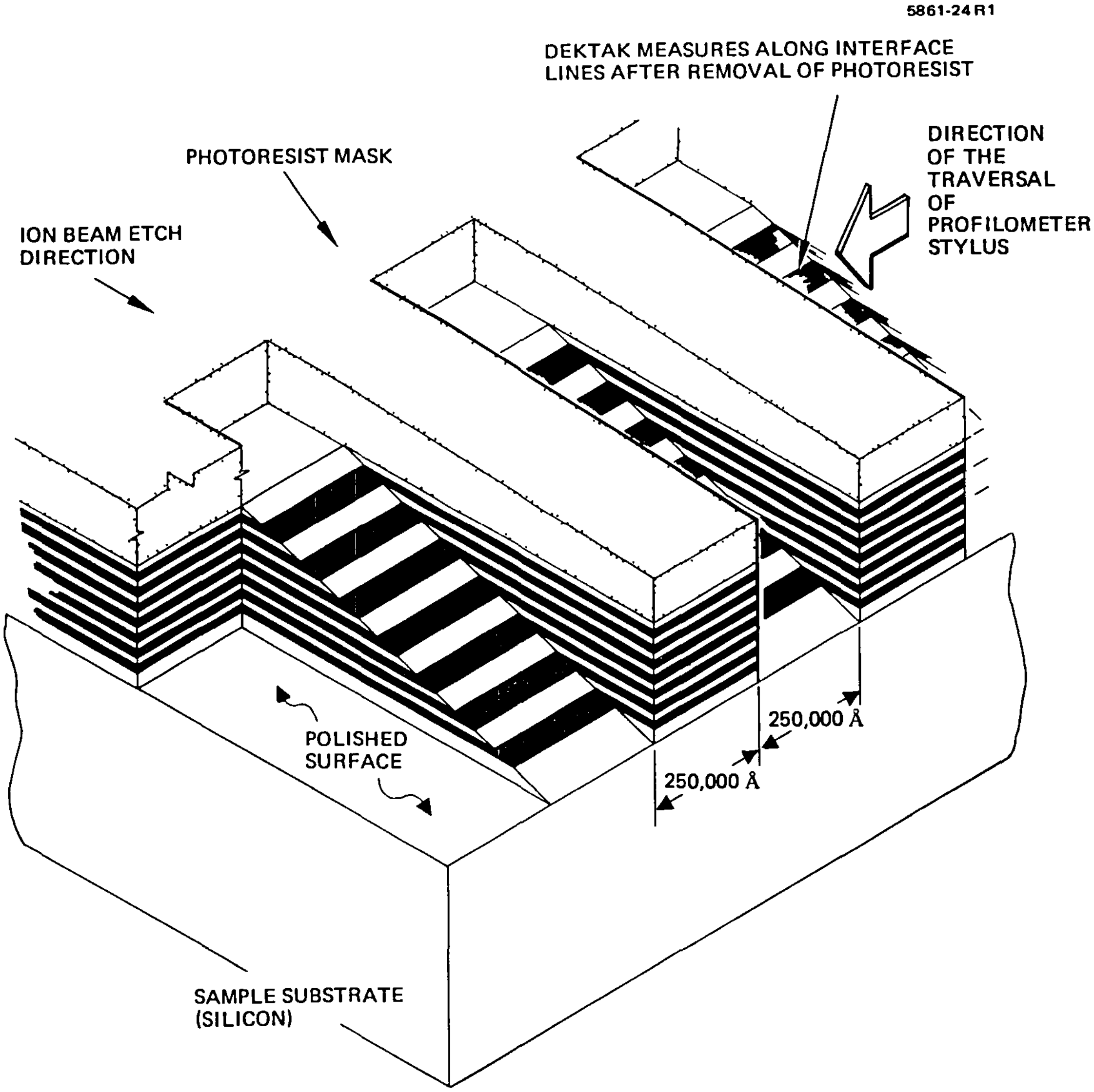

Figure 2. Ion-machining technique used to measure the layer thickness of the multilayer erosion monitor deposition sample.

A. TEST PROCEDURE

Small pieces of the thin-film-erosion-monitor material are spotwelded to the thruster components selected for erosion measurements. A portion of the monitors mounted on all thruster components except the screen and accelerator electrodes is masked to aid in determining the number of layers that have been eroded during thruster operation. Those monitors mounted on the screen and accelerator grids are perforated, with the monitor hole-pattern matching that of the screen grid. Photographs which show typical examples of the erosion monitors mounted on various thruster components are presented in Figure 3.

B. ANALYSIS OF EXPOSED MONITORS

Thruster operating times are scaled to remove several of the erosion-monitor layers. After the tests, the monitors are removed from the various thruster components for analysis. To facilitate determining the number of layers removed, a "diagnostic etch" is performed on each monitor by ion-beam machining a groove through the remaining layers. By loosely positioning a mask above the surface, as shown in Figure 4, a tapered groove is machined to facilitate identifying layer interfaces at the boundary of the region masked during the test.

Once the number of copper layers remaining has been determined, the erosion rate, W, is calculated using the following expression:

$$W = [(N - N' + 0.5)\ \delta_{Ta,Mo} + (N - N')\ \delta_{Cu}/\gamma_{Ta,Mo}]/\tau \quad , \qquad (1)$$

where N and N' are the initial and final number of copper layers, respectively; δ is the layer thickness; τ is the test time; and γ adjusts for the increased erosion rate of copper (Cu). The first term in the numerator represents the thickness of eroded tantalum (Ta) or molybdenum (Mo), with the factor, 0.5, introduced

