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A SURVEY OF KAUFMAN THRUSTER CATHODES

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Abstract

A survey is presented of various cathodes which have been developed and used in the Kaufman ion thruster. The electron-bombardment type ion source used in the thruster is briefly described. The general design, operating characteristics, and power requirements are shown for each type of cathode from the refractory metals used in 1960 to the plasma discharge hollow cathodes of today.

A detailed discussion of the hollow cathode is given describing starting and cyclic operating characteristics as well as more fundamental design parameters. Tests to date show that the plasma hollow cathode is an efficient electron source with demonstrated durability over 10,000 hours and should offer further performance and life improvements.

Introduction

Plasma and ion sources have evolved from the imagination and ingenuity of many researchers in plasma physics. The Penning discharge, the duoplasmatrons, and numerous gaseous conductor devices have led to a better understanding and practical application of plasmas.

Since 1958 the NASA Lewis Research Center has conducted research on plasma and ion propulsion for space application. Analyses have shown that thrust devices with specific impulses in the 1000 to 5000 seconds range are needed to accomplish various space missions. The Kaufman ion thruster is a means of fulfilling this need.

The high specific impulse - low thrust characteristic of the Kaufman electron-bombardment ion thruster, however, necessitates long thrusting times to generate the total impulse required for most missions. Long-life durability and reliability of thruster components, particularly the cathode, were early recognized as pacing requirements in the thruster development program.

This paper is a survey into the evolution and development of cathodes for the Kaufman thruster. It compares the power requirements, performance characteristics, and durability of various types and designs of cathodes. It discusses the present state of the art and mentions future requirements.

The four major types of cathodes discussed in this paper are: (1) refractory metal, (2) oxide coated, (3) liquid mercury, and (4) hollow.

The hollow cathode, which shows the greatest promise for durability and versatility is described in more detail than the other types. Recent hollow cathode starting and cyclic operating tests are described.

A cutaway sketch of the first successful Kaufman ion thruster[1] used in 1960 is shown in figure 1. Although the components have gone through extensive developmental programs, the basic operation of the electron-bombardment ion source has not changed. Neutral propellant atoms (most investigations at LeRC used mercury vapor) enter the chamber through an orifice and are distributed in the chamber. Electrons which are emitted from a cathode provide the means of ionizing the atoms. The electrons are accelerated through a potential (35-50 V) and bombard neutrals causing ionization (10.4 eV for mercury). The ions are then accelerated by means of a screen and accelerator located at the downstream end of the chamber.

The energized electrons from the cathode must be in abundance for the thruster to perform properly. Superimposed on this cathode requirement of a sufficient quantity of electrons, are long lifetime, reliability and low power consumption (watts of cathode heater power per ampere of emission current hereafter to be called specific heating power sometimes referred to as emission efficiency[2]).

The ionizing electrons must also have long trajectories to efficiently ionize the propellant. A magnetic field roughly parallel to the thruster axis is used to increase the path length of primary electrons in which electron-atom interactions can occur. A uniform magnetic field was initially used; however, it was determined that a divergent field gave better results.[3]

A range of thruster sizes from 5-cm to 1.5-m diam have been studied. (Ref. 4 gives details of the 1.5-m thruster data.) Table I shows the range of emission currents which vary from 0.2 to 19 A. required for the 5-, 15-, and 30-cm thrusters. At the present time the 30-cm and the 5-cm diam thrusters are being extensively developed. The 30-cm thruster is suitable for primary propulsion.[5,6] The 5-cm thruster could be used for attitude control and station keeping duties for long duration (greater than 2 years) satellite missions.[7,8]

The Kaufman thruster has been flown twice in space. The first flight, SERT I (Space Electric Rocket Test I), was a suborbital test performed on a 10-cm diam thruster in 1964.[9] The second flight (SERT II) was an orbital test of two 15-cm diam thrusters.[10] SERT II was launched in 1970 and had one thruster that operated for 5 months and another for $3\frac{1}{2}$ months.

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Refractory Metal Cathodes

Tantalum Wires

The cathode first employed for ion thrusters consisted of a long 0.015-cm diam tantalum wire filament.[1] The wire extended across the ion chamber perpendicular to the thruster axis (Fig. 1) or along the axis of the chamber on heavier support rods. Various filament lengths (6-9 cm) were tested. These cathodes were easy to make and install and gave reproducible results. However, they had a high specific heating power characteristic (670 W/A) and because of evaporation and ion sputtering had a short lifetime (100 hours).[11]

Tantalum Ribbon

A variation from the wire cathode was the ribbon filament. This type of cathode (Fig. 2) had a large surface area (5.1 cm x 0.36 cm) with a small cross-sectional area (0.005 cm thick), which resulted in a more favorable specific heating power (average of 120 W/A). It was positioned at the center of the discharge chamber backplate and was bent into a V shape (Fig. 2). It was possible to obtain a 1500-hour lifetime running the thruster at low propellant utilization efficiency and low thruster power efficiency.[12] The lower thruster performance lessened the ion bombardment sputtering rate of the filament, which coupled with evaporation was the major cause of erosion. Running at higher efficiencies caused an order of magnitude decrease in lifetime. Thicker filaments would extend the life of a cathode, but this configuration would require excessive heating power.

Oxide Coated Cathodes

In order to reduce the specific heating power, various cathode designs utilizing oxide coatings were investigated. It is theorized that oxides of alkali metals such as barium yield free metal upon heating.[2,13] Free barium diffused over a thermionic emitter greatly reducing the work function, allowing the cathode to emit at lower temperatures and reducing the specific heating power.

Nickel Matrix

One design was the oxide impregnated nickel matrix cathode (Fig. 3). By providing a configuration that is thick enough (several millimeters) to withstand sputtering erosion and containing oxide throughout, long lifetimes could be possible. The matrix consisted of 90 percent nickel power and 10 percent by weight mixture containing approximately 57 percent barium carbonate, 42 percent strontium carbonate, and less than 1 percent of various impurities. The average pore size was 2 - 25 μ. A typical size for the cathode design was 0.55 cm diam and 1.5 cm long. A heater embedded into the matrix provided the thermal energy required to decompose the oxide. The operating temperature of the oxide was 1200^{o} K, which is considerably less than 2400^{o} K temperature of tantalum ribbon. The reduction of operating temperature lowered the specific heating power to 30 W/A. A constant emission current could not be maintained without increasing the heater power as the test proceeded. This action eventually led to heater burnouts. It was surmised that ion bombardment of condensed sputtered materials on the oxide surface caused degradation of the emitting cathode, thus requiring progressively higher surface temperatures.[14] The average lifetime of the nickel matrix cathode was 190 hours, which is too short for thruster application.

