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**LONG LIFETIME HOLLOW CATHODES FOR
30-CM MERCURY ION THRUSTERS**

by Michael J. Mirtich and William R. Kerslake
Lewis Research Center
Cleveland, Ohio 44135



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Michael J. Mirtich and William R. Kerslake
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Abstract

An experimental investigation of hollow cathodes for 30-cm Hg bombardment thrusters was carried out. Both main and neutralizer cathode configurations were tested with both rolled foil inserts coated with low work function material and impregnated porous tungsten inserts. Temperature measurements of an impregnated insert at various positions in the cathode were made. These, along with the cathode thermal profile are presented. A theory for rolled foil and impregnated insert operation and lifetime in hollow cathodes is developed. Several endurance tests, as long as 18 000 hours at emission currents of up to 12 amps were attained with no degradation in performance.

Introduction

In previous parametric investigations⁽¹⁻³⁾ of hollow cathodes for 30-cm Hg thrusters it was found that the proper choice of cathode materials and tip orifice dimensions were necessary to assure minimum tip erosion and integrity of the cathode. It was also shown experimentally that a parameter that most strongly affected cathode lifetime^(3,4) was the low work function material used to both initiate and sustain a cathode discharge. Adequate lifetime of the cathode depended heavily on maintaining the emissive mix at low enough temperatures so as not to be dispensed too quickly during cathode operation. Experimental and theoretical work has continued on hollow cathodes to find a desirable low work function material, proper thermal environment for the low work function container, and/or a dispenser to provide proper release of emissive mix to assure long lifetime.

Presented in this paper are the results of testing hollow cathodes for use as both main and neutralizer cathodes in 30-cm thrusters. The cathodes were tested in bell jars, where the insert material and its position relative to the cathode tip were varied. Neutralizers and main cathodes were run at emission levels of 2 amps and between 7 and 12 amps, respectively. The cathode keeper and collector voltages were monitored, along with temperature measurements recorded at the cathode tip and behind the cathode tip heater. Test data are presented for (1) a 10 000-hour test of a main cathode with a rolled foil recessed insert, (2) an ongoing 18 000-hour test of a main cathode with an impregnated insert, and (3) a neutralizer cathode test of 15 000 hours.

The second half of the paper presents a theoretical estimate of lifetimes of both rolled foil inserts and impregnated porous tungsten inserts. A theory for porous tungsten insert operation in hollow cathodes is developed. The theory incorporates reported evaporation rates of active material from the porous tungsten insert and the influence of the insert size, temperature, and cathode orifice dimensions on cathode design. The model developed is used to predict cathode lifetime and performance as a function of operating conditions.

Apparatus and Procedure

Hollow Cathodes and Inserts

Figure 1 shows a sketch of a typical cathode configuration used in these studies. The hollow cathodes were made of 6.35-mm diameter tantalum tubing with a wall thickness of 0.38 mm and had a 1.22-mm thick 2 percent thoriated tungsten disk electron beam welded to the tube. A straight-through 3.40 mm orifice was used for a neutralizer cathode and the orifices of the main cathode were 0.76 mm in diameter with a 45° chamfer. All the main cathodes were fabricated and assembled by Hughes Research Laboratories.

Table I summarizes the various cathode configurations tested. Two types of radiation fins (used to reduce tip operating temperatures) were used on the main cathodes. One type had a Ta fin 1.75 cm in diameter that was electron beam welded to the cathode as shown in figure 1. The other type of radiation fin had attached to it a 0.8-cm long collar, to extend the radiating area. Figure 1 shows this collared fin that was used on cathodes 2 and 3. The cathode inserts were of two types, coated rolled Ta foil and impregnated porous tungsten. Rolled foil inserts used in cathodes were made of 0.012-mm thick tantalum foil 15-cm long and 1.27-cm wide, rolled into a coil, and dipped three times into an emissive mix. A flow passage of about 1.5-mm diameter existed along the center of the insert. The emissive mix (R-500) was a barium carbonate and strontium carbonate mixture containing a nitrocellulose binder and suspended in a mixture of organic solvents. Commercially available (semicon type 84-S), porous tungsten inserts were used. The inserts were impregnated with a low work function material, barium calcium aluminate. The impregnated inserts were hollow cylinders 2.54-cm long, with a 5.3-mm outside diameter and an inside diameter that varied from 2.54 to 3.82 mm.

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Tip heaters were either tungsten wire encapsulated in flame sprayed Al_2O_3 or tantalum wire enclosed in tantalum tubing (swaged heaters). Radiation shielding made of 0.015-mm thick tantalum foil was wrapped around the tip heaters. An open loop wire keeper with a hole 6.25 mm in diameter was spaced 1.5 mm from the cathode. To simulate the thruster anode a 7.5-cm diameter Ta disk was placed 1.9 cm from the keeper. Flow rates were measured using precision bore glass capillary flow tubes and time averaged liquid mercury flow rates were obtained for short periods of time.

Vacuum Facilities

Cathodes 1, 2, 4, and 5 were run in 0.5-m diameter bell jars. An oil diffusion pump, using a liquid nitrogen baffle, kept the bell jar pressure in the low 10^{-6} torr range. Mercury from the hollow cathodes was condensed on a liquid nitrogen cold trap. Cathodes 3, 6, and 5 (which was removed from a bell jar at 500 hr) were run in ports attached to the 7.5-m diameter by 22-m long facility (tank 6) in the electric propulsion laboratory at Lewis Research Center.

Experimental Results and Discussion

Orifice Erosion

It was shown in Ref. 3 that for given operating conditions the proper choice of cathode orifice dimension was necessary to minimize tip erosion and insure long cathode lifetime. It was further shown in Refs. 1 and 3 that the use of a 0.76-mm orifice with a 45° chamfer eliminated tip erosion for emission currents up to 15 amps. Thus, this orifice was used for all the main cathodes which operated at emission currents of 10 amps or more. No noticeable change in orifice dimension was observed in the cathodes for runs even as long as 18 000 hours. This is shown in the photomicrograph of figure 2 taken of cathode 2 run at 12 amps emission for 10 600 hours. The tip orifice is still 0.76 mm in diameter.

For the neutralizer (cathode 4) run for 15 000 hours there was a slight increase in orifice size. Figure 3 shows the increase in orifice dimension as a function of time for cathode 4, which was run at 2 amps emission current and 500 mA keeper current. An elastic mold impression was taken of the orifice at 8600 hours and a photomicrograph at 15 000 hours. There was a linear increase in orifice size increasing from 0.40 initially to 0.48 mm at 15 000 hours. This change in orifice dimension of the neutralizer cathode, as will be shown later, did not affect its performance in a bell jar.

Cathodes and Low Work Function Inserts

As pointed out by Ref. 5 the mechanisms which con-

trol the operation of hollow cathodes are not well known. Reference 6 operated cathodes without low work function material and found such cathodes hard starting with very high flow requirements. It was further shown by many experimenters^(1, 3, 6, 7) that high voltages, high temperatures, and high mercury flows occurred during steady state spot mode operation with no low work function material present. These conditions can lead to short cathode lifetime.^(3, 6, 7) For example, Ref. 7 found that tip erosion rates of 8-cm neutralizers operating with no inserts or emissive mixture increased by two orders of magnitude.

The availability of low work function material in the cathode is necessary to obtain satisfactory cathode performance. A sufficient supply of low work function material is necessary to initiate and sustain a cathode discharge at low keeper voltages.^(3, 7) Reference 8 showed that a low cathode keeper voltage is an important parameter in achieving efficient thruster operation. With a fixed discharge voltage in a thruster a low cathode keeper voltage increases the available energy in the discharge for propellant ionization, and hence, leads to increased propellant utilization.

Reference 3 also showed that the amount of low work function material is not as important to cathode reliability and lifetime as its location in the cathode. Placing emissive mix (R-500) on rolled foil inserts and recessing the inserts from the cathode tip allowed the low work function material to run at a cool location in the cathode and did increase lifetime. However, associated with a recessed insert is an increase in keeper voltage,⁽³⁾ which as mentioned, degrades thruster performance. Thus, tests were conducted on a variety of insert designs, insert positions, and cathode configurations to reduce the performance penalty associated with recessed inserts, and still maintain long lifetimes.

Rolled Foil Inserts

Reference 3 reported a test of a 0.76-mm straight-through orifice cathode with a 1.27-cm insert, recessed 1.9 cm from the tip which ran from 3880 hours at 15 amps emission with no noticeable change in performance. However, because of the recessed insert position, an unacceptable keeper voltage for 30 cm thruster operation was experienced. Thus two tests were run concurrently with identical inserts, located 0.95 cm from the tip (half the recessed distance of the Ref. 3 3880-hr cathode), but placed in cathode configurations that were not thermally identical. Cathode 1 had no radiation fin to cool the tip, while cathode 2, had a radiation fin, with a collar to extend the radiating area (see fig. 1).

Cathode 1 was run in a bell jar with a collector current of 12 amps, a keeper current of 300 mA, and

an equivalent Hg flow of 170 mA (see Table II). Two thermocouples were used to monitor temperature, one at the cathode tip and one behind the flame sprayed heater (1.5 cm from the tip). The tip thermocouple became inoperative after 900 hours. To initiate a discharge, only 34 watts of tip power was needed to obtain a tip temperature of 1055° C, a temperature that was typically required.

After the discharge was established the tip heater was turned off, and the keeper and collector voltages and thermocouple readings were recorded as a function of time (Fig. 4).

As was typical of other R-500 coated rolled foil inserts, the values of keeper and collector voltage increased, after a cathode had been run for about 20 hours. This was interpreted to mean that during preheat and initial startup an excess of low work function material was released. From figure 4 it can be seen that the tip temperature during operation was 1450° C and the temperature behind the tip heater 1080° C. (These temperature values are also shown in Table II.) After 700 hours the keeper and collector voltages began to rise, indicating depletion of low work function material has already begun. In addition, after nine restarts and 1360 hours, cathode 1 would not relight and the test was terminated.

