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A PRELIMINARY INVESTIGATION OF CHARGE-EXCHANGE EROSION OF ACCELERATOR GRID SUPPORTS

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Cleveland, Ohio
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ABSTRACT

A preliminary investigation was carried out to reduce or eliminate concentrated charge-exchange ion erosion on the downstream grid support structures of two grid accelerator systems for electron-bombardment ion thrusters. The tests indicated that the charge-exchange erosion was a function of both the number of primary ion current carrying holes on the support periphery and the support diameter. In general, the depth erosion rate decreased while the erosion area and volume erosion rate increased with increasing support size. An electrically isolated support design was tested which appeared to eliminate concentrated charge-exchange erosion on both the cover cap and the accelerator grid for some sample locations.

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SUMMARY

A preliminary investigation was carried out to reduce or eliminate concentrated charge-exchange ion erosion on the downstream grid support structures of two grid accelerator systems for electron-bombardment ion thrusters. The tests indicated that the charge-exchange erosion was a function of both the number of primary ion current carrying holes on the support periphery and the support diameter. In general, the depth erosion rate decreased while the erosion area and volume erosion rate increased with increasing support size. An electrically isolated support design was tested which appeared to eliminate concentrated charge-exchange erosion on both the cover cap and the accelerator grid for some sample locations.

INTRODUCTION

Electron-bombardment ion thrusters which operate at specific impulse values between about 2000 and 3000 seconds and at about 2.5 kilowatts of power are of interest for a variety of space missions (refs. 1 and 2). These characteristics, along with thruster operating life requirements, result in thruster design diameters between 20 and 30 centimeters. Both two grid (refs. 3, 4, and 5), and composite grid (refs. 6 and 7) accelerator systems are presently being studied for use on these size thrusters. Two grid accelerator systems have been the subject of extensive study while composite grids are as yet in a relatively early stage of development. Selection of a grid system type will depend both on the mission constraints and the usual criteria of reliability, lifetime, and performance.

It is likely that some number of inter-electrode grid supports will be required for reliable operation of two grid systems, especially for the 30 centimeter diameter thruster.

Grid supports serve to reduce the variation in grid-to-grid spacing due to thermal loading during operation. A simple calculation was made to estimate the grid-to-grid spacing variation under various thermal loading. Briefly, this calculation indicated that with initial grid dish depths less than about 2.5 cm, one or more grid supports will probably be required to prevent grid-to-grid spacing variations greater than 0.5 mm.

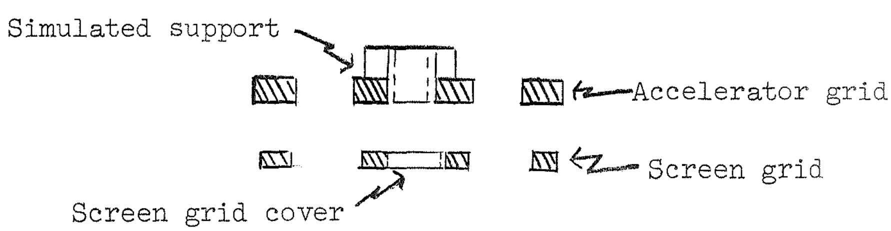
Tests at the Lewis Research Center and elsewhere have shown extensive charge-exchange ion erosion damage to the grid support structures tested. Figure 1 shows a center support used on the grid set described in reference 3. Erosion due to both primary and charge-exchange ion impingement is evident. Primary ion impingement can be avoided merely by keeping the support out of the local primary ion flux. In a life test performed at Hughes Research Laboratory (under contract NAS3-14140), charge-exchange erosion about 0.25 mm deep occurred in a 450 hour life test. In the test, charge-exchange erosion occurred in the form of long grooves.

Charge-exchange interactions are, of course, inevitable in the acceleration region of this thruster type. It can be shown that, at a fixed propellant utilization efficiency, the charge-exchange ion production increases as the square of the ion current density. It is of primary importance that the charge-exchange erosion such as that shown in figure 1 be eliminated or significantly reduced. The extent of the erosion on present support designs must be known to assume that grid lifetimes will be sufficient for proposed mission times.