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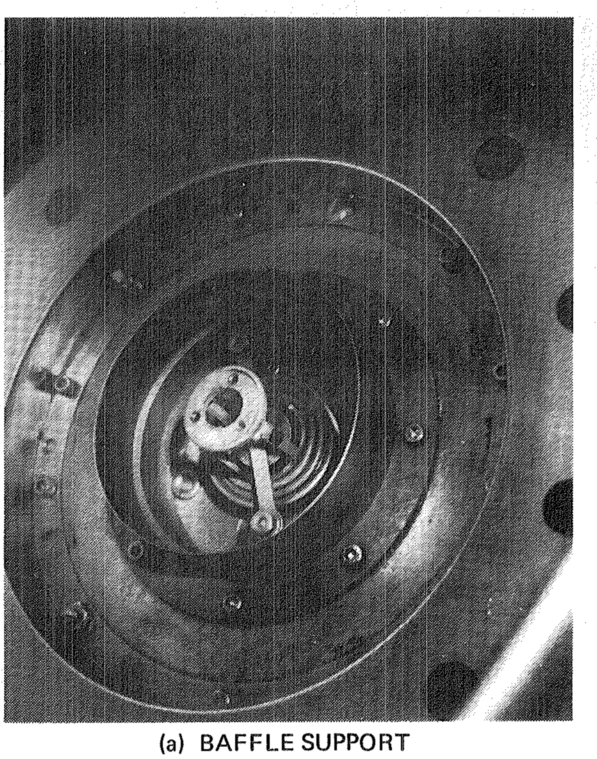
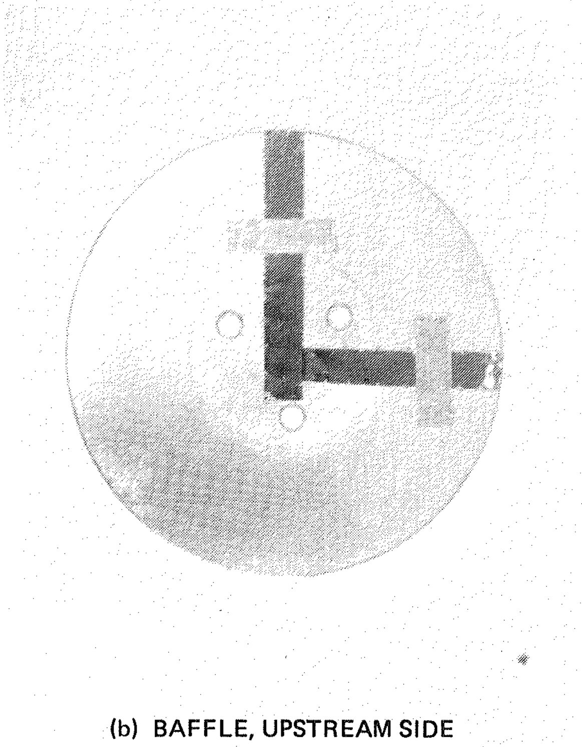
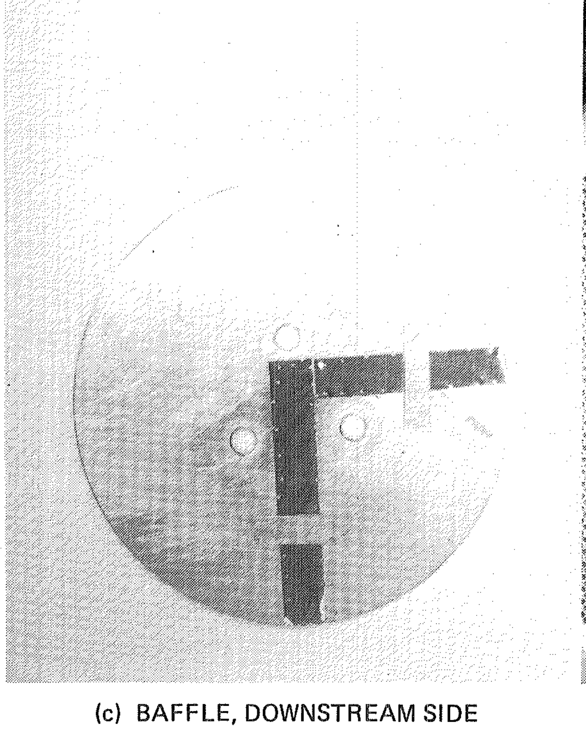


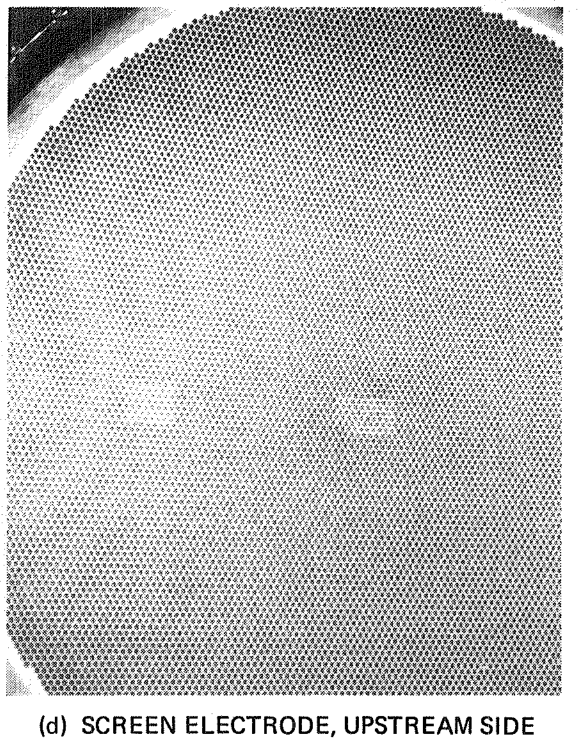
(a) BAFFLE SUPPORT



(b) BAFFLE, UPSTREAM SIDE

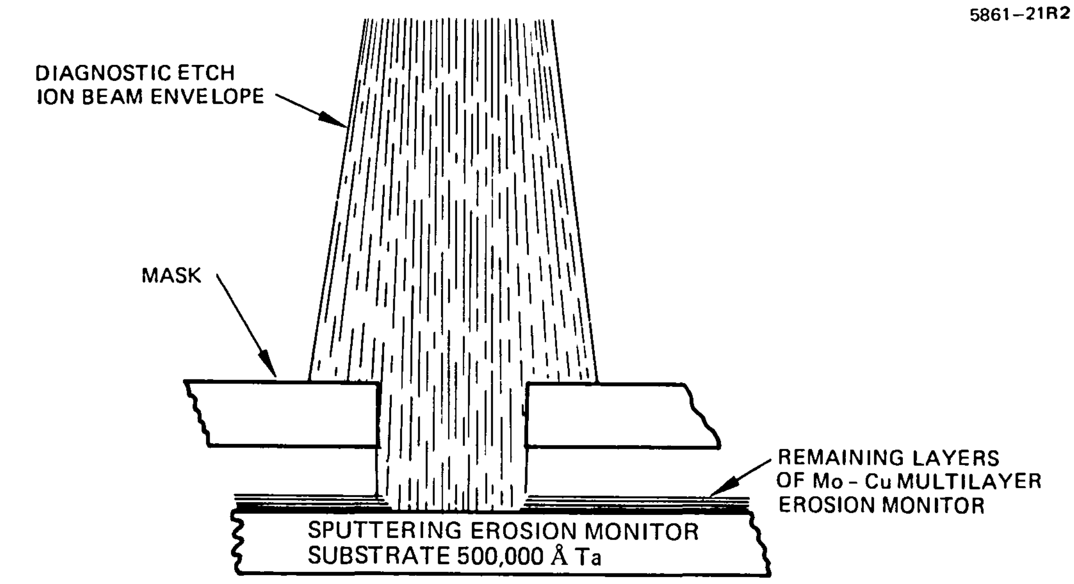


(c) BAFFLE, DOWNSTREAM SIDE



(d) SCREEN ELECTRODE, UPSTREAM SIDE

Figure 3. Multilayer erosion monitors, as mounted on internal thruster surfaces for erosion measurements.



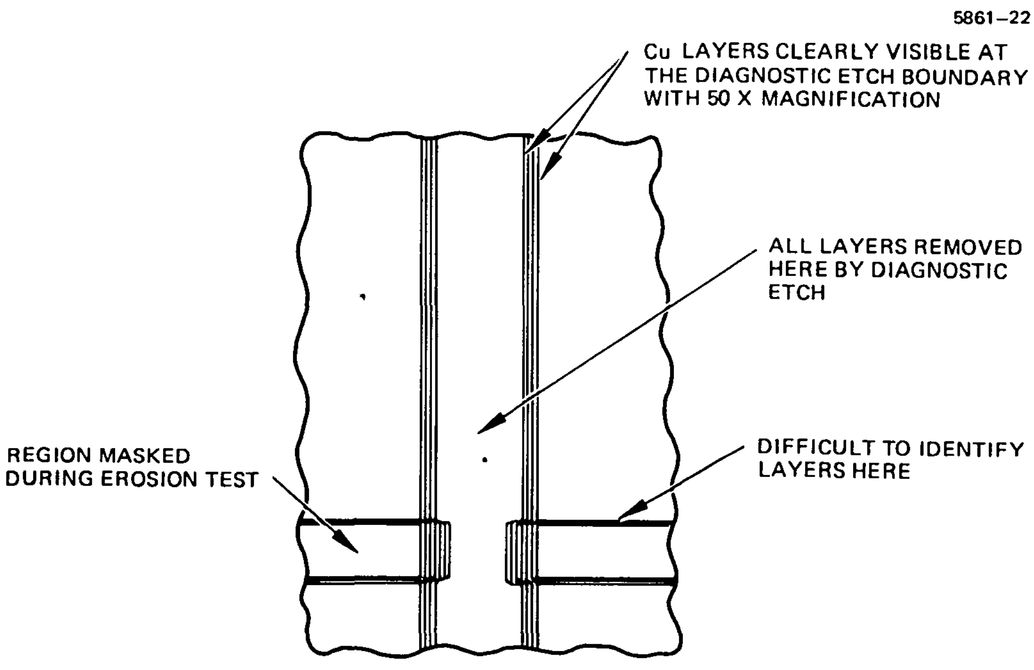


Figure 4. Diagnostic etch used for analysis of erosion monitors.