Cathode 2 was of the same configuration (insert, position, thermocouple locations, radiation shielding, etc.) except it had a radiation fin with a collar. Because of the collar-radiation fin a total of 90 watts of tip power was required to initiate a discharge (tip temperature = 1055° C). Subsequent restarts required less power, 60 watts, because the tip temperature needed to initiate a discharge was lower (920° C).

The total test time of this cathode was 10 600 hours. The plots of keeper and collector voltage, as a function of time are shown in figure 5. The cathode was restarted 30 times at random intervals. The life of this cathode can be divided into four regions. In region 1 (first 6500 hr) the collector and keeper currents were kept at 12 amps (spot mode) and 300 mA, respectively, with an equivalent Hg flow of 170 mA. In this time period the keeper voltage rose from 8.5 to 10 volts at 200 hours and remained at 10 volts until 6400 hours. The cathode tip temperature remained at an average of 925° C and the thermocouple on the cathode 1.5 cm from the tip remained at 825° C. In this time period (6400 hr) the cathode relighted easily 19 times at the same tip temperature and there were no changes in keeper voltage, indicating that the low work function material (insert) was encased in a cool cathode region. The tip heater resistance was monitored periodically during the tests and the cold resistance (as measured

with a Wheatstone bridge) (0.96 ohm) did not change during this first 6400 hours. At 6417 hours (region 2) there was a facility failure and a thin film of oil was spread all over the bell jar and the cathode itself. The tip heater hot resistance after the bell jar failure was lower. Also the power needed to get the tip temperature up to 920° C increased to 85 watts indicating a change in the optical radiation properties of the cathode and cathode tip (higher emittance). The cathode relighted, but at a tip temperature of 1030° C, and the keeper and collector voltages increased to 12 and 17 volts, respectively. A corresponding rise in tip and cathode temperature accompanied the voltage increases. This increase in temperature was probably due to a combination of a lack of sufficient low work function material or a poisoning by the oil. A relight at 8300 hours reduced the voltages and temperature. Between 8500 and 9000 hours, a series of bell jar failures (similar to the one at 6400 hr) further changed the characteristics of the cathode. This is considered region 3. The flame sprayed heater lead broke off at 9000 hours and a new heater lead placed on the heater failed to improve the heater. A pulsed start⁽⁹⁾ was necessary to relight the cathode at 9000 hours. From 9000 hours until the test was terminated at 10 600 hours, the cathode was run at 10 amps emission current (instead of the prior 12 amps) to match the emission current in the operating 30 cm engineering model thrusters. At 10 600 hours the cathode was removed to replace the tip heater, and in the process of placing a new tip heater on the cathode the cathode itself broke into two pieces.

Shown in figure 6 are the temperature levels of cathodes 1 and 2 as a function of emission current. This data was taken with no tip heater power and before any degradation in performance level. Adding a radiation fin lowers the temperature levels at the tip and behind the tip heater at all emission current levels. In addition the temperature levels are less sensitive to emission current for the cathode design with a radiation fin. This feature is desirable, for 30-cm Hg thrusters are required to operate at throttled current conditions, and as will be shown later, it is desirable to operate cathodes within a limited temperature range. Also, as was noted by the shortened lifetime of cathode 1, high temperature levels lead to rapid low work function depletion and shortened lifetime. For cathode 2, with the radiation fin, emission current levels of 15 amps seem to have sufficiently low temperatures (980° C at the tip, 850° C 1.9 cm from the tip) to assure prolonged lifetime.

Impregnated Inserts

A test was started with an impregnated insert. In cathode 3, a configuration identical to cathode 2. The

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insert (2.54 by 0.548- by 0.25 cm) was also recessed from the cathode tip 0.95 cm and electrically attached to the cathode with 0.51 mm (20 mil) Ta wire. This cathode 3 was part of a cathode-isolator vaporizer test that is described in more detail in Ref. 10. To initiate a discharge approximately 95 watts was applied to the tip heater. Once a discharge was obtained the tip heater was turned off. The discharge was kept in the spot mode at an equivalent mass flow 140 mA and for the first 2100 hours the collector current was held at 12 amps. The keeper current was set at 500 mA throughout the test. A plot of the keeper and collector voltages as a function of time are shown in figure 7. To see if a lower collector current had an adverse effect on cathode lifetime the current was reduced at 3000 hours to 7 amps emission for the next 1000 hours. This did not lead to any degradation trend. At 4000 hours the emission current was raised to 10 amps. At 5500 hours the emission current level was raised to 10.6 amps (in line with the EMT emission current level at full thruster).⁽⁸⁾ At 5500 hours the experiment was shut down for 2 months due to facility limitations and the C-IV assembly was exposed to 1 atmosphere (summer of '75). As can be seen from the figure, this exposure and storage did not affect the performance level or lifetime. This cathode 3 configuration has been restarted 48 times at a tip temperature of approximately 1025° C. The original flame sprayed tip heater failed at 8350 hours and a new swaged heater, placed parallel to the tube axis, was installed and attained an initial startup tip temperature of 1025° C. Although not shown on figure 7, the tip temperature during operation was around 960° C, a little higher than that of cathode 2. However, because of different thermal environment configurations, it is difficult to account for temperature differences between an impregnated and rolled foil insert cathode. The keeper voltages, which can be compared (similar keeper and keeper distances) were approximately the same (~10 V).

As shown in figure 7, there was little or no discernible change in keeper voltage at a given emission current level. This cathode 3 has operated for a total of 18 000 hours (as of August 1976), is still running, and shows no signs of changing performance level.

An impregnated insert (2.54-cm long, 0.55-cm o. d., 0.25-cm i. d.) was placed in cathode 4 and was recessed 1.25 cm from the tip. The neutralizer-type cathode with a 0.40-mm diameter orifice was run in a bell jar at 2 amps emission current to a collector and 580 mA to the keeper. Shown in figure 8 is a plot of keeper and collector voltages, and tip and cathode (behind heater) temperatures as a function of time. The test operated for 15 000 hours at nearly constant keeper/collector voltages and tip temperatures. At 14 080 hours a facility pressure rise caused a small crack in the cathode tip

and the test was terminated 920 hours later. The cathode was run with the insert recessed for the first 1600 hours. Unusually high keeper and collector voltages (19 and 10.5 V, respectively) were associated with the recessed impregnated insert. These voltage levels led to high tip and cathode tube temperatures. It was decided at 1600 hours to move the insert up to the tip to measure the effect of insert position on keeper and collector voltages and temperature levels. This move resulted in decreases in the baseline keeper and collector voltages to 14 and 15 volts, respectively (fig. 8). The drop in voltage levels reduced the tip temperature and cathode temperature behind the 0.95-cm swaged heater to 850° and 550° C, respectively (data read at 2000 hr). The baseline keeper and collector voltages for the impregnated insert located at the tip of cathode 4 are the same as that for the 1.27-cm recessed rolled foil insert neutralizer reported in Ref. 3. (See fig. 8 of Ref. 3.) This probably means that the rate of low work function material dispensation for the two different cathode configurations are similar. Cathode 4 was run for a total of 15 000 hours and survived a total of nine facility failures. Points-in-time at which the facility failed are indicated by an X on figure 8.

After a facility failure there was a change in keeper and collector voltage levels. However, even after nine facility failures the keeper and collector voltages at 15 000 hours were the same as at 10 000 hours running time. At 14 080 hours a blown fuse in the power panel (another facility failure) allowed the hot cathode to be exposed to a few microns of pressure. Subsequently, it was observed that to keep the cathode in the spot mode an increase in mass flow was necessary. A crack had developed in the side of the cathode at a point where the cathode tip was electron beam welded to the cathode. Upon removal of the cathode at 15 000 hours this crack was clearly visible and is shown in figure 9. The test was terminated at 15 000 hours. It is felt that the exposure of the hot cathode to a few microns of pressure caused the crack.

The success of neutralizer cathode 4 and the thruster performance penalty associated with a recessed impregnated insert⁽⁸⁾ led to a decision to use test cathode 5, a main cathode, with a flush insert. Cathode 5 was operated the first 70 hours for comparative purposes with the insert recessed, to obtain voltage and temperature levels at the recessed insert position. At 70 hours the insert was moved flush to the tip. Shown in figure 10 is a plot of cathode 5 keeper and collector voltage, tip temperature, and cathode temperature behind the heater as a function of Hg mass flow for the two insert positions at a keeper current of 600 mA and collector current of 10.6 amps. The radiation fin in an EMT cathode does not have a collar and hence has less radiating area than that

of cathodes 2 and 3. Thus, at the same emission current levels, cathode 5, with a recessed insert 0.63 cm from the tip, ran at a higher tip temperature than cathode 2 or 3 (compare figs. 6 and 10).

From figure 10 it can be seen that the recessed insert increases both keeper and collector voltages, tip and cathode temperatures at all mass flow rates. This behavior was similar to that observed in a thruster.⁽⁸⁾ Temperatures of the tip and cathode tube for both insert positions were nearly independent of mass flow rate as it was varied from 130 to 230 mA. Moving the insert up to the tip, beside causing reductions in keeper and collector voltage, also reduces the cathode temperature levels. Figure 11 shows the temperature distribution profile of cathode 5 with two insert positions at an equivalent mass flow of 140 mA. Moving the insert to the tip caused a drop in temperature of 150° C at the tip and at the C-A thermocouple (behind the heater) of approximately 325° C. As of July 31, 1976 cathode 5 has operated for 3000 hours at an emission current of 10.6 amps and has exhibited no degradation trends.

