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HOLLOW CATHODES WITH BaO IMPREGNATED, POROUS TUNGSTEN INSERTS AND TIPS

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TECHNICAL PAPER proposed for presentation at
Tenth Electric Propulsion Conference sponsored
by the American Institute of Aeronautics and Astronautics
Lake Tahoe, Nevada, October 31 - November 2, 1973

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Abstract

The technology of impregnated materials is described and some inherently advantageous characteristics of impregnated cathodes are discussed. Thermionic emission measurements are presented for oxide coated and impregnated cathodes. Five cathode configurations with barium oxide impregnated porous tungsten inserts and/or tips have been fabricated and tested. Reliability, durability, and stability of operation are characterized. One of the cathodes has accumulated over 9000 operational hours, another has been cycled on and off more than 800 times.

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Introduction

The Lewis Research Center is presently engaged in the development of an 8 cm, 4.45 to 8.9 millinewton (1 to 2 mlb) thrust auxiliary propulsion system for north-south station keeping. The proposed thruster is intended to operate for 20 000 hr and be capable of 10 000 on/off cycles. It is therefore crucial that the main cathode and the neutralizer systems be optimized with respect to reliability, durability, and stability of operation. To this end, hollow cathodes have been fabricated and tested which have impregnated porous tungsten inserts and tips. For ease of reference these cathodes will be referred to as impregnated cathodes. The impregnate is an emissive mix composed of four molar parts barium oxide, one part calcium oxide, and one part aluminum oxide. The impregnated cathode has inherent advantages, which are itemized and discussed below. The emphasis of the experiments reported herein has been to determine the operational characteristics and durability of impregnated cathodes.

Impregnated Thermionic Cathodes

The impregnated thermionic cathode has become widely used in traveling wave tubes, magnetrons, and klystrons. It was first developed by R. Levi,(1) as a replacement for the oxide coated cathode in certain applications. Levi's early experiments(2,3) showed the impregnated cathode to have several inherently desirable characteristics. The sintered tungsten structure is mechanically very strong. Porous tungsten prior to being impregnated can be machined into complicated shapes to close tolerances. To a lesser degree it can also be machined after impregnation. The impregnated cathode is also very resistant to gas poisoning. The poisoning of impregnated cathodes has been thoroughly studied by Jenkins and Trodden.(4) If the surface becomes contaminated the cathode can be regenerated by reheating, since the emissive mix is contained inside the porous tungsten. This property is of particular importance where cathodes must be ground tested and exposed to atmospheric conditions prior to launch. The impregnated cathode is also inherently protected from sputtering damage resulting from position ion bombardment. The emission characteristics and the barium evaporation rate of impregnated materials can be adjusted to be consistent with operational conditions and mission requirements. Both the emission current and the barium evaporation rate are dependent on the molar ratios of constituents, the porosity, and the surface conditions. One further advantage is the reproducibility of fabrication and uniformity of inserts.

On the other hand the oxide coated cathode has a higher thermal efficiency. An oxide coated cathode can produce a given current density at temperatures 200° to 250° C lower than an impregnated cathode; This fact results from the lower work function, ϕ_0, of the oxide coated cathode. ϕ_0 equals 1.4 eV for B BaO compared to 1.7 eV for Ba.(5) It must also be determined if all the BaO inside the porous tungsten can be made available for surface activation.

Fabrication

The insert and tip material was fabricated by pressing four micron tungsten powder at pressures of 9.0×10^6 N/m^2 (24 000 psi) and then sintering in dry hydrogen at 2350° C. The void volume can be varied between 12 and 28 percent. Levi found that above a 17% void volume the pores are almost all connected.(3) Since the evaporation rate is a monotonically increasing function of porostiy, a porosity less than the maximum attainable is probably desired. The porosity of the material used in this study was about 20%.

The resulting porous tungsten material can be made machinable by impregnating with copper. After machining, the copper is removed by acid leading and vacuum firing. The copper serves as a lubricant allowing machining of a wide range of sizes and shapes. Tolerances can be achieved which are comparable to machined steel.

As previously mentioned, the emissive mix consists of four molar parts barium oxide, one part calcium oxide, and one part aluminum oxide. Reference 6 reports K. Dudley's results on molar composition of impregnates. The resulting evaporation rate and emission are strongly dependent on the molar proportions of BaO and CaO.

The impregnating process consists of heating the powdered barium calcium aluminate and porous tungsten to a temperature of 1800° C in dry hydrogen at one atmosphere. Capillary forces result in the tungsten absorbing the barium calcium aluminate. If it is either necessary or convenient, further machining may be done at this stage in the fabrication. A scanning electron microscope (SEM) was used to characterize the surfaces of the impregnated porous tungsten material. Figure 1 is a SEM picture at 300X magnification of an impregnated insert surface. The surface is characterized by machine marks, the pores and the boundaries of individual tungsten particles. A 1000X magnification picture of the same insert is shown in figure 2. An x-ray analysis of the particle indicated shows that it contains barium. A third photograph (fig. 3) shows the insert after it was broken in half. The SEM pictures shown are at magnifications of 60X, 1000X, and 3000X. The associated x-ray spectrum shows a strong barium signature.

Activation Procedure

The impregnated cathodes are brought to operational status, activated, by the following procedure. First, the cathode is baked out at 500° C for an hour or longer. Next, the temperature of the impregnated material is increased to 1150° to 1200° C and a voltage of at least 300 volts applied for five to ten minutes. A sufficient vapor pressure of barium results from the reaction between the barium aluminate and the tungsten to cover the insert surface with an adsorbed layer of barium. This barium layer lowers the work function of the tungsten surface. The CaO component of the mix has been found to increase emission current and decrease evaporation rate. As this process occurs the emission current from the cathode will rise to some maximum value in five to ten minutes. When this occurs, the cathode is allowed to cool to 1050° to 1100° C and aged at this point for two to three hours. Figure 4 is a series of SEM photographs at 60X, 1000X, 3000X magnification of a surface so activated. An x-ray analysis of the surface area shown accompanies the photographs. The peaks are as indicated in the figure.

Apparatus and Procedure

The experimental setup is shown in figure 5. The hollow cathodes were mounted to porous tungsten vaporizers at ground potential.(7) All cathodes were tested with enclosed keepers mounted on Al_2O_3 insulating sleeves. The Al_2O_3 sleeves were positioned over the cathode heater and tip. A positively biased collector was positioned downstream of the keeper electrode. The purpose of the collector was to simulate the ion beam, in the case of neutralizer tests, or to simulate the anode in cathode tests.

Alternating current power supplies were used to operate all vaporizer and tip heater supplies. Two separate keeper supplies were used, a (1000 V, 100 mA) ignitor supply and a (38 V, 1.5 A) discharge supply. The ignitor supply was used only for initiating the discharge. Either current or voltage could be regulated on the discharge supplies. During tests, the keeper current was set and the voltage was allowed to seek its equilibrium value. The collector supplies were capable of current or voltage regulation. In the case of cathode tests, the collector voltage was limited to 40 volts and the current set. For neutralizer tests, alternately both current and voltage were set. It was desired to keep the simulated coupling voltage below 20 V and the collector current equal to the thruster beam current being simulated.

Vaporizer temperature was measured in all tests with iron constantan thermocouples. In specific instances measurements of the cathode tip temperature were also made with chromel-alumel thermocouples or an optical pyrometer.