to account for the unknown fraction of the principal-metal layer remaining above the highest visible copper layer. Adopting this definition of the unknown remaining layer thickness, the uncertainty in the number of eroded layers is ±0.5. Thus, the erosion-rate uncertainty, U, can be expressed as

$$U_{Ta,Mo} = \pm \delta_{Ta,Mo}/2\tau \quad . \tag{2}$$

The second term in Equation (1) accounts for the copper layers eroded, and the factor $1/\gamma$ converts copper layer thickness to equivalent tantalum or molybdenum layer thickness.

C. REVIEW AND COMPARISON OF PAST TEST RESULTS

Table 1 presents a summary of erosion-rate measurements obtained during short-term and endurance tests of the 30-cm thruster. The results are presented for the screen electrode, which is considered the principal life-limiting component of the 30-cm thruster, since it must be thin* for good performance, yet is constantly exposed to a high flux of energetic plasma ions, particularly near the centerline. The screen-electrode measurements were selected for the comparison because (1) a relatively large amount of short-term test results are available at this location, (2) erosion-monitors located on the screen grid are usually easier to interpret and show a higher degree of precision than those located elsewhere, and (3) quantitative results of the longest endurance test conducted to date are available for the screen electrode but unavailable for the baffle, which was eroded away before the conclusion of the test. The results of Table 1 were listed after reviewing the test data available in the References and Bibliography and then selecting those results for which the thruster configuration,

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*Other critical components, such as the baffle and pole piece, can be thick enough to withstand long-term erosion damage and not degrade performance.

Table 1. Summary of Erosion-Rate Measurements Obtained During Short-Term and Endurance Tests of the 30-cm Thruster

Ref	Test Date	Facility (1)	Duration (hr)	Thruster S/N	Optics S/N	J_b (A)	V_D (V)	J_E (A)	η_m (%)	J^{++}/J^{+} £	J^{++}/J^{+} Ave	Chamber Pressure (Torr)	Screen Erosion Rate (Å/hr)	Uncertainty (Å/hr)	Erosion Monitor Technique
2	1974	ES	10,000	701	701	1 4 (2)	37 (2)	7 9	89 (2)	-	-	1 x 10^{-6}	350 (3)	-	Micrometer
3	1976	ES	4,165	901	801	2 0	36 1 (4)	11 0 (5)	96 1 (6)	-	-	∼1 x 10^{-6}	312	-	Micrometer
15	1977	ES	590	903	819	2 0	36 0	11 0	-	-	-	∼1 5 x 10^{-6}	350	50	Micrometer
10	1975	RL	15	301-B	653	2 0	37 0	10 0	-	-	-	-	288	20	Erosion Monitor
11	1977	RL	6	801	817 (7)	2 0	36 0	11 1	97 2	0 5	0 19	∼1 x 10^{-6}	523	50	Erosion Monitor
11	1977	RL	6	801	817 (7)	2 0	36 0	11 1	95 7	0 5	0 19	∼1 5 x 10^{-6}	523	50	Erosion Monitor
12	1979	RL	6	301-J	653	2 0	36 0	11 1	87 3	0 5	0 18	∼1 0 x 10^{-6}	529	50	Erosion Monitor
12	1979	RL	6	301-J	653	2 0	36 0	11 1	87 6	0 5	0 17	∼1 0 x 10^{-6}	530	50	Erosion Monitor
12	1979	RL	6	301-J	828	2 0	36 0	10 7	91 7	0 5	0 16	∼1 0 x 10^{-6}	544	50	Erosion Monitor
12	1979	RL	6	301-J	828	2 0	36 0	10 7	91 0	0 4	0 17	∼2 0 x 10^{-6}	540	50	Erosion Monitor
16	1977	ES	937	903	LeRC 41	2 0	32 0	11 6	98 5	-	-	∼1 5 x 10^{-6}	80-100	20	Micrometer
4	1981	XEOS	4,263	J-1	LeRC 41	1 96	32 0	12 0	92 3	-	0 1 (9)	3 5 x 10^{-6}	64 (8)	-	Micrometer
12	1979	RL	8 3	301-J	828	2 0	32 0	12 0	86 8	-	-	∼1 0 x 10^{-6}	214	36	Erosion Monitor
12	1979	RL	12	301-J	828	2 0	32 0	12 0	88 1	0 3	0 1	∼1 0 x 10^{-6}	235	25	Erosion Monitor

NOTES
(1) ES = Hughes El Segundo Facility, RL = Hughes Research Laboratories, XEOS = Xerox Electro-Optical Systems

(2) Time-averaged value for 10,000-hr test

(3) Extrapolation to J_b = 2 A gives an erosion rate of ≈350 Å/hr (Ref 13)

(4) V_D = 35 1 V for 629 hrs

(5) J_E = 10 6 A for 629 hrs

(6) η_m = 92 1% for 629 hrs

(7) ℓ_g = 0 030"

(8) Measured value was 44 8Å/hr A correction of 0 7 was applied to the measured value to account for the erosion-rate reduction corresponding to a test-chamber partial pressure of nitrogen equal to 3 5 x 10^{-7} Torr

(9) Ref 14

operating conditions, and vacuum-test-facility conditions were well documented. As indicated, the 10,000-hr, 4,165-hr, and 590-hr endurance-test results are in fairly good agreement (when the 10,000-hr test results are extrapolated to J_b = 2 A), and nearly the same as the 15-hr erosion-monitor test results obtained during 1975. The laminar-thin-film measurements obtained after 1975 give highly consistent erosion rates which are substantially higher than the endurance-test results. From the results of Table 1, one might conclude that the wear rates determined by the thin-film-erosion-monitor technique demonstrate good precision, but their accuracy is poor. Further, it appears that the erosion-monitors consistently yield higher base-metal sputtering rates.

SECTION 3

MASKED-SUBSTRATE EROSION MONITORS

Poor agreement between the erosion rates obtained during past erosion-monitor and endurance tests led to the development of a direct-measurement technique for performing short-term tests. The objective was to enable the erosion rates of laminar-thin-film monitors and sputter-deposited layers to be compared to those of the corresponding bulk materials. The approach we selected utilizes a polished sample of the material of interest (either bulk or sputter-deposited) onto which a repeating-pattern mask has been deposited. The function of the mask is to provide a series of "bench marks" which can later be used in interpreting depth measurements performed by moving a surface-profilometer stylus across the exposed sample. In developing the masked-substrate technology, the following mask requirements were specified:

- The mask must be easily and completely removed after exposure of the sample so that the "bench marks" are preserved
- The mask dimensions and spatial frequency must be selected so that several pattern lines can be crossed in a normal traversal of the surface-profilometer stylus and so that "edge effects" are minimized
- The mask should have high enough electrical conductivity to prevent electrostatic charging and possible deflection of incoming ions
- The mask height should be the minimum required to protect the substrate region during exposure to the sputtering ions.

