N72-27825

NASA TECHNICAL MEMORANDUM

NASA TM X- 68110

NASA TM X- 68110

5-CM DIAMETER ION THRUSTER DEVELOPMENT PROGRAM SUMMARY, JUNE 1972

by A. J. Weigand
Lewis Research Center
Cleveland, Ohio
July, 1972

This information is being published in preliminary form in order to expedite its early release.

E-7048

5-CM DIAMETER ION THRUSTER DEVELOPMENT

PROGRAM SUMMARY, JUNE 1972

by A. J. Weigand

Lewis Research Center

SUMMARY

The 5-cm diameter mercury ion bombardment thruster has reached a stage in its development where preparations are being made for flight applications. All system components have been tested for endurance and steady state and cyclic operation. Most tests are still proceeding, but as of June 1972, the following results have been obtained: acceleration system (electrostatic type) 3100 hours continuous running, acceleration system (translation type) 2026 hours continuous running, cathode-isolator-vaporizer assembly 5000 hours continuous operation and 190 restart cycles with 1750 hours operation, mercury expulsion system 5000 hours continuous running, neutralizer 5100 hours continuous operation. The results of component optimization studies such as neutralizer position, neutralizer keeper hole, and screen grid geometry are included. Extensive mapping of the magnet field within and immediately outside the thruster are shown. A technique of electroplating the molybdenum accelerator grid with copper to study erosion patterns is described. Results of tests being conducted to more fully understand the operation of the hollow cathode are also given. This type of 5-cm thruster will be space tested on the Communications Technology Satellite in 1975.

INTRODUCTION

The 5-cm-diameter mercury ion bombardment thruster (Kaufman thruster) has application for attitude control of small communication, weather, and surveillance satellites and station-keeping of satellites in synchronous orbit. Although 15-cm thrusters (SERT II) have demonstrated the use of electric thrusters for space application, the 5-cm design has yet to be tested. Within the past year the United States and Canada have agreed to a joint satellite mission. This program, called the Communication Technology Satellite, will provide radio and telephone communications to all parts of Canada, including the remote northern section. Although communications is the primary purpose of the satellite, experiments of advanced technology will also be conducted. A 200-watt traveling wave tube, a liquid metal slip-ring, and a 5-cm ion thruster will be tested in space for the first time.

The 5-cm thruster program at Lewis Research Center has gone from an advanced technology study to a more development oriented program with test results keyed to CTS milestone dates and deadlines. To accomplish this transition in a short time, many durability and optimization tests have been recently conducted. All major components of the thruster have been or are being endurance and cyclic tested. These tests include the accelerator system (both electrostatic and translation type), cathode-isolator-vaporizer assembly, neutralizer, and mercury expulsion system.

The neutralizer keeper hole has been sized to give low coupling voltage at stable, low-flow conditions. The neutralizer position with respect to the thruster has been changed to eliminate accelerator grid erosion due to ions from the neutralizer. The accelerator screen grid geometry has been optimized to provide the lowest possible drain current to the accelerator.

The magnetic field of a standard 5-cm thruster has been mapped both inside the chamber and immediately downstream of the accelerator grids. Heater studies, startup tests, and insert design tests have been performed with the hollow cathode. The use of dished accelerator grids is also described. Other progress that has been made over about the past year on the development of the 5-cm thruster is reported herein.

This summary is an accumulative effort of all those researchers studying the 5-cm thruster. Shigeo Nakanishi worked on the expulsion and thruster life tests and optimized the neutralizer position. Walter Lathem was responsible for the vector grid program and participated in the endurance tests. Bruce Banks designed and fabricated the pillow-shape-square aperture screen grid and the multiple size hole screen grid. He also developed the method of dishing grids. Wayne Hudson has been studying the relationship between the operation of the hollow cathode and the insert and tip heater. He is also involved in both the neutralizer life test and keeper optimization study and has helped analyze the accelerator grid erosion tests. Ted Sheheen performed hollow cathode studies emphasizing breakdown characteristics for various cathode configurations with and without a barium carbonate coated insert. John Power contributed the magnetic field mapping data, developed the method of electroplating copper onto molybdenum for grid erosion studies, and is involved in the composite grid program.

Testing to Flight Conditions

It is recognized that a flight system, such as the 5-cm thruster, should be tested in actual mission conditions as early as possible during development. In order to accomplish this testing, various components (main cathode, neutralizer, grids, etc.) were tested in bell jars. Although the complete thruster system was not used, the apparatus was designed to simulate thruster operation. Screens with proper voltages were used to simulate the anode in the discharge chamber for main cathode studies and to simulate the beam potential for neutralizer studies. After optimizing the components and determining the steady-state characteristics, they can be integrated into the thruster system.

The 5-cm mercury bombardment ion thruster will be flight tested on the Communication Technology Satellite (a joint project between the United States and Canada). The launch date is in 1975. The thruster will be tested for attitude control and station-keeping and should perform for the 2-year mission of the spacecraft. (A hydrazine resistojet will perform these functions during normal satellite operation.) The anticipated maximum thruster duty cycle is 12 hours on, 12 hours off. Hollow cathodes will be used for the thruster main cathode and neutralizer. The only physical difference between the main cathode and neutralizer is the keeper orifice diameter which is 0.25 cm and 0.08 cm, respectively. Other cathodes of this type have been life tested for over 13,000 hours (ref. 1) and cyclic tested for more than 3200 restarts (ref. 2). In both tests a flame sprayed alumina tungsten rhenium element was used for the tip heater. A test was set up to duplicate a typical operational duty cycle of the main cathode on board the satellite.

Figure 1 shows the operating sequence. It consists of four parts. During the warmup portion, the tip and vaporizer heaters were turned on. After waiting 15 minutes (which depends on the vaporizer time constant), the keeper high voltage was applied and a discharge was obtained (10 - 20 millisecond delay). The cathode ran for 10.5 hours at normal operating conditions (tip heater power was zero). Shutdown consisted of turning the vaporizer heater and keeper off. Everything remained off for a 1.6 hour cooldown. This was the time required for the cathode assembly to reach room temperature.

A prototype cathode-isolator-vaporizer assembly (CIV), designed and fabricated by Hughes Research Laboratories, is presently being cycle tested. (The isolator and vaporizer are an integral part of the cathode but have no bearing on its operation.) Figure 2 shows a cross section of the CIV. One should note the use of a flame sprayed alumina, tungsten rhenium tip heater element. This heater is more reliable than the swaged heaters previously employed. (A more detailed account of the CIV is given in ref. 3.) This CIV has successfully restarted 190 times with an accumulated run time of 1750 hours.

A prototype ion thruster with an electrostatic beam deflection acceleration system and neutralizer has been tested for over 3100 hours. The thruster functioned continuously for the test. There were five restarts necessary because of power supply failures and facility problems.

