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OXIDE-CATHODE DURABILITY IN MERCURY ELECTRON-BOMBARDMENT ION THRUSTOR

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SUMMARY

The results of lifetime testing of oxide cathodes in mercury discharge chambers at emissions of 0.3 to 0.5 ampere per square centimeter are presented. High cathode erosion rates, probably due to ion sputtering, necessitated the construction of heavy layers of wire-reinforced oxide to provide lifetimes up to 5000 hours. An oxide-coated brush cathode gave the best lifetime of any cathode operated in an actual thrustor. Operation at low discharge voltages greatly extended the lifetime of cathodes. Calculated and measured losses of the oxide coating are compared. If additional cathode improvements can be made, the program goal of 10 000 hours may be reached. The brush cathode also survived shaking, thermal shock, and heat cycling that would be required for a space mission. Miscellaneous cathode types were also tested, but proved to be less durable than the thick oxide type.

INTRODUCTION

For the space missions in which electron-bombardment mercury ion thrustors are to be used, thrustor lifetimes of 10 000 hours are required. The environment of the thrustor discharge chamber is highly adverse to long cathode life (refs. 1 to 3). Positive ions fall out of the discharge and strike the cathode and the chamber walls with an energy approximately equivalent to the discharge voltage. Sputtered particles are ejected from the cathode, while material from the other parts of the chamber may recondense on the cathode and thereby poison it.

An intermediate neutral density (between that of a vacuum tube and that of a mercury arc lamp) of the discharge chamber is the worst case for cathode sputtering. At the low neutral densities of a vacuum tube, too few ions are formed to do appreciable damage to an oxide coated cathode and a long lifetime results. At the near-atmospheric pressure of

the mercury arc lamp, the bombarding ions undergo many collisions while falling through the cathode sheath and strike the surface with less energy than the sputtering threshold. Mercury arc lamps have lifetimes of many thousands of hours and use a cathode with a relatively thin oxide coating. Any cathode used in the intermediate neutral density of an electron-bombardment thrustor must therefore be thick enough to withstand prolonged ion bombardment or to renew its surface constantly. Also, a mechanism to reduce the bombarding ion energy below the sputtering threshold could serve to extend cathode lifetime.

Many previous investigations of thrustor cathodes have been made, and a summary is included herein to assist the reader in relating the present investigation with those previous investigations.

The first type of cathode tested in a mercury bombardment thrustor was thoriated-tungsten wire. The thoria was quickly removed by positive ion bombardment as it diffused to the surface. In less than 20 minutes, the emission of the thoriated tungsten was reduced to that of pure tungsten. To increase the emission, tantalum ribbon cathodes with larger emission areas were tried (ref. 1). With either the tungsten or the tantalum cathodes, however, thick filaments with an excessive heating current were required in order to extend the lifetime beyond 150 hours (ref. 2).

The next type of cathode investigated consisted of an oxide-impregnated sintered metal. Reference 2 presents test results for a 90-percent nickel powder and 10-percent emissive oxides cathode. In further investigations, the amount of oxide was gradually increased to 50 percent in an attempt to supply more oxide to the cathode surface. It was hoped that the increased oxide supply would reduce the operating temperature and extend the lifetime. A sintered-tungsten-matrix cathode with an improved heater design avoided the temperature limitations of nickel but still failed after only 161 hours. All sintered matrix cathodes, however, still seemed deficient in oxide, or at least ceased emitting after a few hundred hours.

Sintered metal-oxide mixtures containing less than 50-percent metal were difficult to fabricate. As a way of increasing the oxide content of the cathode, foam metal matrices of less than 50 percent theoretical crystal density were considered. A tungsten foam of 6-percent density, impregnated with mixed oxides, was endurance tested as a cathode in this investigation, and while it improved the lifetime of the sintered-matrix cathodes, it was still far short of a desired 10 000-hour lifetime.

Two types of heavily coated oxide cathodes received additional testing in this investigation. These were (1) the thick-oxide-layer cathode (tantalum ribbon wrapped with tungsten wire and coated with oxides) of reference 2 and (2) the oxide-coated brush cathode of reference 3.

The initial success of oxide-coated brush cathodes, as reported in reference 3, were followed by failures apparently due to chemical attack on the bristles by the emissive oxides. Therefore, wire brushes of different materials less susceptible to chemical

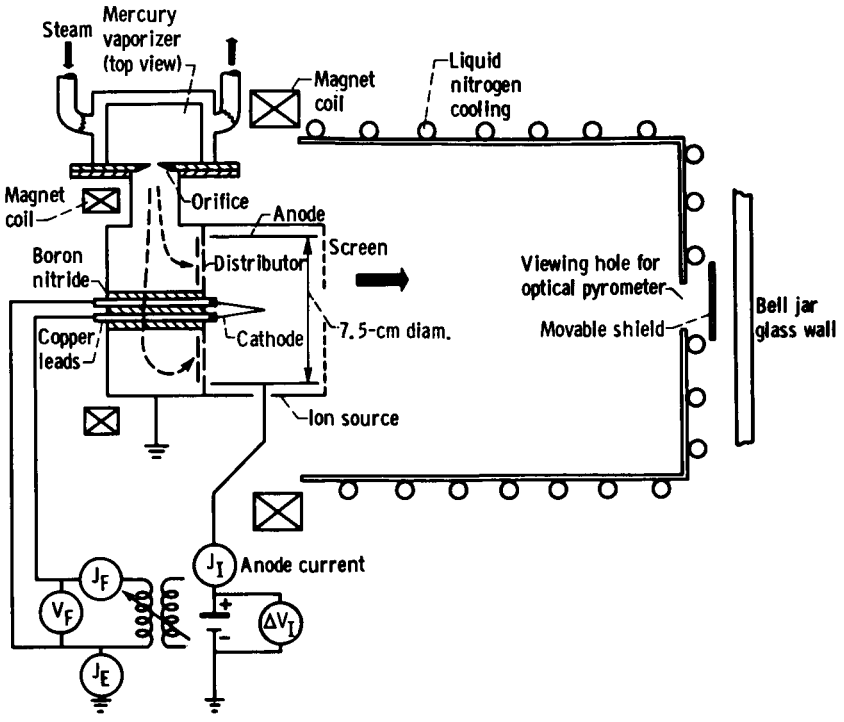
attack were fabricated and tested, and the results are given in this report. Also, cathode activators were utilized in an attempt to lower the cathode operating temperature and lessen the chemical attack of the oxides on the bristles. Brush cathodes were also subjected to a number of tests that simulated some of the conditions likely to be encountered during a space mission, namely, vibrations, thermal shock, and heat cycling.

Concurrently with the testing of the heavily coated oxide cathodes, other investigators were testing cathodes with promise of long lifetimes in mercury ion thrustors. Reference 4 reports a lifetime of over 3000 hours with an "oxide magazine" cathode that continuously fed a block of oxides to a heated tungsten screen. Reference 5 reports similar cathode operating times with a "liquid-mercury pool" cathode, which draws emission from a mercruy surface within a small tungsten nozzle. Little erosion of the tungsten nozzle was noted after several thousand hours, although high thrustor efficiencies were somewhat difficult to obtain.

The results of continued lifetime tests of several oxide cathodes operated in the discharge of simulated and actual electron-bombardment ion thrustors are presented in this report. Lifetime improvements were sought by (1) operation at a low (near or below sputtering threshold) discharge voltage, (2) avoiding destructive arc damage through the use of a current regulated supply, (3) building up thicker layers of oxide and wire, (4) the use of different types of oxides, and (5) the addition of nickel powder to improve the conductivity of the oxide coating. The analysis of erosion mechanisms and the correlation of results with operating parameters are also presented as guides to estimating maximum cathode lifetimes.