Insert Temperature Measurement

As discussed previously, the thruster performance is improved with an impregnated insert located at the tip. Moving the insert up to the tip, as in cathode 5, did cause a drop in the cathode tip temperature. However, the actual insert temperature change was not measured. To measure the insert temperature and evaluate its lifetime potential, an identical insert and cathode similar to cathode 5 was used. As shown in the sketch of cathode 6 in figure 12, a hole (0.15 cm) was drilled in the side of the cathode tube 0.23 cm from the tip upstream face. A Pt-PtRh thermocouple was spot welded to the outside surface of the insert. Al₂O₃ beading prevented the thermocouple from shorting or reading the tube wall temperatures. The insert was placed at the tube tip and was electrically connected to the tube. Thermocouples were also placed on the tip and behind the tip heater. During preheat it was necessary to take the tip temperature to 1000° C with a corresponding insert temperature of 1030° C to initiate a discharge. After a discharge ($J_c = 10.6$ A, $J_k = 500$ mA) was initiated and the tip heater power turned off, the temperature profile shown by the open symbols was obtained. As shown by the open symbols, the tip ran at 940° C while the insert ran hotter, at 1050° C.

The hole in the cathode for the insert thermocouple was sealed and the insert was recessed 0.63 cm from the tip. A new hole was drilled 0.86 cm from the tip and the tip heater and CA thermocouple moved back 0.63 cm and the insert thermocouple reattached. The thermal profile for this configuration is shown by the solid symbols of figure 12 and indicates that the cathode

tip temperature and the temperature behind the heater are hotter than corresponding cathode temperatures with the insert at the tip. Both of these external thermocouple readings are consistent with those of cathode 5, shown in figure 11. With the insert recessed 0.63 cm the insert temperature (750° C) runs cooler than the tip temperature (1120° C), even though the cathode tube temperatures partially surrounding the insert are warmer than the insert. Thus, for the insert position selected an impregnated insert ran cooler (~810° C) than one located at the tip. But, with the insert at the tip, this relatively high insert temperature, does not appear to be too high to impose a lifetime constraint during cathode operation of 15 000 hours. This will be shown in the next section.

The temperature trends indicated by cathode 6 seem to shed some light on the predominant source of the emission mechanism involved in sustaining a discharge current. With the insert recessed from the tip, it would appear that the amount of available low work function material at the tip was limited and caused a higher discharge voltage. Higher tip temperatures were necessary to supply the electrons needed to sustain the discharge. Moving the insert against the tip allowed the cathode to run cooler (lower keeper and collector voltage, see fig. 10) since now the large source of low work function material available from the insert is being used to sustain the discharge. With the insert against the tip the source of electrons appears to be the insert, more so than the cathode, and these electrons cause a local increase in plasma density, a higher rate of surface ion bombardment, and an increase in insert temperature.

Theoretical Lifetime of Hollow Cathode Inserts

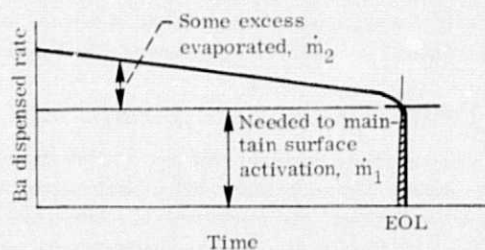
This section of the paper will describe the theory of hollow cathode insert operation and the factors that might control its lifetime. The insert types discussed are R-500-coated tantalum foil^(3, 7) and barium-aluminate-impregnated porous tungsten⁽¹¹⁾ (Semicon, type 84-S). The first part of the discussion will cover areas that apply to each type of insert, then each insert type will be discussed individually in detail.

The insert, when heated, undergoes a chemical reaction and produces barium or barium oxide vapor. This vapor is dispensed to the insert surface and other interior surfaces of the hollow cathode. Reference 12 indicates that for good cathode operation, emission should occur from the insert as well as from the cathode tip. The dispensed barium is absorbed by the surfaces, thus reducing the electron work function and enhancing surface electron emission. As the absorbed barium is constantly being lost from the surface by reevaporation and ion bombardment, it must continually be replaced by the barium dispensing insert. The end-of-life (EOL) of

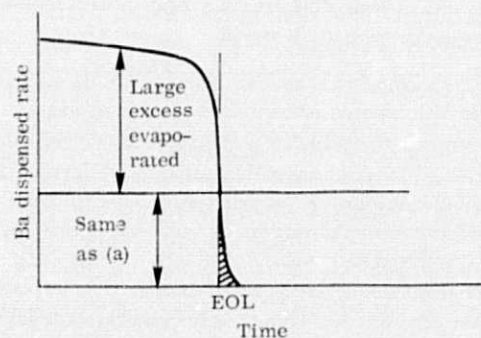
the insert is defined as the point where the dispensed barium (added to the activated surface) is less than the barium lost from the activated surface. A fully activated surface is generally thought⁽¹³⁾ to contain a complete monolayer coverage of barium atoms or $\theta = 1.0$, where θ is the monolayer fraction of barium. Sufficient activation of the surface to produce satisfactory electron emission may exist at values of θ as low as 0.4.

If an insert is operated at temperatures that are too high, excess barium is dispensed, θ is greater than 1.0 and the excess quickly evaporates from the cathode surfaces. Since the total amount of barium in the insert is fixed, high insert temperatures will lead to early exhaustion of barium and short cathode lifetimes. If an insert is operated at temperatures that are too low, insufficient barium is dispensed to replace that lost by surface evaporation or ion bombardment, and the surface becomes insufficiently activated to provide adequate emission. The sketches below indicate the rate of barium dispensed with time for optimum, high, and low insert temperature levels. In each case, the cathode surface is assumed at the same temperature level, and thus the same amount of barium is needed to replace that lost by evaporation.

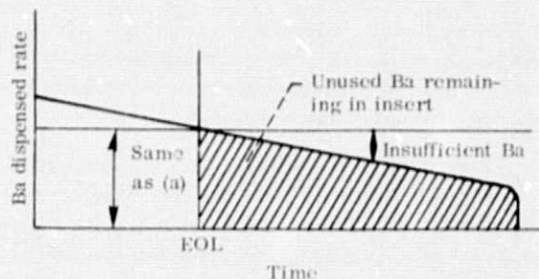
The integral area under each curve represents the total barium dispensed by the insert and is assumed the same for each sketch.



(a) Optimum temperature.

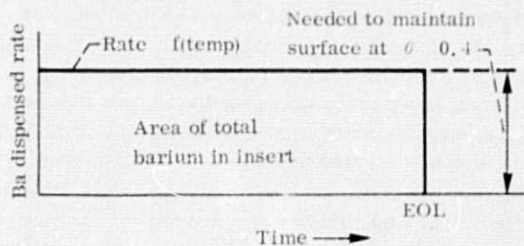


(b) Temperature too high.



(c) Temperature too low.

The optimum temperature of each insert depends upon its design (choice of chemical reaction to produce barium) and the desired activation state of the cathode (level of required emission). Figure 13 indicates the optimum insert temperature to achieve maximum life for each insert type. To the left of the optimum temperature, the insert is too cool and unused barium remains in the insert at EOL (as shown by sketch (c)). Curve (1) of figure 13 is an ideal insert lifetime and is based on the assumptions that there is no excess rate of barium dispensed from the insert, or is there any barium remaining in the insert at EOL. These assumptions are equivalent to the sketch below:



(d) Ideal insert.

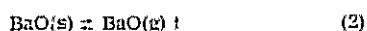
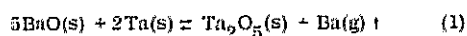
From curve (2) of figure 13 (impregnated insert curve) the maximum lifetime of near 100 000 hours is predicted at 950° C. If a working lifetime of only 30 000 hours is required, however, the insert operating temperature may be in the range of 880° to 1100° C. The assumptions involved in calculating the impregnated insert curve of figure 13 are: (1) the minimum loss rate of barium equals the rate evaporating to vacuum from the insert surface when covered with 0.4 fraction monolayer barium,⁽¹³⁾ (2) the rate of barium production as a function of temperature and reaction (operating) time is given by the data of Ref. 14; and (3) the barium vapor, once evaporated from the surface, does not return. The figure 13 curve for the R-500, rolled-tantalum foil insert is estimated by the authors and is based on a higher chemical reaction rate of the barium oxide/tantalum reaction of the foil insert than that of the barium aluminate/tungsten reaction of the impregnated insert.

For comparison of figure 13 with conventional (cathode in hard vacuum) cathode operation, impregnated-type cathodes typically operate at 1100° C and are activated for periods less than 1 hour at 1200° C. (15) Oxide cathodes (i. e., BaO on nickel) operate at 700° C for long life (10⁵ hr) or 800° C for normal life (10⁴ hr), and are briefly activated at 1100° C. The R-500 tantalum foil insert design contains a layer of BaO approximately 10 times thicker than a conventional oxide cathode. This thicker layer is necessary to give an adequate life with the higher rate tantalum-BaO reaction.

Each insert type will now be discussed individually to describe in detail the type of chemical reactions evolved and factors which may influence the rate of these reactions and hence the lifetime of the insert.

Rolled-Foil Insert

The R-500-coated tantalum rolled foil insert is not one of the standard or conventional oxide cathodes usually manufactured. (15) It was invented to meet the requirements for hollow cathode operation in the SERT II flight thruster program. (6) Many life tests have been completed with this type of insert and lifetimes up to 20 000 hours have been recorded. (16, 17) The cathodes on the two SERT II flight thrusters still function normally 6 years after launch. (18) The theory of operation of rolled-foil inserts has been discussed previously, (2, 19) and lifetime predictions have been made for a limited range of operation. Estimation of rolled-foil insert lifetimes over an extended range of temperature may be predicted using the following reactions:



The equilibrium vapor pressure of barium gas as a function of reaction temperature for reaction (1) is given in Ref. 20 and has been replotted in figure 14. Also plotted in figure 14 are vapor pressure curves for evaporation of BaO, reaction (2), and other reactions that will be discussed in the section on impregnated inserts.