The components of the thruster included a CIV and neutralizer. Both had swaged tip heaters. This type of heater is easier to fabricate than the flame sprayed type. Since there was to be no cyclic testing, the swaged heaters were used. The ion extraction system was an electrostatic dual-grid system capable of vectoring the beam in any direction. This component is shown in figure 3. The accelerator strips were 0.25 cm wide and 0.05 cm thick. The screen grid had a square array of circular holes of three different diameters. Figure 4 shows the screen geometry. The three diameters were 0.253, 0.287, and 0.318 cm. The smallest holes were in the center of the grid; the largest along the perimeter. The screen-to-accelerator spacing was 0.075 cm. A beam current of 25 mA was extracted with a positive voltage of 1000 volts and negative voltage of -1000 volts. During the first 1000 hours of testing, the beam was unvectored. The second 1000 hours were run with the beam vectored at various angles and in various positions. For each angle setting, the beam was vectored toward each accelerator element for one-quarter of the total time. For example, the first vectored angle was 2°. During the first 144 hours, the beam was vectored toward the elements on the top (fig. 3). The beam was rotated 90° (by changing the voltages on the elements) toward the elements on the right. This orientation was maintained for another 144 hours. The beam was changed by 90° again so that it was vectored toward the elements on the bottom of the figure. The final position was with the beam toward the elements on the left. The total accumulated time was 576 hours. This approach was used for every beam vectoring angle tested. Chronological order of vectoring with the number of hours at each angle was 2° (576 hours), 3° (192 hours), 4° (96 hours), 5° (48 hours), 6° (32 hours), 7° (24 hours), 8° (16 hours), 9° (12 hours), and 10° (8 hours). The total time of operating in a vectored mode was 1004 hours. It was felt that the time interval at each vector angle simulated flight conditions. After completing the 2004 hour sequence, the sequence was started again. As of June 1, 1972, the second 1000 hours of unvectored operation have been completed and almost 100 hours of 2° vectoring have been surpassed.

Extraction System Optimization

An optimization program was undertaken to determine the screen design that gave the lowest direct ion impingement on the electrostatic accelerator grid. Each aperture of the accelerator grid was a square while the usual screen aperture is circular. This geometry produces different beamlet shapes than the circular accelerator-screen design. Damage of the accelerator grid due to direct ion impingement could obviously be a problem.

The results of another test (ref. 4) that used various screen hole geometries (triangles, rectangles, and hexagons) showed that to get a square beamlet, a "puffy" or pillow-shape-square aperture screen is needed (fig. 5). Different open area screens were fabricated and tested. The results showed that the 50 percent open area gave the lowest impingement current. However, the improvement over the circular hole screen was not great.

Another attempt at improvement in the screen grid design was the use of a multiple size hole configuration. The beam profile of the 5-cm thruster shows a high concentration of current in the center of the thruster. The high current density tends to cause erosion (both direct impingement and charge exchange erosion) problems in this area. To alleviate the erosion, a multiple size hole screen was tested (fig. 4). The holes were made smallest in the center of the grid. Two other size holes were used, the largest along the perimeter of the grid. This design lowered the drain current sufficiently to allow its use in the 3100 hour electrostatic vectoring grid life test. (The measured drain current to the accelerator is less than 100 μA for a beam of 25 mA without vectoring.)

Accelerator Grid Plating

The accelerator-screen design optimization program consisted of testing many configurations. Each one had to be tested for a sufficient amount of time to allow visible erosion of the accelerator grid. It was also desired to keep the accumulative amount of erosion low so that the same accelerator grids could be used for all tests. A method was developed that could allow short erosion tests and prevent excessive accumulative erosion.

The procedure entailed electroplating copper onto the molybdenum accelerator grids. The copper plating thickness was approximately 0.5 micron. The plating adhered to the molybdenum substrate quite well, and a uniform thickness could be applied. Because of the difference in appearance of the two materials, runs on the order of 2 hours were sufficient to determine sputtering damage. After each test, the plating was removed without affecting the molybdenum, and the grids were recoated for another test. The down time between runs was 1 day, which is shorter than the time required to observe erosion on uncoated accelerator grids. A more detailed account of the optimization tests and the plating procedure is given in reference 5.

The no-moving-part, electrostatic dual-grid system is the preferred extraction system for the 5-cm thruster. However, another system, the translational screen-grid system, has been life tested for more than 4050 hours and shows capability as being an alternate extraction system. This design (fig. 6) consists of two match-drilled molybdenum grids with circular holes in a hexagonal array. A system of springs mounted on the screen grid allow the screen to move and provides vectoring.

Beside the preliminary operational and endurance testing performed at Hughes Research Laboratories, extensive testing was conducted at Lewis (ref. 6). The operational characteristics of the translational screen-grid vectoring system were studied. Response times of the springs, which deflect the screen as a function of power dissipated in the springs, were determined. The zero power cooling characteristics were also measured.

Results indicated that by using 14 watts on the springs, a maximum deflection of 16.4° could be obtained in 1 minute. It was also shown that an ion beam deflection of 10° was maintained with a heating power of 1.2 watts to the springs.

The translational screen-grid system was endurance tested for 2026 hours (ref. 7). All engine components, except the grid, were later used in the electrostatic grid endurance test. The screen grid had a hexagonal array of circular holes 0.024 cm diameter on 0.029 cm center-to-center spacing. The accelerator had matched hexagonal array of circular holes 0.024 cm diameter. The screen thickness was 0.006 cm, and the accelerator thickness was 0.013 cm. The screen-to-accelerator spacing was 0.012 cm. The beam current was 25 mA. The positive voltage to maintain the discharge was 1000 volts, and the negative voltage was -1000 volts. The beam was vectored 10° for the entire test. (The screen grid was displaced 0.032 cm to obtain the vectoring.)

Examination of the grids after the test showed very little erosion. Extrapolation of the erosion rate indicated a possible grid life of 10,000 to 20,000 hours (ref. 7). Additional testing in another facility has accumulated another 2024 hours on the translating screen system. This testing is continuing at 4050 total hours.

Other prototype components of the 5-cm ion thruster are being life tested. The mercury expulsion system includes a mercury reservoir tank, rubber diaphragm, and nitrogen gas supply (fig. 7). This system is being tested in a bell jar. A CIV assembly is connected to the tank. The cathode has completed 5000 hours of continuous operation. The isolator is supporting the normal thruster operating potential. There are no signs of deterioration from any of the components.

Extensive tests have been performed on the enclosed-keeper hollow cathode neutralizer. A life test of a prototype Hughes neutralizer is at 5100 hours and still operating. The dependence of neutralizer coupling characteristics and stable operating conditions on keeper hole diameter has also been investigated. An optimum diameter (0.08 cm) has been incorporated into the design so that the neutralizer has low coupling voltage (<20 volts) and can run at low flows (~ 2 mA neutral flow) stably.