Mercury was fed to the vaporizer from a pressurized, 0.5 mm diameter capillary burette. Mercury flow rates could then be determined precisely from the rate of change in height of the mercury column. The flow rates are expressed in terms of equivalent milliamperes of neutral flow. This equivalent current is that current which corresponds to each mercury atom having one electronic charge. A flow rate of one milligram per second is equal to 481 equivalent milliamperes.

All tests were conducted in a 46-cm diameter bell jar with an oil diffusion pump and liquid nitrogen cooled baffle. Pressures in the low 10^{-6} torr pressure range were achieved.

Results and Discussion

Thermionic Emission

Prior to testing impregnated cathodes with mercury discharges the thermionic emission properties of oxide coated materials and impregnated materials were measured. Fresh cathode tips with flame sprayed heaters were radiation shielded and mounted in a bell jar. The standard enclosed keeper was replaced with a planar anode. The cathode tip to anode spacing was 0.15 cm, and the anode could be biased with any voltage between 25 and 300 volts. The thermionic emission current was measured as a function of collector anode voltage and tip temperature. The emission current-temperature results for five different configurations are shown in figure 6. Configuration #1 had a coating of $BaCO_3$ emissive mix, (appendix A) on the outside of the cathode tip, but had no cathode insert. As the figure shows, configuration 1 had the most thermionic emission current at the lowest temperature. Current was measured as low as 842° C and reached 30 milliamperes at 1032° C. Configuration #2 is a standard cathode with a rolled foil insert, but with no $BaCO_3$ emissive mix on the tip. The emission current was considerably less at a given temperature than that for configuration 1. The reduction may be attributable to the emitting surface being inside the cathode, thus reducing the effective electric field, collecting of thermionic emitted electrons, and area of the emitter. Configuration #3 is an impregnated porous tungsten tip. The emission curves of configuration #3 and #1 are parallel, with the impregnated emission curve about 150° C higher. Configuration #4 is configuration #1 after it was cleaned thoroughly with H_2SO_4. The cathode was cleaned to simulate a depleted condition that might result from sputtering and long term barium evaporation. The emission currents measured for configuration #4 are comparable to configuration #3 between 900° and 1000° C, but its emission falls off above 1000° C. The fifth configuration is for a cathode with an impregnated porous tungsten insert and a thoriated tungsten tip. The insert was a right circular cylinder 0.19 cm in diameter and 0.95 cm long. It was positioned 0.05 cm back from the tip (fig. 4). This particular impregnated insert compares favorably with the rolled foil insert that was tested; it produced the same amount of current at temperatures 100° C lower. The extent to which these two results are typical of the two classes of inserts has not been explored. It is expected that the emission current-temperature characteristic is very sensitive to the rolled foil insert manufacturing techniques and the activation procedure for the impregnated insert.

Figures 7 and 8 exhibit the variation of the emission current with respect to anode voltage at constant temperature. The cathodes tested are the configuration #1 and #3 discussed above. The nature of the two sets of curves appear similar with one slight exception. The emission currents of the impregnated tip operating in the temperature limited region very nearly saturates at 260 volts. This is true even at the highest temperature where measurements were made. The emission current of the oxide coated, tipped cathode continued to increase. Increasing the anode voltage beyond 260 volts could give increased emission current for the oxide tip, but not for the impregnated tip.

Cathode Tests

I. Cathode with Impregnated Insert

Several different cathode configurations have been tested in bell jars with collector electrodes simulating ion beams. Some of these cathodes are still running as of the publication date. The values given for hours of operation and cycles are as of printing date. The first cathode to be discussed is shown in figure 9. Its various dimensions and operating characteristics are summarized in tables 1 and 2. The cathode insert is a right circular cylinder of oxide impregnated porous tungsten 1.91 mm in diameter and 0.762 cm long. The insert is mounted inside the 3.18 mm diameter cathode tube body; a 0.51 mm diameter tantalum wire is electron beam welded to the back of the insert, and is spot welded to the cathode body. The insert is 0.25 mm in back of the cathode tip. Tip power is provided by a swaged tantalum heater that is wrapped tightly around the cathode body. An alumina insulator sleeve is mounted over the heater. The enclosed keeper in turn mounts over the insulator sleeve. The keeper to cathode tip spacing is 1.02 mm, the tip orifice is 0.25 mm, and the keeper orifice is 1.5 mm. The cathode tip is made of 2% thoriated tungsten and the keeper is made of tantalum. A chromel-alumel thermocouple is spot welded to the body at a point just behind the tip heater. No radiation shielding was incorporated in this design.

This cathode has been operated at the conditions of a main cathode for the SIT-5, 5 cm diameter thruster. It has successfully completed 9000 hours and 164 restarts. Furthermore, it has experienced 12 exposures to air and 8 facility failures. In the most common failure nodes the bell jar pressure increases to the 10 to 100 milliton level and oil backstreams from the diffusion pump into the test chamber. The combined oxidation and discoloration of cathodes has caused the cathode surfaces to increase in emissivity. It consequently requires more power to reach the same tip temperature. After each of these events the cathode was reactivated by baking it out at 500° C for twenty four hours and then heating the body to the 800° to 850° C temperature range for 15 minutes. The durability of this cathode under such atypical and harsh conditions is impressive.

The cathode was initially started without the preliminary activation procedure described above, that now is considered to be desirable. The cathode body was heated to 850° C with 32 watts of tip heat. Large tip powers were required for starting because of the lower thermal efficiency of the swaged tip heater and insufficient radiation shielding. Later experiments with flame sprayed heaters indicate 20 watts is more than sufficient for starting. After a ten minute preheat the mercury vaporizer was turned on. The initial start was achieved when the mercury flow rate reached about 60 equivalent milliamperes.

The cathode was operated in the plume mode at 36 to 40 equivalent milliamperes of mercury. The keeper current was set at 0.2 amp which resulted in a keeper voltage of 16 volts. The keeper voltage was insensitive to an increase in keeper current; it increased to 18 volts when the current was doubled to 0.4 ampere. The tip heater was run at about 5 watts during most of the experiment partially to offset the insufficient radiation shielding and partly to prevent mercury condensing in the cathode if the discharge went out. During operation the cathode body temperature, as measured by a thermocouple behind the heater, operated at 600° C. More than an ampere of collector current could be drawn from the cathode but it was operated at 0.31 amperes of emission yielding a collector voltage of 36 volts.

The cathode was recycled by shutting all power supplies off simultaneously. Allowing the cathode to cool down for thirty minutes resulted in a cathode body temperature below 50° C. Restarting consisted of first turning on the tip heater and vaporizer supplies and allowing the cathode to heat up for 10 to 15 minutes. Then the ignitor supply, keeper discharge supply, and anode supply were turned on. Usually, the discharge ignited immediately; when it did not, the ignitor was cycled 1 minute on-1 minute off until the discharge did ignite.

The cathode keeper voltage and collector voltage as a function of the mercury flow rate are shown in figure 10. These data were taken after 7500 hours of operation. It should be noted that as a result of the increase in the emissivity of the cathode surfaces both keeper and collector voltages were 1 or 2 volts higher than at the start of the run. This emissivity change could be offset by a 4 watt increase in the tip power. When this was done, the keeper and collector voltages returned to original values. The keeper voltage was very insensitive to mercury flow rate and keeper current except at the lowest flow rates tested. The collector voltage at 0.3 amp collector current, however, decreased monotonically with increasing Hg flow and could be used to control the flow through the cathode.