APPARATUS

Because of the long duration of the cathode tests, many of them were made in a simulated ion thrustor operated in a glass bell jar. Inasmuch as the cathode lifetime was usually longer in the simulated thrustor, final endurance tests and occasional shorter tests of the cathodes were made in an actual thrustor located in a vacuum tank. Descriptions of the bell jar and vacuum tank facilities are given in references 1 and 4, respectively. In either facility, the pressure with a thrustor operating was about 3×10^{-6} millimeter of mercury. Figures 1 and 2 are schematic diagrams of the simulated and actual ion thrustors. The major operational difference between the simulated ion thrustor and the actual ion thrustor was that no accelerator grid nor ion-extraction field was used with the simulated thrustor. Actual thrustor diameters were 5, 10, or 20 centimeters depending on the specific test, whereas the simulated thrustor diameter was 7.5 centimeters. Unless otherwise noted, the screen and accelerator grids were made of molybdenum and were the only metal thrustor parts (apart from copper wires and the cathode) not made of stainless steel.



(a) Schematic diagram.

Figure 1. - Schematic diagram of simulated ion thrustor operated in bell jar.

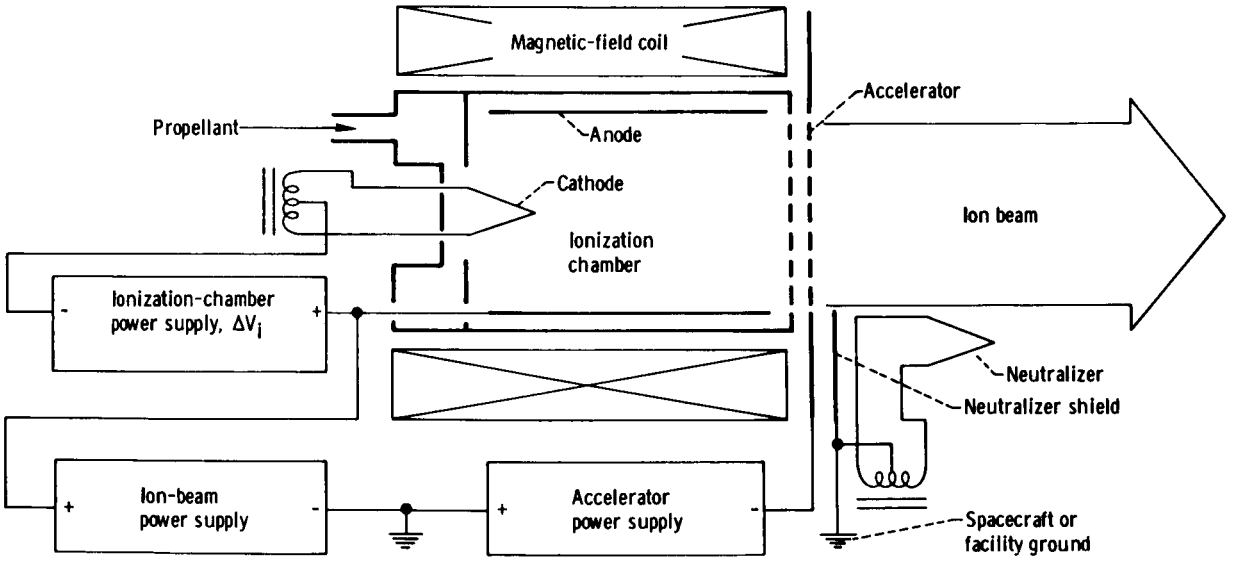
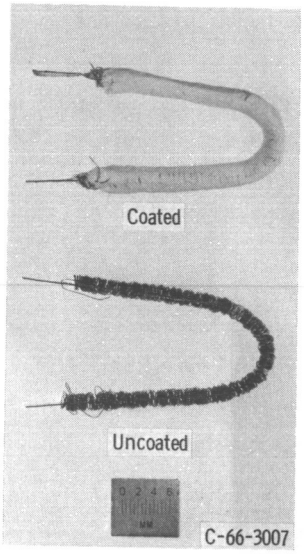
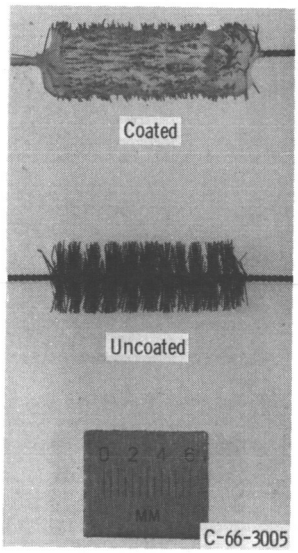


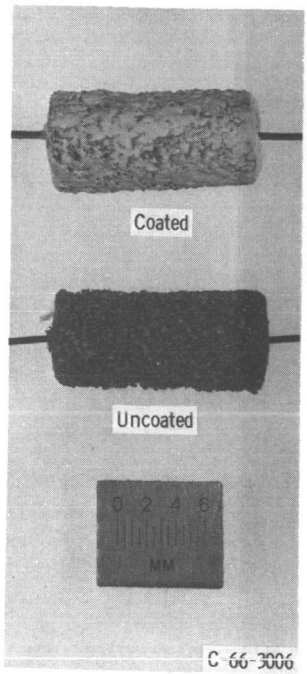
Figure 2. - Schematic diagram of actual thrustor.



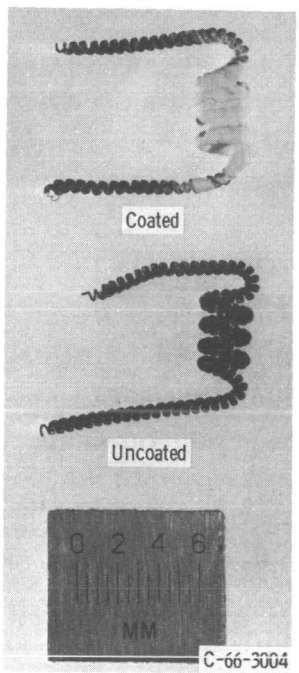
(a) Thick-oxide-layer cathode.



(b) Brush cathode.



(c) Foam cathode.



(d) Basket-weave cathode.

Figure 3. - Various uncoated and oxide-coated cathodes. Coating, Radio Mix No. 3.

Many details of the construction and coating of the cathodes will be presented in the RESULTS AND DISCUSSION because they were often intimately related to the results obtained. Photographs of the various cathode types tested are shown in figure 3.

Radio Mix No. 3 (57 percent $BaCO_3$, 42 percent $SrCO_3$, and 1 percent $CaCO_3$) was the standard coating for all cathodes unless otherwise noted. The coating was prepared as a slurry of the carbonate powders, hand ground in a mortar with a pestle until a fine dispersion of the solids was obtained. The liquid in the slurry was either distilled water or a mixture of amyl acetate and nitrocellulose binder. The slurries with either liquid contained approximately 50 percent solids. The wetting of the powders and the fluidity of the slurry were increased by adding 1 percent of Aerosol-OT, a wetting agent, to the distilled water. The cathode (either thick-oxide-layer or brush) was built up in successive coatings until all voids were filled. The use of the wetting agent permitted the slurry to carry the powders more easily into the fine crevices between the wires of the cathode. The carbonate coating was slowly dried at room temperature (no external heat).

Some tests (unreported), where the cathode was rapidly dried under heated conditions, resulted in poor emission and early failure. Apparently, rapid solvent evaporation caused the carbonate to lift off the heater wires resulting in a high thermal resistance at the interface. Even the addition of powdered nickel to

the coating of a rapidly dried cathode (additional unreported tests) was not successful in preventing low emission or arcing.

One major disadvantage in using the nitrocellulose binder for coating either the brush cathodes or the extremely thick-oxide-layer cathodes was the occurrence of voids trapped within the solidified binder. Subsequent coatings of slurry could not reach or fill these voids and the cathode appeared (incorrectly) to be completely solid. The presence of voids in the coating resulted in poor heat conduction and quick burnout of the cathode.

TEST PROCEDURE

Most cathode endurance tests in the simulated thrustor were run at constant emission current, discharge voltage, magnetic field strength, and mercury propellant flow. The heating power to the cathode was varied to maintain constant emission current. In some tests the discharge voltage that also affected the emission current was also varied over a range of values. The discharge conditions were chosen over a range of values to determine the optimum design of a cathode for long life. This range of conditions, however, was restricted to those believed to be suitable for actual thrustor operation. Emission current densities were usually 0.3 to 0.5 ampere per square centimeter. The thickly coated cathodes generally would operate only at a specific discharge voltage in the range of about 25 to 35 volts. At higher voltages, the emission current would increase until arcing occurred, that is, the emission current could not be controlled by the heater current. Generally, at some lower voltage, the cathode emission would rapidly decay, although for several tests, the cathode continued to emit at a discharge voltage near 20 volts.