A study to optimize neutralizer position is presently being conducted. Using data obtained from tests performed on the 30-cm ion thruster (ref. 7), the neutralizer for the 5-cm thruster has been positioned farther downstream and radially away from the accelerator grid (between 2.5 and 3.8 cm downstream and about 5.1 cm radially out). The two life tests previously mentioned had the neutralizer in this approximate position. Both tests maintained coupling voltages of less than 15 volts. Complete mapping of neutralizer coupling voltage as a function of radial and axial distances from the grid has been determined. It has been found that coupling voltage is independent of neutralizer position as long as keeper current is greater than 0.35 A (ref. 9). The range of distances tested was 2.5 to 5.0 cm both radially and axially. This optimization study is being put into a report authored by Shigeo Nakanishi.

ADVANCED TECHNOLOGY EFFORTS

The 5-cm thruster provides a ready test article for advanced technology components because of the small size (and usually expense) of its parts and modest facility requirements.

Grids

The use of composite grids as screen components showed promise because of the decrease in accelerator to screen gap which raised the beam current to accelerator voltage ratio. It was found that facility backsputter hindered the testing of the glass coated grids (ref. 11). In addition, bubbles in the insulating coating caused premature grid failure. However, other composite grid designs are being considered and tested.

The use of uniform, nonporous, insulating oxide coatings on various metals is being pursued. The oxide coating is achieved by introducing air into a furnace containing the metal substrate. Preliminary results show that a zirconium alloy (zircaloy 2) may have desirable qualities.

Another composite type grid tested is the ceramic screen design. A machineable ceramic milled to a thickness of 0.38 mm was tested. The accelerator design was a linear strip configuration. The preliminary results indicated backstreaming from the neutralizer couldn't be stopped, and there was high drain current. Smaller apertures will be tested in a final attempt to rectify this problem.

The ratio of beam current to acceleration voltage depends, among other things, on grid-to-grid spacing. Due to nonuniformities and thermal warping in standard two-grid systems, the spacing between grids could be made only as small as these distortions before they shorted during operation. A method of dishing two matched molybdenum grids by means of hydroforming has been developed (ref. 11). The dished grids will thermally warp uniformly, and not short. Dished grids for the 30-cm thruster have been tested and show potential as the ion extraction system for high-thrust, low specific impulse electric propulsion missions. Dished grids for the 5-cm thruster have been fabricated and tested. A thrust of 1.8 mlb from a 5-cm thruster has been obtained using these grids. A total voltage of 3000 volts was used to obtain this amount of thrust (accelerator voltage was -1000 volts, and the positive voltage was 2000 volts.) This corresponds to a specific impulse of 1800 seconds for a utilization efficiency of 40 percent.

A single-axis electrostatic beam deflection grid system has been optimized and endurance tested for over 1350 hours. Details will be given in a report to be written by Walter C. Lathem.

Ion Chamber

All 5-cm thruster testing both here and at HRL has involved the use of permanent magnets to provide the magnetic field necessary to contain the plasma. To better define the effects of using different numbers of magnets on the magnetic field, an experiment was set up to map the magnetic field inside and immediately downstream of the thruster. Four, seven, and eight magnets were used, and all three orthogonal components of the field were measured. The results indicated there were slight differences in the field caused by changing the magnet locations and numbers. Typical results are shown in figure 8. These data are for the eight-magnet case. The magnetic probe was placed along the geometric axis and moved to various locations inside and outside the thruster. It was found that the magnetic field axis was displaced 2 - 3 mm from the geometric axis for all the tests. This result was attributed to the pole pieces employed and indicates that the fabrication of these components should be controlled so that composition of the material is uniform. Off-axis field distribution could cause uneven wear of the extraction system. No specific action is being taken to modify the thruster, but durability tests will be carefully watched for possible effects.

Hollow Cathode

To further understand the operation of the hollow cathode, thermionic emission studies of various cathode configurations have been studied. The cathode configurations investigated have included (1) a cathode with a porous tungsten-barium oxide tip, (2) a cathode with a standard tantalum foil insert coated with barium carbonate, (3) a cathode with barium carbonate coated on tip, and (4) a bare cathode. Preliminary results show that with no mercury flow the cathode coated with barium carbonate on the tip has the highest emission for the various temperatures tested.

Another study that pertains to the hollow cathode consists of investigating various designs of tip heaters. An optimum design of the heater would require the least amount of power consumption for startups and normal operating conditions. Three designs are being studied. They are the swaged tantalum heater, alumina flame-sprayed tungsten rhenium heater, and an internal "bayonet" heater.

The hollow cathode, which is used as the main cathode and neutralizer has been extensively studied. Beside the cyclic characteristic study, the determination of the effect of keeper hole on neutralizer operation, and the heater geometry test, other experimental studies are being conducted. One investigation determined the effect of external circuit inductance on the volt-ampere operating characteristics of an enclosed keeper hollow cathode. Typical data are shown in figure 9, which shows that the characteristics are a function of external inductance. Figure 10 shows the dependence of the volt-ampere characteristic on mercury flow rate.

Although the hollow cathode has demonstrated reliable cyclic starts, other methods of starting the cathode are being studied. One investigation consists of starting the cathode without tip heat with and without a barium carbonate coated insert. This technique requires high voltages (1 kV or more depending on geometry of cathode and flow rate) to initial breakdown. The reduction in power consumption makes this approach appealing to flight operation. The preliminary experimental results indicate that the oxide coated insert provides improved running characteristics. Endurance cyclic tests are being initiated to investigate this design.

SUMMARY OF ENDURANCE TESTING

The following list enumerates all of the various cyclic and endurance tests completed or in progress as of June 1, 1972:

Neutralizer

1. Endurance testing a prototype Hughes Research Laboratories neutralizer with a swaged heater. Completed 5100 hours of continuous, steady-state operation as of June 1, 1972.

Cathode

2. Successfully cycled one enclosed-keeper hollow cathode, for a total of 3200 cycles and another for 321 cycles. Both cathodes had flame sprayed alumina tungsten rhenium heaters of the type chosen for flight application.

3. Have begun cycling a prototype cathode-isolator-vaporizer assembly. One hundred and ninety restarts have been performed and 1750 hours of steadystate operation accumulated.

Mercury Expulsion System

4. Have completed 5000 hours of continuous operation.

Thruster

5. One-thousand-hour test completed in July 1971. Used an electrostatic dual-grid beam deflection system. Screen had square array of circular holes 0.39 cm diameter on 0.44 cm center-to-center spacing. Accelerator strips were 0.25 cm wide and 0.025 cm thick. Screen-to-accelerator spacing was 0.13 cm. Beam current was 25 mA with positive voltage at 1200 volts and negative at -1200 volts. Vectoring data was taken during first 100 hours. Planned duration of test was 1000 hours. Accelerator grids suffered charge exchange and direct ion erosion. Grids were made thicker and ion optics were redesigned (ref. 12).

6. Five-hundred-and-forty-hour test completed in September 1971. Used electrostatic deflection extraction system. Screen had square array of circular holes 0.39 cm diameter on 0.44 cm center-to-center spacing. Accelerator strips were 0.25 cm wide and 0.012 cm thick. Screen-to-accelerator spacing was 0.16 cm. Beam current was 25 mA

with positive voltage at 1000 volts and negative at -1000 volts.