II. Impregnated Insert Cycling Test

A second cathode similar to the one shown in figure 9 was tested on a 2 hour 15 minute period cycle at an 85 milliampere equivalent flow rate. The only physical difference between this cathode and the one described in section I is that the cathode on cyclic test has a flame sprayed encapsulated tungsten rhenium heater. The cathode parameters are the same as listed in table 1. The cathode was operated at 16 volts keeper voltage and 0.27 ampere keeper current. The collector voltage was set at 40 volts which resulted in 0.60 ampere of anode current. These levels of emission current and Hg flow correspond to values expected for 1 mlb thrusts. The cathode operated without tip heat and required 22 to 24 watts for starting. The tip temperature at starting was 1050° C as measured by an optical pyrometer. The operating conditions are summarized in table 3.

The test cycle that was followed is diagramed in figure 11. The on-off condition of the four power supplies are plotted with a common time axis to clarify the sequencing of the test cycle. The cycle is 2 hours and fifteen minutes long. At time zero, the mercury vaporizer and the tip heater are turned on, after fifteen minutes the high voltage ignitor and the discharge supply are turned on. If the discharge ignites the cathode tip heater is turned off. The cathode operates for one hour, then all supplies except the collector supply shut-off and the cathode cools for 1 hour.

The cathode has so far completed 943 cycles and 1150 operational hours. In figure 12 the time required for the cathode to ignite is plotted for each cycle. Many times the cathode discharge ignited before the ignitor supply and the keeper supply were turned on. So far the cathode has never failed to ignite.

No significant long range trend of any of the operational parameters has been noted. Figure 13 is a plot of collector voltage and keeper voltage as a function of keeper current. The keeper voltage is very constant for the keeper current range 0.1 to 0.44 amperes; but the collector voltage has a significant minimum, between 0.2 and 0.25 ampere.

III. Cathode Impregnated Tip

The third cathode configuration is shown in figure 14 and its dimensional parameters are listed in table 4. It has an impregnated tip that was MoNi brazed to the cathode body. The 0.2 mm diameter tungsten heater wire is potted in a spool piece that was inside the cathode body. This design reduced the area over which the input power was radiated. The heater efficiency was increased such that 13.5 watts of tip heat resulted in a tip temperature of 1050° C. However, the cathode discharge did not couple well to the collector. This may have been caused by the constriction behind the cathode tip orifice which could effect either the seating of the discharge or the mercury flow.

This cathode did demonstrate excellent starting characteristics; at 1050° C it could consistently be started with the keeper discharge supply at its upper limit of 38 volts.

IV. Cathode Impregnated Insert and Tip Combination

Because a cathode with an impregnated tip and potted heater exhibited good starting characteristics, a cathode was designed which has a similar type heater and a combination impregnated insert and tip (fig. 15). This design is an attempt to combine the easy starting of the impregnated tip with the operational characteristics of the impregnated insert.

The cathode tip has been increased in diameter to 5.6 mm; the tubular insert has an inside diameter of 1.5 mm and an outside diameter of 3.0 mm. The 0.20 mm diameter tungsten heater wire was potted around the insert body and contained by a molybdenum shell. The cathode tip was connected to the tantalum tube by a Mo-Re, 0.05 mm thick tube which was intended to reduce the heat leakage away from the cathode tip.

This cathode has been run at the anticipated conditions for a thruster operating in the one to two millipound thrust range (table 6). The mercury flow is 86 equivalent milliamperes and an anode current of 1.6 amperes was obtained with an anode voltage of 40 volts. The cathode would operate without the keeper supply on, but it was run with a 0.1 ampere of keeper current at 12 volts. The cathode has operated for 2650 hours, with 59 restarts. Initially the cathode could be started at low voltage (38 volts), but over the first 400 hours of operation the length of time required to start the cathode gradually increased from 5 minutes to more than 30 minutes. Subsequently the cathode was restarted using the regular 1000 V ignitor.

The preliminary indication is that after the initial activation the cathode tip had a sufficiently low work function that a discharge could be initiated without high voltage. The fact that the tip surface gradually degraded over several hundred hours probably indicates that Ba evaporated from the tip surface faster than it was replenished. Additional radiation shielding would cause the cathode tip to run at a higher temperature, which might cause the cathode tip to be self-replenishing. Reactivation of the cathode did reinstate the low voltage starting condition, but only for a few starts. Further more detailed study is indicated.

V. Neutralizer with Impregnated Insert and Tip

A fifth cathode was tested as a neutralizer configuration for thrusters in the 1 to 2 mlb range. This cathode had an impregnated cathode tip that was held in place by mechanically swaging a tantalum tube around it (fig. 16). The body of the cathode was turned down to 0.25 mm wall thickness over a 1.0 cm length to reduce heat flow down the tube. A separate insert was installed inside the cathode with a 0.5 mm tantalum wire electron beam welded to it. The other end of the wire was spot welded to the cathode body. The cathode keeper orifice was 0.75 mm and the cathode tip to keeper spacing was 1.5 mm (table 7).

The collector and keeper voltage-current characteristics were measured at mercury flow rates of 1.7, 2.4, 3.7, and 6.7 equivalent milliamperes (fig. 17). At all flow rates the keeper voltages were higher than with rolled foil inserts, ranging from 20 to 25 volts. The keeper voltage was not a sensitive function of keeper current at any of the flow rates. In contrast, the collector current at a collector voltage of 20 volts was a very strong increasing function of keeper current at all flow rates.

Concluding Remarks

Hollow cathodes with impregnated porous tungsten tips and inserts have many inherently desirable characteristics. Mechanical strength, machinability, reactivation following poisoning or ion bombardment, more controlled evaporation rate, and reproducibility of fabrication make the impregnated insert an appealing alternative to rolled foil oxide coated inserts. Hollow cathodes with impregnated inserts have been tested to evaluate their durability and operational characteristics. One particular cathode has operated for over 9000 hours; it has been reactivated several times after contamination by facility failures. Another cathode has demonstrated an on-off cycling capability of more than 943 cycles, it also continues to operate. It has been determined that the operating characteristics of cathodes with impregnated inserts are equivalent to cathodes with rolled foil inserts.

Overall, the impregnated cathode represents a viable, versatile, and durable addition to hollow cathode technology as applied to electron bombardment thrusters.

Appendix A

The barium carbonate emissive mix used on the rolled foil inserts in this paper is a 70:30 blend of equimolar coprecipitates of barium and strontium carbonates along with sodium and ammonium carbonates used as the precipitants. The following are specified for the mixture:

Barium carbonate ($BaCO_3$)	55.2-59.2%
Strontium carbonate ($SrCO_3$)	40.8-44.8%
Water (H_2O)	0.10%
Insoluble in HCl	0.010%
Water soluble salts	0.15%
Chloride (Cl)	.001%
Sulfide (S)	.001%
Heavy metals (as Pb)	.002%
Iron (Fe)	.002%
Sodium (Na)	.20%
Particle size (microns)	3.0-5.0
Apparent density	0.29-0.33

The formulation is suspended in a binder consisting of butyl alcohol, butyl acetate, and pyroxylin cotton.