This paper presents the preliminary results of a program directed toward eliminating or significantly reducing the charge-exchange erosion of grid supports. A number of geometrical and field shaping concepts were tested. Three short (up to 50 hours) tests were used to evaluate possible grid support designs and a longer test of 141 hours duration was carried out to verify final designs.

APPARATUS AND PROCEDURE

In most cases, simulated grid supports were used. The simulated supports in general blocked areas on both the accelerator and screen grids and protruded downstream of the accelerator grid. Actual grid supports are expected to be electrically similar to the protruding portion and mechanically able to fit within the simulated sizes tested. These simulated supports had common features which are described in sketch (a).



(a)

A cover cap of variable geometry was placed on the downstream side of the accelerator grid and some number of holes were blocked on the screen grid to avoid direct ion impingement on the cover cap. Both the accelerator grid cover caps and the screen grid covers were attached by tapping the appropriate grid holes which allowed the studded cap to be screwed onto the grid. Variable size caps were made by merely attaching them to the studs as shown in sketch (a). In general, the accelerator and screen caps covered equal numbers of holes. In some tests, however, the screen grid was blocked to a larger diameter. Most samples were fabricated from copper to provide an accelerated life test and also to allow easy machining of parts. The sputtering yield of copper is about three times that of molybdenum for normal mercury ion bombardment (ref. 8).

A total of four tests were run with several supports evaluated on each test. The 30-cm diameter thruster used in tests I, II, and III (up to 50 hrs in duration) was nearly identical to that described as the Task I thruster in reference 9. The thruster used in test IV (141 hrs duration) was similar to the Task V thruster of reference 9. The same accelerator grid set was used for all four tests. The screen grid was 0.8 mm thick with 4 mm holes on a center-to-center spacing of 4.50 mm. The accelerator grid was 2.54 mm thick with 3.26 mm holes. Average values of some thruster operating parameters for each test are given on table I.

Tests I, II, and III were all conducted in a 1.5 m diameter by 4.5 m long vacuum facility which had a stainless steel target 2.9 m downstream of the accelerator grid. The last test (IV) was carried out in a 7.6 m diameter by 21.3 m long vacuum facility (ref. 10). The background pressures in the small and large facilities were about 8×10^{-6} and 4×10^{-7} torr, respectively, during the tests.

The charge-exchange erosion was evaluated with the surface analyzer described in reference 11. This surface analyzer was capable of detecting depth changes as small as 2×10^{-5} mm and provided the most accurately measured values of erosion presented herein. The volume erosion presented in table II was calculated by use of the surface analyzer traces and a planimeter. Surface analyzer traces were taken across the eroded area which passed through the area of deepest erosion. The volume was then calculated by the assumption that the erosion was in the form of a volume of revolution. Although the depth measurements were quite accurate, sources of error (such as original surface roughness and planimeter inaccuracy) existed in the volume calculation. The volume erosion rates were estimated to be accurate to about 30 percent.

RESULTS AND DISCUSSION

The short duration tests will be discussed first, followed by presentation of the results of a 141 hour test. Table II gives geometries of test supports and test results.

It is difficult to specify the failure criteria for grid support erosion. The SERT II thruster suffered charge-exchange erosion to the extent that small pits eroded through the grid in about 2000 hours. This erosion did not lead, however, to failure of the grid system. On the other hand erosion in the region of a grid support could be more critical than normal charge-exchange erosion. No attempt will be made, therefore, to define an acceptable level of either depth or volume erosion.

Test I

Six small grid supports of variable geometry were tested for several reasons:

(1) To minimize the blockage of the screen grid for best discharge chamber performance (ref. 12).

(2) To minimize the mass of the grid system.

(3) To determine if the profile of the accelerator cap would strongly influence the amount or distribution of charge-exchange sputtering.

(4) To reduce the volume available for production of charge-exchange ions (ref. 13), which would strike the grid support.