7. One-hundred-and-forty-one-hour test completed in September 1971. Used translational screen-grid extraction system. Screen had hexagonal array of circular holes 0.24 cm diameter on 0.029 center-to-center spacing. Accelerator had matched hexagonal array of circular holes 0.024 cm diameter. Screen thickness was 0.006 cm and accelerator thickness was 0.013 cm. Screen-to-accelerator spacing was 0.012 cm. Beam current was 25 mA with 1000 volts positive voltage and -1000 volts negative voltage. The beam was deflected 10° for the entire test. Test terminated because of swaged tip heater burnout.

8. Two-thousand-and-twenty-six-hour test completed on January 1, 1972. Same apparatus as 141-hour test No. 7. Neutralizer position was changed. Beam vectored 10° for entire test. An additional 2024 hours of running in undeflected mode has been performed in another facility. This test is still in progress.

9. Twenty-six-hundred-hour test achieved as of May 11, 1972. Used electrostatic beam deflection system. Screen had square array of circular holes 0.253 cm diameter in center section, 0.287 cm diameter in middle annular region, and 0.318 cm diameter in outer perimeter area. Center-to-center spacing is 0.39 cm. Accelerator strips were 0.25 cm wide and 0.05 cm thick. Screen-to-accelerator spacing was 0.075 cm. Beam current was 25 mA with positive voltage at 1000 volts and negative voltage at -1000 volts. First 1000 hours had unvectored beam. Chronological order of vectoring with times of each setting were 2° (576 hrs), 3° (192 hrs), 4° (96 hrs), 5° (48 hrs), 6° (32 hrs), 7° (24 hrs), 8° (16 hrs), 9° (16 hrs), and 10° (12 hrs). The sequence has been repeated. One thousand hours of undeflected operation and 100 hours in the 2° deflection position have been completed with the test still in progress.

Concluding Remarks

The 5-cm diameter ion thruster has undergone extensive developmental studies during the past year. All components have been or are being endurance and cyclic tested. Complete thruster systems are being endurance tested. No outstanding identifiable technical problems have arisen which would preclude the successful use of this thruster on a flight program.

REFERENCES

1. Rawlin, Vincent K.; and Kerslake, William R.: SERT II - Durability of the Hollow Cathode and Future Applications of Hollow Cathodes. J. Spacecraft Rockets, vol. 7, no. 1, Jan. 1970, pp. 14-20.

2. Weigand, A. J.; and Nakanishi, S.: A Survey of Kaufman Thruster Cathodes. NASA TM X-67918, 1971.

3. Hyman, J., Jr.: SIT-5 System Development. Paper 72-492, AIAA, Apr. 1972.

4. Byers, David C.; and Banks, Bruce A.: Beam Focusing Characteristics of Variously Shaped Grid Holes. NASA TM X-67922, 1971.

5. Hudson, W. R.; Lathem, W. L.; Power, J. L.; and Banks, B. A.: Optimization of Electrostatic Dual-Grid Beam-Deflection System. NASA TM X-68096.

6. Lathem, Walter C.; and Hudson, Wayne R.: Operational Characteristics of a Translation Screen Grid Beam Deflection System for a 5-cm Kaufman Thruster. NASA TM X-68008, 1972.

7. Lathem, W. C.: Grid-Translation Beam Deflection Systems for 5-cm and 30-cm Diameter Kaufman Thrusters. Paper 72-485, AIAA, Apr. 1972.

8. Bechtel, R. T.: Effect of Neutralizer Position on Accelerator Wear for a 30-Centimeter Diameter Ion Bombardment Thruster. NASA TM X-67926, 1971.

9. Nakanishi, S.; Lathem, W. C.; Banks, B. A.; and Weigand, A. J.: Status of a Five-Centimeter-Diameter Ion Thruster Technology Program. Paper 71-690, AIAA, June 1971.

10. Bechtel, Robert T.; Banks, Bruce A.; and Reynolds, Thaine W.: Effect of Facility Backsputtered Material on Performance of Glass-Coated Accelerator Grids for Kaufman Thrusters. Paper 71-156, AIAA, Jan. 1971.

11. Rawlin, V. K.; Banks, B. A.; and Byers, D. C.: Design, Fabrication, and Operation of Dished Accelerator Grids on a 30-cm Ion Thruster. Paper 72-486, AIAA, Apr. 1972.

12. Lathem, Walter C.: A 1000-Hour Test of a Dual Grid, Electrostatic Beam Deflection Accelerator System on a 5-Centimeter-Diameter Kaufman Thruster. NASA TM X-67908, 1971.

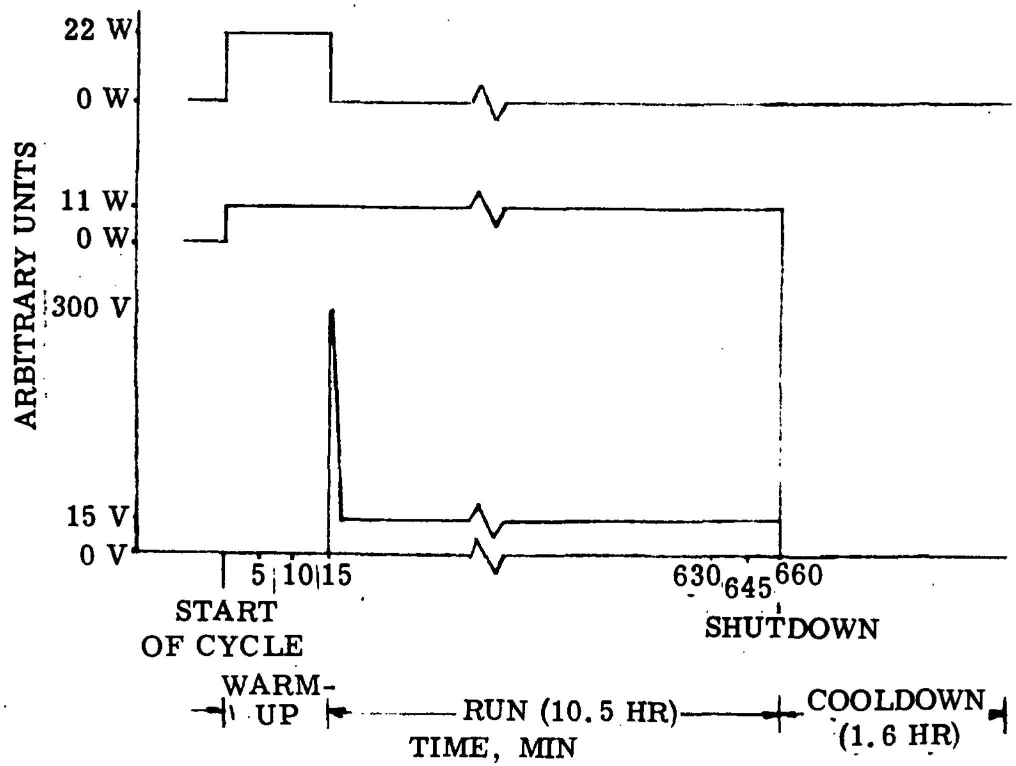


Figure 1. - Cyclic test operational sequence.