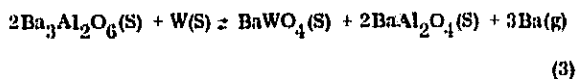
Reactions (1) and (2) are equilibrium reactions and the rate of consumption of the reactants (left side of reaction) will be zero if the vapor pressure of the gaseous product (right side of reaction) is equal to or greater than the pressure value of the curve. The rate of consumption can be estimated by how fast the gaseous product is removed from the reaction. It can be seen from figure 14 that for a given temperature, reaction (1) will cause barium to be consumed at a rate that is about 2½ orders of magnitude faster than reaction (2). Reaction (1) will dominate early in life when there is physical contact between BaO and Ta. After initial reactions,

however, voids will develop in the BaO/Ta interface and the BaO must evaporate to reach the Ta before reaction (1) can proceed. Therefore, the rate controlling reaction for most of the insert lifetime will be reaction (2) instead of reaction (1). (Note that the vapor pressure of Ta is so low (less than 10⁻¹² torr) at the temperatures of fig. 14, that it is negligible.) As soon as the evaporated BaO reaches the Ta surface, reaction (1) will convert it to Ba, and it will be dispensed from the insert. Equilibrium liquid-gas Ba vapor pressure is four orders of magnitude higher than the vapor pressure of Ba produced by reaction (1). Therefore, the Ba vapor produced by reaction (1) will escape freely except for a small quantity in a tightly adsorbed surface monolayer.

As an example of the use of these reactions, consider reaction (2) at 1100° and 1200° C. The vapor pressure of BaO is approximately 10 times greater at the higher temperature, the consumption of BaO would be also 10 times greater, and the insert life would be 1/10 of that lifetime at the lower temperature. The rolled-foil insert design will provide for 15 000-hour cathode lifetimes when used at the correct (i. e., 1100° C or less) operating temperature. The relative open design of the roll foil and the use of the highly reactive Ta to reduce the BaO, results in a dispenser capable of producing relatively large quantities of barium at a lower temperature than for the impregnated insert design. Thus, for thrusters whose cathodes operate at cool temperatures, such as the 8-cm diameter thruster, (7) the rolled foil insert is an appropriate choice. The 30-cm diameter thruster with warmer cathodes, however, may have short insert lifetimes, as indicated by cathode 1 in Table I. To increase the insert life, the cathode may be cooled by adding a radiation cooling fin and collar to the cathode tip. Such a design operated for 10 600 hours (cathode 2 in Table I). The disadvantage of a cooling fin on the tip is that increased heater power is then required to bring the cathode up to starting temperature. Heater lifetime becomes a problem, and there is increased demand on the thruster power processing. Larger design margin probably can be achieved if an insert with a lower Ba reaction rate is used. Such an insert is the impregnated type discussed next.

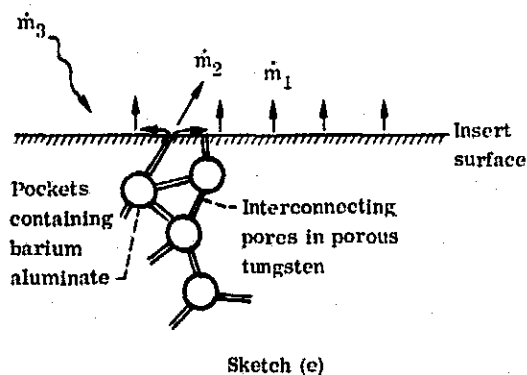
Impregnated Insert

The porous-tungsten impregnated insert (type 84-S) tested and theoretically described herein, operates in general as does the rolled-foil insert. The major differences are in the physical construction and in the chemical reactions used to produce barium. Several reactions between the barium aluminate impregnate and the porous tungsten of type 84-S material are possible. (21) The most likely reaction⁽²¹⁾ is:



The equilibrium vapor pressure for reaction (3) as a function of temperature is plotted on figure 14. If reaction (3) were the only reaction that takes place, it is seen that only half of the barium aluminate ($\text{Ba}_3\text{Al}_2\text{O}_6$) put in the insert can be converted to free Ba and be useful for activation of the cathode. The other half remains in the insert as BaWO_4 and BaAl_2O_4 and is unavailable to produce free barium. Because of other possible reactions and specific operating temperatures or conditions, cathodes or inserts made of impregnated porous tungsten may be capable of dispensing between 1/3 and 2/3 fraction of total barium impregnated. (14, 21) In addition, operating inserts do not emit a constant dispensed rate of barium with time as might be implied from reaction (3), but rather emit a high initial rate followed by a time decaying rate as shown earlier in sketch (a). 1 J scale is shown on the sketch because the magnitude of the dispensed rate is dependent on the operating temperature level. The EOL occurs when the integrated area under the curve equals the total barium available.

A model to represent the dispensing of barium with time can be described with the help of sketch (e) which is a cross section through a porous tungsten impregnated insert.



Reaction (3) proceeds in the pockets containing barium aluminate. Barium vapor is produced locally at a pressure predicted as a function of temperature by curve 3 of figure 14. The local barium vapor must flow through the pores before reaching the surface. This flow results in a pressure or concentration drop which increases with time because the barium must flow from deeper within the porous material as the barium aluminate near the surface becomes depleted. This depletion causes the dispensed barium rate to decrease with time for a constant temperature.

Because barium has a high vapor pressure relative

to the equilibrium barium pressure of reaction (3), any excess barium over one monolayer at the surface will evaporate quickly (represented by \dot{m}_2 in sketch (a) or (e)). In addition to any excess barium evaporation, there is also barium evaporation from the barium monolayer. This barium loss is represented by \dot{m}_1 and is a function of temperature. The evaporation of barium from a monolayer has been determined to be a function of the monolayer fraction coverage. (13) The EOL of the insert occurs when the dispensed rate falls below \dot{m}_1 evaporated from that surface needed to sustain satisfactory activation or emission. Ba vapor, \dot{m}_3 , reflected from nearby walls, may add Ba to the surface and extend the insert life. The effect of reflected Ba vapor on insert life will be discussed later.

In this paragraph, insert dispensing rates into vacuum will be computed for various operating temperatures between 1050° and 1227° C using measured data of Ref. 14. The vacuum dispensed rate is presented as vapor pressure of barium (leaving the insert surface) as a function of operating time and is plotted in figure 15 for four temperatures. The EOL bars at the end of each curve were calculated by integrating the total barium dispensed and comparing this value with the amount of barium aluminate in the 30-cm EMT design impregnated insert. The EOL was the point when the integrated dispensed value equalled one-half of the total barium impregnated. The half value was calculated from measured mass of impregnate and was 0.0105 gm per cm² of insert surface area. (The mass of barium aluminate impregnate was 0.22 gm and the insert surface area, 7.50 cm².)

As indicated in figure 15, higher operating temperatures produce more barium, but shorter lifetime, as indicated by the EOL bars at the right-end of the curves. The EOL ranged from about 10⁵ hours at 1050° C to only 10³ hours at 1300° C. (The data of Ref. 14 was extended to longer operating times by plotting the log of the evaporation rate (vapor pressure) against the log of time and making an extrapolation of the curve. The data of figure 5 in Ref. 14 was extended to 1300° C by a linear extrapolation of lower temperature data.) Comparing the computed evaporation rates of figure 15 with the theoretical vapor pressure of reaction (3), shows that reaction (3) gives a higher vapor pressure than figure 15 and that the difference magnitude increases with time in accord with the depletion model presented earlier.

In order to relate the Ba vapor pressure values of figure 15 with Ba loss rates from Ba-monolayer covered surfaces, figure 16 was prepared. Figure 16 is a cross-plot of figure 15 and also includes curves for Ba evaporation (13) from Ba surfaces with $\theta = 0.4$ and $\theta = 1.0$. In addition, reaction (3) from figure 14 is replotted so that three Ba rates can be compared together. Because

the Ba dispensed rate decreased with time,⁽¹⁴⁾ dispensed rate curves are shown for various time intervals. A well-activated surface⁽¹⁵⁾ has Ba coverage between $\theta = 0.4$ and $\theta = 1.0$, although emission below $\theta = 0.4$ is possible. Ba in excess of one monolayer, $\theta > 1.0$, quickly evaporates at its normal vapor pressure which is eight orders of magnitude greater than that leaving a surface with $\theta = 1.0$. It can be seen from figure 16, that there is seldom enough barium produced to obtain complete surface coverage ($\theta = 1$) and the best activation state. Also, the value of θ will decrease with time at constant temperature.

The next step is to compare the dispensed rate of barium with loss rates from cathode surfaces in the actual environment of the cathode geometry. In prior sections the rates were discussed for loss directly to vacuum, and this rate probably represents a high limit of the loss rate and hence a pessimistic (short) insert lifetime. In the actual environment, the confining geometry of the cathode tube will tend to reflect Ba vapor back to the insert surface. This reflected Ba vapor will cause a higher equilibrium concentration of Ba, both on the surface and into the pores. The beneficial effect of this reflected Ba could be two-fold. First, the surface will reach a higher state of activation due to the increased Ba concentration, and the cathode operating temperature can be lower and still give the same emission. Secondly, any Ba vapor traveling back into the pores will tend to raise the local Ba vapor pressure. This increase in the pores at the site of reaction (3) will shift the equilibrium to the left and result in a slower rate of consumption of the barium aluminate impregnant. Both this effect and the first will lead to longer insert lifetimes.