The mask arrangement that we used at the beginning of the study is illustrated in Figure 5. The pattern consists of a series of aluminum "islands" that were sputter-deposited onto a polished substrate of the material under investigation (molybdenum and copper in this case). The aluminum served to protect the underlying regions, providing "bench marks" for later measurements of the

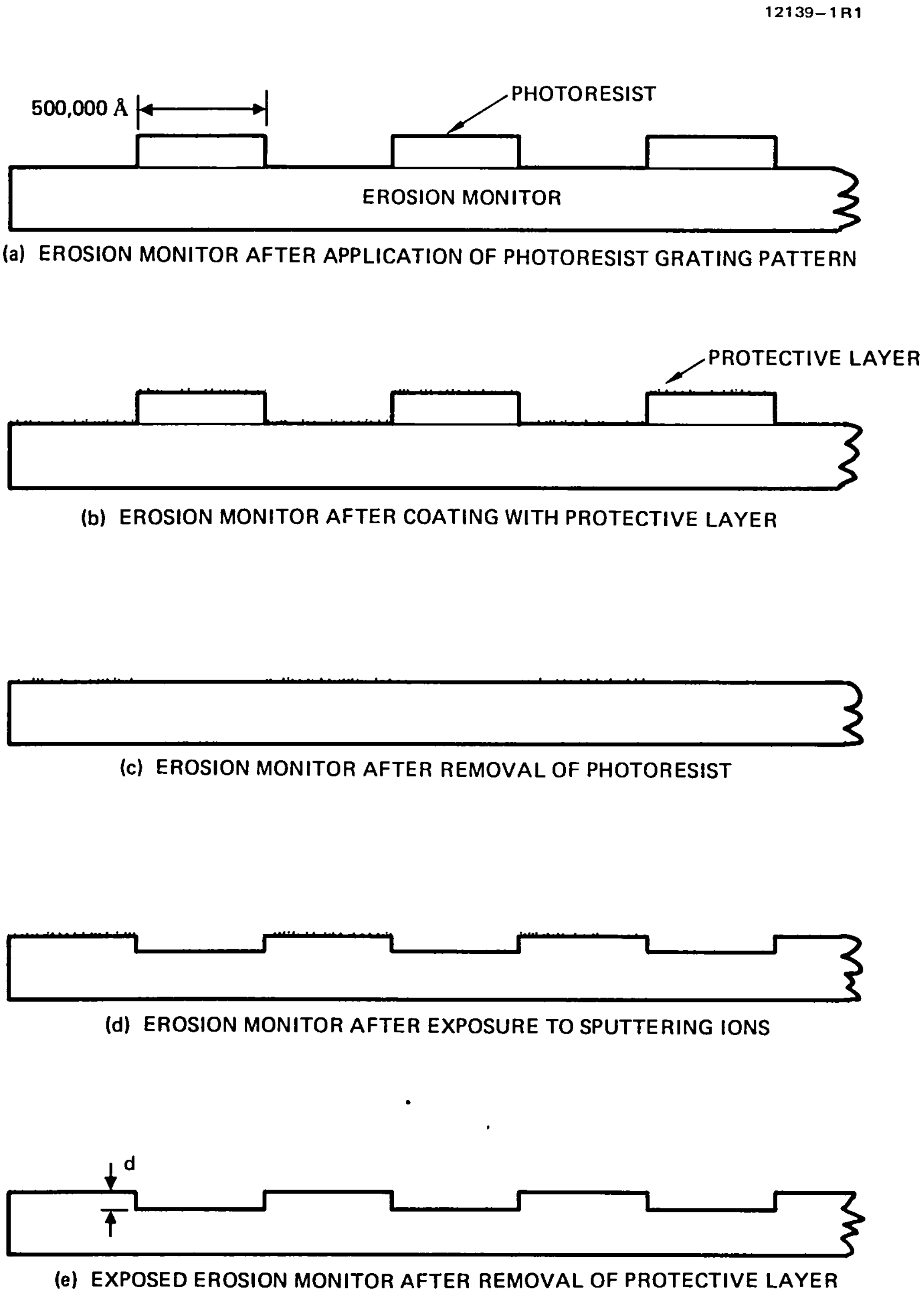

Figure 5. Masked-substrate technique developed under this program.

sputter-erosion depth. Figure 6(a) shows a surface-profilometer measurement showing the highly repeatable aluminum masking pattern (not to scale) on a polished copper substrate. An enlargement of one of the island regions is presented in Figure 6(b), showing that the surface of the substrate is very smooth compared to the mask dimensions (7500-Å mask height) and that well-defined substrate and island regions exist.

After exposing small pieces of the masked materials to the plasma ions, the protective mask was removed using a dilute solution of NaOH, without altering the etch profiles of the molybdenum or copper substrates. The aluminum-mask technology was demonstrated using bulk and sputter-deposited samples of molybdenum and copper exposed to a 500-eV argon ion beam. The results of the mask-technology demonstration test are presented in Table 2, which shows that the sputtering rates of molybdenum and copper are nearly the same for both sputter-deposited thin-films and bulk samples. These results confirmed an earlier similar finding[9] in which it was shown that the erosion rates of sputter-deposited and bulk molybdenum exposed to a 150-eV argon ion beam agreed to within 10%.

Attempts to use the aluminum-mask technology in mercury discharges were unsuccessful because of difficulties encountered in removing the aluminum masking pattern from the substrate. Apparently mercury reacts with the aluminum mask, forming an amalgam that is difficult to remove. Figure 7 presents a comparison of bulk-molybdenum samples covered with a rectangular masking pattern of aluminum. The sample of Figure 7(a) had been exposed to a 500-eV argon ion beam, and the sample shown in Figure 7(b) had been tested in a 30-cm mercury thruster. The appearance of this latter sample suggests that not all of the aluminum mask could be removed, this would lead to an apparent high erosion rate. We performed an energy-dispersive x-ray analysis (EDAX) of the sample shown in Figure 7(b), and the results are presented in the form of the dot map shown in Figure 8. The dot intensity is proportional

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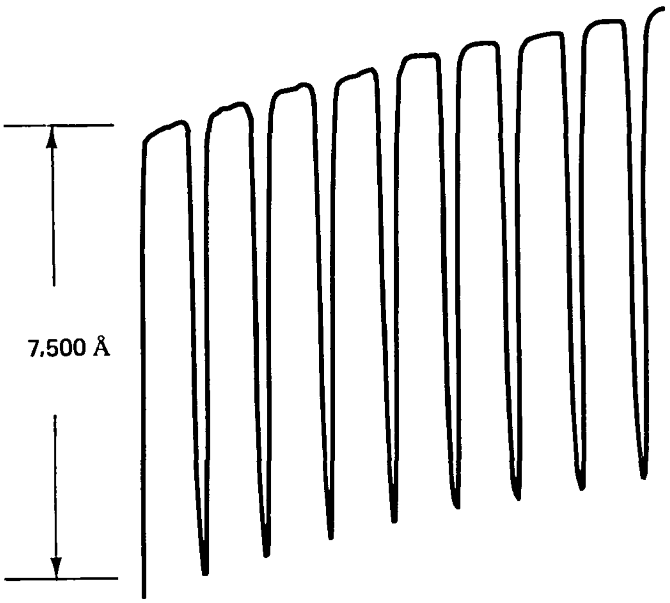
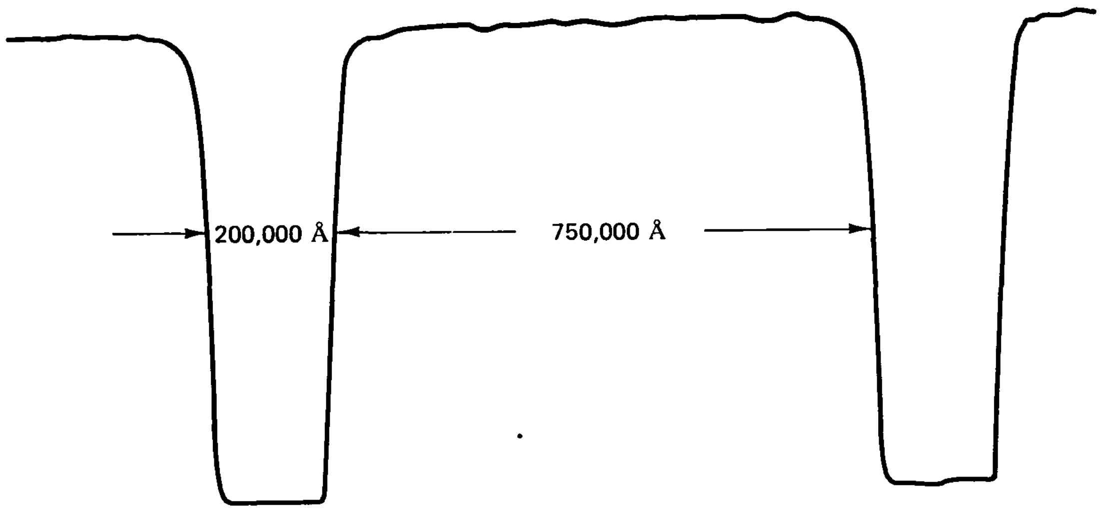