Thick-Oxide Layer

By increasing the oxide surface exposed to the chamber environment, the lifetime of the cathode could be extended. A design which incorporated this idea is shown in figure 4. This concept is called the thick-oxide-layer cathode. It consists of a hairpin-shaped tantalum ribbon filament with 0.007-cm diam tungsten wire wrapped around it. The purpose of the wire was to provide a substrate on which the oxide layer can be secured. A barium carbonate-water slurry was applied to the metallic structure. The slurry was allowed to dry and repeated applications were made until the desired thickness and density was obtained. The specific heating power of this cathode was greatly dependent on propellant flow and distribution. However, an optimization program[13] resulted in a lifetime of 1000 hours in a simulated thruster (no accelerator grid) at 10 W/A and 615 hours in a 10-cm diam thruster (4 W/A). A phenomenon which caused the most damage to the cathode was arcing from the cathode to anode. The arcs occurred at random during the tests. The onset of these high current arcs damaged the thick-layer oxide and caused the specific heating power to increase. The resulting higher surface temperatures caused rapid evaporation of the barium and eventual cathode failure. A second series of tests was able to eliminate the arcing problem by using a current regulated power supply in the discharge circuit.[11] The maximum lifetime achieved was 5000 hours at 10 W/A specific heating power in a simulated thruster.

Sputtering erosion caused a gradual attrition of the oxide coating and a progressive increase in specific heating power. Various baffles and shield structures were tried in an attempt to reduce ion bombardment of the cathode surface. The results were generally unsatisfactory because cathode emission was seriously impaired.

Two disadvantages of the thick-oxide-layer cathode were: (1) cathode emission from hot spots rather than from the entire cathode surface and, (2) large radial thermal gradient within the cathode which caused chemical corrosion of the overheated cathode structure.[15] To overcome these limitations the brush cathode was designed.

Brush

The basic oxide brush cathode[16] is shown in figure 5. This cathode consists of thin tungsten or tantalum wire bristles (0.008-cm diam) extending radially from heavier tantalum wires (usually four with 0.05-cm diam) like a radial wire brush. Typical over-all dimensions are 1-cm diam and a range of lengths from 1.2 cm for a 5-cm diam thruster to 10 cm for a 20-cm thruster. Tantalum was used because it possessed the mechanical strength necessary at the cathode operating temperature of 1200° K. The brush cathodes were assembled and then the commercial oxide coating applied. To assure good cohesion a pressing process was used. A range of pressures from 0.7×10^5 nt. per sq. m. to 18×10^5 nt. per sq. m. (2×10^3 psi to 5×10^4 psi) were applied.

Initial tests gave good results which showed that the brush cathode had little arcing problems and had fewer hot spot occurrences than the thick-oxide layer cathode. Lifetimes were very encouraging ranging from 1250 hours for a 20-cm diam thruster (specific heating power of 20 W/A) to 3900 hours for a 7.5-cm diam simulated thruster (specific heating power of 15 W/A). Oxide losses due to ion-bombardment sputtering, normal evaporation, and low voltage arc damage were small. However, further tests showed that chemical attack of the bristle and core wires continued to be a problem.[11] A carbon activator (2-10% by weight of the carbonate mixture) was added to reduce operating temperature, to reduce chemical attack, and to increase activation. However, some cathodes (~1 in 10) never emitted.

A variation of the brush cathode is the indirect heated cathode (Fig. 6). This cathode was investigated because it was designed to protect the cathode heater element from ion-bombardment and provide a uniform heating surface. The heater was coiled around a threaded rod and inserted into an insulated tube. This section was placed inside a swaged tantalum tube. A 0.45-centimeter tantalum tube supported the assembly. A 0.5 centimeter diameter tantalum brush was wrapped around the tantalum tube, and an oxide coating was added. Similar results were obtained with this cathode as with the brush cathode including surface deterioration. Also, there was a gradual increase in specific heating power until the cathode heater failed.

Oxide Magazine

At this stage of development it was speculated that in order to achieve long cathode life a large quantity of emissive material must be present with minimal heater coverage. One solution was the oxide magazine cathode[17] of figure 7. This cathode was composed of a screen heater element at one end of a tube containing barium carbonate. A spring loaded piston was located at the other end and enabled the oxide to be in contact with the heater at all times. A lifetime of 4179 hours was achieved with one cathode at a specific heating power of 22.7 W/A.[17] Although the oxide magazine cathode had the longest tested lifetime and was the original configuration considered for SERT II flight test,[18] it did have disadvantages.[19] Exposure to air caused chemical deactivation of the oxide, and it could not be preflight tested in flight qualified systems. (This restriction is true for all previously mentioned oxide coatings.) While the specific heating power was low enough for flight operation (8-12% of total thruster power), the power required by the hollow cathode was lower.

Mesh Spiral (Flower) Cathode

Work at Hughes Research Laboratory supplemented the cathode studies at Lewis Research. One configuration, the flower cathode,[20] is shown in figure 8. A tantalum wire mesh composed of 0.0228 cm diam wires woven in a 20x20 per cm mesh was cut into strips approximately 1.3 cm by 35.6 cm. It was folded into a compact volume and placed in a cylindrical section 3.18 cm in diameter. The mesh was oxide coated. This design provided a large surface area for electron emission and a small area (the edge of the mesh) for ion sputtering. Penetration of the plasma into the folds of the cathode is reduced. This lessens the effect of ion sputtering on the majority of the cathode surface. The large surface area also ensured a thin oxide coating which minimizes or eliminates hot spots, one of the major causes of thick-oxide layer cathode failures. The results of durability tests showed that this configuration could operate for at least 1000 hours at a specific heating power of less than 40 W/A. Inactivation of the coating could cause local overheating and cathode failure. Inability to preflight test the cathode was another limitation.

The specific heating powers of the various refractory metal and oxide cathodes are compared in figure 9. Specific cathode heater power data from several references are shown as functions of specific cathode emission current. These parameters are the power and emission current values for each configuration divided by the cathode surface area. Except for the tantalum wire and ribbon data and the oxide magazine cathode data below 0.4 A/cm^2, all points fall below the 40 W/A SERT II specifications. It should be noted that the ordinate scale has been broken to include all data. It was not possible to find data that correlated specific heating power for all types of cathodes to exact operating conditions (thruster size, propellant utilization efficiency, neutral mercury flow rate, etc.). However, the relative levels of specific cathode heater power give an indication of the merit of each configuration.