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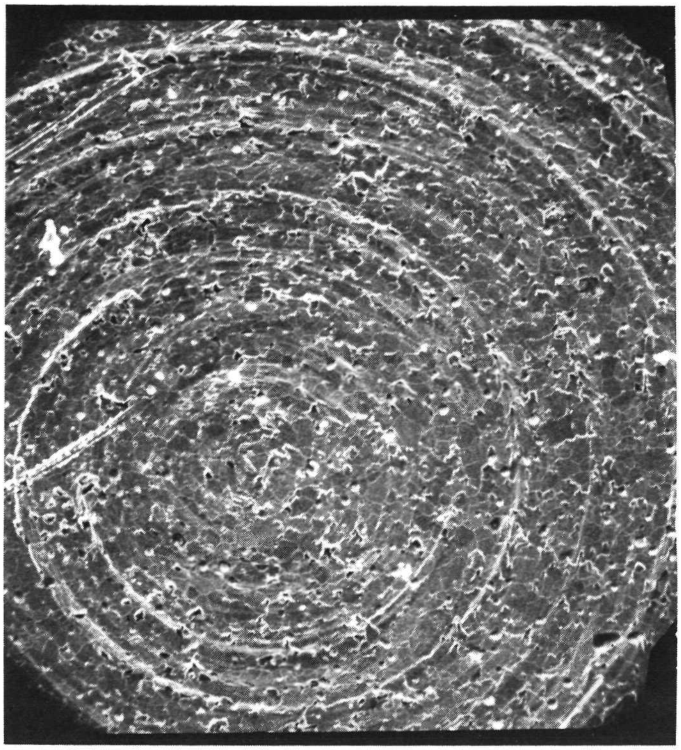
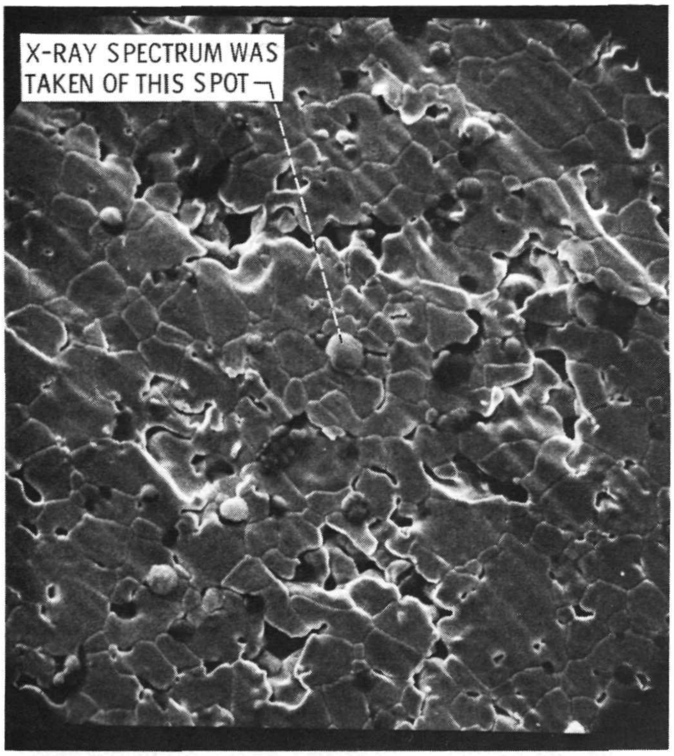


Figure 1. - Scanning electron microscope picture at 300 magnification of an impregnated insert surface. The electron beam was accelerated through 25 kV and tilted at 30^0.



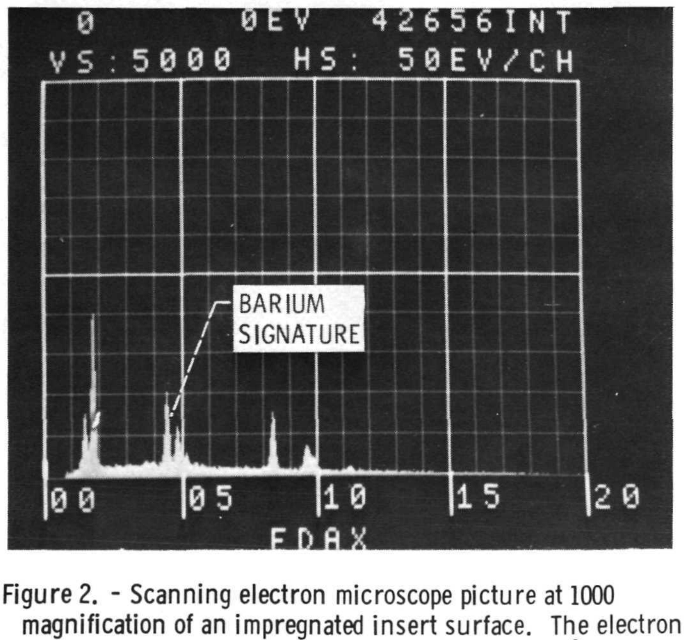


Figure 2. - Scanning electron microscope picture at 1000 magnification of an impregnated insert surface. The electron beam was accelerated through 25 kV and tilted at 30^0. The particle indicated in the picture was analyzed. The x-ray spectum is shown.

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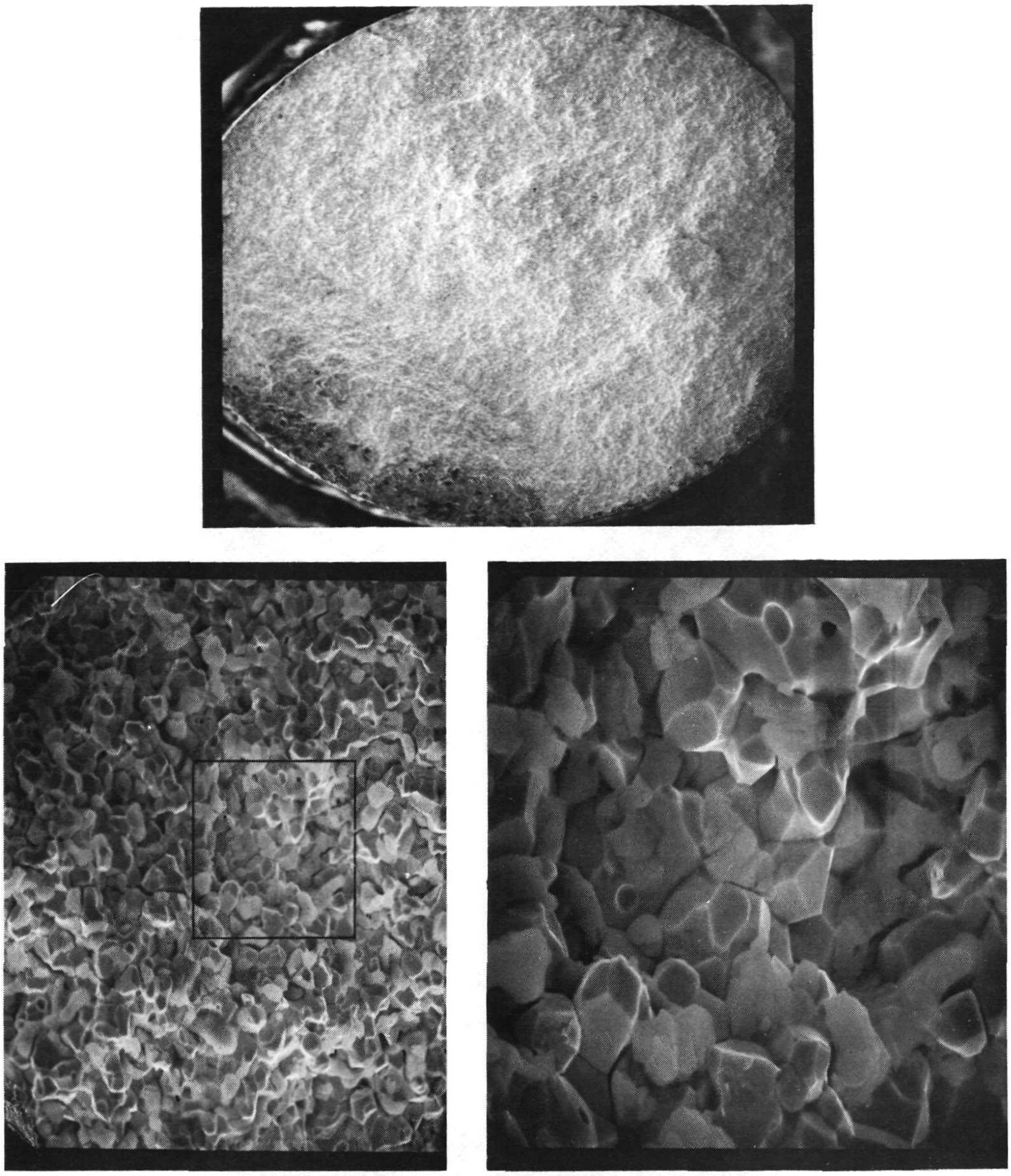