To quantitatively estimate the increase in insert lifetime requires the development of a Ba-flow model that estimates how the Ba vapor is reflected and where it is eventually lost. An optimistic (low) limit for Ba loss would be that Ba lost only through the cathode orifice. The pessimistic limit would be the vacuum loss rate and could occur if the Ba vapor condenses on nearby cool surfaces acting like a "cold-trap." In the present EM 30-cm thruster cathode design, the actual barium loss is probably between these two limits. The authors believe that most of the barium lost travels upstream and possibly condenses near the vaporizer, a region of about 100°C .

At 300°C the equilibrium gas-solid vapor pressure⁽¹⁵⁾ of Ba is 5×10^{-8} torr. If the Ba reevaporates at this value it would return at a sufficient rate (see fig. 16) to maintain fairly high cathode surface activation. Predicting if the Ba will reevaporate is very sensitive to temperature and 300°C is a pivotal point. Much higher, that is, 400°C , gives a Ba vapor pressure of 8×10^{-6} torr

which represents a super abundance of Ba, and much lower, that is, 200°C , gives 6×10^{-11} torr, which represents insignificant amount of Ba. (If the Ba can be prevented from permanently condensing, a greatly enhanced insert life should result. One design to accomplish this would incorporate a flow restriction baffle/orifice inside the cathode tube between the isolator and the insert where the temperature is $>100^{\circ}\text{C}$.)

Even if no restricting baffle/orifice is in place, the natural geometry of the insert inside the tube and the length of the tube itself will tend to restrict the upstream flow of Ba. The pressure drop associated with this flow will cause a local enhancement of barium pressure and a favorable equilibrium shift in reaction (3). Calculating the exact flow conduction pressure drop to the vaporizer region is difficult because of the cathode tube-insert geometry. To "first order" the flow pressure drop will be low, however, and the barium loss processes may be close to vacuum evaporation if surfaces less than 300°C are present.

Impregnated Insert Temperature Measurements

To predict lifetime margin requires measurements of actual insert temperatures and measurements of the effect of cathode geometry on local increases in Ba vapor pressure with its subsequent suppression of insert reaction rates. Measurement of the insert temperature is difficult because of the confining size of the cathode tube and the presence of a gaseous discharge inside the tube. The data of figure 12 are an early result of insert temperature measurements made on a main cathode for inserts recessed and flush with the tip. The forward placed insert operated at 1060°C while a recessed insert operated at only 750°C . The higher temperature is near the temperature theoretically predicted for maximum lifetime. The recessed impregnated insert is at a low enough temperature that poor chemical activity will cause insufficient barium production for normal operation.

The effect of cathode geometry on inhibiting the loss rate of barium may be inferred by the inspection of the data of figure 17 which shows the loss rate from an EM design impregnated insert measured after heating for 1000 hours at constant temperature.⁽²²⁾ Also shown are two calculated curves. The lower curve predicts the barium loss due to flow out through the neutralizer size tip orifice. The higher curve is for a loss rate of barium to vacuum as if the confining tube walls were absent. The insert was placed inside a cathode tube with a 30-cm EM design neutralizer tip (0.040-cm diam orifice) on one end and a solid cap on the other. The capped end of the tube was clamped in a 150°C heat sink block. Two different insert/tubes were heated at each temperature. The measured insert weight loss (presumably Ba)

falls between two curves. The data falls closer to the vacuum evaporation curve indicating that significant amounts of barium evaporated and condensed in the area of the heat sink at the curved end of the tube. This fact was confirmed by visual observations of deposits in this area, although quantitative analysis verification was not completed at the time of this writing. (The one low data point at 1300° C is assumed to be anomalous.

The results of these tests indicate that at higher temperatures the tube walls may suppress barium production by about half. But at lower temperatures, the production rate is not suppressed. Another interpretation is that at the high temperatures, the total reaction of barium may be nearing completion (one-half of total Ba available for dispensing) and the production rate slows down.

These data of figure 17 and a comparison with the theoretical insert lifetime models do confirm that the present 30-cm EM design insert is near optimum. The insert temperature is adequately hot to dispense sufficient Ba for good cathode performance and life, and yet not too hot that the predicted lifetime is below the 30 000-hour design life. The Ba loss rate of figure 17 may be even further reduced if the "heat sink" area temperature is nearer actual vaporizer temperature (300° C), and the barium condensed at the 150° C temperature, partially returns to the insert pores. The data of figure 17 predict an insert lifetime of 30 000 hours at 1100° C and 10 000 hours at 1000° C. Confirmation of these predictions will require additional insert heating tests where Ba loss rate is measured several times to establish a time-rate curve that may be extrapolated to EOL. Actual life tests of inserts in operating thrusters will be the final proof of a design, and a 15 000-hour life test of a 30-cm EM thruster⁽²³⁾ is underway to demonstrate thruster (and cathode) lifetime.

Conclusions

Life tests of main cathodes for the 30-cm thruster indicate no wear for time periods as long as 18 000 hours at emission current levels up to 12 amps. The orifice of a neutralizer cathode increased slightly over a 15 000-hour test when run at 2 amps emission current. This increase in orifice did not affect performance level in a bell jar test. Thus, tip erosion is not a life-limiting factor for the cathodes used in 30-cm thrusters.

It was shown experimentally that the lifetime of a cathode and the efficiency of the generation of plasma discharges depend heavily on the rate of dispersion of low work function material contained in the insert. The efficiency of the generation of a plasma discharge improves with elevated insert temperature, for this increases the rate of dispensation of Ba. On the other

hand, the lifetime in general increases with lower temperature, down to a limit. Theoretical calculations were carried out to describe the operation of both rolled foil and Ba impregnated tungsten inserts. These calculations predicted the lifetime as a function of operating temperature range for each type. Insert temperature measurements were made as a function of cathode design and operating conditions. On the basis of these insert temperature measurements, the theoretical analysis and thruster performance data,⁽⁸⁾ it was felt that 30-cm cathode designs have been developed which allow sufficient lifetime and also lead to satisfactory thruster performance.

A series of life tests were performed to verify the approaches used in 30-cm cathode design. A 0.40-mm orifice cathode with an impregnated insert was duration tested at 2 amps emission for 15 000 hours with negligible change in performance. A 0.76-mm orifice cathode (3) described in Table I with an impregnated insert recessed 0.95 cm from the tip has been successfully endurance tested for 18 000 hours at current levels up to 12 amps emission with little or no change in baseline keeper voltage or other performance level.

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TABLE I. - SUMMARY OF CATHODE CONFIGURATIONS TESTED

Cathode number	Orifice diameter, mm	Type of insert	Insert dimensions	Insert position distance recessed from tip, cm.	Radiation fin diameter	Total run hours
1	0.76	Rolled foil coated with R-500	2.54- by 15.2-cm	0.95	None	1 360
2	.76	Rolled foil coated with R-500	2.54- by 15.2-cm	.95	1.75-cm fin + 0.8-cm long collar	10 600
3	.76	Impregnated	2.54-cm long by 0.54-cm o. d. by 0.23-cm i. d.	.95	1.75-cm fin + 0.8-cm long collar	>18 000 (still running)
4	.40	Impregnated	2.54-cm long by 0.54-cm o. d. by 0.25-cm i. d.	(a) 1.27 (<1600 hr) (b) At tip (>1600 hr)	None	15 000
5	.	Impregnated	2.54-cm long by 0.54-cm o. d. by 0.38-cm i. d.	(a) 0.635 (<70 hr) (b) At tip (>70 hr)	1.75 cm	>3 000
6	.76	Impregnated	2.54-cm long by 0.54-cm o. d. by 0.38-cm i. d.	(a) 0.635 (b) At tip	1.75 cm	Short test

TABLE II. - OPERATING CONDITIONS OF CATHODES TESTED

Cathode number	Preheat tip power, W	Mass flow, mA	Number of restarts	Keeper current, mA	Emission current, amps	Cathode temperatures, °C	
						Behind tip heater	Face of tip
1	34	170	9	300	12	1080	1450
2	90 (Initially) 60	170	30	300	12	825	925
3	95 (Initially) 79	140	48	500	Varied (12, 12.2, 7, 10, 10.6)	----	960
4	54	(60-80)	38	580	2	875 (<1600 hr) 580	1150 (<1600 hr) 920
5	64	140	9	600	10.6	(a) 825 (insert recessed) (b) 510 (insert at tip)	1120 (insert recessed) 950 (insert at tip)
6	90	140	10	600	10.6	(a) 735 (heater, and insert recessed) (b) 520 (insert at tip)	1120 (recessed insert) 940 (insert at tip)

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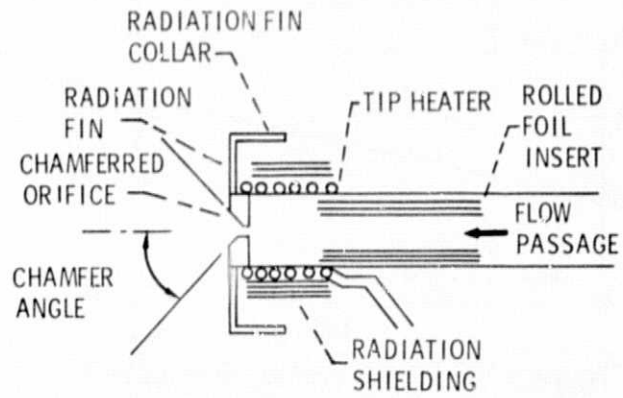


Figure 1. - Cathode configuration for 0.76 mm orifice cathodes.