Cathode temperature was measured by a calibrated optical pyrometer, and the value was used to estimate a relative cathode emission current. (A spectral emissivity of 0.35 was assumed to correct the brightness temperature reading.) Generally, however, a time plot of cathode heating power necessary to maintain the constant emission current was the most reliable data to determine cathode activation or deactivation.

For actual thrustor operation, a constant beam current (accelerated through constant voltages) was maintained by small adjustments to the discharge voltage and by varying the cathode power as needed. The magnetic field strength was also varied to obtain the least discharge-chamber power per beam ion.

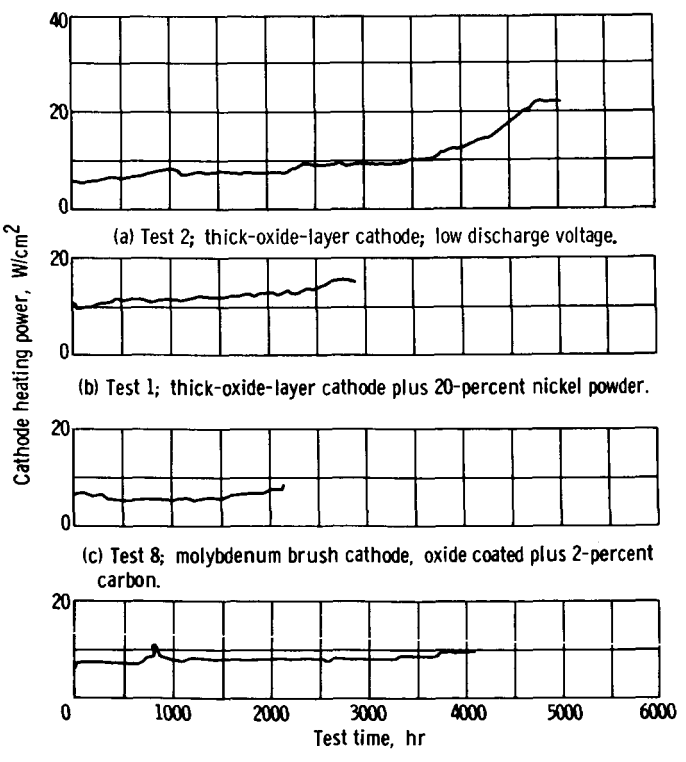
The correlation of cathode lifetime for specific cathodes to operating parameters was difficult for several reasons: (1) The extreme length of many tests limited the number and variety of conditions under which cathodes could be tested. (2) Test conditions were sometimes changed during tests when it became evident that the initial operating conditions were not conducive to long life. (3) Newly designed cathodes would not always

operate at the conditions of a previous test, making a direct comparison of cathodes difficult. Additional procedures, unique to specific tests, are described in the following section.

RESULTS AND DISCUSSION

Thick-Oxide-Layer Cathode

This section presents several methods used to extend the lifetime of the thick-oxide-layer cathode. For one method, thicker oxide coatings were used on the cathode. For another, ion-bombardment sputtering of the cathode was reduced by reducing the incident ion energy, either by lowering the discharge voltage, or by using a protective grid around the cathode. Finally, arcing damage to cathode was eliminated as a factor in cathode lifetime by the use of a current-regulated power supply in the discharge circuit. All the tests of reference 2 were made before this supply was used, but only tests 1 and 2 of this report were made without the current-regulated supply.



(a) Test 2; thick-oxide-layer cathode; low discharge voltage.

(b) Test 1; thick-oxide-layer cathode plus 20-percent nickel powder.

(c) Test 8; molybdenum brush cathode, oxide coated plus 2-percent carbon.

(d) Test 10; platinum brush cathode, oxide coated plus 2-percent carbon.

Figure 4. - Cathode heating power as function of test time. (See tables I and II for additional information.)

In test 1, 20-percent nickel powder was added to the oxide coating to increase thermal and electrical conduction with the intention of decreasing the cathode hot spots and the susceptibility of the cathode to arcing. The test was free of arc damage and was only terminated because the mercury supply for the discharge was exhausted. About one-fourth of the original oxides remained on the cathode when the test was ended at 2929 hours. The cathode heating power for this test and several others is plotted in figure 4 and listed in table I.

The longest cathode test to date was test 2 at 5019 hours. The primary reason for this lifetime was probably low ion-bombardment damage resulting from an extremely low discharge voltage of 16 to 20 volts. The threshold for mercury ion sputtering

TABLE I. - TEST CONDITIONS FOR OXIDE CATHODES

Test	Conditions and specifications	Thermal emission, A/cm^2	Ion discharge chamber voltage, V	Cathode emitting area, cm^2	Cathode heating power, W/cm^2	Mercury flow, A	Thrustor diameter, cm	Lifetime, hr	Remarks
1	(a), (b)	0.52	25	4.2	12.0	0.16	7.5	2929	Propellant supply exhausted
2	(b)	.93	19	4.3	10.1	.16	7.5	5019	Oxide depleted
3	(b), (c)	.27	29	16.0	2.5	.16	7.5	650	Intentionally stopped
4	(b)	----	--	4.3	10.4	----	---	3903	Evaporation only test
5	↓	----	--	↓	6.4	----	---	329	↓
6	↓	----	--	↓	5.8	----	---	650	↓
7	↓	----	--	↓	11.5	----	---	161	↓
8	(d), (e)	.33	32	3.8	6.4	.08	7.5	2156	Burnout at support
9	(d), (f)	----	20 to 60	2.4	21.4	.09	↓	39	No activation
10	(d), (e), (f)	.34	26	4.9	8.0	.09	↓	4383	Facility power interruption
11	(d), (g)	.50	30	7.9	7.5	.10	↓	735	Pressed coating, core burnout
12	(d), (e)	.25	30	15.7	3.8	.16	↓	3903	Ref. 3
13	(d), (h)	.11	35	1.9	7.9	.03	5.0	1553	Ref. 3
14	(d)	----	--	2.5	7.5	----	---	4422	Evaporation only test
15	(d), (g)	----	--	15.7	8.6	----	---	554	Sudden activation test
16	(d)	----	--	1.8	13.2	----	---	3500	418 000 Heat cycles
17	(d)	----	--	2.0	13.2	----	---	2300	275 000 Heat cycles
18	(i)	.84	32	3.8	10 to 31	.09	7.5	1283	Heater burnout
19	(j), (h), (k)	.05	35	10.2	1.05	.04	5.0	302	Intentionally stopped
20	(h), (ℓ)	~1.2	35	~.8	2 to 6	.16	7.5	473	Excessive power at end of test
21	(h), (ℓ)	~1.0	40	~.8	3 to 7	.04	5.0	550	Excessive power at end of test

[a] Cathode coated with 80-percent $BaCO_3$ and 20-percent powdered nickel. Heater and matrix as described in footnote b.

[b] Thick-oxide-layer - tantalum-ribbon-heater cathode, 0.013- by 0.36- by 5.1-cm. Matrix wire, 0.007-cm-diam tungsten wound around ribbon heater 20 times per cm; coating, Radio Mix No. 3 with nitrocellulose binder.

[c] Cathode matrix wires were increased to four times normal and extra heavy coating was approximately 0.5 cm thick.

[d] Brush cathode. Standard coating, Radio Mix No. 3 slurry with water and Aerosol-OT wetting agent.

[e] Brush cathode was formed into partial circle and mounted between two parallel copper rods.

[f] Cathodes made of platinum alloy wire containing 5-percent nickel.

[g] Cathode coatings were pressed at 3.5×10^6 newtons per square meter (10^4 psi).

[h] Thrustor operating conditions: net accelerating voltage, 4000 V; accelerator voltage, -1000 V; magnetic field at screen, 30 gauss; beam current, 0.02 A.

[i] Tungsten-foam cathode.

[j] Nickel-foam cathode.