a MEASUREMENT SHOWING MULTIPLE "PEAKS" AND "VALLEYS" OF MASKED REGION (THE POINTED "VALLEYS" IS AN ARTIFICE CAUSED BY THE FINITE SLEW RATE OF THE PROFILOMETER RECORDER)



b MEASUREMENT SHOWING ENLARGEMENT OF ONE OF THE "PEAK" AND "VALLEY" REGIONS

Figure 6. Surface-profilometer measurements of masked-substrate material. (Highly magnified vertical coordinate. The actual width-to-height ratio of the mask is about 100:1.)

Table 2. Summary of Surface Profilometer Measurements of Etch Depth in Thin-Film and Bulk-Material Samples that were Exposed to a 500-eV Ar^+ Beam

Sample	Average Etch Depth
Molybdenum	
Bulk	2300 Å ±200 Å
Thin Film	2500 Å ±200 Å
Copper	
Bulk	4800 Å ±200 Å
Thin Film	5000 Å ±200 Å

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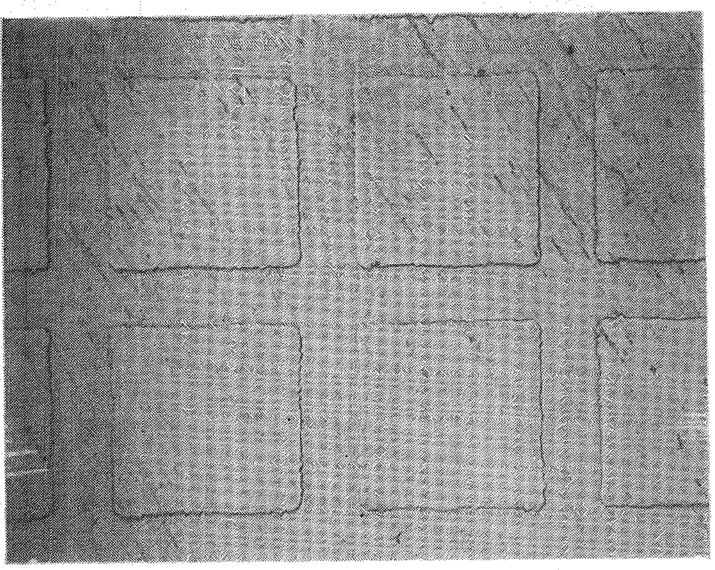
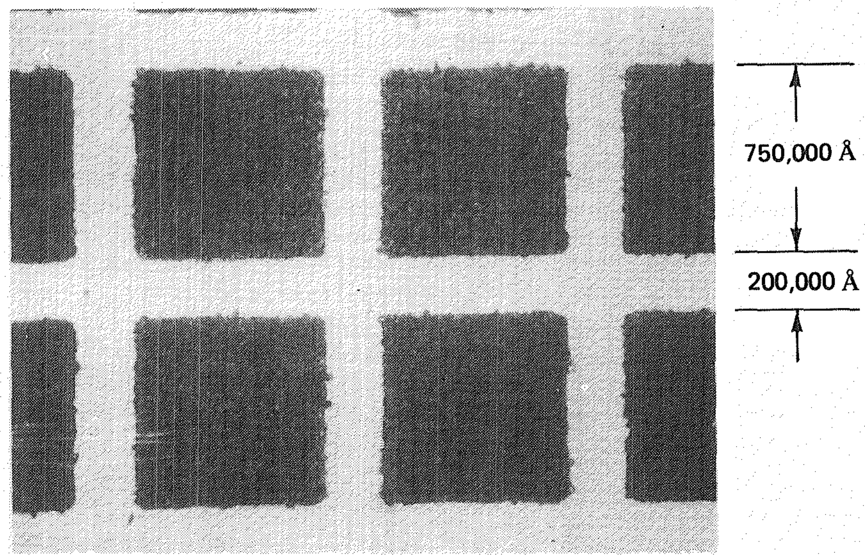


a. SAMPLE THAT HAD BEEN EXPOSED TO Ar^+ BEAM.



b. SAMPLE THAT HAD BEEN EXPOSED TO Hg^+ BEAM.

Figure 7. Comparison of bulk-Mo samples that had been exposed to Ar^+ and Hg^+ beams (after mask removal). 300X magnification.

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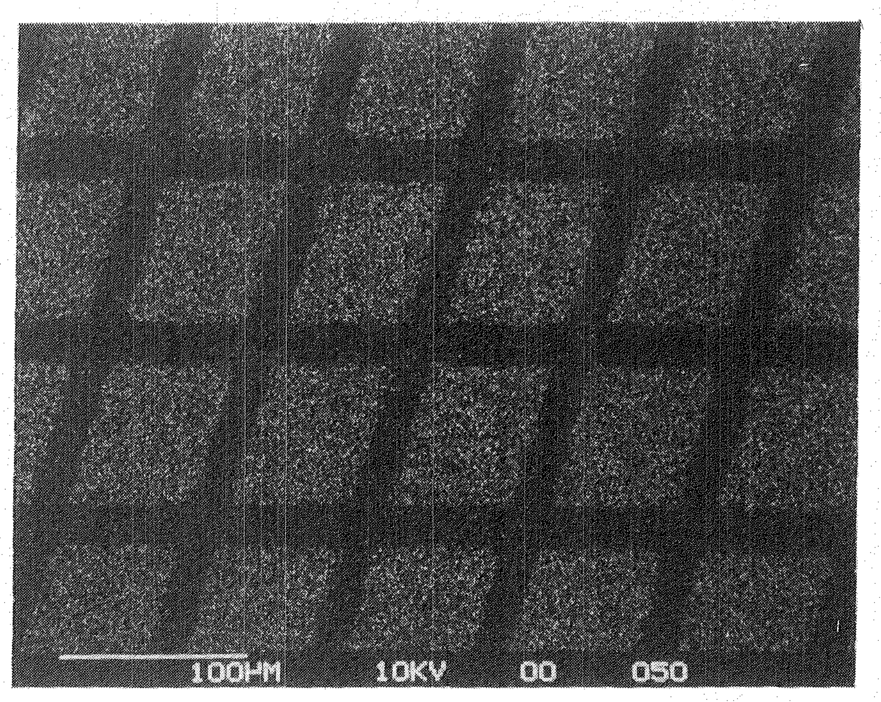

Figure 8. EDAX dot map showing Al pattern remaining on bulk-Mo sample that had been exposed to Hg^+ beam.

to the amount of aluminum present, and the pattern shown confirmed the presence of aluminum in the "islands" of the erosion-monitor sample.