Liquid Mercury Cathode

Another set of tests conducted at Hughes Research used a liquid mercury pool as an electron emission source.[21,22] Figure 10 illustrates the basic design of the cathode. Mercury is force fed into an annular reservoir structure fabricated of molybdenum. Cohesive forces keep the mercury pool intact. The liquid metal level in the divergent nozzle, pool-keeping structure is stabilized by keeping the rate at which mercury is pumped into the cathode equal to the rate of mercury evaporation. The annular gap must be maintained between 2 and 12 μ, which proved to be a fabrication problem. A high voltage pulsing power supply (~30 kV) with negligible power capacity is necessary to obtain the initial discharge. The electrons are emitted from arc spots on the liquid surface, and the neutral atoms are evaporated due to absorbed discharge power. This cathode design requires no heater power while operating, nor does it need any vaporizer power. However, an electromagnetic feed pump uses the same power level as a conventional vaporizer. Test results show that a low specific heating power is possible (10 W/A) and lifetimes in excess of 3000 hours have been achieved. This cathode can be preflight tested, which is a desirable feature.

Hollow Cathode

The development of a hollow cathode configuration had proceeded to the point where it warranted consideration for the SERT II program.[19,23] It had lifetime tests in excess of 10,000 hours and a specific heating power normally much below 40 W/A (the SERT II design specification). It finally became the flight version cathode.[18] An experimental hollow cathode used for both the SERT II (15-cm) and 5-cm thrusters is shown in figure 11. The main components of the hollow cathode assembly are a 0.32-cm diam tantalum tube, a 0.1 cm thick, 2 percent thoriated tungsten disk electron beam welded to the tube, a tungsten-rhenium heater coil, a coating of aluminum oxide for insulation, and 10 or more wraps of 0.001 cm thick tantalum foil for heat shielding. The tungsten disk had a tapered orifice with a 0.02-cm diam upstream and 0.03-cm diam downstream. An insert made of 0.001 cm thick tantalum foil is coated with a commercial mixture containing barium carbonate to facilitate starts, rolled into a coil, and installed within the tubing. The foil is approximately 10 cm long and 1.8 cm wide. A strip 2.5 cm by 0.16 cm is cut from the foil to provide an open cavity in the vicinity of the orifice. To facilitate initial startups by providing a sufficiently high electrical gradient, a loop of 0.15-cm diam tantalum wire with a nominal inside diameter of 0.63 cm was placed approximately 0.15 cm downstream of the tip. This electrode is called the keeper. A more detailed description of the SERT II cathode can be found in reference 24. A similar cathode designed for the 30-cm thruster has been developed to give efficient performance.[25] A larger cathode tube diameter, 0.64 cm as compared to 0.32 cm for the 5- and 15-cm thrusters, is necessary for the 30 cm thruster emission requirements and long lifetime. It was experimentally determined that a workable orifice size should be between 0.08-cm to 0.160-cm diameter. The spacing between the keeper and tip is 0.2 cm.

A second hollow cathode configuration has also been tested. It is called the enclosed keeper cathode. The difference between the open and enclosed keeper configuration is that the enclosed design has a ceramic tube connecting the keeper and cathode (Fig. 12). A 0.025 cm tantalum disk is used as the keeper cap. The enclosed keeper cathode reduces radiated heat losses and provides positive spacing and alinement.[25] It also extends the range of stable operation to low propellant flow rates (down to ~2 mA neutral flow).

The advantages that the hollow cathode has over previous oxide and refractory metal cathode designs are its ability to be retested after exposure to air, the ability to be ground tested before launch, and a heating requirement of only 2% of total power consumption (SERT II: 15 W tip heater and 30 W total for isolator, keeper, and tip power).[17] The corresponding specific heating power is 15 W/A. (The 30-cm and 5-cm thruster hollow cathode have operated at less than 10 W/A and about 40 W/A, respectively.) These advantages outweigh the fact that a keeper electrode to aid in starting and a baffle to control discharge voltage had to be developed. (With mercury as a propellant, the hollow cathode normally operates at about 10-15 volts. The baffle reduces the coupling between the cathode and the higher discharge voltage of 30-40 volts.) A redesigned feed system to introduce propellant through the cathode as well as into the discharge chamber is required with the hollow cathode but can be readily accomplished.

In flight the hollow cathode has proven to be a reliable electron emitter by its performance during the SERT II mission. No cathode problems were encountered during startups or operation of the SERT II thruster.

Operating Procedure

Mercury vapor is fed to the cathode by means of a 0.147 cm thick porous tungsten plug welded to the feed tube. The bulk density of the plug is 70% of that of solid tungsten and the average pore diameter is 5 μ. A swaged tantalum heater element is brazed to the vaporizer tubing. Neutral flow is controlled by varying the heater power. Typical 5-cm thruster vaporizer temperature as measured by a thermocouple is 573° K (40 mA equivalent flow).[26]

A heater located at the tip of the cathode (Figs. 11 and 12) prevents mercury condensation in this area and provides the surface temperatures (approximately 1200° K) required to decompose the barium carbonate located on the insert into free barium. The barium provides a minimum of 100 μA of thermionic emission.

A positive potential of several hundred volts on the keeper is necessary to initiate the hollow cathode discharge. Once the discharge has started the voltage is lowered to about 15 volts for steady state operation.

For the hollow cathode three basic requirements for initiating a discharge must be present.[27] There must be sufficient thermionic electron emission, sufficient neutral mercury density, and sufficient accelerating potential for the thermionic electrons. The starting procedure described above fulfills these requirements.

Cyclic Starts

As previously mentioned, the 5-cm thruster is potentially applicable for satellite station keeping and attitude control. For such a mission it will be necessary to start and stop the thrusters at least once every 24-hour duty-cycle period. The thrusters will operate for 25 percent to 80 percent of the cycle period (24 hr). It is, therefore, necessary to determine whether the cathode can cycle for many sequences (~4000 for 10 year mission). A reliable starting procedure is also essential. A program was undertaken to demonstrate long cyclic lifetime and determine a consistent starting sequence for both the open and the enclosed hollow cathodes.