[k] Cathode shape, hollow cylinder (0.94-cm i.d., 1.9-cm o.d., 3.5-cm long).

[ℓ] Basket-weave cathode formed from a double spiral of 0.014-cm-diam tungsten wire wrapped with 0.003-cm-diam tungsten wire.

of barium oxide is about 22 volts (ref. 6). This cathode may have lost its oxide primarily by evaporation, although the cathode was intentionally caused to arc about 25 times during a motion-picture study of arcing. The arcing study was made early in test 2 before the endurance capability of the cathode was realized. The amount of oxide lost by arcing was thought to be less than 50 percent of the total oxide coating. Test 2 proceeded at a slowly increasing heating power until about 3700 hours, at which time a rapid increase in heating power was required for the remainder of the test to maintain a constant emission current. During the last 1000 hours, many areas of the cathode (tantalum heater ribbon) were void of oxide, and much power was lost by radiation because the exposed heater ribbon was much hotter than nearby oxide covered areas. The test was terminated because of excessive heating power and the almost complete absence of oxide coating (about 10 percent remained by visual observation).

To increase the quantity of oxides in the coating, the cathode of test 3 was built up with more layers of wire and oxide until the cross section was nearly circular, and a maximum thickness of 0.5 centimeter (about 1-cm diam) was reached. Test 3 was terminated (to permit further testing of other cathode designs) after 650 hours of low, steady heating power. The basic objective of this test was achieved when the extra thick coating emitted well and was arc free.

Motion pictures of arcing. - Thick-oxide-layer cathodes failed in several tests after a repeated series of heavy-current (~10 A) arcs. Motion pictures were taken of these arcs to study the manner and type of damage to the cathode. It was concluded that each arc destroyed about 1 percent of the cathode surface. Several arcs, therefore, might result in minor damage to the cathode, but repeated arcs would lead to cathode failure.

Pictures were taken with color film at 600 frames per second and with black and white film at 3000 frames per second. The camera was located at the same viewing location as the optical pyrometer (see fig. 1). Generally, a bright area would be seen on the cathode surface first, followed by a plasma luminosity, extending part way between the cathode and anode, that traveled radially outward and spun around the cathode at radii of several centimeters. The frequency of rotation was 30 to 100 cycles per second. The shape of the luminosity zone varied but maintained roughly a length equal to the width. The hot area on the cathode surface would often erupt in a shower of luminous flakes of material that would spin and fall away from the cathode. The arc lasted about 0.2 to 2 seconds, usually until the fuse blew in the discharge power supply. In addition, often at times other than when the rotating luminosity was observed, nondestructive sparks would be observed on the distributor surface. These sparks (for the same test and hence the same magnetic field direction) would rotate either clockwise or counterclockwise in random paths and then die out after two to five rotations. Arcs in the discharge chamber

could be initiated either by pulsing the magnetic field strength or increasing the discharge voltage.

Type of cathode coating. - There appeared to be no difference in cathode activation or lifetime by the use of barium carbonate or Radio Mix No. 3 as a source of oxides. No activators were added to the thick-oxide-layer cathodes and activation was thought to occur primarily from ion bombardment or by emission. There was also possible activation by tantalum or tungsten (used in the cathode) chemically reacting with barium oxide to produce the free barium needed for activation. However, two facts indicate that chemical activation might be minor: (1) there was little loss of either tantalum or tungsten from the heater-matrix and (2) in a 1000-hour test reported in reference 2, a pure nickel (chemically inactive) cathode was successfully activated without tantalum or tungsten being present.

Cathode grids. - In an attempt to shield the cathode from the full energy of the bombarding ion, a series of grids was placed around the thick-oxide-layer cathode. The grids were approximately 2 centimeters in diameter by 6 centimeters long and made of tantalum sheet metal with either a series of small drilled holes (fig. 5, grid A) or overlapping baffles (fig. 5, grid B) to permit flow of electrons and neutrals through the grid. The grid was biased both negatively and positively with respect to the cathode, and part or all of the neutral mercury propellant flow was directed inside the grid. A discharge was difficult to obtain without direct flow of neutrals into the grid area. Best operation (maximum emission current reaching anode) was obtained with the grid biased 10 volts more positive than the cathode. Typically, the grid current was 10 percent or more of the emission current.

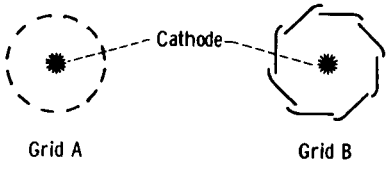


Figure 5. - Cross section of cathode grids; end view.

The use of grids around the normal thick-oxide cathode resulted in cathode-with-grid lifetimes (not reported in table I) of 604 and 713 hours in the simulated thrustor. Cathode failure was caused by loss of emissive material and consequent high heating power. When the cathode grid was tested in an actual thrustor (10-cm diam), the discharge loss (after several modifications to reduce losses) was a high value of 1200 to 1800 electron volts per beam ion. The maximum propellant utilization efficiency was only 60 percent. Although only 10 percent of the electrons were captured by the grid, the high-energy primary electrons were apparently not getting through the grid and into the main volume of the discharge chamber. Primary electrons are necessary in the discharge chamber to produce efficient ionization with most propellants. Further tests with cathode grids were not conducted because the cathode lifetimes were not significantly extended and the thrustor performance was markedly reduced.

TABLE II. - MATERIAL AND SIZE OF BRUSH CATHODES

Test	Brush		Bristles		Heater wires (core)		Activator added to coating, percent carbon
	Length, cm	Diameter, cm	Material	Diameter, cm	Material	Number times diameter, cm	
8	2.22	0.55	Molybdenum	0.005	Molybdenum	2 × 0.025	2
9	1.25	.63	Platinum	.005	Platinum	2 × 0.025	2
10	2.50	.63	Platinum	.005	Platinum	2 × 0.025	2
11	2.50	1.00	Tantalum	.008	(a)	2 × 0.050	None
12	5.00	1.00	Tantalum	.008	Tantalum	4 × 0.050	None
13	1.20	.50	Tungsten	.005	Tantalum	2 × 0.025	None
14	1.25	.63	Platinum	.005	Platinum	2 × 0.025	2
15	5.00	1.00	Tantalum	.008	Tantalum	4 × 0.050	None
16	1.25	.47	Tantalum	.005	Tantalum	2 × 0.025	None
17	1.25	.51	Tantalum	.005	Tantalum	2 × 0.025	5.1

[a]Alloy of 90-percent tantalum and 10-percent tungsten.

Oxide-Coated Brush Cathodes

Results of additional tests with oxide-coated brush cathodes (others were made and reported in refs. 3 and 4) of this investigation are tabulated in table I. Dimensions of the brushes are given in table II. In all the tests, it was not completely clear how any brush cathode had been activated or exactly from where the electrons were emitted. However, some of the causes of brush failure were definitely established; for example, failure of the heater wires due to chemical attack or failure due to flaws or strains introduced during the fabrication of the brush.

The first tests with oxide-coated brush cathodes were quite successful (ref. 3) and avoided procedures that were later found to lead to quick failures. The ultimate lifetime of a brush cathode will not be established until the exact operation of the barium-dispensing mechanism is known. For example, a cathode may operate indefinitely on its last fraction of oxide if that oxide is shielded from ion bombardment by a maze of protruding bristles. In addition, the method of preparing the coating slurry and finely dispersing the powder in the liquid may be another factor affecting lifetime. The brush cathodes were normally coated in a batch-type operation that was difficult to control or reproduce reliably.

Theoretical model. - If the brush is considered as a uniform grouping of radial bristles, the average distance between bristles at the surface of the brush is 0.050 centimeter. The accepted value (ref. 7) for the thickest oxide layer (even fully activated) that is practical as an emitter in a normal oxide cathode is 0.005 centimeter. It seems

unlikely that the bulk of the oxide surface is emitting electrons. The electrons may be emitted from a barium-coated bristle tip, from a ring (approximately 0.005 cm greater radius than the bristle) of oxide surrounding a bristle, or from thinly oxide coated or bariated sides of bristles exposed by cracks in the brush cathode.