Six samples (1 through 6) were placed at a 7 cm radius. All had one hole blocked on both accelerator and screen grids. Samples 1, 2, and 3 were all cylindrical and differed essentially only in length. Details of geometry are given on table II. Samples 4 and 5 were conical in shape and were of about the same base diameter as sample 3 (the A dimension on table II) and were of height 1.54 and 2.64 mm, respectively. Sample 6 was nearly hemispherical, 5.34 mm in diameter and 2.0 mm long.

Figure 2 presents sample 1 after 20 hours of operation and shows that charge-exchange erosion occurred in the form of a pit, roughly in the center of the sample (all photographs presented in this report are at 10× magnification). Similar erosion occurred for all samples of test 1 and some erosion characteristics for samples 1, 2, and 3 are shown on table II. The erosion rates per 1000 hours are tabulated to allow easy comparison of samples tested for different times during different tests. Accurate erosion data were not obtained for samples 4, 5, and 6 due to their geometry; however, visual inspection indicated that the erosion of these samples was approximately the same as for the cylindrical samples. It is seen from table II that both the maximum depth and volume erosion depths were about constant for the three cylindrical samples (which varied in length by about a factor of four). On the longest cylindrical sample (3) faint ray patterns similar in type to those shown in figure 1 accompanied the pit erosion. The rays were, however, too shallow to detect on the surface analyzer due to the original surface roughness.

The near independence of erosion on both the sample length and profile was assumed to indicate that charge-exchange erosion was primarily a function of the number of blocked holes of the screen grid and the primary ion distribution around the perimeter. As will be seen, this conclusion was born out through the program.

Test II

In this test, several different types of grid support were tested and they will be described separately.

Samples 7 and 8 had accelerator caps about 12 mm in diameter and were 0.36 and 0.76 mm long, respectively. These caps covered seven holes of the accelerator grid and the appropriate seven holes of the screen grid were blocked. These samples, and all others in test II, were inspected after both 20.5 and 50 hours of testing. Figure 3 shows the erosion on sample 8 after 50 hours, and the details of erosion are given on table II. The original surface of sample 7 was quite rough and it was judged that the erosion rates for sample 8 were most representative of 7 hole samples.

Compared with the one hole samples of test I, both the diameters of erosion and the volume erosion rates increased by about a factor of two while the maximum depth erosion rates decreased by about a factor of two. The number of holes on the sample perimeter which carried primary ion flux increased from 6 to 12 as the sample diameter increased from one to seven holes. It would therefore appear that for this diameter sample the total erosion is roughly proportional to the number of holes on the perimeter of the sample. Comparison of the erosion rates at 20.5 and 50 hours also indicates that the maximum depth and volume erosion is nearly linear with time for these test periods.

Sample 9 was made from a commercially obtained ceramic feed through. Sample 9 blocked one hole in both the accelerator and screen grids. An insulator was tested in order to determine if local fields could be built up by impinging charge-exchange ions which would repel further ion flux. When fabricated, a small dimple was left on the downstream surface. This dimple was not measured previous to test II. The profile of sample 9 was measured at 20.5 and 50 hours (table II) and it is seen that essentially no change occurred in the dimple depth due to charge-exchange erosion in that time period. A ray pattern was observed on the top of the sample after 50 hours. Because of the backsputtered tank material, it is possible that the surface of the ceramic was somewhat conductive during operation. Such a conductive coating could have prevented the maintenance of local fields.

Sample 10 was a long thin rod about 6.85 mm long by 1.6 mm in diameter. One hole was blocked in both accelerator and screen grids. This shape was selected in order to determine if the erosion problem could be circumvented merely by placing sufficient material on the downstream side of the accelerator grid. The geometry prevented use of the surface analyzer and the value of pit depth given on table II was obtained with a microscope. The erosion was in the form of a deep pit, similar to the samples of test I, on the end of the rod. The depth erosion rate was about the same as those of the samples of test I. The volume erosion rate was not estimated because no surface analyzer traces could be obtained.