The experimental setup is exactly like the bell jar test of reference 27. A 50 cm diameter by 50 cm long cylindrical bell jar which maintained a pressure of $5x10^6$ torr or lower was used. A 2.54 cm x 3.91 cm tungsten screen was used as a simulated anode. The anode (collector) could be moved longitudinally with respect to the cathode. A potential of 40 volts was maintained on the anode for all tests. The only variation in testing compared to that of reference 27 was that an automatic timer controller was used to start and stop the various power supplies during cyclic operation. (Table II gives the component power supply capacities.) Mercury was supplied from a 20 millimeter diameter, precision-bore, calibrated glass tube. The neutral flow rate was determined by taking periodic mercury level readings. The optimum cyclic sequence for both cathodes is shown in figure 13. The cycle consists of turning on the vaporizer and cathode tip heater at time zero. A delay of 3.5 to 10 minutes, depending on keeper hole size and vaporizer size, was necessary to allow cathode and vaporizer to reach the required conditions, e. g., tip temperature of 1200° K and nominal flow of 45 mA. When the keeper electrode was activated, a near-instant discharge was obtained (10-18 msec delay). Oscilloscope photographs of the starting voltage surge showed that the required potential varied from 190 to 600 volts. After a discharge started, the keeper voltage was reduced to 10 - 20 volts (automatically by means of a ballast resistor), and the cathode tip power was turned off. The cathode ran in this mode for 7 minutes. At the end of the run, the vaporizer and keeper power supplied were turned off. A cooldown period of 15 minutes followed the shutdown.

One cathode has been tested for 1476 cycles and another for 321 cycles using this optimum sequence with no apparent degradation of performance. The former cathode was actually operated for a total of 3200 cycles; the first 1724 cycles being conducted with non-optimum sequences.

The bell jar was opened a number of times to inspect the cathode. For the convenience of keeping all power settings and timers constant, a commercial oxide mixture was put on the outside surface of the cathode tip. This coating assured starting within the 10-minute warmup period, of the first cycle after exposure to air. It is felt to be unimportant after several hours of running. Tests are being conducted to determine the exact mechanism that causes delayed starts and sometimes non-starts after exposure to air. This problem can be overcome at least temporarily by increasing the tip temperature and allowing a longer warmup (~20 min).

Diagnostics

Although the Kaufman ion thruster has developed into an efficient system, the exact physics of thruster operation are not fully understood. The operation of the hollow cathode is also vague. The external discharge plasma from a SERT II type hollow cathode was studied[28] and electron temperature and density profiles obtained. A cylindrical Langmuir probe was used to analyze the discharge. The characteristics of a spot mode (ref. 29) and plume mode operation were obtained. The spot mode corresponds to a high current and low voltage condition. (Typical values for the 5 cm diameter hollow cathode are 0.2 A and 15 V, respectively.) The plume mode has a low current (0.1 A) and a high voltage (50 V) characteristic. The method by which probe traces are used to calculate electron density, plasma potential and electron temperature is given in the appendix of reference 28. Although this reference has described some aspects of a theoretical model, a satisfactory model which describes the electron emission mechanism, the flow and spatial distribution of electrons, ions, and neutrals, the form of the potential gradients, and ion distribution in the discharge has yet to be developed.

Conclusion

A variety of cathode designs have been used for the electron bombardment ion thruster. The different types range from the early refractory metal type to the presently used hollow cathodes. The search for a reliable flight cathode has yielded many other cathode configurations that can be easily made and have moderate lifetimes. However, the hollow cathode has proven to be the best design to date for electric propulsion application. Empirically developed configurations have overcome all of the problems encountered to date without indicating a fundamental limit to the concept.

The hollow cathode is capable of long lifetimes, reliable cyclic starts, and low power requirements for operation. Nevertheless, a detailed analysis of the operation of the hollow cathode has not yet been achieved.

TABLE I

RANGE OF EMISSION CURRENT REQUIREMENTS FOR 5-, 15-, AND 30-CM THRUSTERS

Thruster size, cm	Range of Emission Current, A
5	0.2-0.5
15	1.3-3.1
30	7.5-19.

TABLE II

CATHODE COMPONENT POWER SUPPLY CAPACITIES

Component	Voltage Limit, Volts	Amperage Limit, Amps
Vaporizer	5	5
Cathode tip	15	15
Keeper	600	No load
(High voltage)	40	.020
Keeper		
(Low voltage)	50	.200
Anode	100	1

References

1. H. R. Kaufman, "An Ion Rocket with an Electron-Bombardment Ion Source," NASA TN D-585 (1961).

2. W. H. Kohl, Handbook of Materials and Techniques for Vacuum Devices (Reinhold Publishing Corp., 1967).

3. R. T. Bechtel, J. Spacecraft Rockets 5, 795 (1968).

4. S. Nakanishi and E V. Pawlik, J. Spacecraft Rockets 5, 801 (1968).

5. J. P. Mullin, T. Barber, and C. Zola, "A Survey of Solar Powered Electric Propulsion for Automated Missions," AIAA Paper 68-1120 (1968).

6. P. D. Reader and J. D. Regetz, "A Delta-Boosted, Electrically Raised High Power Synchronous Satellite," AIAA Paper 69-1104 (1969).

7. R. A. Boucher, J. Spacecraft Rockets 1, 164 (1964).

8. K. I. Duck, R. O. Bartlett, and R. J. Sullivan, "Evaluation of an Ion Propulsion System for a Synchronous Spacecraft Mission," AIAA Paper 67-720 (1967).

9. R. J. Cybulski, D. M. Shellhammer, R. R. Lowell, E. J. Domino, and J. T. Kotnik, "Results from SERT I Ion Rocket Flight Test," NASA TN D-2718 (1965).

10. W. R Kerslake, D. C Byers, V. K. Rawlin, S. G. Jones, and F. D. Berkopec, "Flight and Ground Performance of the SERT II Thruster," AIAA Paper 70-1125 (1970).

11. W. R. Kerslake, "Oxide-Cathode Durability in Mercury Electron-Bombardment Ion Thrustor," NASA TN D-3818 (1967).

12. H. L. Milder and W. R. Kerslake, "Evaluation of Filament Deterioration in Electron-Bombardment Ion Sources," NASA TN D-2173 (1964).

13. W. Knauer, G. Hager, H. Gallagher, and E. Stack, "Investigation of the Discharge in Electron Bombardment Thrustors," AIAA 66-244 (1966).

14. W. R. Kerslake, "Cathode Durability in the Mercury Electron-Bombardment Ion Thrustor," NASA TM X-52037 (1964).

15. P. D. Reader and E. V. Pawlik, "Cathode Durability Tests in Mercury Electron-Bombardment Ion Thrustors," NASA TN D-4055 (1967).

16. W. R. Kerslake, "Preliminary Operation of Oxide-Coated Brush Cathodes in Electron-Bombardment Thrustors," NASA TM X-1105 (1965).

17. D. C. Byers, "Performance of Various Oxide-Magazine Cathodes in Kaufman Thrusters," NASA TN D-5074 (1968).

18. W. R. Kerslake, D. C. Byers, J. F. Staggs, "SERT II Experimental Thrustor System," NASA TM X-52323 (1967).

19. R. T. Bechtel, G. A. Csiky, D. C. Byers, "Performance of a 15-Centimeter Diameter, Hollow-Cathode Kaufman Thrustor," NASA TM X-52376 (1968).