Every oxide cathode is a dispensing cathode and is in equilibrium with its surroundings (ref. 8). The dispensed barium may be produced in several ways, such as, emission, ion bombardment, or chemical reduction. As the emitted current does not pass through the bulk of the oxide, activation by emission can probably be ignored except for an area close to the bristles. Activation by ion bombardment (barium oxide is sputtered into barium ions and oxygen ions; negative oxygen ions leave and positive barium ions fall back to the cathode) may be a major activating mechanism. Conventionally, only traces of activators are required to activate ordinary oxide cathodes by chemical reduction. These traces are often overlooked as to their origin. However, oxide cathodes when operated in the mercury bombardment ion thrustor seem to require much more, perhaps two to three orders of magnitude more, surface replacement of barium. Hence, the source of the activation mechanism should be that much more obvious. Chemical activators are discussed in detail in the section Chemical activators, but one experimental observation that was very difficult to explain was why some (about 1 in 10) oxide brush cathodes never seemed to activate, even with chemical activators present.

The usual emission decay with time (increased heating power required in the case illustrated in fig. 3 of ref. 3) of the brush cathode may be caused by several mechanisms: (1) As the test proceeded, oxide material was depleted from the prime emitting sites, and a higher temperature was necessary to supply the emitting site with additional active material. (2) As the test proceeded, condensed sputtered material from the discharge chamber built up on the cathode surface thereby partially poisoning it or increasing the surface work function. (3) As the oxide layer was worn back into the brush, fewer ions from the discharge reached the oxide surface and, therefore, fewer sputtered barium ions were produced for activation. The emitting surface work function increased and a higher temperature was required to maintain a given emission.

Chemical attack of brush wires. - The equilibrium vapor pressures of barium produced by the reduction of barium oxide with several metals are listed in the following table for a reaction temperature of 1200° K (ref. 9):

Reducing metal	Barium vapor pressure, torr
Carbon	1.5×10^{-3}
Tantalum	3×10^{-5}
Tungsten	1×10^{-6}
Molybdenum	1×10^{-8}
Platinum	No reaction

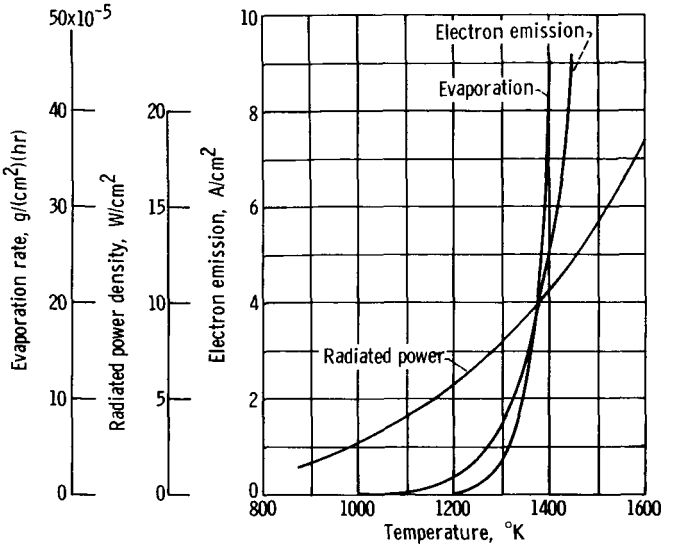


Figure 6. - Thermal properties of barium oxide cathode. Total emissivity, 0.5 (used to calculate radiated power).

The magnitude of the vapor pressure indicates the rate of reaction between barium oxide and the reducing metal, if the barium is free to escape. Chemical reactions are very sensitive to temperature, and a temperature rise of about 90° K at 1200° K is enough to increase the barium vapor pressure one order of magnitude.

Typical 1-centimeter-diameter brush cathodes had a surface temperature of about 1300° K (required for emission, fig. 6) and a core temperature of about 1450° K. This radial temperature gradient was the result of heating power being added at the center core and flowing outward to heat the surface. The higher temperatures at the core could critically increase the chemical reaction rate and cause failure of the wires. Burnout of the core wires could be explained by the following events: The first step was a slow uniform chemical attack on all wire surfaces. Because the bristle wires were thinner, they were proportionally reduced a greater fraction of their diameter. The resulting thinner bristle was a poorer heat conductor, thus increasing the radial temperature and accelerating the chemical attack. Once the thin bristle wires failed, there was no conduction path for the heat to escape, and the core wires increased in temperature until they melted.

Several attempts were made to reduce chemical attack on the brush wires. First, the radial temperature gradient was lowered by using tungsten bristles. Tungsten has approximately twice the thermal conductivity of tantalum and resulted in a significant improvement in the brush lifetimes of reference 4. Next, an attempt was made to increase the thickness of the bristles. This approach was unsuccessful because the total cross-sectional area of bristles seemed to be a constant for a given brush and core size; that is, fewer larger bristles could be held tightly by the brush. Bristle wires larger than 0.013 centimeter in diameter could not be made into acceptable brushes (with four core wires, 0.050-cm in diam).

In another attempt to reduce the radial temperature gradient, 20-percent powdered nickel was added to the oxide mixture. This cathode (data not listed in table I) burned out after 20 hours and apparently never became properly activated because a high heating power was required.

The next approach was to use brush wires that were less chemically active such as molybdenum, or chemically inactive such as platinum. Table I presents the results of molybdenum (test 8) and platinum (tests 9 and 10) brushes. The molybdenum brushes had sufficient mechanical strength and good chemical resistance, but, because of poor emission, the required operating temperature in several tests (not listed in table I) was excessively high, and the core wires melted after evaporating much of the oxide coating. Only in test 8 with good activation (for unknown reasons) was the cathode heating power low and the lifetime quite long (2156 hr). The results of the platinum brush tests 9 and 10 were similar to those of the molybdenum brushes. The first brush failed because of poor activation, while the next platinum brush activated well and had a lifetime of 4383 hours (fig. 4). Two percent carbon was added as an activator to all the molybdenum and platinum brush cathodes.

It is perhaps significant that all the long-life brush cathodes had low (4 to 6 W/cm^2 based on the brush surface area) applied heating power. Figure 6 shows that any oxide cathode should lose about 8 watts per square centimeter of power by radiation at normal operating temperature. The additional heat required to balance radiation losses could come from either ion bombardment or joule heating of the oxide by emitted electrons. Reference 2 indicates that, at normal ion densities in the discharge chamber, the heating due to ion bombardment is about 0.1 watt per square centimeter, which is negligible. The joule heating, if it did occur, would be near a bristle and at the brush surface, and hence the core would escape chemical attack as the joule heating current would not need to pass through the deep oxide layers of the brush. A lower applied heating power means a lower radial temperature gradient and, perhaps, elimination of chemical attack problems.

Chemical activators. - Initially, chemical activators were added so that the cathode might operate at a lower temperature and the chemical attack of the brush wires would be reduced. Later, activators were added when there was insufficient activation by other processes.

Reference 4 presents results of adding several powdered activators to the oxide coating. In order of decreasing chemical activity they are titanium, carbon, tantalum, and tungsten. Powdered tantalum or tungsten did not apparently have a fast enough reaction rate for good activation nor did powdered titanium result in good activation when tested. A well activated (low heating power) brush cathode was obtained when powdered carbon was added in stoichiometric quantities to barium carbonate. Stoichiometric quantity was defined as one atom of carbon for every atom of barium or 5.7 percent by weight of carbon. Carbon was the only activator tried in subsequent tests with brush cathodes. Experimentally, it was found that 2 to 10 percent quantities of carbon aided the activation of brush cathodes. Sometimes brush cathodes, however, failed to activate even with powdered carbon present.