IMPREGNATED INSERT BROKEN IN HALF

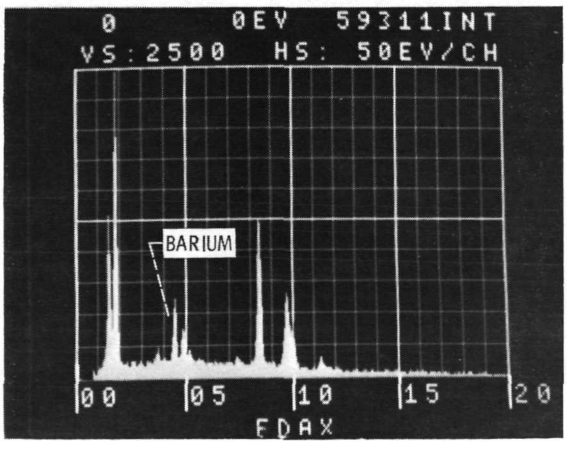

Figure 3. - SEM pictures are shown at magnifications of 60, 1000, and 3000. The electron beam is accelerated through 25 kV and tilted 20^{0}. An x-ray spectrum that corresponds to the 60 magnification picture is shown.

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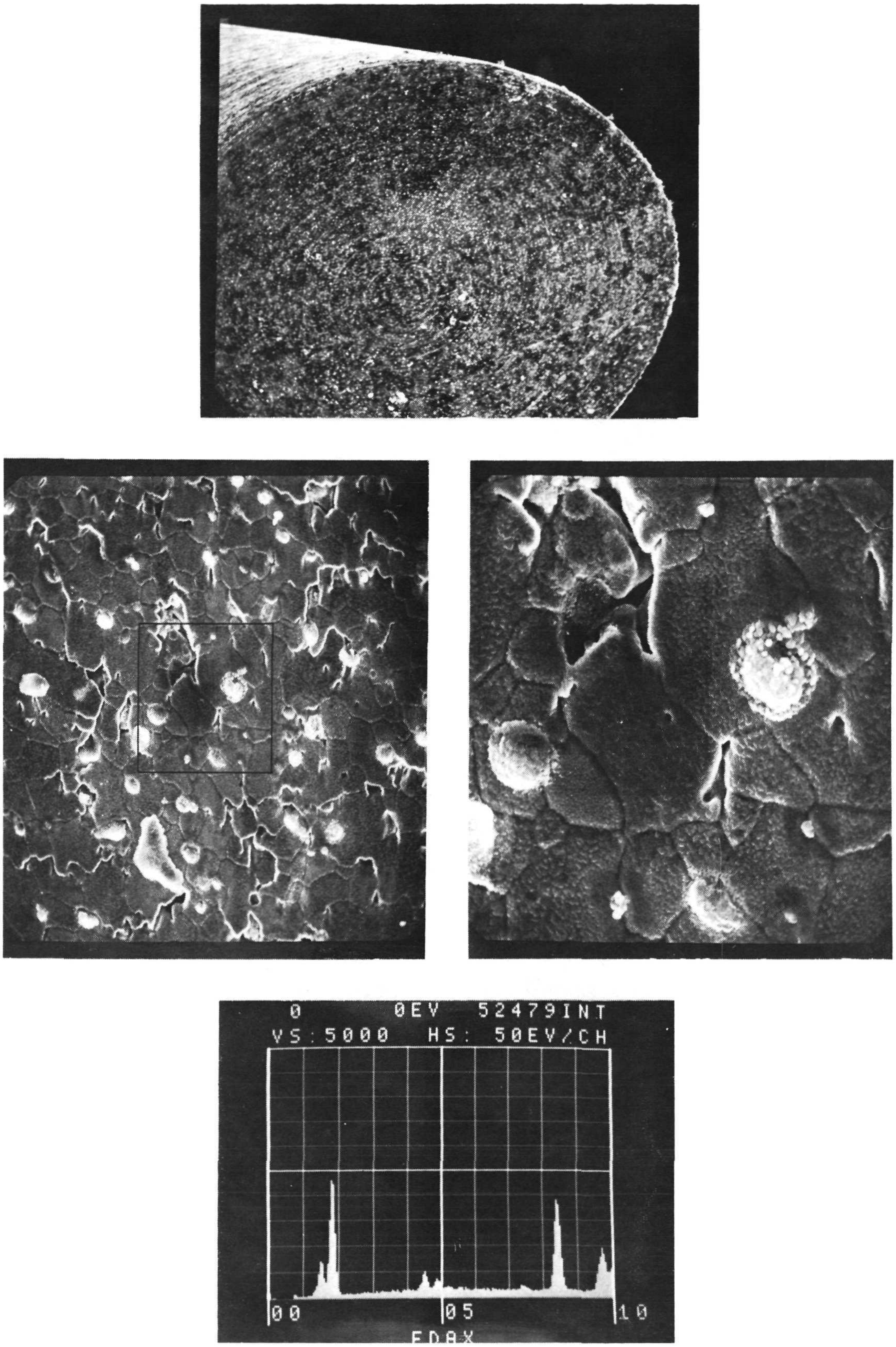

Figure 4. - SEM pictures at magnifications of 60, 1000, and 3000.

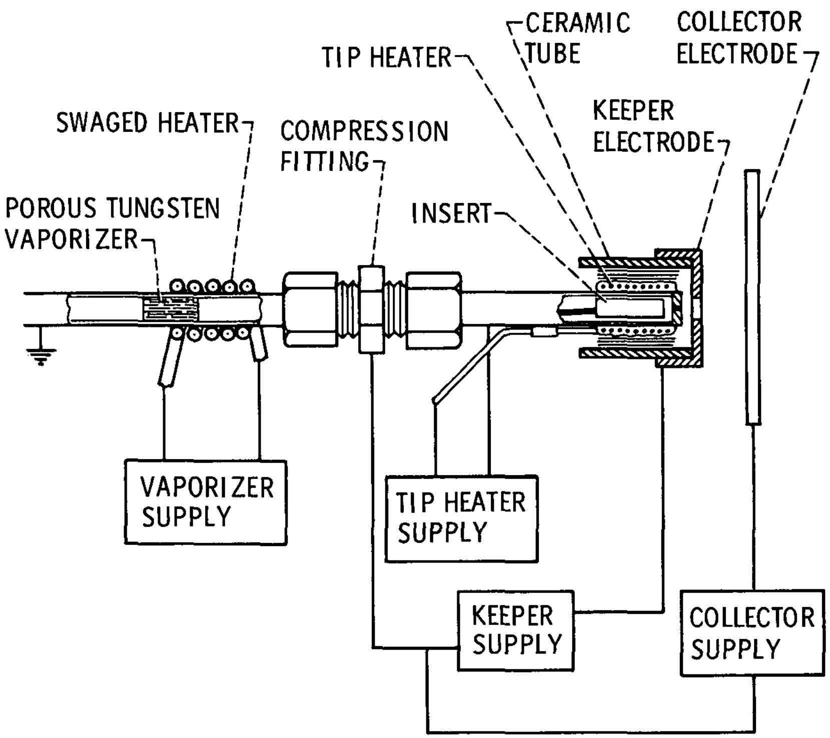

Figure 5. - Electrical Circuit For Cathode Testing.