We next investigated a similar mask arrangement using niobium as the mask material, with removal of the mask accomplished by firing the sample in a hydrogen furnace. Again, we found that samples exposed to an argon ion beam performed satisfactorily, but the niobium pattern on a sample exposed to a mercury-discharge plasma could not be removed in this manner. We concluded, therefore, that both the aluminum and niobium masking/removal technologies might be useful in inert-gas thruster applications, but a different approach is required for a mercury discharge environment.

An alternative mask arrangement was developed using niobium as the mask material, but with a thin (1,000 Å) layer of silicon dioxide placed under the mask to facilitate its removal. The arrangement is illustrated in Figure 9. To prevent the niobium from charging up (which could result in ion deflection) the insulating layer of silicon dioxide has been eliminated from the region where the "fingers" join, electrically connecting the mask to the substrate.

A. TEST PROCEDURE

Small pieces of masked samples of bulk and sputter-deposited molybdenum and copper were spotwelded to the baffle (discharge side) of the 30-cm thruster, S/N 301J. Pairs of each type of sample were used to provide an indication of the precision of the method. A total of up to twelve samples were tested simultaneously.

B. POST-TEST ANALYSIS

After exposing the samples to the mercury plasma, the niobium mask was lifted off by dissolving the silicon dioxide layer using hydrofluoric acid. Negligible acid-etching of the substrate was confirmed by removing the mask from samples which had not been exposed, and then performing surface-profilometer measurements. Figure 10 presents a surface-profilometer measurement (not to scale) of a sputter-deposited molybdenum sample which had been exposed to a 36-V mercury discharge for 24 hours. The erosion pattern is well-defined, and there is little distortion of the protected region. The erosion depth in this example is about 7,000 Å, and the variation in the depth of adjacent unprotected regions results in an uncertainty of less than ±500 Å.

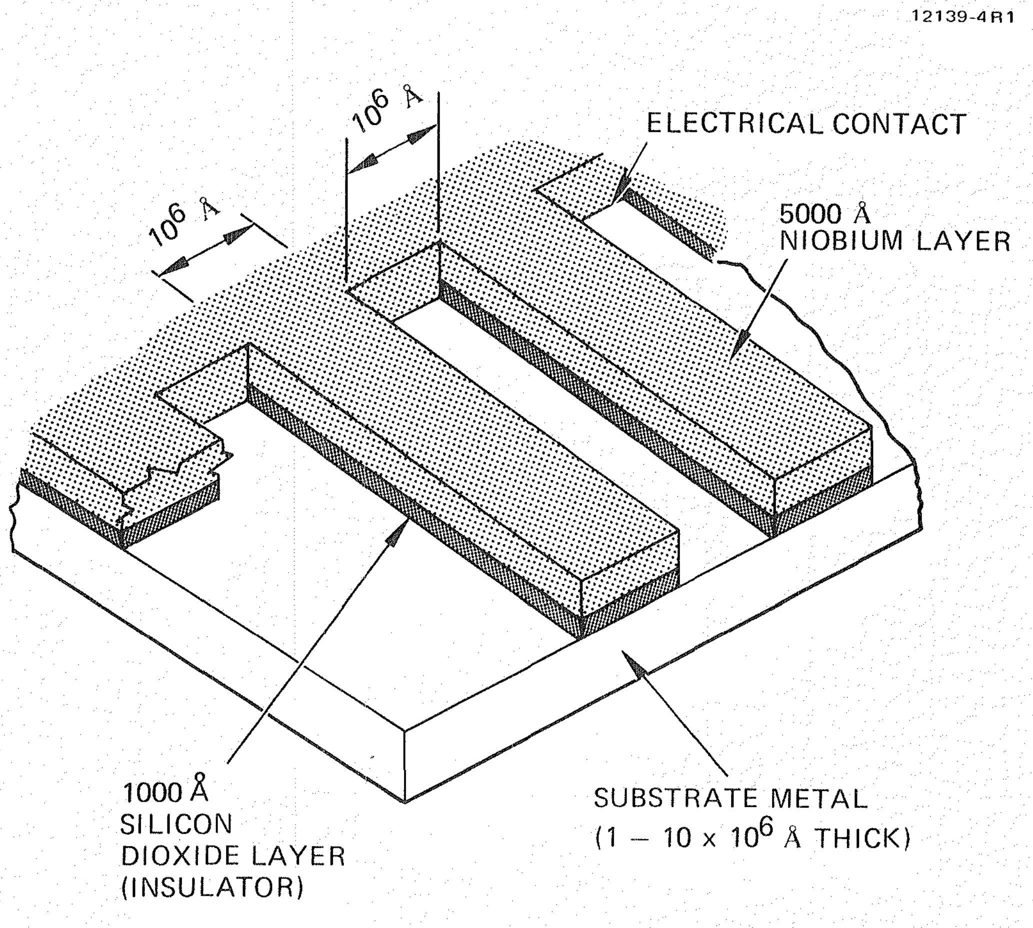

Figure 9. Protective masking-pattern arrangement used in preparing bulk and sputter-deposited erosion-monitor samples.

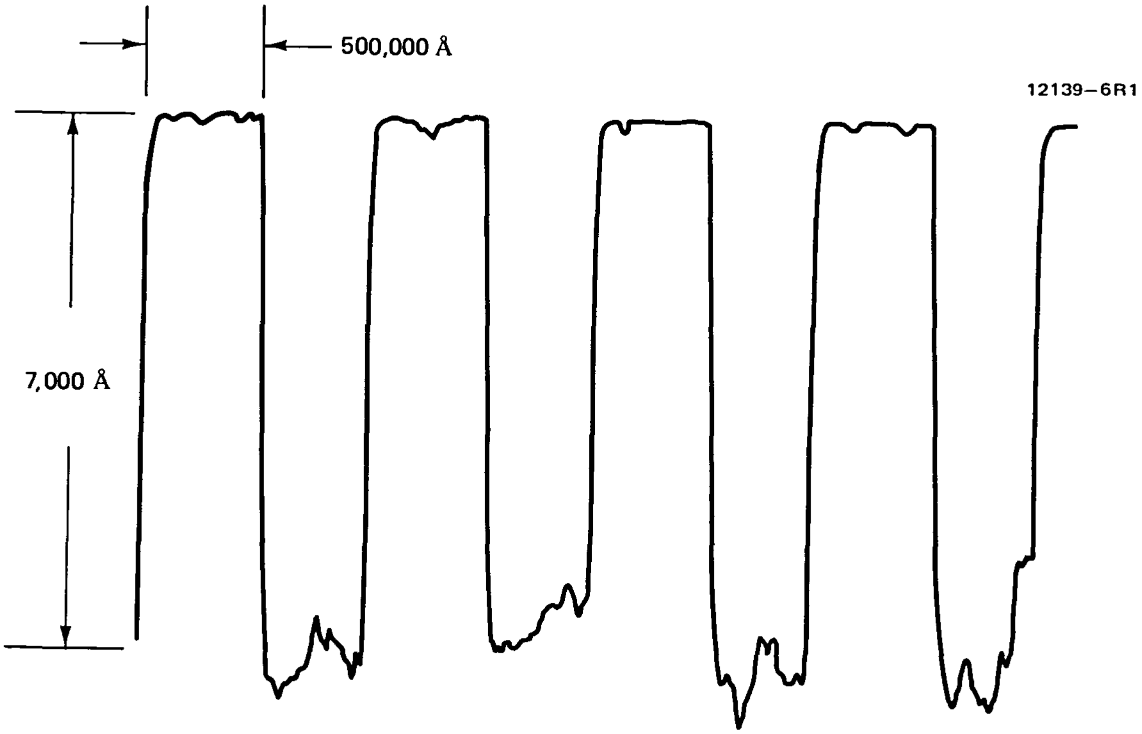

Figure 10. Surface-profilometer measurements of an exposed sample illustrating the erosion pattern. Sample is Mo and the erosion depth is $\approx$7,000 Å.