20. W. Knauer and H. Gallagher, "Low Work Function Cathode Development," Hughes Research Laboratories, NASA CR-54682 (1966).

21. P. D. Reader and H. J. King, "Systems Characteristics of Liquid Cathode Thrusters," AIAA Paper 69-237 (1969).

22. J. Hyman, Jr., W. O. Eckhardt, J. R. Bayless, J. A. Snyder, and J. W. Pfeifer, "High-Temperature LM Cathode Ion Thrustors," Hughes Research Laboratories, NASA CR-105424 (1969).

23. V. K. Rawlin and E. V. Pawlik, J. Spacecraft Rockets 5, 814 (1968).

24. D. C. Byers and J. F. Staggs, "SERT II Flight-Type Thruster System Performance," AIAA Paper 69-235 (1969).

25. R. T. Bechtel, "Component Testing of a 30-Centimeter Diameter Electron Bombardment Thruster," AIAA Paper 70-1100 (1970).

26. P. D. Reader, S. Nakanishi, W. C. Lathem, and B. A. Banks, "A Sub-Millipound Mercury Electron-Bombardment Thruster," AIAA Paper 70-616 (1970).

27. V. K. Rawlin and W. R. Kerslake, "Durability of the SERT II Hollow Cathode and Future Applications of Hollow Cathodes," AIAA Paper 69-304 (1969).

28. G. A. Csiky, "Measurements of Some Properties of a Discharge from a Hollow Cathode," NASA TN D-4966 (1969).

29. R. F. Kemp and D. F. Hall, "Ion Beam Diagnostics and Neutralization," TRW Systems Group, NASA CR-72343 (1967).

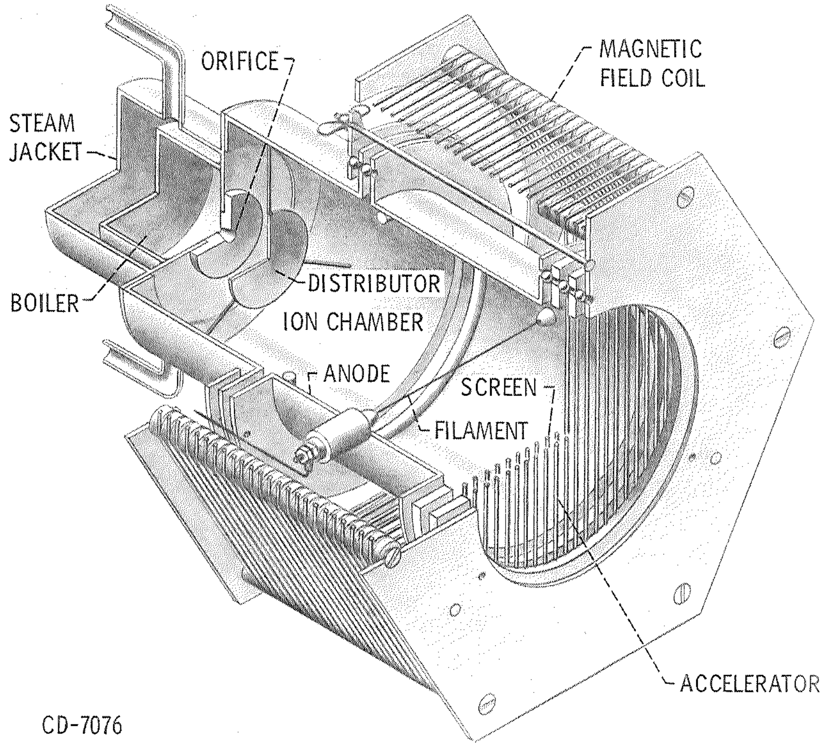

Figure 1. - Cutaway sketch of Kaufman ion thruster.

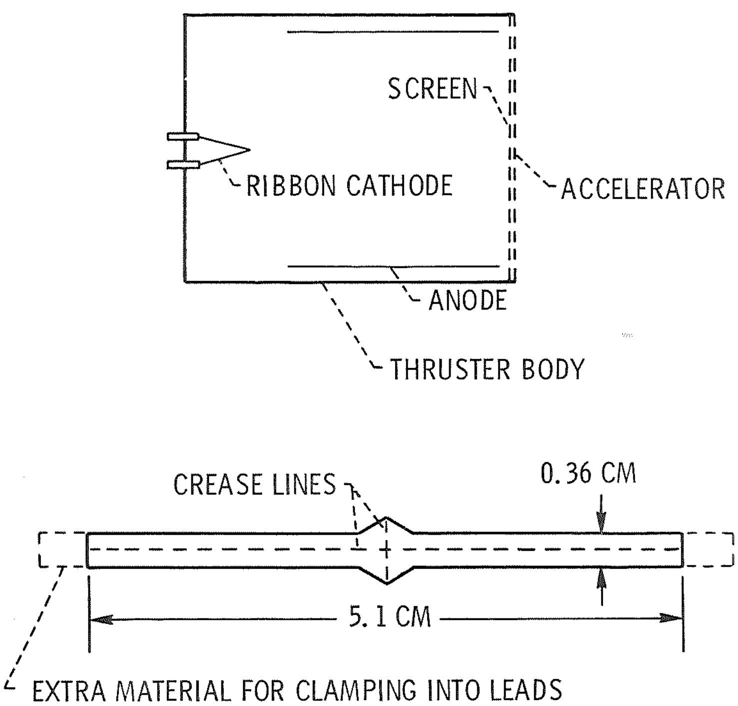

Figure 2. - Ribbon filament geometry and location in thruster.

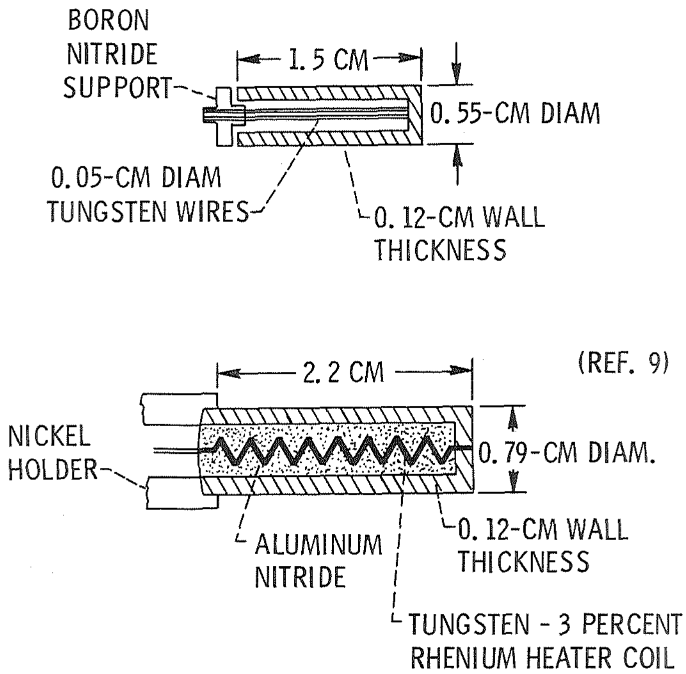

Figure 3. - Oxided-impregnated nickel-matrix cathodes.