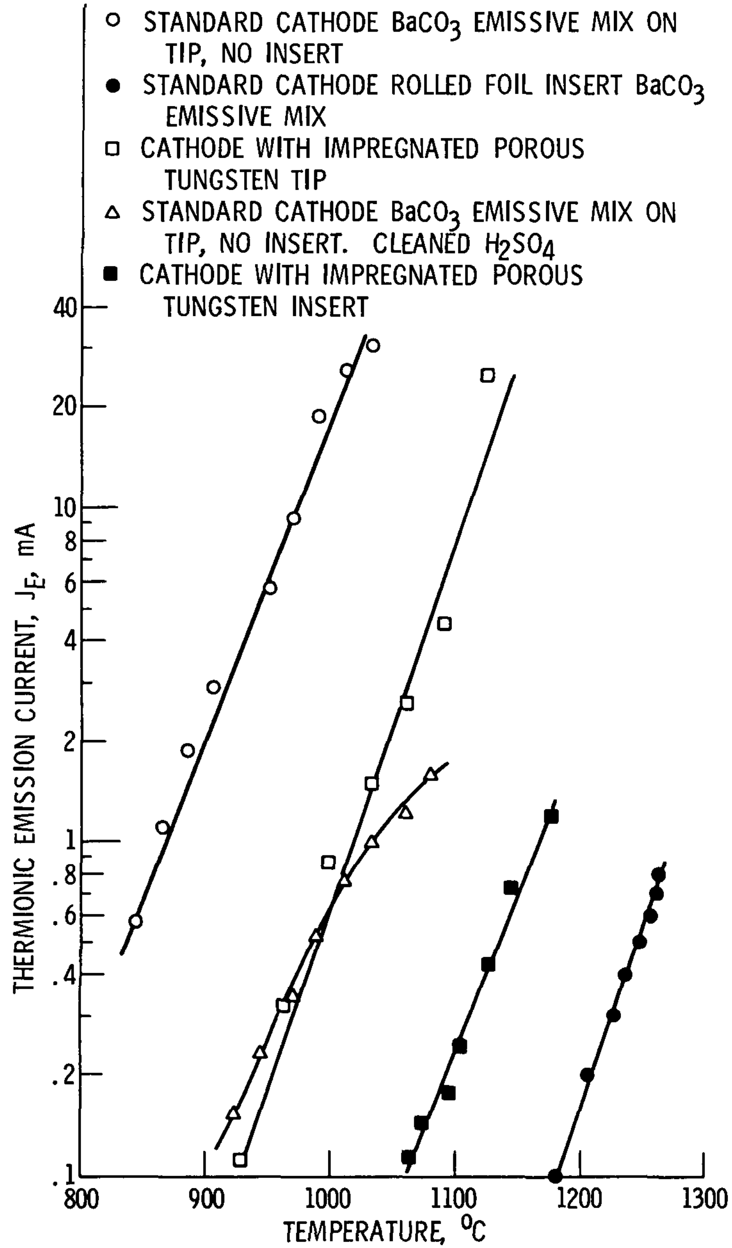

Figure 6. - The thermionic emission current is plotted as a function of temperature for five hollow cathode configurations.

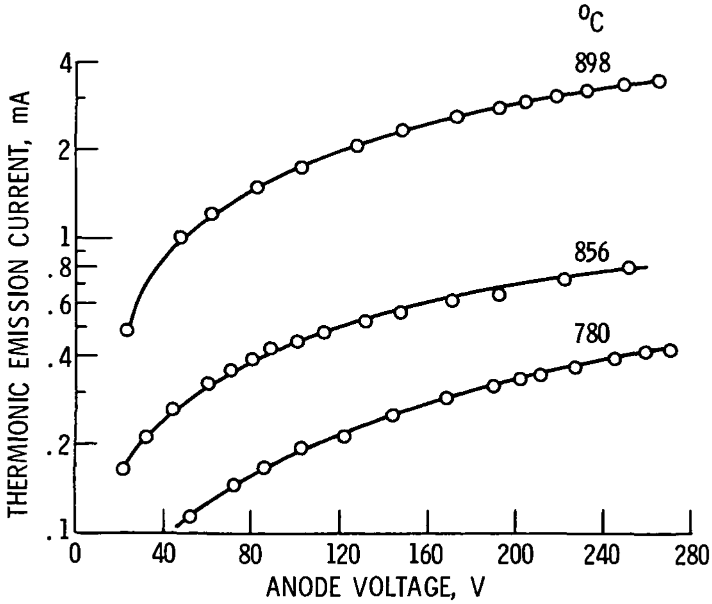

Figure 7. - Thermionic emission current as a function of anode voltage for a standard cathode coated with $BaCO_3$ emissive mix on the tip.

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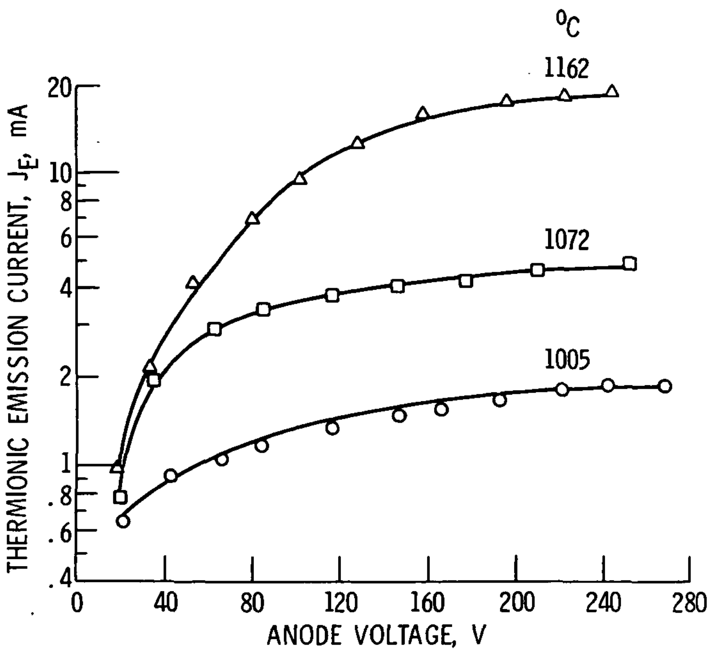

Figure 8. - Thermionic emission current as a function of anode voltage for a cathode with a porous tungsten tip.