In normal, thinly coated oxide cathodes, the amount of free barium needed to activate a cathode is very small, less than 0.1 percent. Even considering a thick coating, such as a brush, the maximum amount of barium that could be adsorbed by barium oxide crystals (to be dispersed over the cathode lifetime) is small, and the quantities of free barium needed are very small. Why, then, are such large amounts of activator necessary in the brush cathode? One strong possibility is a reaction between the activator and the carbonate that occurs during the initial conditioning of the cathode. If carbon dioxide cannot escape freely from the thick coating and if the cathode temperature is raised to emitting temperatures, the activator will react with the oxygen in the carbonate by the following reaction:

$$BaCO_3 + C = BaO + 2CO$$

Hence, large amounts of activator (up to 5.7 percent) may be consumed before it could react with the oxide and produce free barium. Such a possibility may explain why the short-lived tests with molybdenum and platinum brushes with 2-percent carbon did not activate. Such reactions probably do not occur in thinly coated cathodes because the carbon dioxide escapes long before the temperature rises enough to promote the carbonate-activator reaction.

Pressed-brush cathodes. - Pressing increases the density of $BaCO_3$ in the coating and therefore enables larger amounts of oxide to be stored in a given size brush cathode. The density of a barium carbonate crystal is 4.29 grams per cubic centimeter. In a finely divided powder, the bulk density is less than 0.8, and in a cathode coating (unpressed), it is usually 1.0 ± 0.2. Pressing at pressures of 0.7×10^5 newtons per square meter (2×10^3 psi) increased the density of the carbonate in the brush cathode to 1.5 to 2.0 grams per cubic centimeter. Pressing also improved the mechanical strength of the coating and resulted in a stronger binding of the coating to the brush. It is not known whether the pressing operation improved or harmed the emitting properties of the cathode.

Pressing the cathode, however, has disadvantages. The increased density of the coating inhibits the escape of evolved gases, including CO_2. This may affect the activation of the cathode. Also, tantalum is susceptible to gas embrittlement and some of the pressed-brush cathodes (ref. 10 and test 11) may have failed for that reason. Furthermore, pressing may cause mechanical damage to the brush structure, particularly if voids are present. Bristles become bent and the core wires kink due to a shortening of both the length and diameter of the brush.

The effect of pressing on the lifetime of the cathode was uncertain. In tests reported in reference 4, a cathode pressed at 1.8×10^5 newtons per square meter (5×10^3 psi) had a lifetime of 1600 hours, whereas an unpressed brush had a lifetime of

1250 hours. Pressing at 18×10^5 newtons per square meter (5×10^4 psi) resulted in a 535-hour lifetime. In similar tests, reported in table I, test 12 (no pressing) lasted 3903 hours, while test 11, pressed at 18×10^5 newtons per square meter (5×10^4 psi), lasted only 736 hours in the simulated thrustor. A compromise pressing of 0.7×10^5 to 1.8×10^5 newtons per square meter (2×10^3 to 5×10^3 psi) is recommended for future tests.

Time-lapse photography. - To document any gradual wear occurring in the cathode, a photograph was taken once every hour during test 12 (3903 hr). The resulting pictures were projected at 24 frames per second, and very little change in size or shape of the brush cathode was noted. There were occasional flashes or hot areas on the surface of the cathode. At 1900 hours, the cathode surface was becoming noticeably darker (probably deposit buildup). At 2500 hours, a sag developed in the cathode as if the core wires were weakened or perhaps had turned in their holder. The center of the brush dropped about 0.3 centimeter and the ends remained fixed. A hot area or crack in the brush coating became noticeable at 2650 hours and was present the remainder of the test. By 3350 hours, the surface coating had become very dark and black in contrast with the hot crack area. In the last frame of the test, the hot area was greatly enlarged.

Individual frames were studied to measure changes in the diameter of the brush cathode. The initial brush diameter was 1.013 centimeters and the final diameter was 0.935 centimeter. The average change in the diameter was only 2×10^{-5} centimeter per hour. For several periods of a hundred hours or more, the brush diameter would apparently increase and then later decrease faster than average. The major result was that the size of the brush changed little (about 8 percent reduced) over the lifetime while 44 percent of the coating was used. The bristles were not wearing away as rapidly as was the oxide coating.

Shake and thermal tests. - The oxide-coated brush cathode of test 15 was pressed at 3.7×10^5 newtons per square meter (1×10^4 psi) and then coated with a thin layer of nitrocellulose. A similar brush cathode was also coated by using a nitrocellulose binder throughout the coating. Both were then placed in a shake test rig and vibrated on each of their axes in turn. The frequency spectrum and amplitude was triple that of the flight level of an Atlas-Agena launch. No change was noted in either brush as a result of shaking. The same brush with the thin layer of nitrocellulose was then placed in a bell jar for a thermal shock test (test 15). The purpose of the thermal shock test was to determine what activation schedule might be used for a space mission.

The full cathode heating voltage was snapped on to heat the previously unheated cathode. The cathode came to full temperature in about 30 seconds and continued outgassing for 2 minutes. The test was continued for 554 hours at the initial heating conditions with no change noted in the resistance of the core wires nor in the cathode appearance. The appearance was documented by time-lapse photography. It appears that no harm resulted from this rapid activation schedule, but more tests (including an emitting cathode

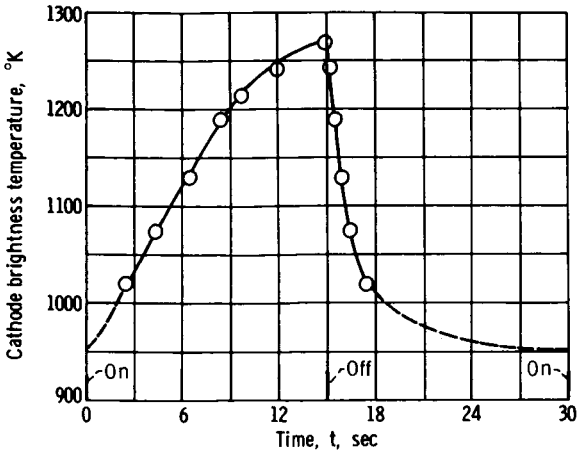


Figure 7. - Temperature response of oxide-coated brush cathode. Test 16; cathode diameter, 0.47 centimeter; length, 1.25 centimeters.

in a thrustor) should be made before incorporating this technique in a flight mission.

Heat cycling tests. - A thrustor used for attitude control of a synchronous-orbit satellite may have 50 000 duty cycles in a 3-year lifetime. Therefore, the brush cathode was heat cycled a number of times to study possible damaging effects.

A brush cathode (test 16 or 17), identical to the one tested in the 5-centimeter-diameter thrustor as test 13, was coated and mounted between two copper leads in a glass bell jar. The bell jar was pumped down to 8×10^{-7} torr and the cathode was heated to 1300° K for 30 minutes to condition the cathode. The cathode was then alternately heated and cooled for 15-second intervals. The thermal response of the cathode to a step application of heater voltage is shown in figure 7. After 10 seconds of heating, the applied voltage and current were approximately constant at 1.9 volts and 12.5 amperes, respectively. The temperatures were determined by a calibrated optical pyrometer. Temperatures below 1050° K were difficult to measure.

The oxide-coated brush cathodes of tests 16 and 17 were heat cycled 418 000 and 275 000 times, respectively, before failure. A carbon activator (5.1 percent carbon) had been added to the coating of the cathode of test 17. The appearance of the core wires after the heat cycling tests was grainy, indicating a thermal fatigue failure rather than a melting failure.

In all brush cathodes, including those that were heat cycled, cracks developed in the oxide coating during the initial heating or conditioning. During the heat cycle tests, no oxide material fell off the brush and the initial cracks became only slightly enlarged, possibly due to greater evaporation from the depths of the cracks close to the core wires.

Cathode Material Loss Mechanisms

Ion-bombardment sputtering and evaporation were the major oxide loss mechanisms from the cathode. Arc damage was negligible with the use of a current-limited supply, and chemical reactions should be minor at normal cathode temperatures ($<1300^{\circ}$ K) unless large amounts of activators are used.