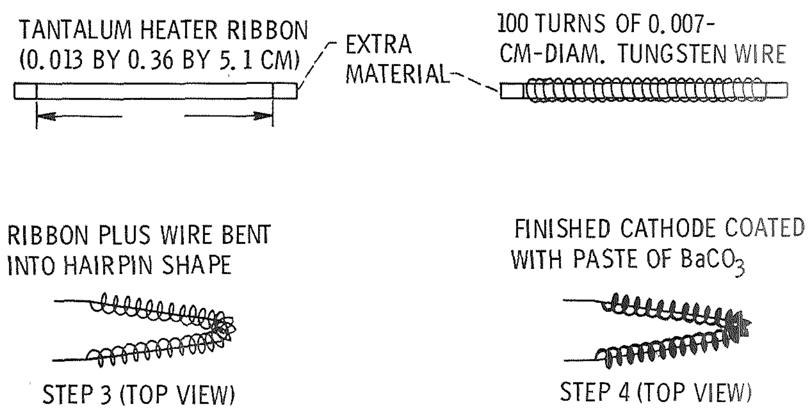

Figure 4. - Thick oxide layer cathode.

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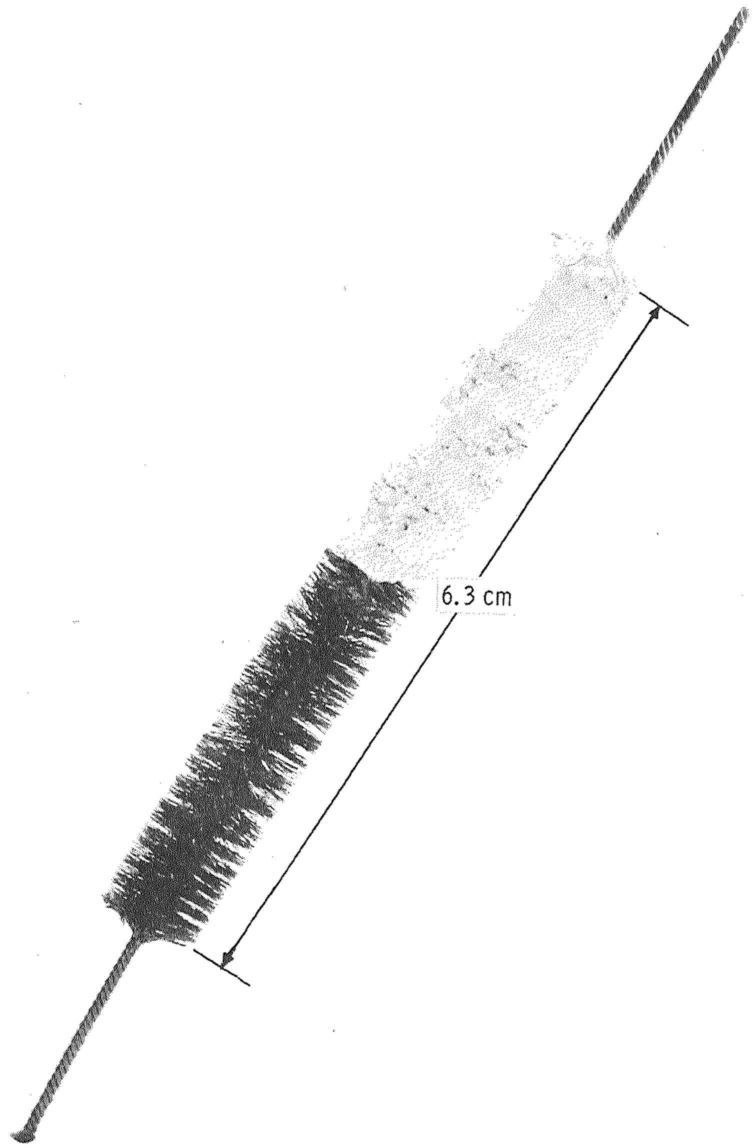

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Figure 5. - Tantalum brush cathode half-coated with commercial carbonate mixture.

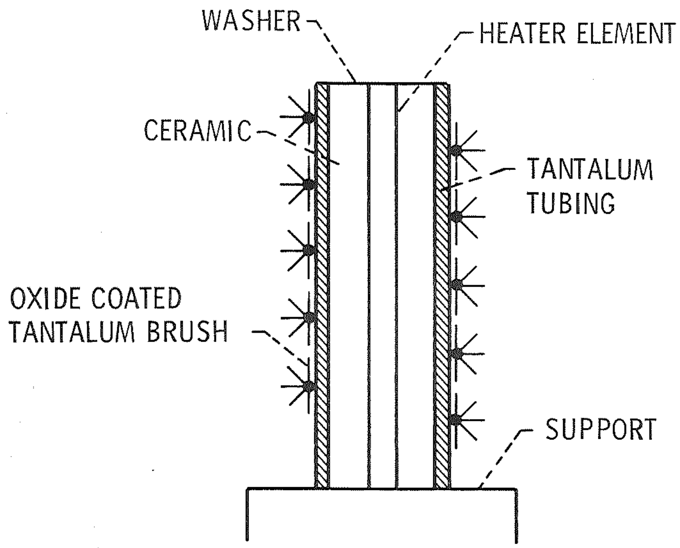

Figure 6. - Indirect heating cathode.