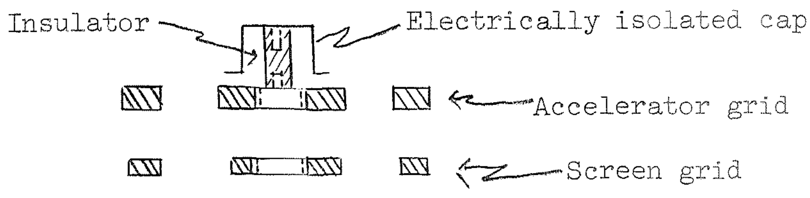
Test III

Samples 13 and 14 were both geometrically similar to sample 2 of test I. Sample 13 was fabricated from copper while sample 14 was made of molybdenum. These two samples were tested in order to determine the difference in volume and depth erosion rates for the two materials. Both the depth and volume erosion rates were reduced by about a factor of two by the change to molybdenum. The effective sputtering yield for molybdenum (atoms per incident ion) was, then, slightly more than half of that of the copper samples.

Samples 15 and 17 covered one and seven holes, respectively, on the accelerator grid. The screen grid was blocked to a larger diameter, however, around each sample. The number of primary ion current carrying holes on the periphery of the blocked screen area was 12 and 18, respectively, for samples 15 and 17. In order to determine the effect of blocking the screen grid to a larger diameter, the erosion of sample 15 (one hole) can be compared with that of sample 13, while that of sample 17 (seven holes) can be compared with that of sample 8 of test II.

The increased screen blockage increased the diameter of erosion by about a factor of three for both samples. The maximum depth erosion rate decreased, however, by about a factor of five for the small one hole sample and between a factor of two to three for the seven hole sample. The volume sputtering rate is also shown on table II. Because the erosion was spread out over a large area, the measured volume erosion rates for samples 15 and 17 contain considerably more uncertainty than for samples 8 and 13. However, for the small one hole samples the measured volume erosion rate increased by about a factor of two when the number of ion current carrying holes on the periphery increased from 6 to 12. The volume erosion rate increased further by about a factor of four for the seven hole sample when the peripheral ion carrying holes increased from 12 to 18. It is possible that for the larger diameter samples, a significant increase occurred in the downstream volume producing charge exchange ions which hit the sample when the screen grid was blocked to a diameter larger than the accelerator grid.

Sample 18 was an electrically isolated cap and is shown in sketch (b) and table II.



(b)

The sample covered seven holes on the accelerator grid and seven holes were blocked on the screen grid. This design was selected due to the partial success of sample 9 in test II. As seen on table II, the standoff had a small flange on the bottom which was added to prevent a short between the accelerator grid and the standoff cap due to backsputtered tank wall flux.

Figure 4 shows sample 18 after 25 hours of operation. No charge-exchange erosion was noticed on any part of its surface. In addition, no concentrated erosion was visually noted on the accelerator grid near sample 18. It is important to note that erosion on the accelerator grid could be more serious than erosion of the grid support cap because of the thin grids of interest for some thruster applications.

Backsputtered flux was deposited on all samples during all tests. During tests I, II, and III (in the smaller vacuum facility), the backsputtered flux was visible as a metallic coating. The amount of backsputtered flux in test III measured with the surface analyzer. The backsputtered flux was also estimated by use of a calculation due to T. W. Reynolds of the Lewis Research Center. The measured value of the backsputtered flux deposition rate was 4.1×10^{-3} centimeters per 1000 hours, which agreed with the calculated value to within 20 percent. The value of the backsputtered flux rate was quite small compared to the depth erosion rates and was therefore ignored.

Test IV

This test utilized several types of electrically isolated cap designs and was carried out in the large vacuum facility described in the section APPARATUS AND PROCEDURE. The test was performed in order to:

(1) Test standoff designs a sufficient length of time to determine that no concentrated charge exchange erosion would occur on either the cover cap or on the accelerator grid with the standoff design.

(2) Test in the larger facility in order to reduce both the back-

sputtered wall flux and the background pressure and any effects arising therefrom.

(3) Test variable standoff designs at several grid radial locations to determine the importance of standoff shape and location.

Sample 19 was located on the thruster axis over the actual center support of the grid system. Because it was on the axis, the ion current density on the periphery of the sample was the highest of any sample. Dimensions of the samples of test IV are given on table II.