SECTION 4

DISCUSSION OF RESULTS

A series of short-term erosion-measurement tests were conducted using the 30-cm thruster, S/N 301J, operated at the nominal conditions presented in Table 3. Up to twelve erosion monitors were mounted in a circular pattern on the discharge side of the baffle, and the test durations varied from 5 to 24 hours. Samples of a given type were tested in pairs, providing some indication of the precision of the measurements. The samples investigated included:

- Mo-Cu laminar thin-films
- Mo bulk material with an Nb/SiO_2 mask
- Mo sputter-deposited material with an Nb/SiO_2 mask
- Cu bulk material with an Nb/SiO_2 mask
- Cu sputter-deposited material with an Nb/SiO_2 mask.

Erosion rates were determined for the laminar-thin-film monitors using the layer-counting procedure described earlier. The direct-measurement erosion rates were determined by measuring the erosion depth at several locations along the traversal of the

Table 3. Thruster Operating Conditions Selected for Erosion-Rate Tests

Operating Parameter	Value
Discharge Voltage, V_D	36 V
Emission Current, J_E	10.7 A
Beam Current, J_b	2 A
Cathode Keeper Current, J_{ck}	1 A
Beam Voltage, V_b	1100 V
Accelerator Voltage, V_A	-300 V
Magnetic Baffle Current, J_{MB}	≥3.8 A
Neutralizer Keeper Current, J_{NK}	2 A
Neutralizer Keeper Voltage, V_{NK}	15.5 V

surface-profilometer stylus and then averaging the results. In a few instances it appeared that the mask "fingers" had undergone thermal distortion,* and it was necessary to scrutinize the exposed monitor until an area was found in which the measuring stylus could be traversed over several consecutive "peak" and "valley" regions. The test results are listed in Table 4. Note that not every test was conducted using all five monitor types and that the duration of the longest test was great enough to completely erode through some of the samples. The results of Table 4

Table 4. Summary of Erosion-Rate Test Results

Test No.	Duration (Hr)	Erosion Rates (Å/hr)			
		Mo-Cu LTF	Mo Bulk	Mo TF	Cu Bulk
3(1)	5.3	299 299	<500 <500	-	-
4	14.5	-	124 138	-	1207
5	24.2	-	162 203	285 283	857 1257
6	13.4	306 306	127 135	-	1049

(1) The average beam current for this test was J_b = 1.62 A, and the measured erosion rates were W = 172 Å/hr. The erosion rates listed were adjusted to J_b = 2 A using the procedure described in Appendix A.

*Laminar-thin-film erosion monitors mounted on the baffle are sometimes observed to "blister". It is thought that the blistering phenomena observed with these monitors and the mask-distortion effects observed on the masked-substrate monitors may occur as a result of electron heating of the thin samples during recycle events in which electron backstreaming occurs.

are plotted in Figure 11, which also shows the erosion rates calculated for bulk molybdenum and copper using the model of Ref. 9. Figure 11 shows that the measured results are independent of test duration. The laminar-thin-film measurements agree with the direct measurement of the erosion rate of a sputter-deposited sample of molybdenum, and the results show good agreement between the measured erosion rates of bulk molybdenum and copper and the theoretical values. The most important result evident in Figure 11 is that the sputter-deposited samples appear to erode nearly twice as fast as the bulk-molybdenum samples.

In the past analysis of the thin-film erosion monitors it has been assumed that copper erodes about twenty times faster than molybdenum (γ_{Mo} = 20 in Equation (1)). However, the calculated and experimental results of Figure 10 indicate that the ratio is closer to γ_{Mo} = 7. We examined the sensitivity of the erosion rates calculated from Equation (1) to the parameter γ using typical values of layer numbers, thickness, and test times. Figure 12 presents erosion rates calculated using N = 7, N′ = 6, δ = 600 Å, and τ = 13.4 hrs (Test No. 6 of Table 4). These calculations show that in the limit as the copper layers erode instantaneously ($\gamma \to \infty$), the calculated results approach an asymptote at W = 291 Å/hr. Furthermore, the error introduced into the calculated results due to uncertainty in the absolute value of γ is less than 10% for $\gamma \geq 7$.

The direct-measurement technique is not suitable for small-area applications, such as the webbing on the screen electrode. In this application, the thin-film technique appears most promising. The precision of this technique was demonstrated under the present investigation and a calibration was obtained under representative plasma conditions.

It would be desirable to extend the work reported here and calibrate the thin-film erosion monitors with bulk-material sputtering rates over a wide range of thruster operating conditions

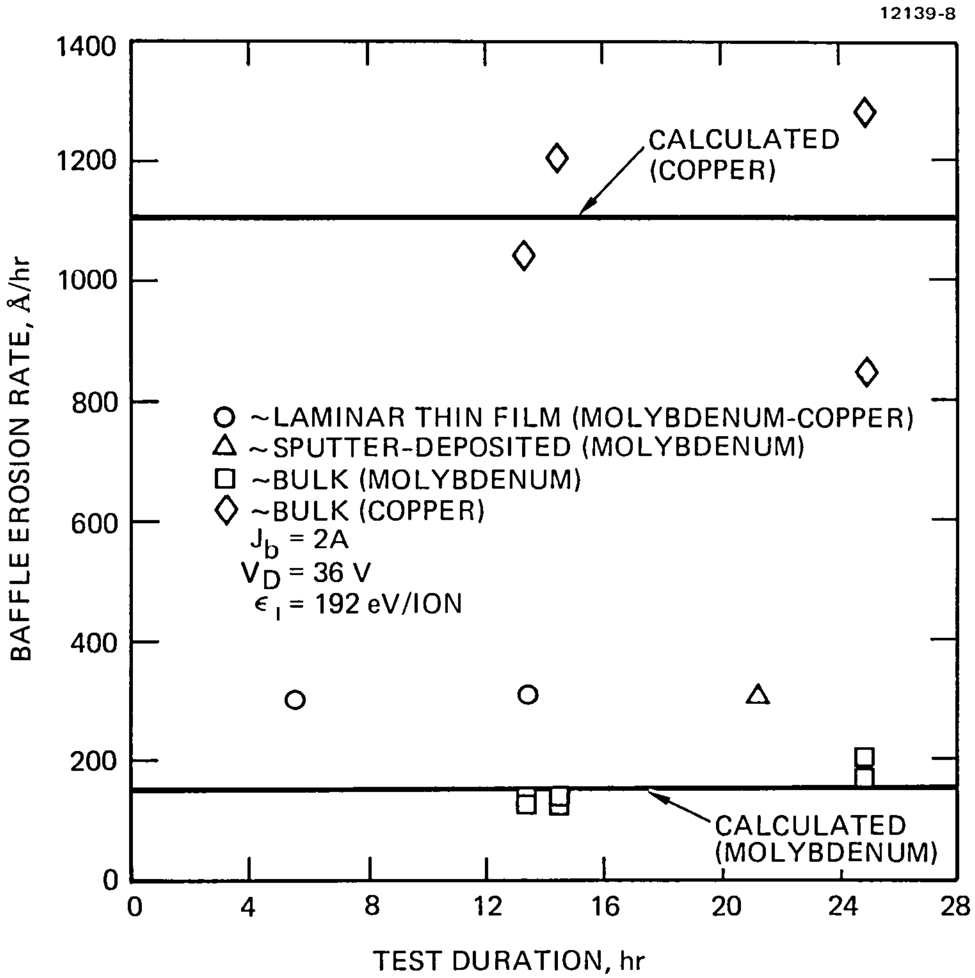

Figure 11. Summary of baffle erosion-rate measurements and comparison with calculated results.