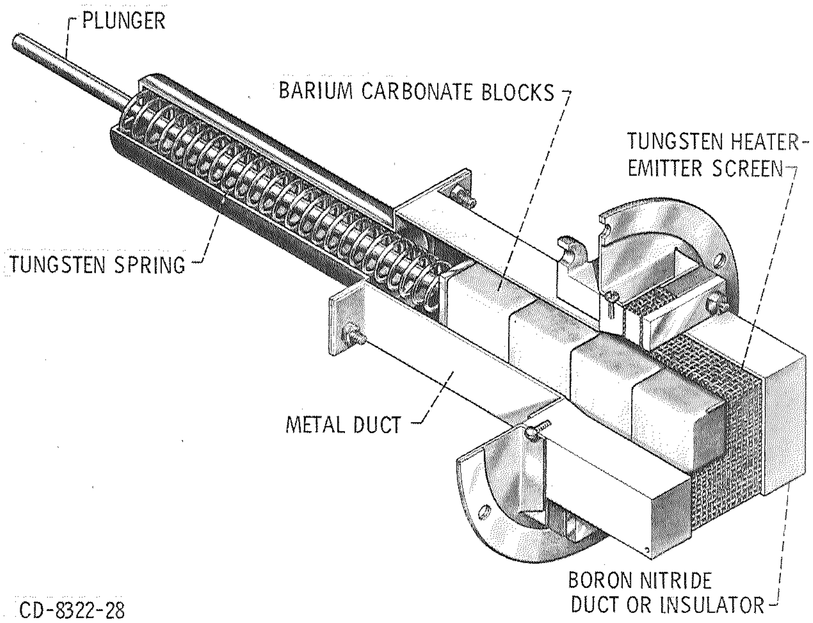

Figure 7. - Typical oxide-magazine cathode.

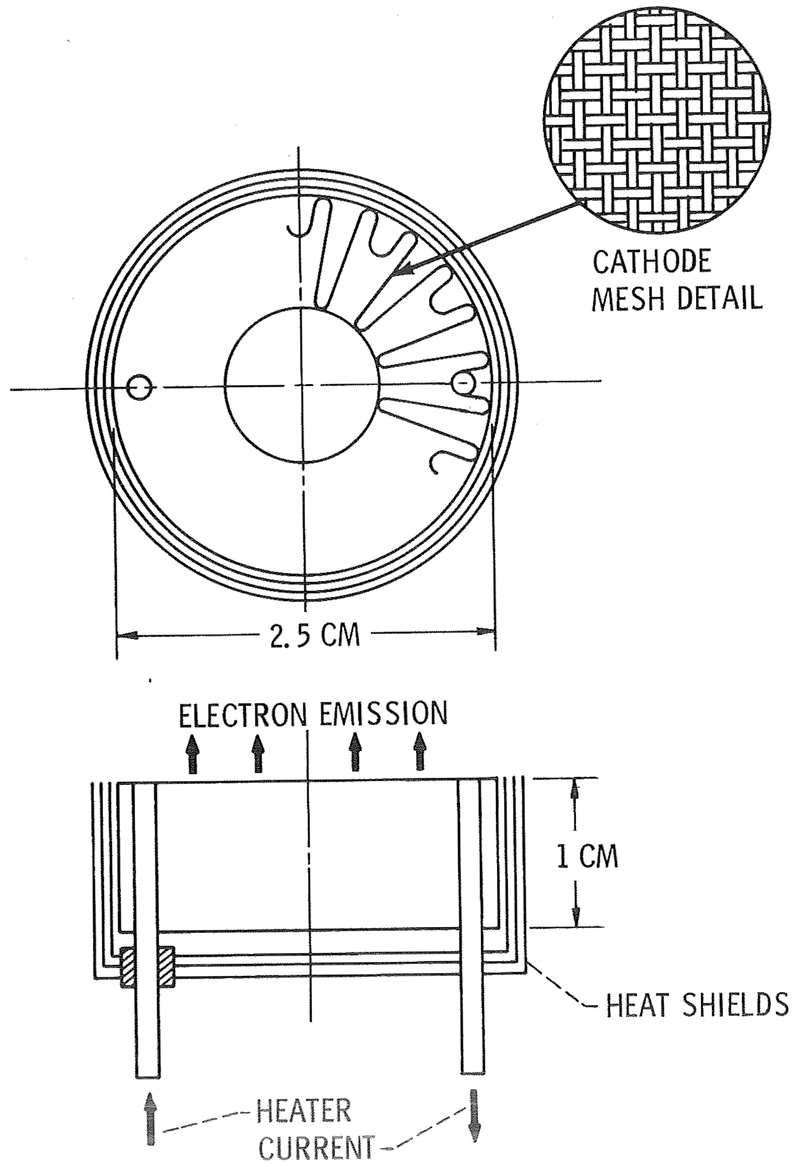

Figure 8. - Flower cathode geometry.

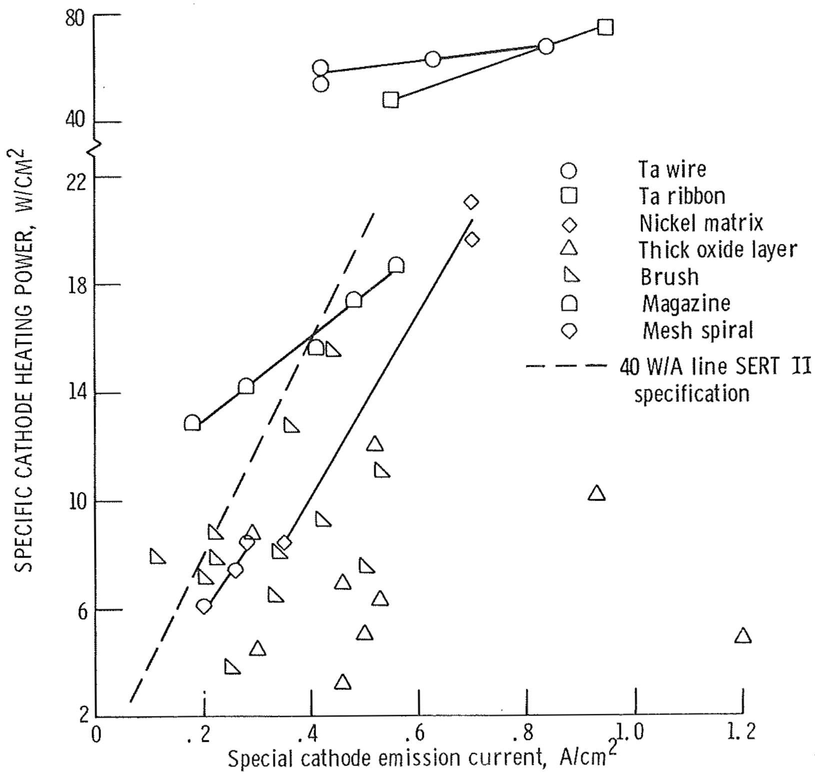

Figure 9. - Specific cathode heating power as a function of specific cathode emission current for refactory metal and oxide coated cathodes.