Samples 20, 21, and 22 all covered seven accelerator grid holes and had seven holes blocked in the screen grid. All were located at a radius of seven cm. Sample 20 was nearly identical to sample 18 of test III except the flange was wider in order to reduce direct ion impingement on the sample. Sample 21 was a cylinder about 12.4 mm long while sample 22 was hemispherical in shape, about 8.1 mm in length.

Samples 23 and 24 both covered one hole in the accelerator grid and were located at a radius of seven and eleven cm, respectively.

In addition to these samples, a flat copper plate 3.18 by 1.9 cm in dimension was attached to the accelerator grid, at a radius of seven cm. Holes were drilled in the plate to match those in the accelerator grid. This plate was attached in order to determine the normal charge exchange erosion on copper in the absence of a grid support.

Figure 5 shows the downstream surface of sample 19 after the 141 hour test. This sample suffered considerable charge exchange erosion on the cover cap. The maximum depth of erosion was 0.292 mm. Due to the complicated geometry of the erosion, no estimate was made of the sputtered volume. Some direct erosion occurred because six holes in the screen were unfortunately not blocked and the primary ions eroded through the flange of the cover cap. This sample (and all others in test IV) was also inspected after three hours of operation when a thruster malfunction caused a test shutdown. At the three hour point, faint ray patterns were already apparent on the downstream surface of sample 19. It is likely, therefore, that the severe charge exchange erosion was not solely due to the presence of direct primary ion impingement because the ions had not eroded through the plugged accelerator holes after three hours of operation. The resistance between the cover cap and the accelerator grid was measured at the three hour and end of test times. In both cases the resistance was greater than 1000 M ohms.

The reason for the severe erosion is not known. It is possible, however, that a short between the sample and the accelerator grid existed during operation.

Samples 20 and 21 (both placed at seven cm radius) did not suffer any visible charge-exchange erosion. Figure 6 shows the downstream face of sample 20 (which was nearly identical to sample 18 of test III) after the 141-hour test. A slight amount of direct ion impingement was noted on both samples 20 and 21. This erosion was due to the fact that the height of both samples was sufficient to intersect the primary ion beam. Sample 21 was about twice as long as sample 20, and therefore received considerably more direct ion impingement. Because neither sample suffered any apparent charge-exchange erosion, it is likely that direct ion impingement is not necessary in order for the standoff design to successfully prevent charge exchange erosion. Inspection of the area surrounding both samples also indicated that no concentrated erosion had occurred on the accelerator grid surface during the test. Sample 22 suffered slight charge-exchange erosion. The depth of erosion was estimated to be less than 0.02 millimeters (the sample shape prevented accurate measurement of the erosion depth). A resistance check indicated that a partial short of about 3×10^5 ohms had developed between the cap of sample 22 and the accelerator grid during the test. It is felt, therefore, that the erosion was due to this partial short and not due to the rounded shape of sample 22.

Sample 24, on a radius of eleven centimeters, is shown in figure 7 after the 141-hour test. Unfortunately, sample 23, which was on a radius of seven centimeters, fell off during the test. It is seen from figure 7 that sample 24 suffered some charge-exchange erosion. Faint erosion was also visible at hour three of the test. The resistance between the sample cap and the accelerator grid was about 2×10^5 ohms. The depth erosion rate for this sample (table II) was more than twenty times less than the nonfloating one hole sample of previous tests. It is not known at present whether the slight erosion that was observed was due to the quasi floating condition of the cap or to the radial location of the sample.

No concentrated erosion was visually noted on the accelerator grid for any of the samples of test IV. Charge-exchange erosion on the accelerator grid is probably more critical than such erosion on the support covers. If diffuse charge-exchange erosion of order 0.1 mm occurred on the accelerator grid, it probably would not have been detected. The surface analyzer could not be used to determine such erosion because of the difficulty in establishing a reference plane that would be unchanged during the test. An accurate evaluation of accelerator grid erosion could be established only by a considerably longer test than carried out in this preliminary program.