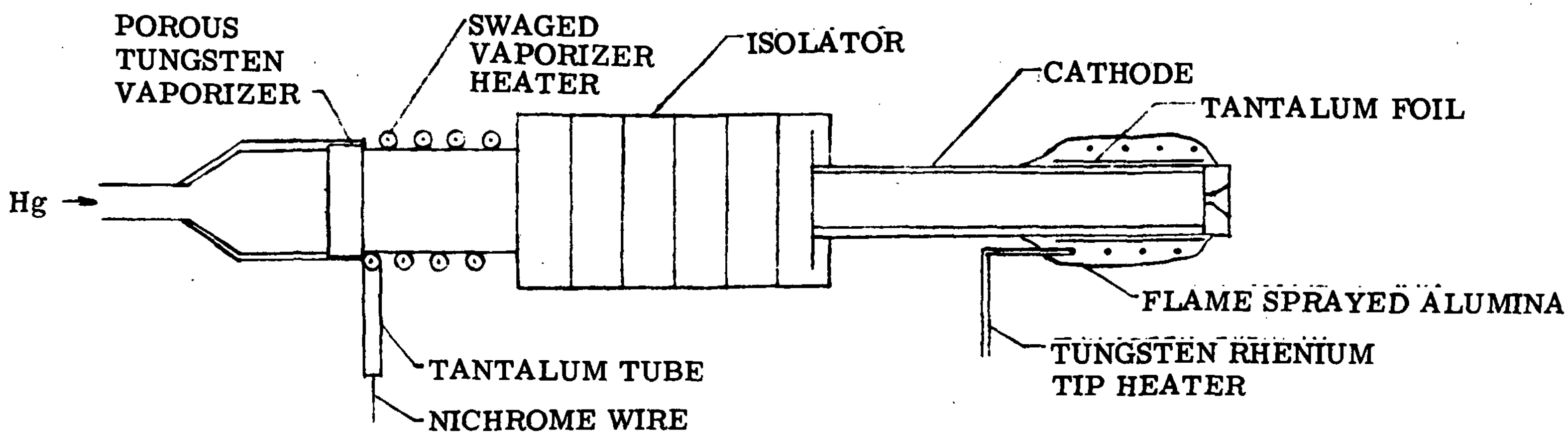
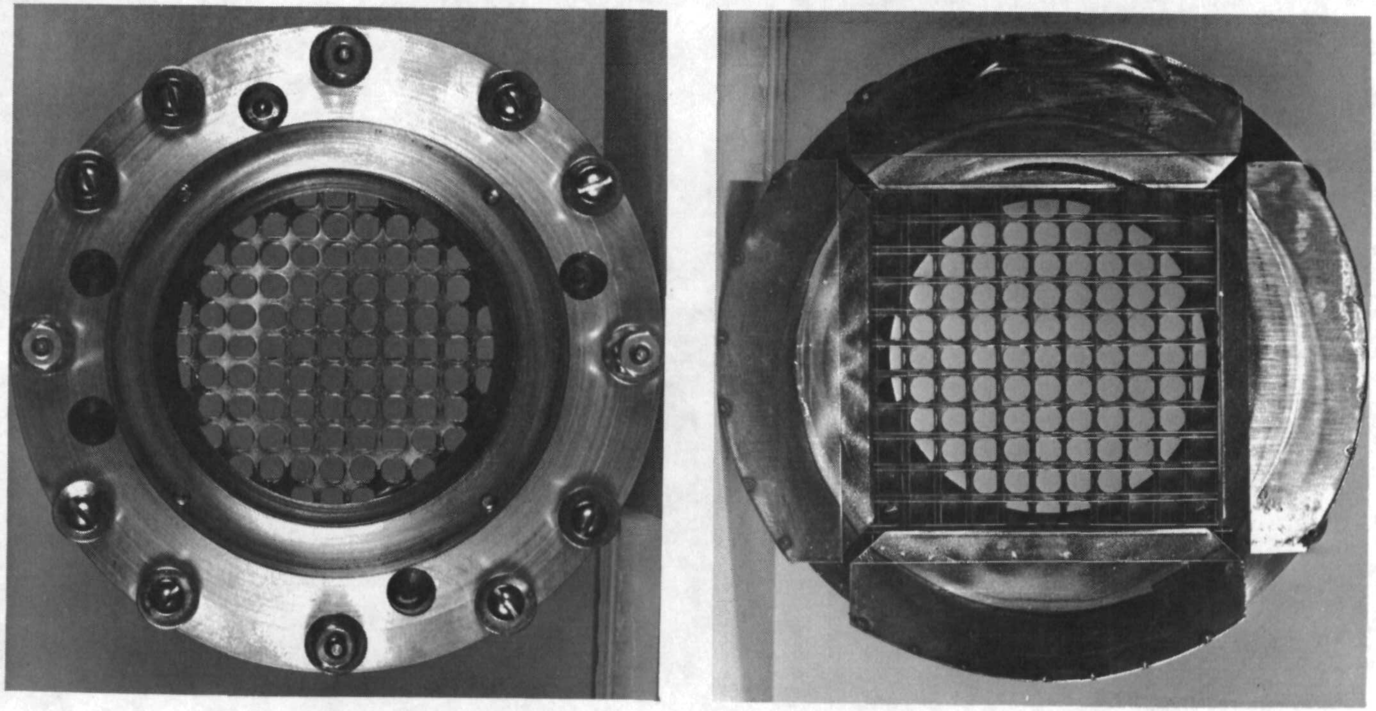


Figure 2. - Cathode-isolator-vaporizer assembly.



(a) Upstream side.

(b) Downstream side.

Figure 3. - Electrostatic beam deflection system.

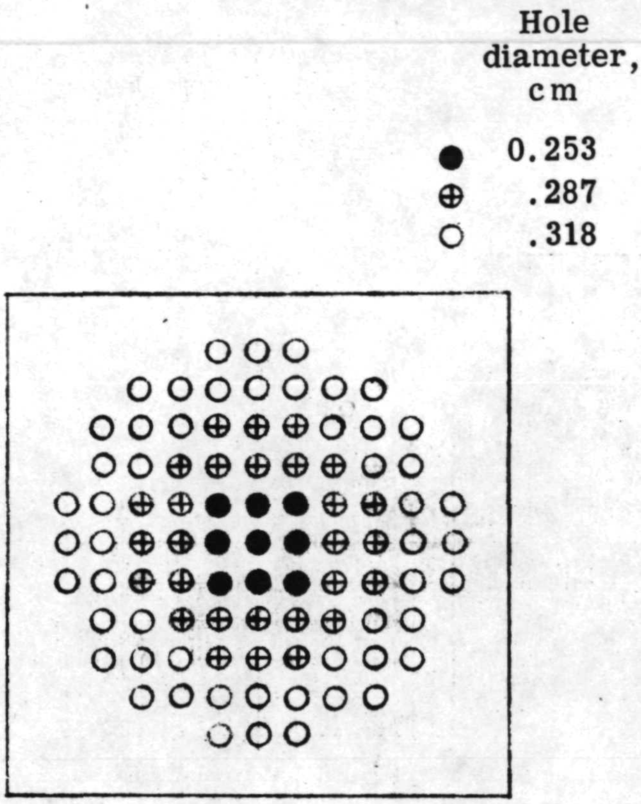


Figure 4. - Multiple-size hole screen grid used for 2000-hour electrostatic vectoring endurance test.