It was also possible that the cathode reacted with gases present in the vacuum system. Pressure rises due to temporary leaks always reduced the cathode emission cur-

TABLE III. - MEASURED AND CALCULATED AMOUNT OF CATHODE LOSSES

Test	Weighings		Chemical analysis			Calculated values					Life-time, hr
	Weight of oxides (start),[a] gm	Ratio of cathode weight loss to oxide weight at start[a]	Fraction metal lost	Fraction oxides lost	Barium to strontium ratio (end)	Fraction of oxides sputtered	Fraction evaporation on basis of -				
							Average temperature	Hottest temperature	Heating power density	Emission current density	
1	0.471	0.350	0.04	[b]0.50	----	0.87	0.00	0.73	1.01	0.09	2929
2	.349	[c].614	.03	.80	1.62	1.5	.03	1.2	[d]1.0	.74	5019
3	2.670	.019	.02	.14	1.87	.13	.03	.55	.00	.00	650
4	.303	.587	-.01	.49	1.75	----	.74	----	.55	----	3903
5	.249	.329	-.01	.38	1.42	----	.01	----	.00	----	329
6	.241	.274	-.03	.22	1.62	----	.00	.02	.00	----	650
7	.261	.192	-.01	.48	.96	----	.18	----	.75	----	161
8	.429	.501	----	-----	----	1.46	.10	2.28	.00	.04	2156
9	.262	.160	----	-----	----	----	.00	1.05	.00	.00	39
10	.464	.956	----	-----	----	1.73	7.6	----	2.3	.07	4383
11	2.118	[c].396	.06	.34	2.13	.17	.04	.32	.00	.01	736
12	2.790	.438	----	.40	3.10	1.2	.00	.31	.00	.02	3903
14	.206	.568	----	-----	----	----	.3	1.61	.01	----	4422
17	.286	.800	----	-----	----	----	----	.49	.49	----	2300
20	.019	[c]2.08	----	-----	----	8.8	[d].46	[d].48	.00	.45	473
21	.029	.483	----	-----	----	2.8	----	.81	.00	.01	550

[a]Weight loss corrected for loss of CO_2 during activation.

[b]Only 0.18 fraction of the nickel powder added to the original coating was lost.

[c]Loss or gain of cathode holder may cause error.

[d]Fraction evaporated calculated for first 90 percent of test only.

rent if the rise was greater than 1×10^{-5} torr. However, the amount of cathode material lost in such cases was probably limited to small quantities of free surface barium. The cathode emission current usually recovered to its previous value when the system pressure returned to the low 10^{-6} torr scale. The calculated barium weight loss for a 3000-hour continuous reaction with either oxygen or water vapor was low (less than 10 percent of the barium normally present in the cathode) at partial pressures less than 1×10^{-6} torr.

Sputtering and evaporation losses. - The method used to calculate sputtering losses was the same as in reference 2 in which the sputtering rate was assumed proportional to the fourth power of the discharge voltage and the first power of emission current density. The method may be in error by a factor of 2 or more, but it was the best available method and served as a basis of comparison.

Calculated fractions of the oxide coating lost due to sputtering are listed in table III. For example, test 3 intentionally stopped short, had a very low loss ratio due to sputtering, which should not have removed more than 0. 13 centimeter of the initial coating. Tests 2 and 8 showed about equal calculated losses of sputtering compared with evaporation at the hot spots and may have failed because of either or part of both mechanisms. Test 12 cathode (3903 hr) probably eroded primarily from sputtering, because even at the hottest temperature, evaporation could only account for a fraction of the lost oxides. Test 11 (736 hr) had low sputtering and evaporation loss ratios and probably failed as a result of chemical attack of the brush wires. Test 9, with an extremely high evaporation rate, probably failed due to excessive evaporation and melting of the core wires caused by poor activation (high cathode heating power).

Calculated values of evaporation should only be used to make rough comparisons because of the large possible errors in determining temperature and the possible abnormal evaporation rates from the irregular cathode surface. Four calculated evaporation losses are presented in table III, based on four different temperatures. A mean or average temperature of the bulk of the cathode surface and a hottest temperature were measured by an optical pyrometer. Two other temperatures were calculated by using figure 6, the cathode heating power, and the cathode emission current density. All the heating power was assumed to be lost by radiation when that power was used to estimate temperature.

Heating only tests. - Cathode heating only tests were used (1) to evaluate the amount of chemical reaction between barium oxide and tantalum or tungsten, (2) to evaluate any abnormal evaporation rate from the irregular surface of the cathode, and (3) to evaluate any effects of the bell jar residual gases on the cathode. These tests were conducted in the absence of a mercury discharge, but in the same bell jar as the simulated thrustor. The heating only tests indicated that there was no major chemical attack or other damage to the heater or matrix wires at normal (1300° K) or low operating temperatures.

For test 4 (3903 hr) there was fair agreement between measured weight loss and calculated evaporation rates listed in table IV. For tests 5 and 6, about 0.3 of the oxides were lost, but calculated evaporation losses were 0.02 or less than initial amounts. For the relatively short test 7 the losses of oxides were less than those calculated, and for test 14 (4422 hr and 2-percent carbon) about half of the oxides were lost. The only conclusion that could be drawn would be that evaporation or chemical attack of oxides was not a large amount for cathodes that had either no activators or were heated less than 10 watts per square centimeter. Oxide losses, due only to heating in a 3×10^{-6} torr vacuum environment, however, may be in the range of one-fourth to one-half of the initial amount for heating values over 10 watts per square centimeter.

Chemical analysis of cathodes. - The coating of any cathode, that was analyzed at the end of a test, was found to have trace deposits (0.1 percent) of stainless steel, that is, iron, nickel, and chromium. One cathode, test 12, was found to contain a large deposit; 1.20 percent iron, 0.13 percent nickel, and 0.24 percent chromium. The probable source of these deposits was condensed material sputtered from the discharge chamber walls.

The metal lost from the tantalum heating ribbon or the tungsten matrix wires of the thick-oxide-layer cathode was very low. The actual amounts are listed in table III for tests 1 through 7. Some tests (4 to 7) actually resulted in a slight increase of the metal weight, possibly due to the formation of a tungstate compound on the surface of the metal. In tests 1 and 2 much of the metal was undoubtably lost by direct arc damage to the cathode.

The metal lost from brush cathodes varied from zero to 30 percent of the original metal brush weight. The brushes that had lesser amounts of metal loss correspond to those brushes that had low radial temperature gradients and little chemical attack. The brushes with greater amounts of loss were those with high core temperatures and subsequent serious chemical attack.

The chemically determined fraction of emissive oxides lost from a cathode during a test agree (within the errors caused by cathode deposits and cathode holder wear) with the fraction lost, determined by direct weighings, before and after the test. The ratio of barium to strontium for Radio Mix No. 3 is 1.58. After the cathode had eroded during a test, the ratio of barium to strontium remained about the same for most tests (see table III). The two greatest exceptions occurred during tests 7 (decreased ratio) and 12 (increased ratio). The causes for these exceptions are not currently known.

Effect of Chamber Wall Material

Inside walls of the discharge chamber, such as the distributor and the screen, are also bombarded by ions and, thereby, are a source of sputtered atoms. These atoms could condense on the cathode surface. (Only in the case of an uncoated refractory metal cathode will the surface be hot enough to reevaporate the stainless-steel elements.) After long oxide-cathode tests, a black coating was usually present on all or part of the cathode surface. The black coating from the cathode of test 12 was analyzed and found to contain iron, nickel, and chromium. To prevent the black coating from forming and presumably poisoning the cathode, the walls of the discharge chamber were (1) coated with Radio Mix No. 3 or (2) made of aluminum or magnesium. Both these metals have sufficient vapor pressure to reevaporate at oxide cathode temperatures. In addition, the surfaces in direct line of sight with the cathode were similarly prepared. Cathode endurance tests conducted in two simulated thrustors made of aluminum or magnesium indicated no cathode lifetime improvement. In the tests with the magnesium thrustor, severe arcing and damage occurred to the distributor, anode, and cathode holder. The damage was thought to be unrelated to the cathode and only to the use of magnesium metal for the thrustor parts.

In test 18 (table I) all the discharge chamber surfaces were coated with Radio Mix No. 3. This coating seemed to have no effect on the operation of the discharge, but might have extended the lifetime of test 18 by a factor of 2 to 5. At the end of test 18 (1283 hr) there was no black coating on the cathode. Even though there was no evidence of a harmful deposit on the cathode, the cathode heating power was excessively high indicating no improvement in cathode activation. Because of the lack of improvement in cathode activation and the difficulty of maintaining such a coating for extended lifetimes, further use of oxide coatings on chamber walls was stopped.