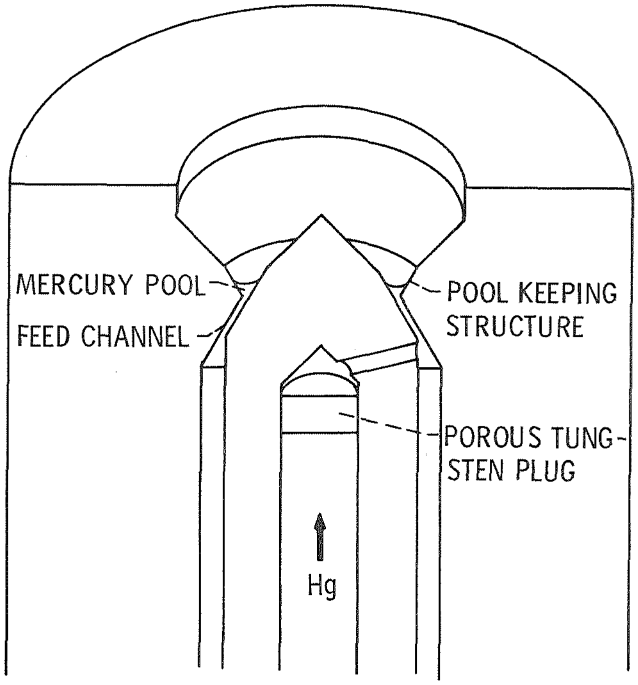

Figure 10. - Annular liquid metal cathode with porous tungsten flow impedance.

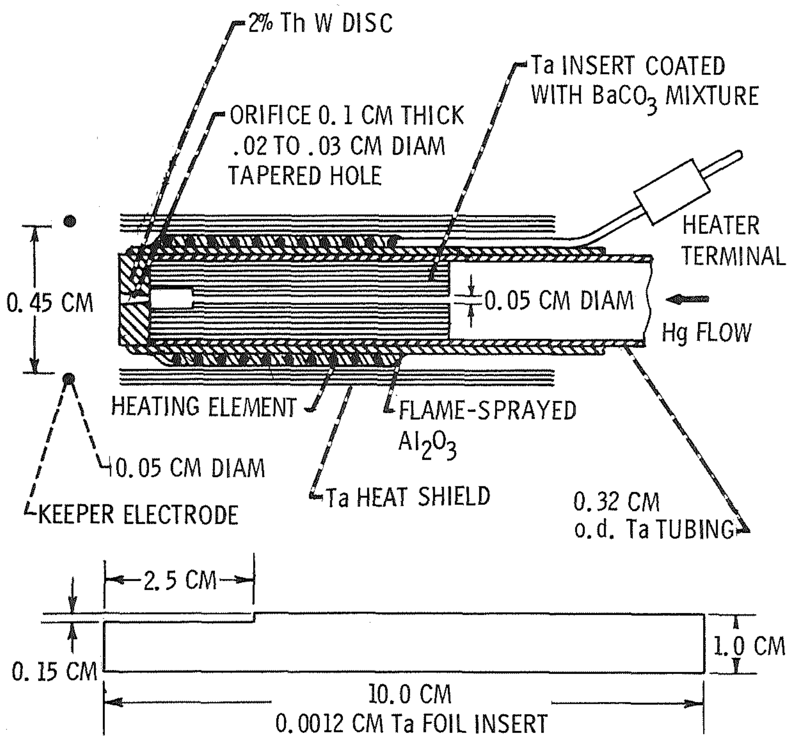

Figure 11. - Open keeper cathode construction.

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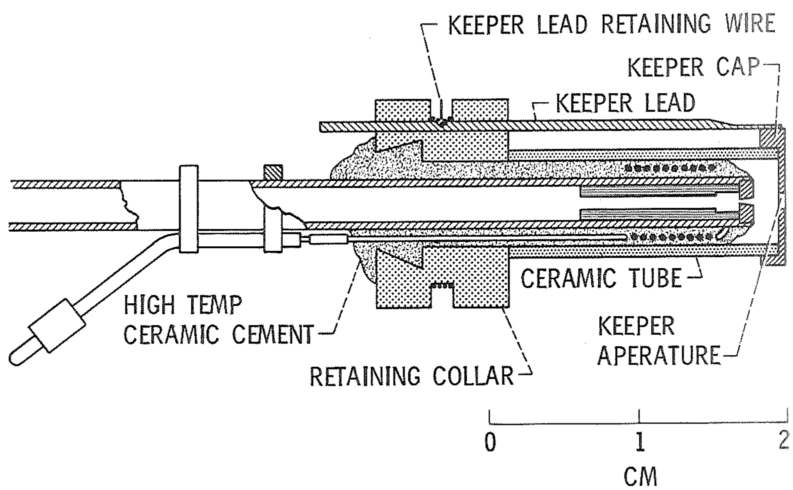

Figure 12. - Enclosed hollow cathode configuration.

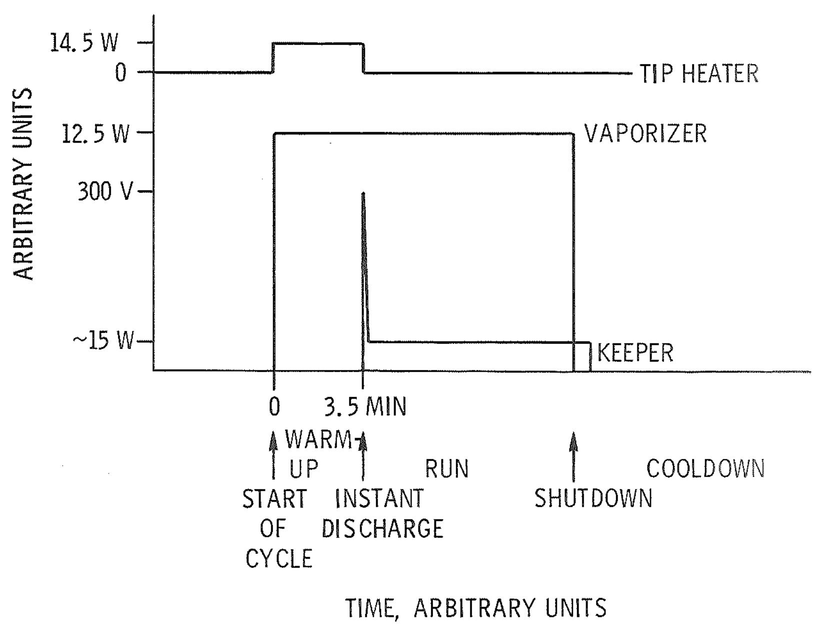

Figure 13. - Optimum cyclic sequence.