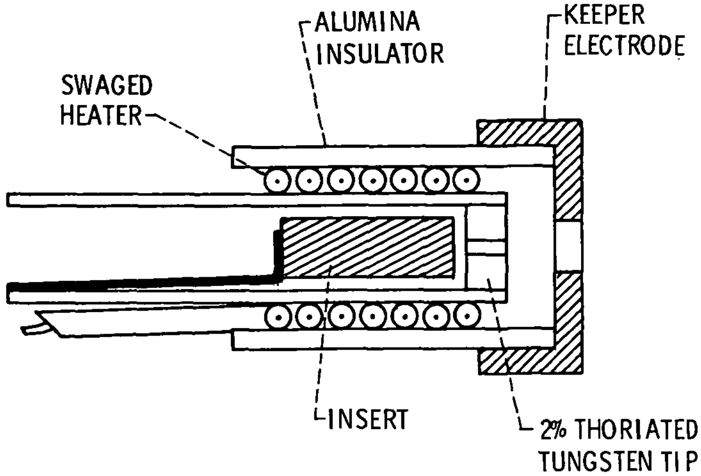

Figure 9. - Cathode impregnated insert.

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Table 1
Cathode Parameters

Diameter cathode tube body	3.18 mm
Cathode tip thickness	1.02 mm
Cathode tip orifice	.25 mm
Tip to keeper spacing	1.02 mm
Keeper orifice diameter	1.50 mm
Insert diameter	1.91 mm
Insert length	7.62 mm
Distance between insert and tip	.25 mm

Table 2
Cathode Operating Conditions

Keeper voltage	16 volts
Keeper current	0.2 amps.
Tip power	5 watts, starting 32 watts
Cathode body temp.	600° C, starting 840° C
Cathode tip temp.	Starting
Vaporizer power	5.0 watts
Mercury flow rate	36 equiv. ma.
Anode voltage	36 volts
Anode current	0.31 amperes
Total power	13.2 watta

Table 3
Cathode Operating Conditions

Keeper voltage	16 volts
Keeper current	0.27 amperes
Tip power	0 watts operating, 24 watts starting
Cathode tip temperature	Starting 1050° C
Vaporizer power	6.0 watts
Mercury flow rate	86 ma equiv.
Anode voltage	40 volts
Anode current	0.60 amperes

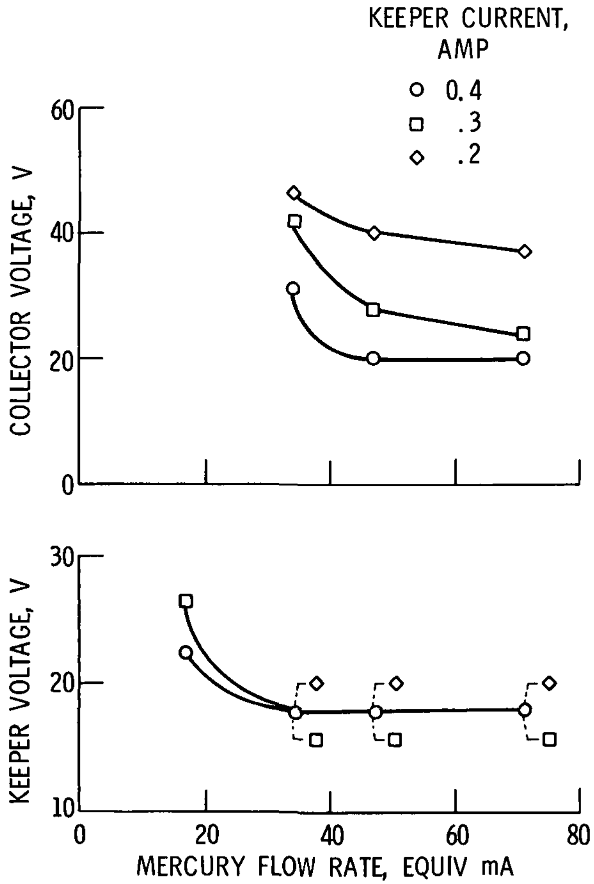

Figure 10. - Keeper voltage and collector voltages as a function of mercury flow rate for keeper currents of 0.2, 0.3, and 0.4 amperes. Data taken after 7500 hours of operation.

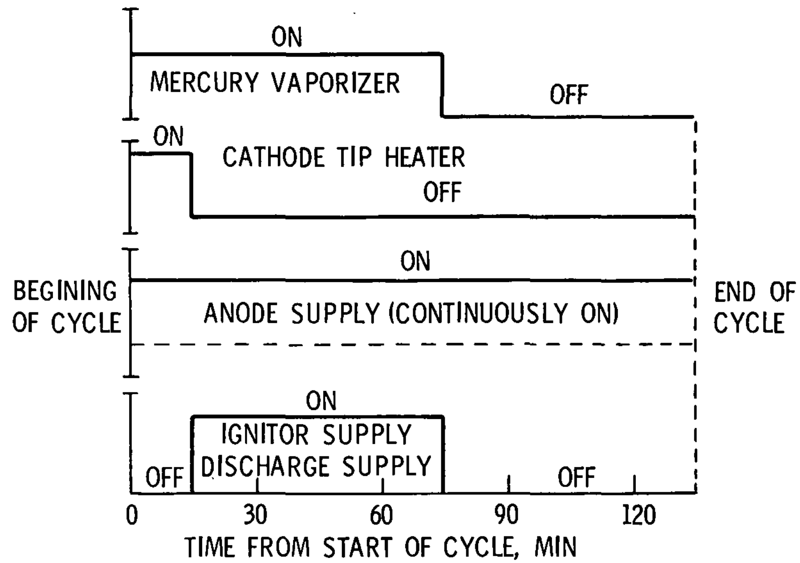

Figure 11. - Test cycle for cathode impregnated insert.