The charge-exchange erosion on the perforated flat copper plate was measured. The depth of a typical charge-exchange erosion pit was about 0.03 mm. As indicated previously the depth and volume erosion rates for copper were about a factor of two more than for molybdenum. The depth erosion ratio for molybdenum would have been about 0.12 millimeters per thousand hours at that radial location (seven centimeters) and local ion current density.

CONCLUDING REMARKS

A preliminary investigation was carried out to reduce or eliminate concentrated charge-exchange ion erosion on the downstream grid support structures of two grid accelerator systems for electron-bombardment ion thrusters. The tests indicated that the charge-exchange erosion was a function of both the number of primary ion current carrying holes on the support periphery and the support diameter. In general, the depth erosion rate decreased while the erosion area and volume erosion rate increased with increasing support size. An electrically isolated support design was tested which appeared to eliminate concentrated charge-exchange erosion on both the cover cap and the accelerator grid for some sample locations.

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TABLE I. - THRUSTER OPERATING PARAMETERS

Test	Screen		Accel		Discharge		Mass utilization
	V	A	V	A	V	A	
I	2700	1.54	900	0.009	38	12.5	0.91
II	3000	1.55	900	0.010	38	12.6	0.91
III	3000	1.50	900	0.010	37.5	12.5	----
IV	2500	1.50	900	0.009	40	12.5	>0.9

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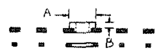
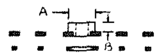
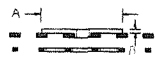
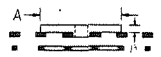
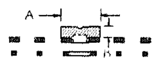
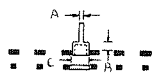
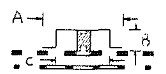
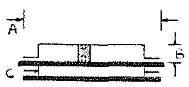
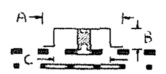
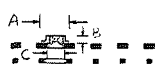
TABLE II. - SAMPLE GEOMETRY AND EROSION

Sample	Test	Geometry				Charge exchange erosion					
		Shape (Not to scale)	A, mm	B, mm	C, mm	Test time, hr	Max. depth of erosion, mm	Diameter of erosion, mm	Volume of erosion, mm^3	Maximum depth erosion rate, mm/1000 hr	Volume erosion rate, mm^3/1000 hr
1	I		5.1	0.36	-----	20	0.142	1.22	0.112	7.1	5.7
2	I		4.9	0.76	-----	20	0.143	1.12	0.110	7.15	5.5
3	I		5.1	1.59	-----	20	0.155	1.22	0.116	7.65	5.8
7	II		11.9	0.36	-----	20.5 50	0.094 0.193	1.88 2.28	0.193 0.494	4.6 3.82	9.42 9.91
8	II		12.2	0.76	-----	20.5 50	0.077 0.180	2.42 2.80	0.295 0.645	3.76 3.61	14.4 12.9
9	II		6.45	3.6	-----	20.5 50	0.22 0.21	---- ----	----- -----	---- ----	----- -----
10	II		1.59	6.85	3.56	50	0.40	----	-----	8.0	-----
13	III		4.65	0.84		25	0.198	1.17	0.144	7.91	5.76
14	III		4.5	0.81		25	0.102	1.27	0.074	4.07	2.94
15	III		5.3	0.76		25	0.041	3.61	0.325	1.64	13.0
17	III		13.5	0.76		25	0.041	6.6	1.16	1.64	46.4
18	III		11.9	6.6	9.7	25	0	0	0	0	0
19	IV		20.6	7.0	14.3	141	0.292	----	-----	2.12	
20	IV		12.2	6.7	10.0	141	0	0	0	0	0
24	IV		4.72	1.01	3.7	141	0.041	----	-----	0.291	-----