Effect of Mercury Vapor on Cathode Activation

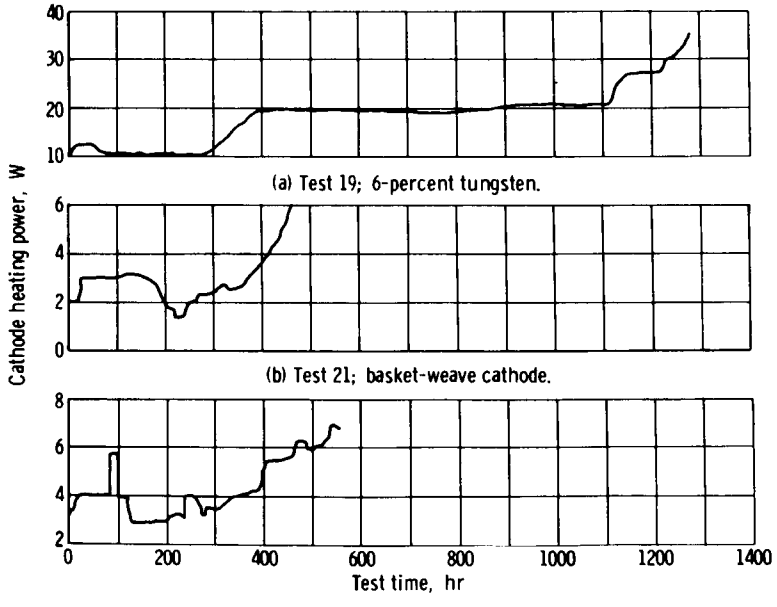
Any possible effect of mercury neutrals on the activation or deactivation of an oxide cathode was investigated by operating a thick-oxide-layer cathode in the simulated ion thrustor with mercury flow but in the absence of a discharge. The tests were made at low emission currents because the anode-cathode voltage was kept below the ionization potential of mercury (10 V) to avoid forming ions that might activate the cathode. At 10 volts, the space-charge-limited current was about 0.3×10^{-3} ampere. The cathode was activated in the absence of mercury (bell jar pressure, 2×10^{-6} torr) by thermal heating only. The tests were inconclusive in that the presence of mercury neutrals (corresponding to a 0.16 A equivalent propellant flow) sometimes increased the cathode

emission to a space-charge limit and sometimes had no effect. The most notable deactivation occurred during small pressure rises caused by the liquid nitrogen supply cycling off. The indicated bell jar pressure might subsequently change only 0.2×10^{-6} torr, but the cathode emission would drop by half. When the liquid nitrogen was replenished, the emission increased slowly to its initial value.

This cathode (4.3 cm^2 area) emitted 10×10^{-6} ampere at 1280° K with 10 volts differential. As the voltage was varied, the emitted current varied as if it were space-charge limited. This data might indicate that emission was eminating only from small active areas conjectured in the "theoretical model" section on the cathode and that these small areas were at a local space-charge limit. The overall space-charge-limited current, as previously noted, should have been 30 times greater.

Oxide-Impregnated Foam Cathodes

By using a foam material (theoretical density, ~6 percent) it was possible to impregnate a greater percentage of active materials and perhaps obtain a longer cathode lifetime. Attaching the foam material to a heater proved difficult because the foams were brittle and, in addition, had many sharp surfaces that made poor heater contact. The most successful cathode consisted of a tungsten-rod heater pushed through a cylinder of tungsten foam material. This cathode, test 18, had a lifetime of 1283 hours, and the heating power against time is presented in figure 8(a). The cause of failure was eventual



(a) Test 19; 6-percent tungsten.

(b) Test 21; basket-weave cathode.

(c) Test 22; basket-weave cathode.

Figure 8. - Cathode heating power for various oxide-coated cathodes.

excessive power, possibly a result of poor heater-foam contact.

Test 19 was of an entirely different designed cathode. A swaged heater coil was placed outside a hollow cylinder of oxide impregnated 5-percent dense nickel foam. Mercury propellant was fed through the center cavity of the cylinder and into a 5-centimeter-diameter thrustor. The cathode (further described in table I) was tested for 302 hours. At this time, no degradation was noted, but the design of the heater required about 100 watts. This power was considered excessive for its intended application in the 5-centimeter-diameter thrustor, and the test was terminated to permit other tests with lower-powered cathodes.

Basket-Weave Cathode

This type of commercially made double coiled tungsten wire cathode (used in fluorescent lamps) was coated with Radio Mix No. 3 and endurance tested in both the simulated thrustor (test 20, fig. 8(b)) and an actual 5-centimeter-diameter thrustor (test 21, fig. 8(c)). The exact emitting area of the cathode was unknown because of its involved structure. The total weight of oxide was only 28×10^{-3} gram and resulted in a thinly coated cathode. The surprisingly long lifetimes in both tests 20 and 21 were probably a result of the cathode structure "hiding" oxide from direct ion bombardment. Table III lists extremely high calculated oxide sputtered ratios of 2.7 and 8.8, which indicate that some process is occurring that reduces ion-bombardment sputtering on the emitting oxides. The calculated fraction of oxides lost by evaporation was high, and perhaps evaporation was a major loss factor in these tests. As many thousands of hours of operating lifetime were required, and no manner was obvious to extend the coating on the basket-weave cathode, further testing was stopped. This type cathode, however, does represent an extremely efficient cathode (6 W heating power per A emission) to operate a small mercury discharge for lifetimes up to several hundreds of hours.

CONCLUDING REMARKS

All oxide cathodes tested required higher temperature for a given emission density than does a normal cathode operated in vacuum. The cathode seemed to be in a continual state of reactivation, and never became fully activated because ion bombardment continually destroyed the active surface. Operation of a cathode under such conditions requires large amounts of oxides or active material reliably dispensed over long periods. An example of poor dispensing was the nickel matrix cathode in which merely increasing the arrival rate of active material to conventional cathode surfaces was not satisfactory. The

normal diffusion of active barium over a cathode surface (such as a porous metal) may have been limited so that ion bombardment destroyed it faster than it was restored, and increasing the barium arriving through a pore was wasted because most of the barium diffused directly from the pore into the vacuum.

Brush or thick-oxide-layer cathodes have proven lifetimes of 3000 to 5000 hours. With a greater understanding of the dispensing mechanisms these lifetimes may be extended by a factor of 2 or 3 merely by using all the oxide built into the cathode. The thickness of the coating, however, cannot be indefinitely extended without the occurrence of problems due to trapped evolved gases (even though the coating has sufficient electrical and thermal conduction). Other ways of supporting large amounts of oxides, such as a foam metal, may also be used to design cathode geometries. From results of time-lapse photography, it was evident that the wire-brush bristles were not wearing back at the same rate as the oxide was being consumed. Hence, if oxides can be continually dispersed into the cathode, the lifetime should be extended. Such an approach has been investigated in reference 4 by dispensing barium oxide to a heated tungsten screen.

Attempts to reduce sputtered metal deposits on the cathode were inconclusive in extending the cathode lifetime. Also, the use of grids to shield the cathode from ion bombardment was ineffective and actually decreased the thrustor efficiency. If some manner of shielding the emissive material (as in the basket-weave cathode) could be incorporated into a larger cathode, an order of magnitude in lifetime would perhaps result. Predominant oxide loss mechanisms may be either from ion-bombardment sputtering, or, in the case of poor activation and subsequent high temperatures, from evaporation. Mercury vapors in densities encountered in thrustors did not harm oxide cathode activation, although cold-trap outgassing or gases leaking into the vacuum system could seriously reduce activation. Oxide-coated brushes survived shake tests (mission launch requirements) and heat cycling (necessary for attitude control application).

If cathode lifetimes greater than several thousand hours are required, the more complex cathodes of reference 4 (oxide magazine) or reference 5 (mercury pool) show promise of better durability in the future. However, the oxide-coated brush cathode reported herein may, with additional refinement, be capable of a 10 000-hour lifetime or greater. Also other uses may arise in short-term experiments where the costs or complexities of using the cathode types of references 4 or 5 are not justified.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 14, 1966,
120-26-02-06-22.

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