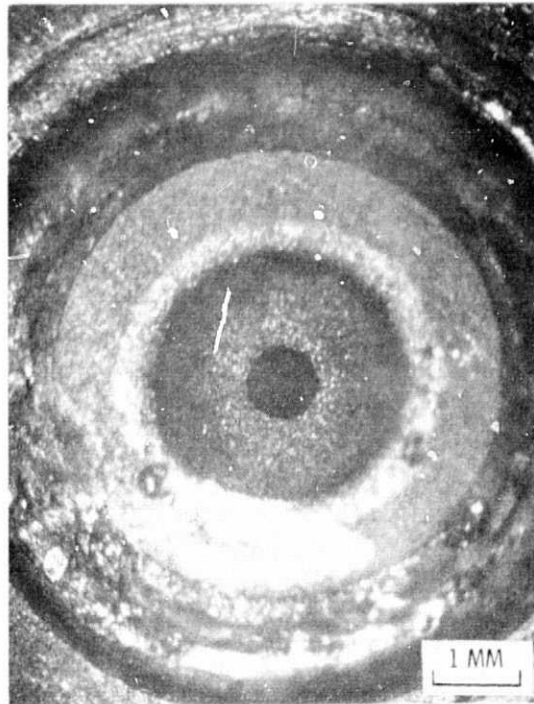


Figure 2. - Photomicrograph of cathode 2 after 10 600 hours at 12 amps.

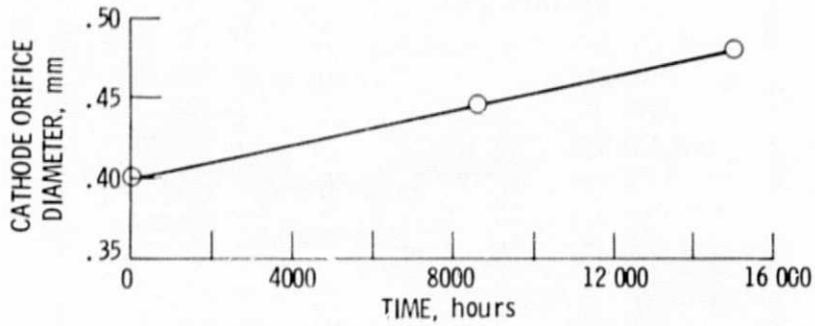


Figure 3. - Neutralizer cathode orifice diameter as a function of time for cathode 4 run at 2 amps emission current.

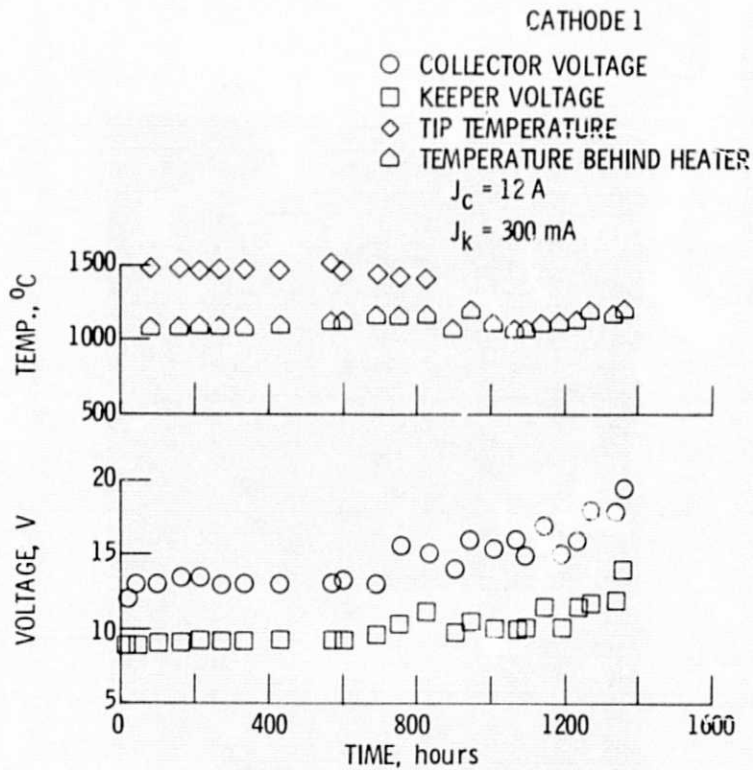


Figure 4. - Collector and keeper voltages as a function of time for cathode 1.

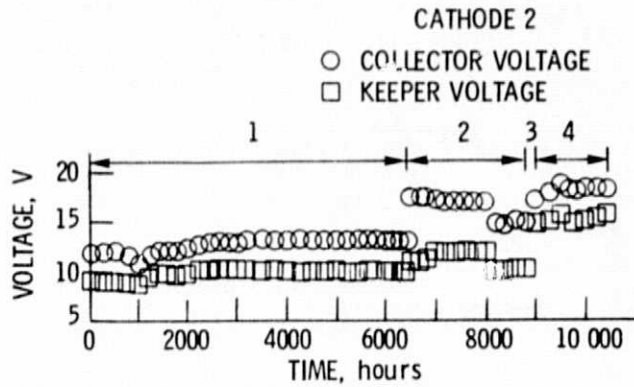


Figure 5. - Keeper and collector voltage as a function of time for cathode 2.

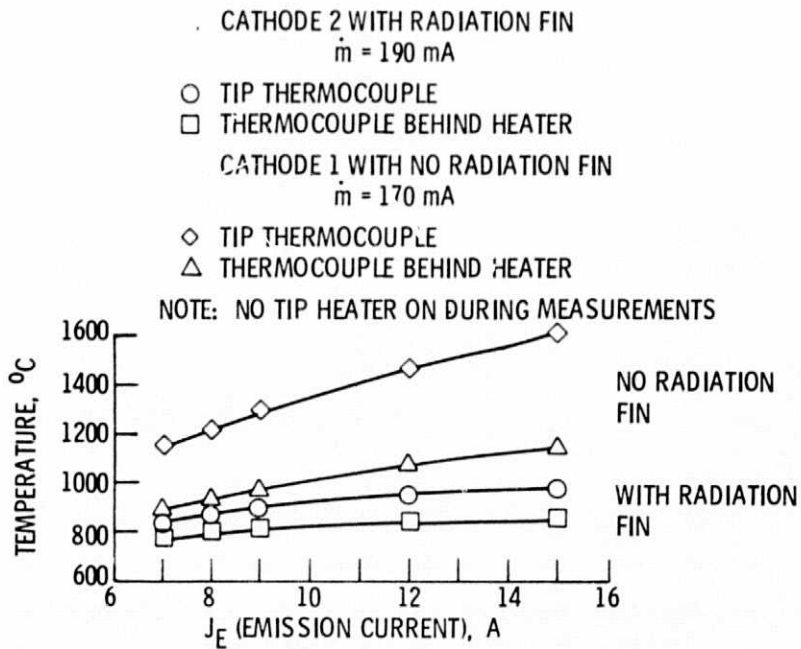


Figure 6. - Temperature as a function of emission current for cathodes 1 and 2.

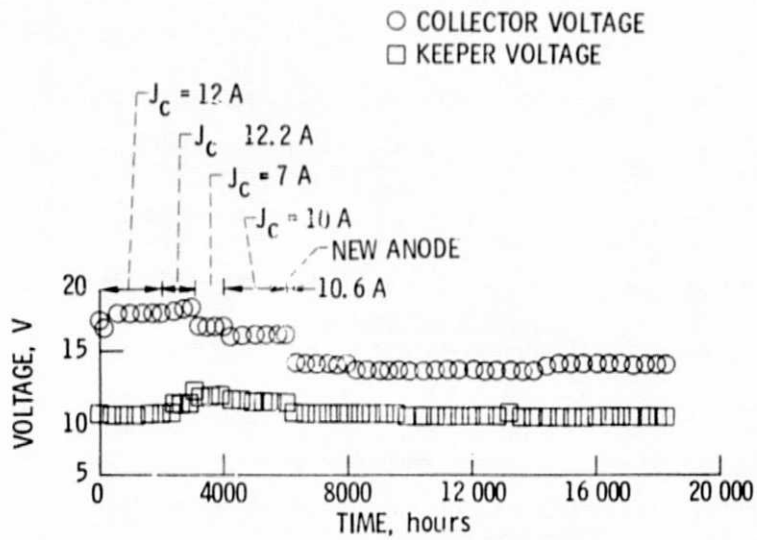


Figure 7. - Keeper and collector voltage as a function of time for cathode 3.

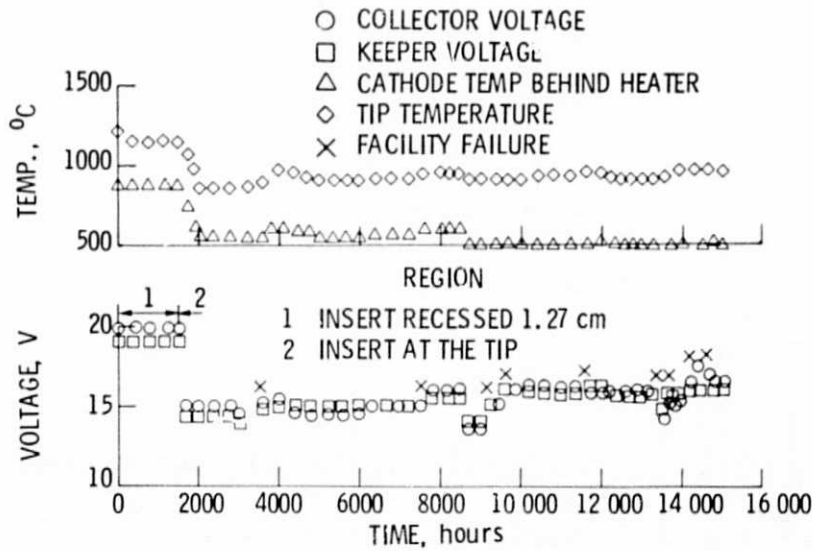


Figure 8. - Keeper and collector voltage, tip and cathode temperature for cathode 4 as a function of time.