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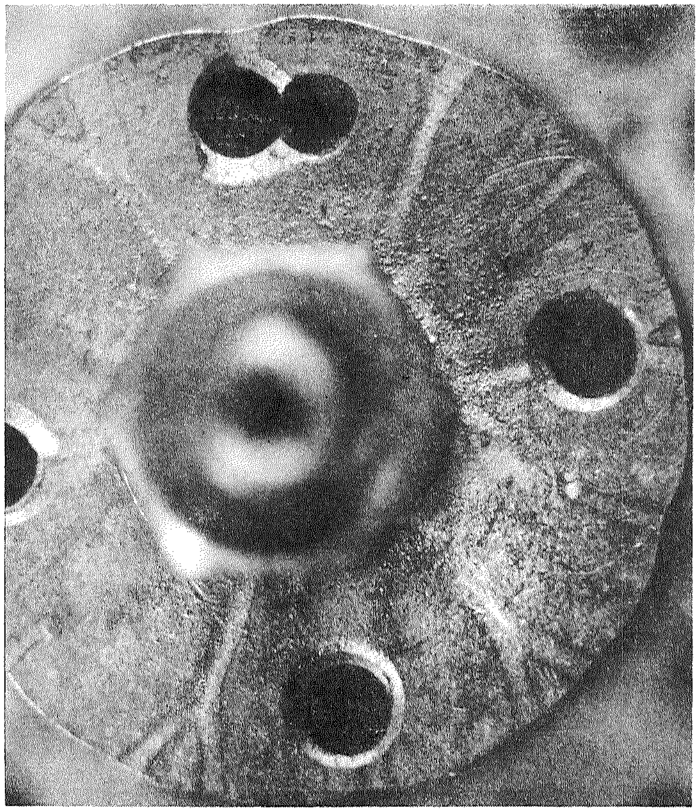

Figure 1. - Charge exchange erosion on center support of Reference 3.

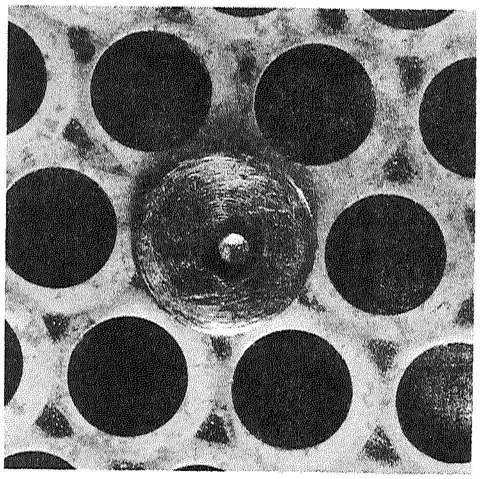

Figure 2. - Charge exchange erosion on sample 1 after 20 hours operation.

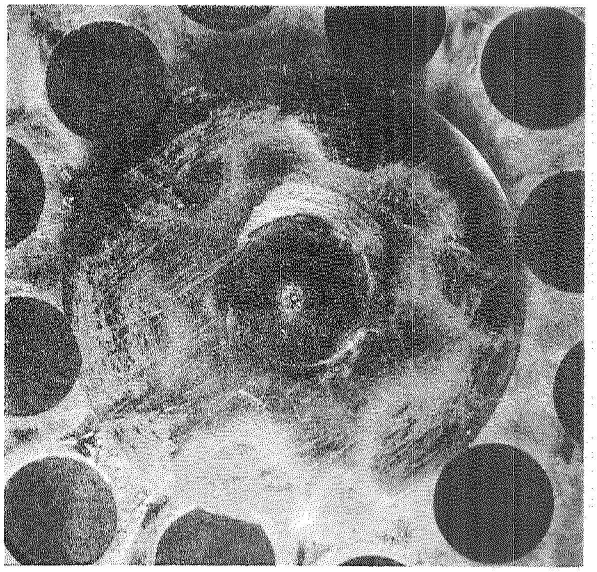

Figure 3. - Charge exchange erosion on sample 8 after 50 hours operation.