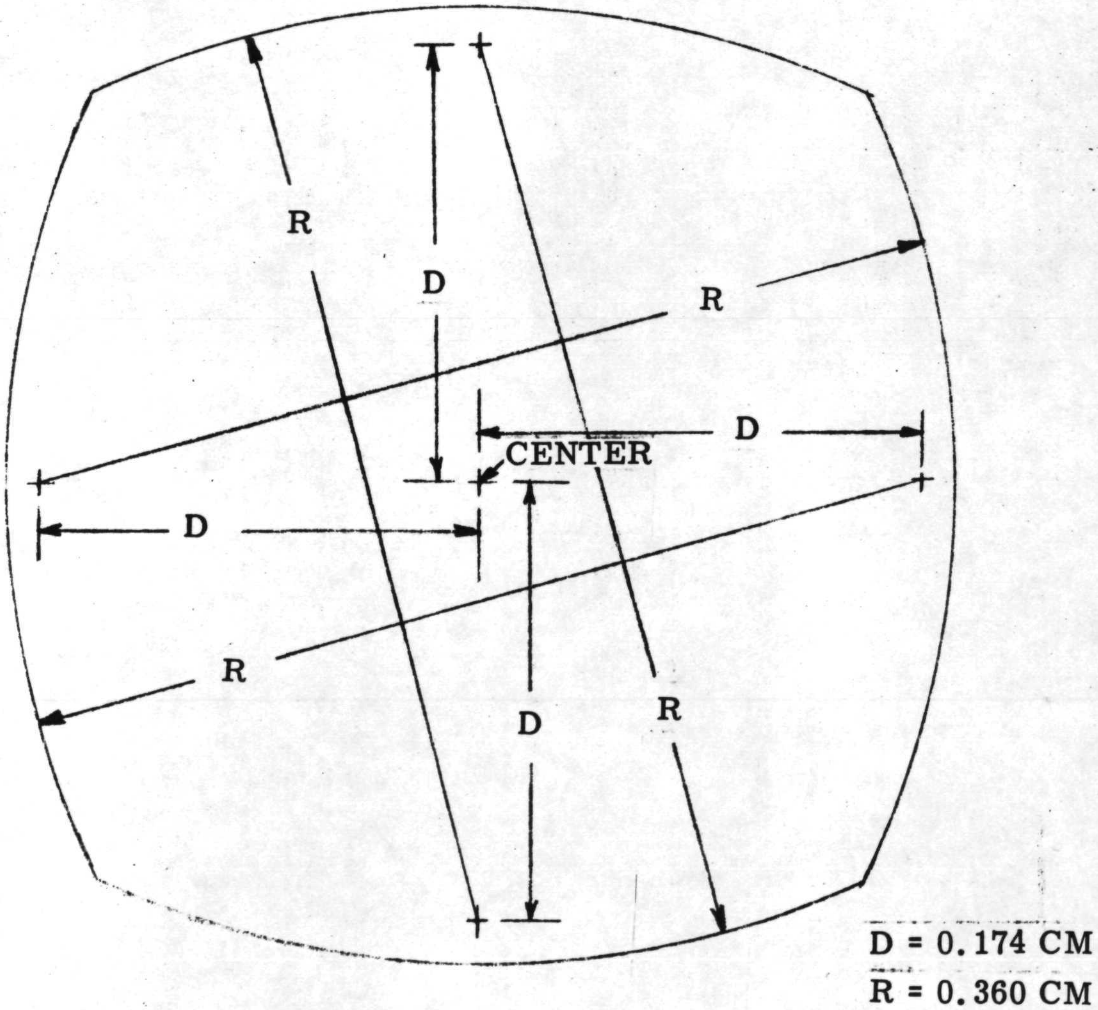
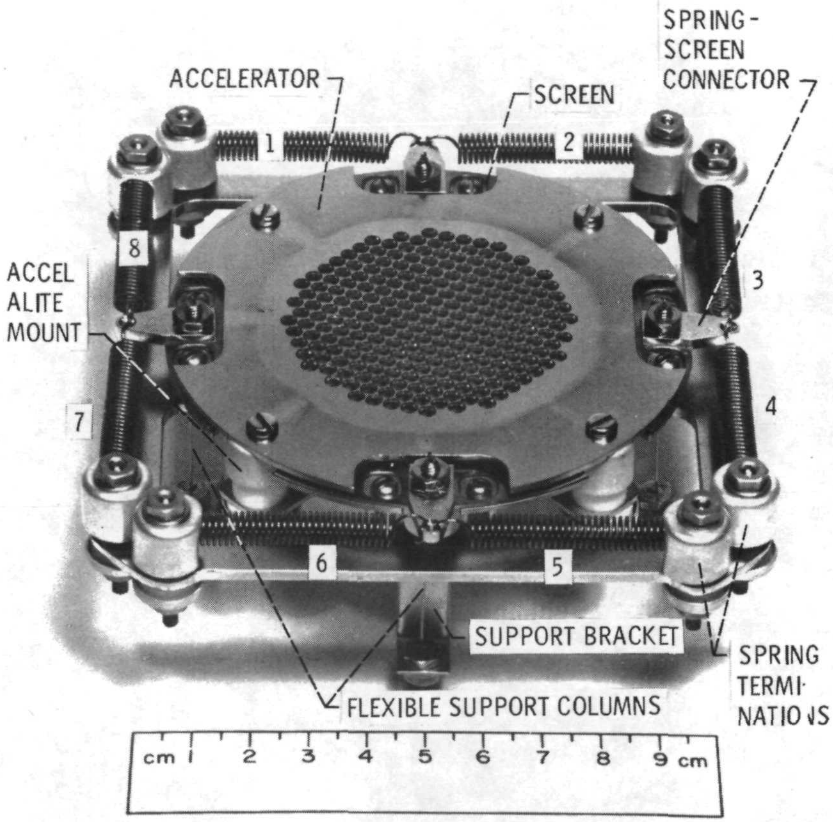


Figure 5. - Pillow-shape-square screen aperture geometry.



CS-62614

Figure 6. - Translational screen-grid vectoring system.