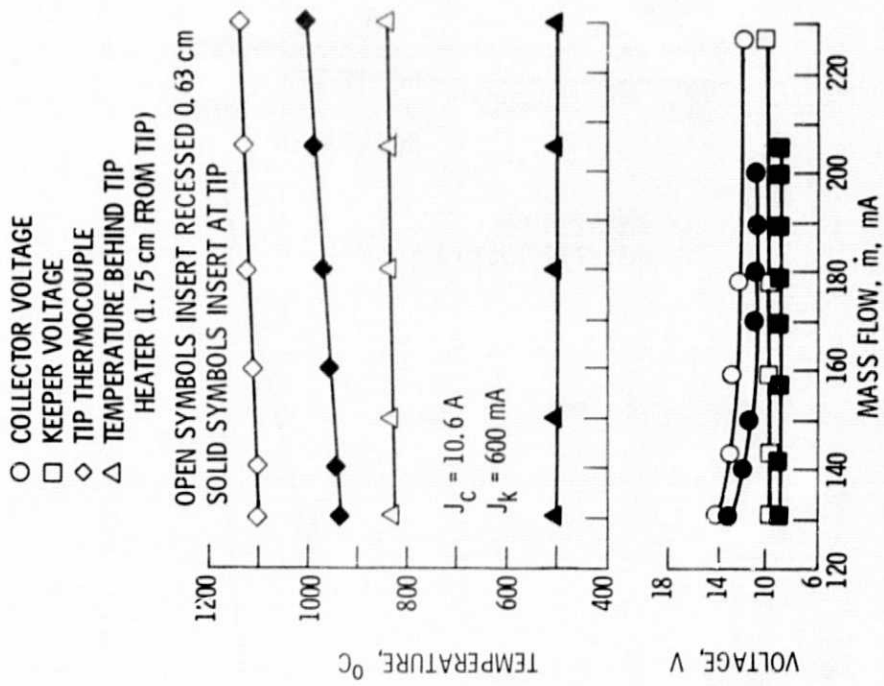


Figure 10. - Variation of temperature, keeper and collector voltages with neutral flow rates for cathode 5 for two insert positions.



Figure 9. - Cathode 4 showing crack in tip.

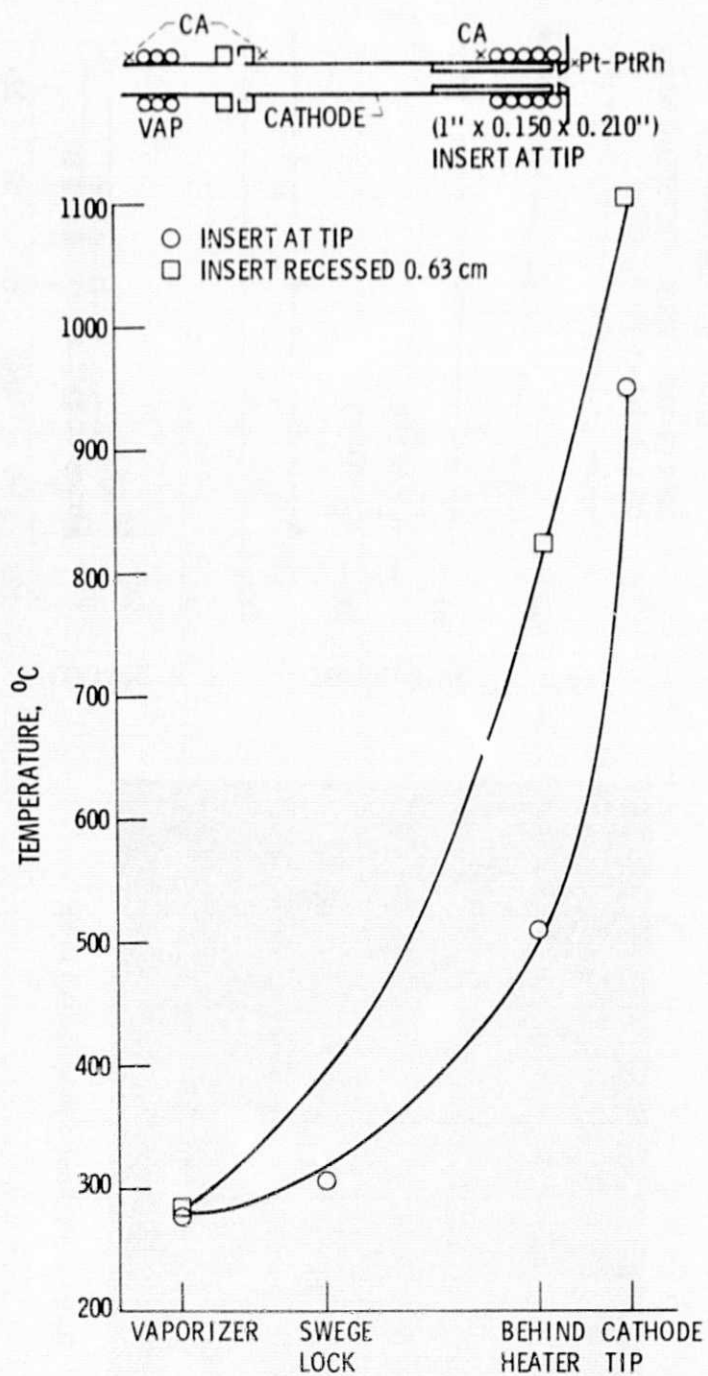


Figure 11. - Plot of temperature profile of cathode 5 at a equivalent Hg mass flow of 140 mA and no tip heaters on.

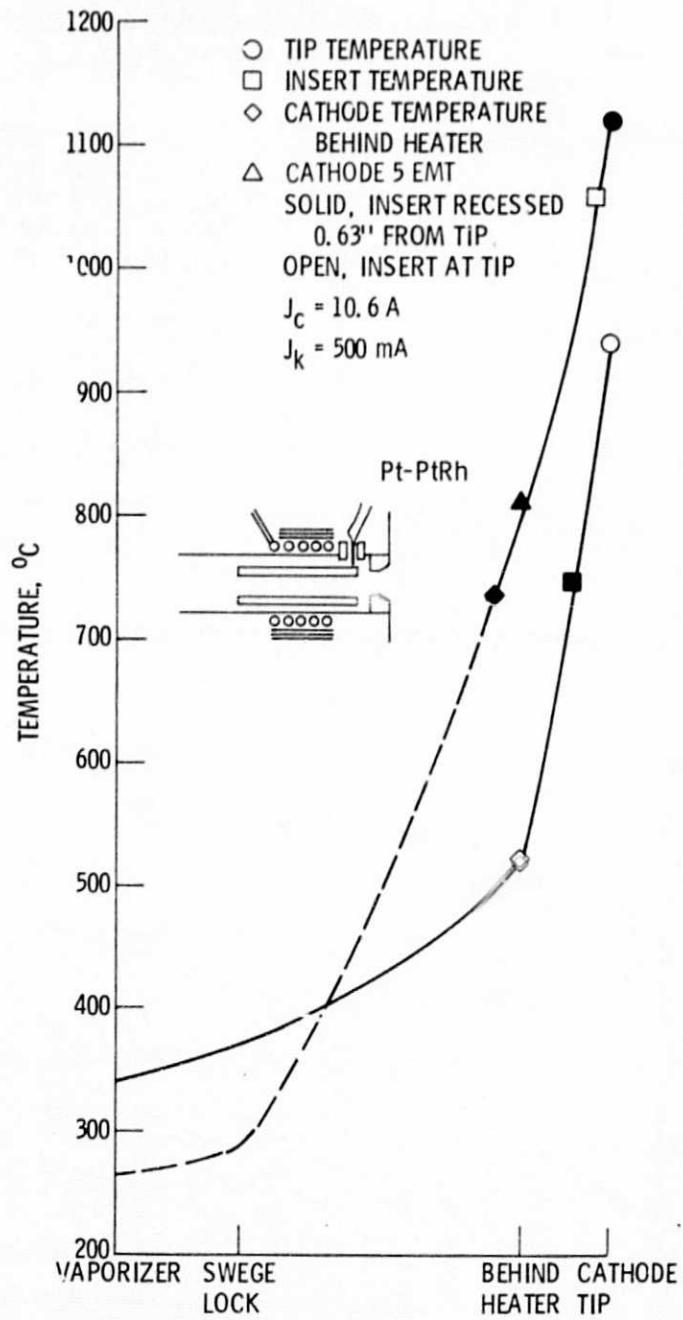


Figure 12. - Temperature profile of cathode 6 and insert temperature.

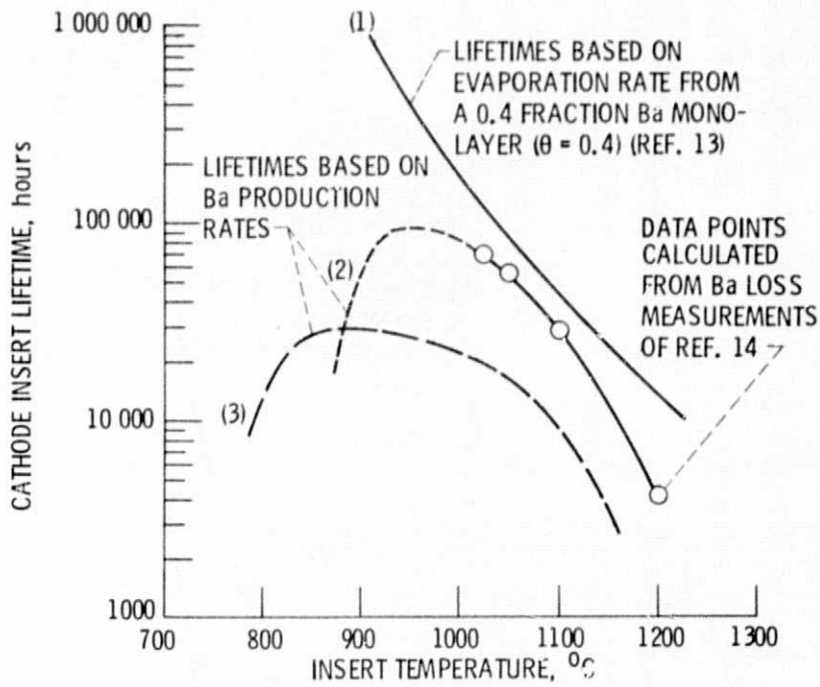


Figure 13. - Estimated cathode insert lifetimes as function of temperatures.