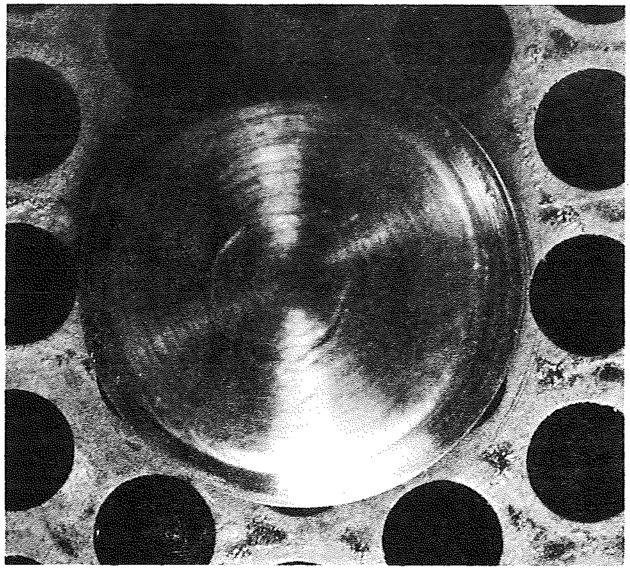

Figure 4. - Sample 18 after 25 hours of operation.

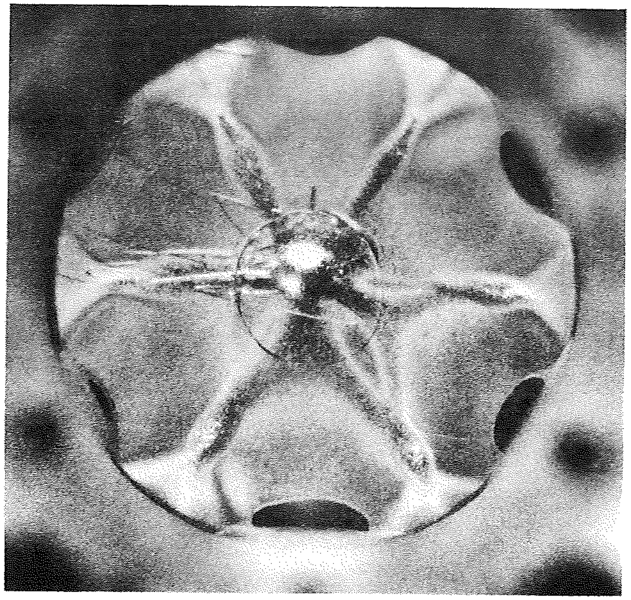

Figure 5. - Charge exchange erosion on sample 19 after 141 hours of operation.

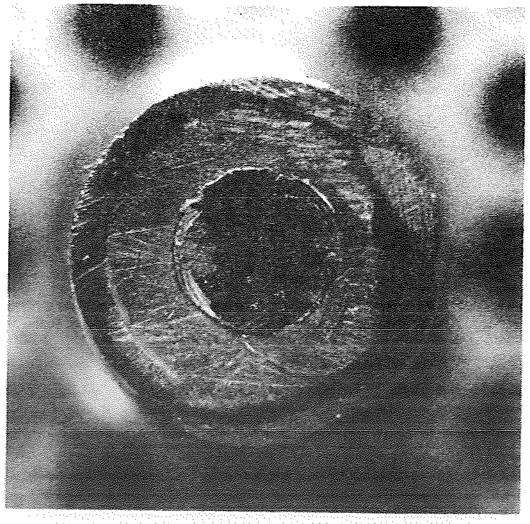

Figure 6. - Sample 20 after 141 hours of operation.

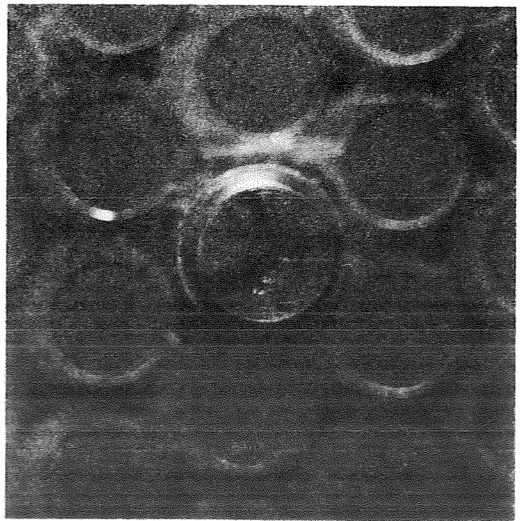

Figure 7. - Sample 24 after 141 hours of operation.