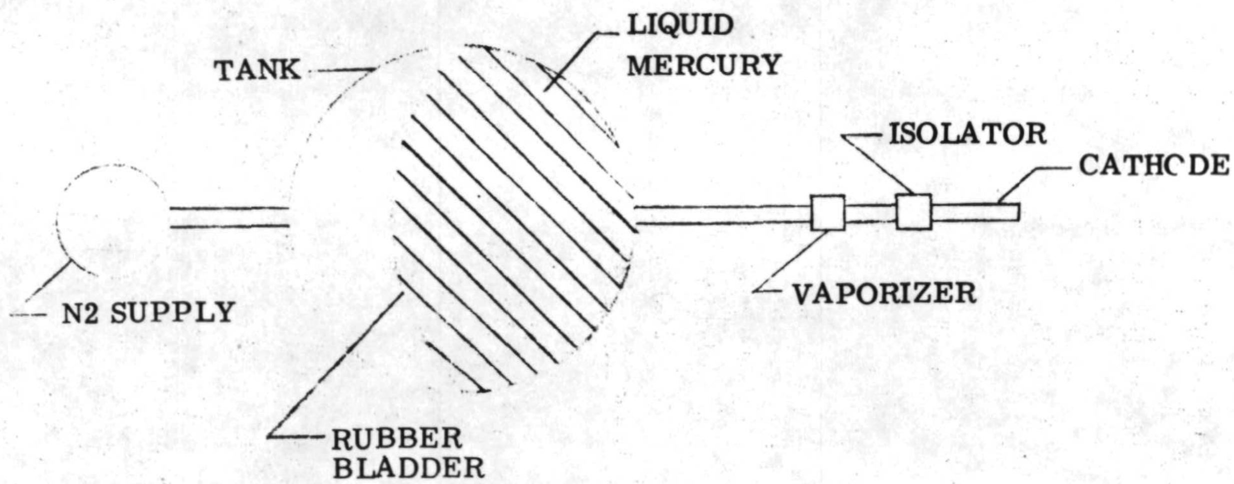


Figure 7. - Mercury expulsion system.

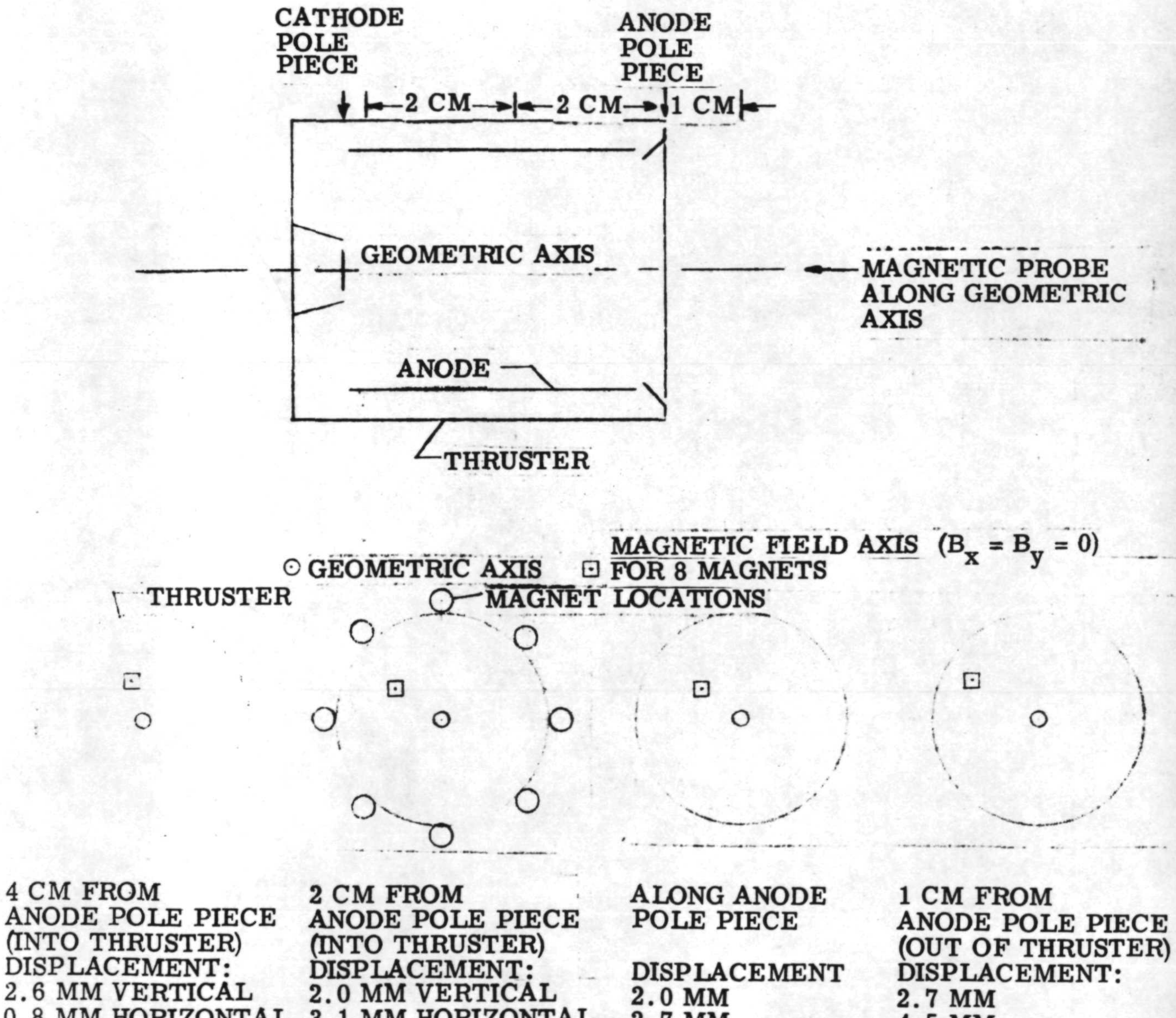


Figure 8. - Displacement of magnetic field axis from geometric axis using eight magnets for various locations inside and outside a 5-cm thruster along geometric axis.