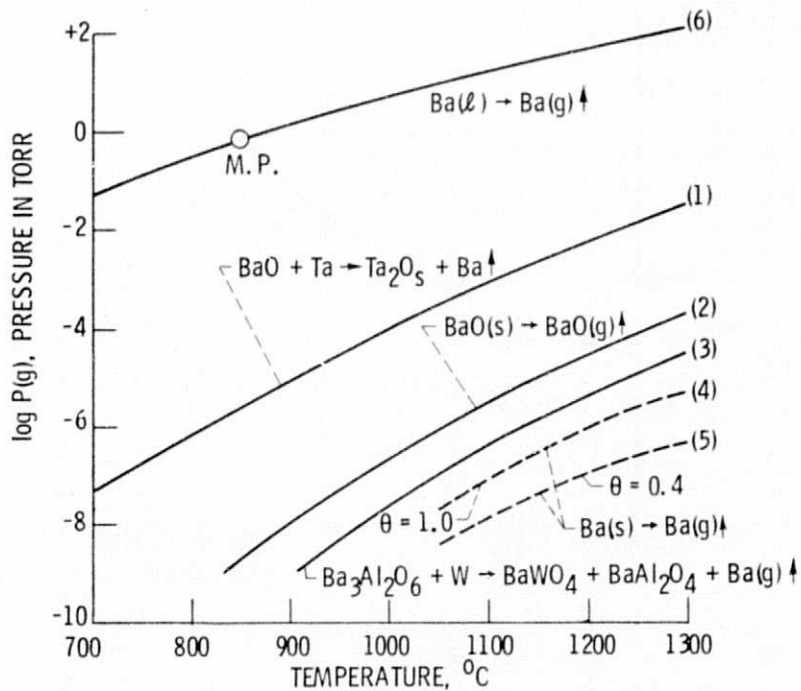


Figure 14. - Vapor pressure of Ba or BaO produced by various reactions and temperatures. (θ is monolayer fraction of Ba on surface.)

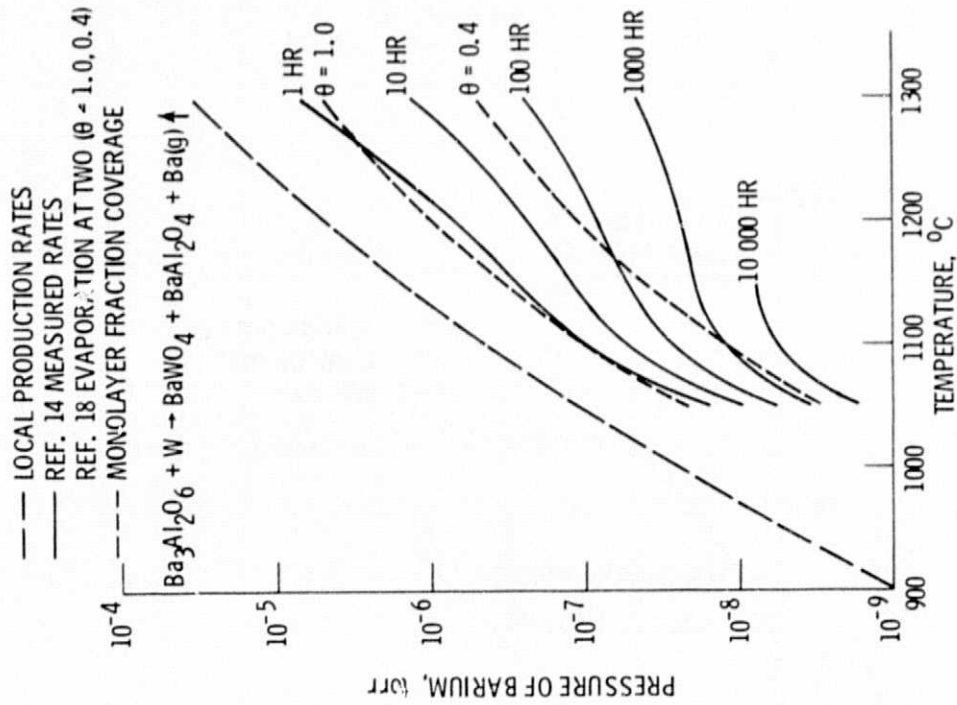


Figure 16. - Comparison of Ba production and evaporation rates for the impregnated insert.

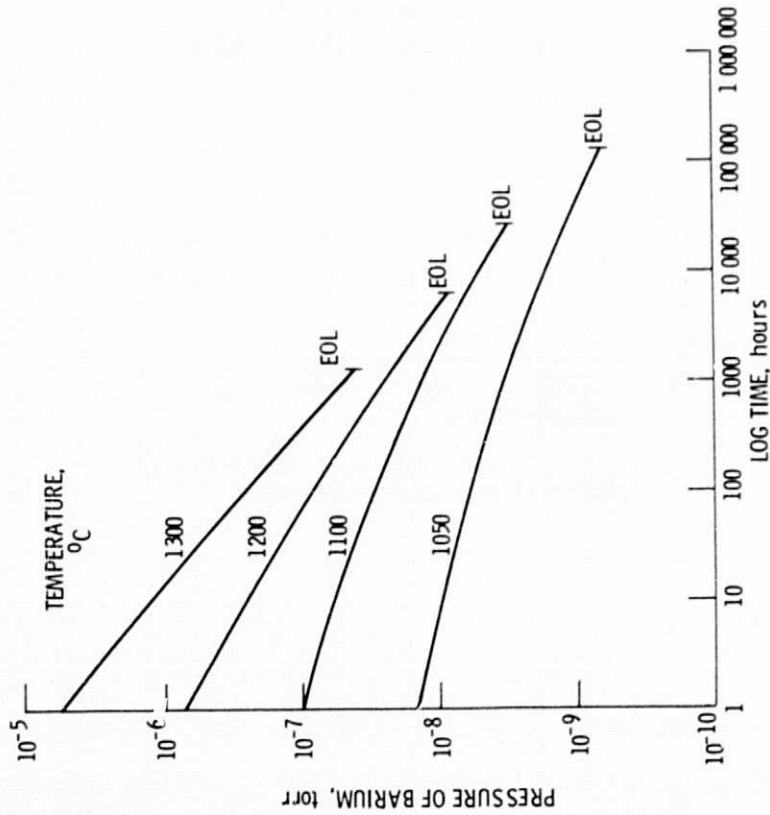


Figure 15. - Vacuum production rate of barium vapor pressure from impregnated insert.

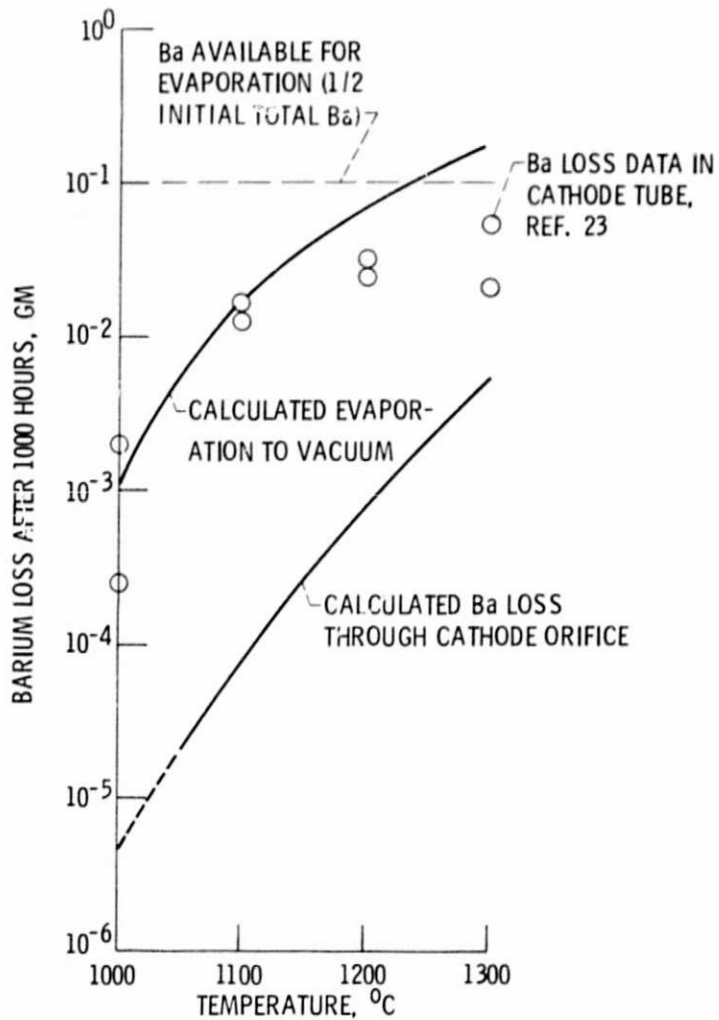


Figure 17. - Impregnated insert weight loss after 1000 hours in heated cathode tube.