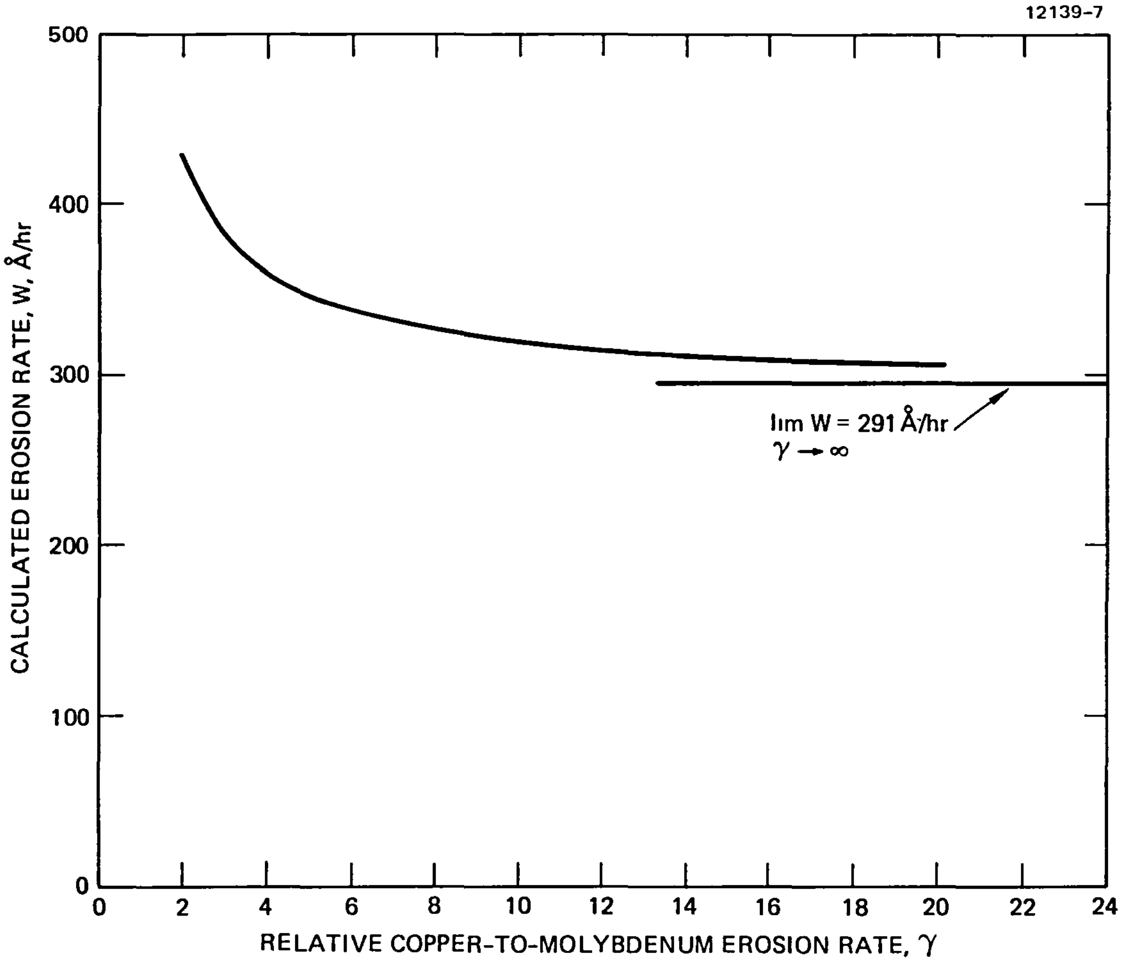

Figure 12. Sensitivity of calculated erosion rates to the relative erosion rate of copper versus molybdenum (γ). Calculations performed using Equation (1), with $N = 7$, $N' = 6$, $\delta = 600$ Å, and $\tau = 13.4$ hr.

(plasma conditions and sputtering yields). This could be done by testing laminar thin-film and masked-substrate monitors under several operating conditions and then using the relative erosion rates to establish a calibration factor.

SECTION 5

CONCLUSIONS

The experimental investigation of the use of thin-film erosion monitors in predicting absolute erosion rates in mercury ion thrusters has resulted in the development of a new direct-measurement technique for performing short-term erosion-rate measurements. Specific conclusions drawn from the study were that:

- Laminar-thin-film (Mo-Cu) and sputter-deposited thin-film samples (Mo) erode at a rate which is nearly twice as great as bulk molybdenum
- The direct-measurement technique using a Nb/SiO_2 mask arrangement performs satisfactorily in mercury discharges, and the results obtained using this approach agree with calculated values of the erosion rates of both copper and molybdenum
- An alternative masking arrangement using either aluminum or niobium for the mask material performed satisfactorily when exposed to high-energy argon ion beams and therefore should be useful in inert-gas thruster applications
- The erosion rates determined using the laminar-thin-film technique are nearly independent of assumed relative rates at which the alternating layers erode, as long as the copper layers erode at a rate greater than approximately seven times that of the material under study.

APPENDIX A

EXTRAPOLATION OF MEASURED EROSION RATES

The measured erosion rate, W, obtained at a beam current, J_b, can be used to estimate the erosion rate, W', corresponding to some other value, J_b', using the model of Reference 9. The appropriate relationships are

$$W' = kW \quad , \tag{A-1}$$

where

$$k \equiv \frac{J_b'}{J_b} \left[\frac{S_+' + \left(\frac{J_{++}}{J_+}\right)' S_{++}'}{S_+ + \left(\frac{J_{++}}{J_+}\right) S_{++}} \right] \quad , \tag{A-2}$$

where S is the sputtering yield, and J_{++}/J_+ is the ratio of doubly to singly charged ion currents. Using $J_{++}/J_+ = 0.3$, $(J_{++}/J_+)' = 0.45$, $S_+ = S_+' = 1 \times 10^{-3}$, and $S_{++} = S_{++}' = 1.48 \times 10^{-2}$ in Equation (A-2) gives $k = 1.71$ for $J_b = 1.62$ A and $J_b' = 2$ A. From Equation (A-1) the extrapolated erosion rate corresponding to $W = 172$ Å/hr and $k = 1.71$ is $W' = 294$ Å/hr.

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83M-0677/D2664

6 June 1983

SUBJECT: Contract No. NAS 3-18914
Endurance Test of a 30 cm Diameter
Engineering Model Ion Thruster
Task XII
Approved Final Report

TO: NASA/Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135
Attn: Mr. Don Hoffman, MS 500-305
Research Support Procurement Section

Pursuant to the requirements of subject contract, forwarded herewith please find one (1) copy of the Approved Final Report. Additional distribution is in accordance with the 1 June 1983 NASA Distribution List. With this submission all requirements of subject contract are completed.

Further communications regarding this contract should be directed to the undersigned at the above address or telephone number, extension 363.

HUGHES AIRCRAFT COMPANY

John E. Murphy, Jr.
Senior Contract Negotiator
Research Laboratories Division

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