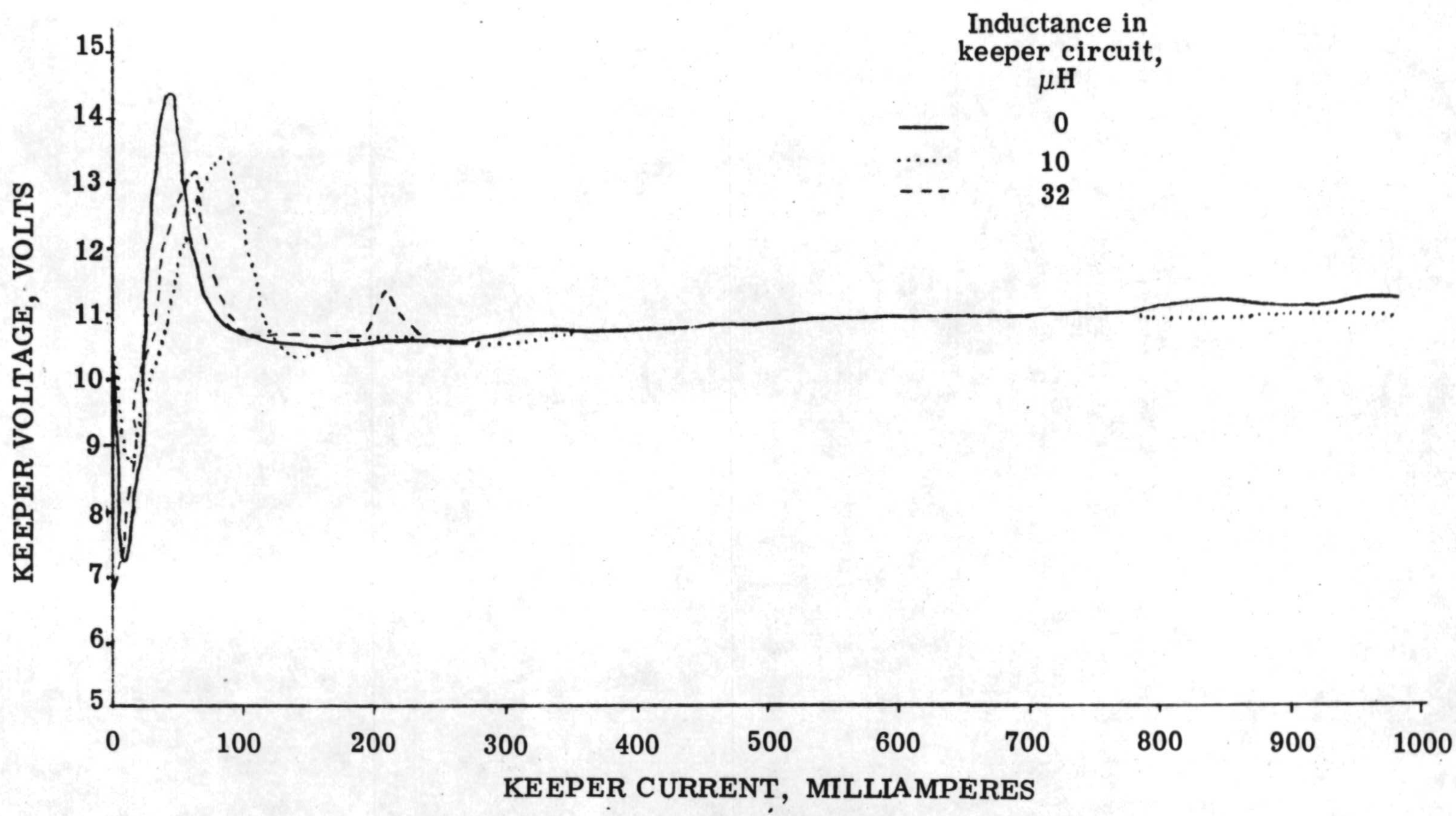


Figure 9. - Effect of external circuit inductance on volt-ampere characteristics of an enclosed keeper hollow cathode. Mercury neutral flowrate equals 199 equivalent milliamperes. Keeper orifice equals 0.076 centimeter.

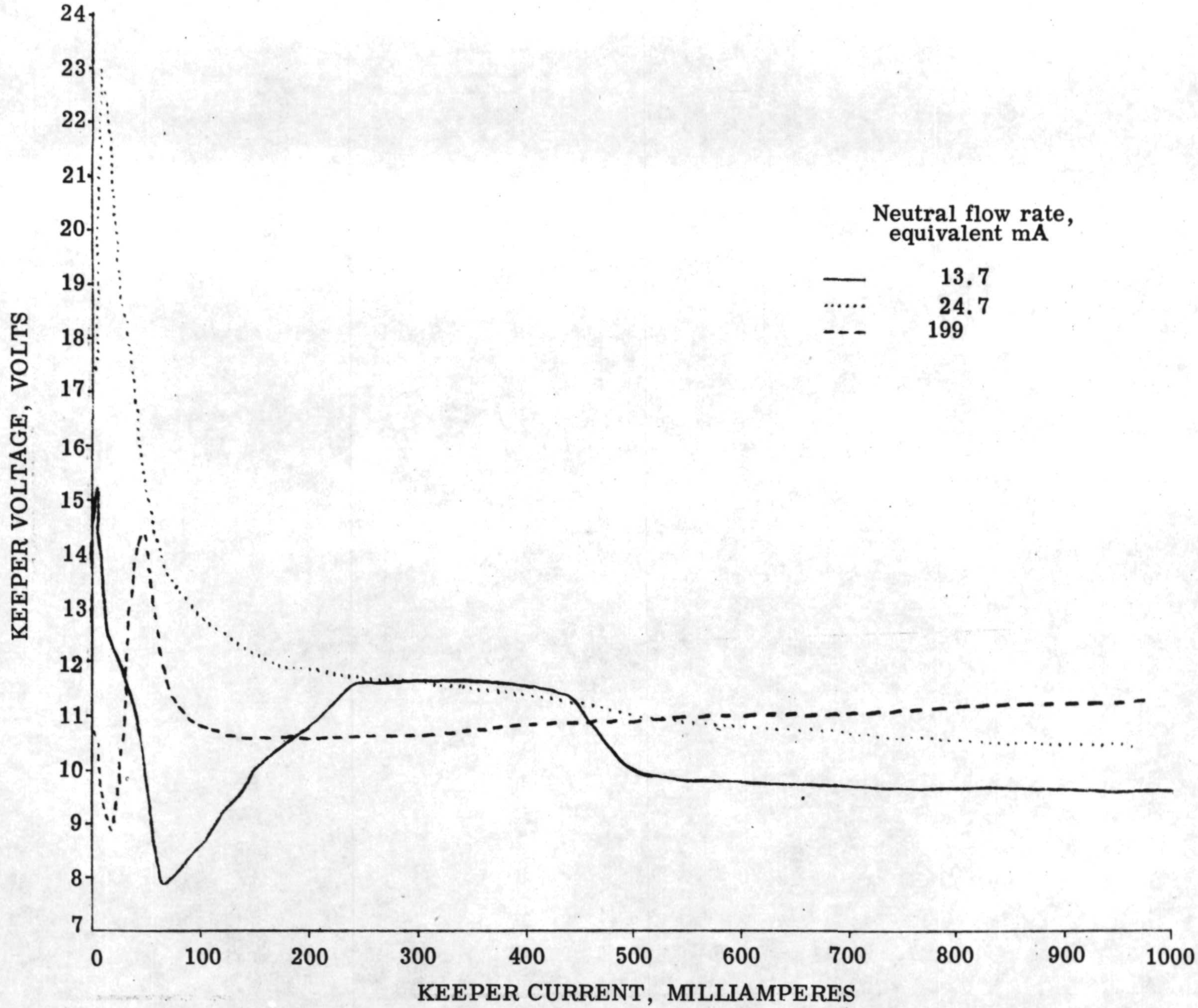


Figure 10. - Effect of propellant flow rate on volt-ampere characteristics of an enclosed keeper hollow cathode. Zero inductance in circuit. Keeper orifice equals 0.076 centimeter.