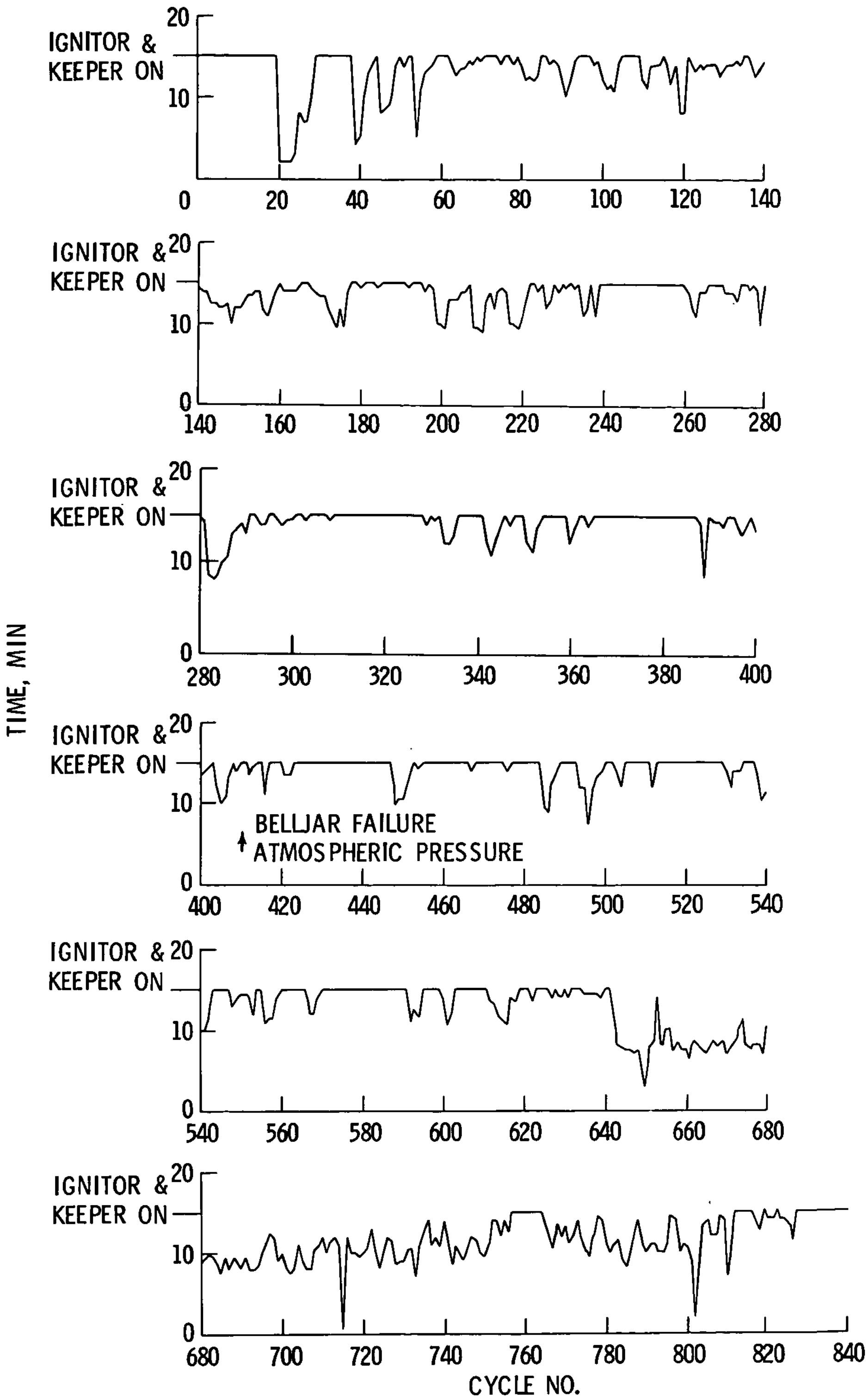

Figure 12. - The time required for the cathode to start is plotted for each cycle. The vaporizer is turned on at time zero and the keeper voltage is turned on after 15 minutes.

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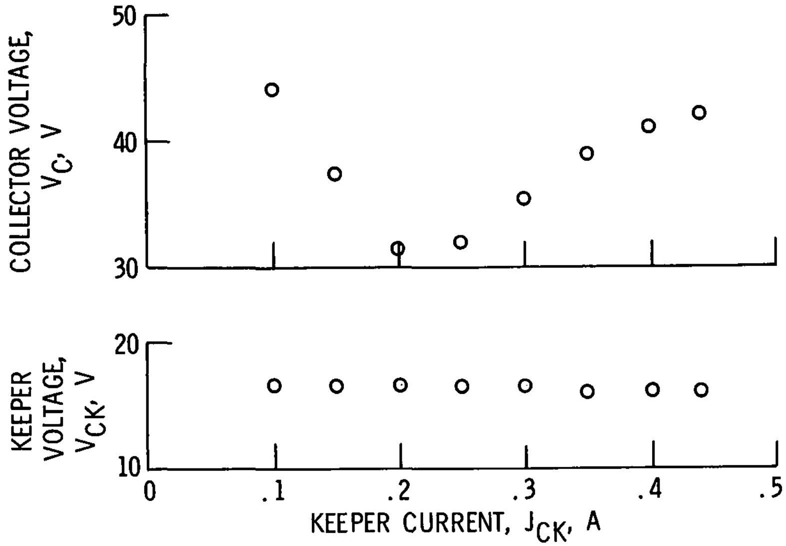

Figure 13. - Collector voltage and keeper voltage is plotted as a function of keeper current. Collector current held constant at 0.55 amps, mercury flow rate at 75 mA.

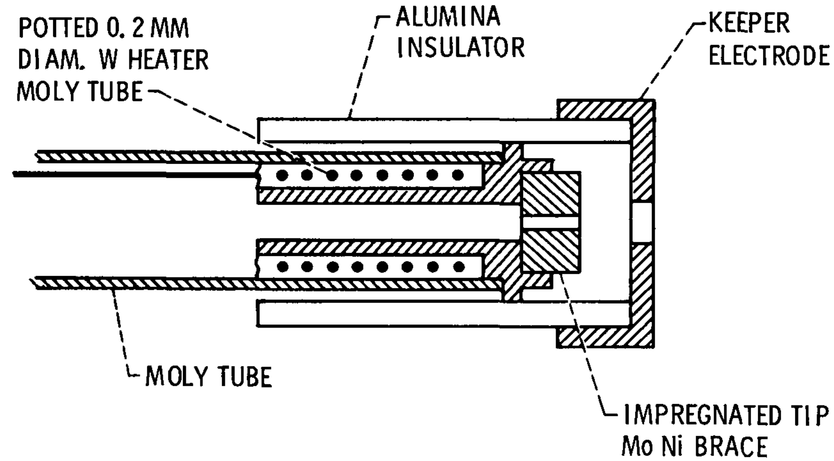

Figure 14. - Cathode Impregnated Tip.

Table 4
Cathode Parameters

Diameter cathode tube body	3.18 mm
Cathode tip thickness	1.02 mm
Cathode tip orifice	.25 mm
Tip to keeper spacing	1.02 mm
Keeper orifice diameter	.75 mm
Cathode heater spool i.d.	.5 mm

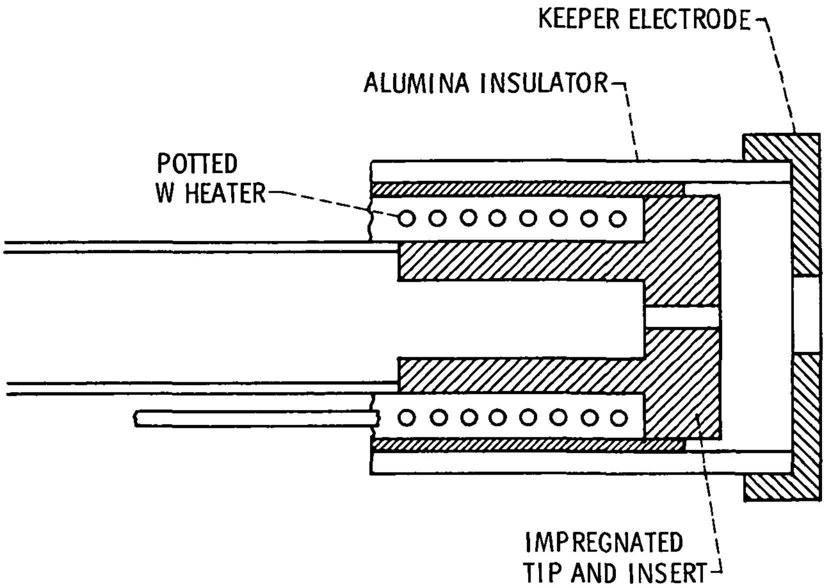

Figure 15. - Cathode Impregnated Tip-Insert.

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Table 5
Cathode Parameters

Diameter cathode body	2.9 mm
Diameter cathode tip	5.6 mm
I.D. impregnated insert	1.5 mm
O.D. impregnated insert	3.0 mm
Cathode tip thickness	1.0 mm
Cathode tip orifice	.25 mm
Tip to keeper spacing	1.5 mm
Keeper orifice diameter	2.5 mm

Table 6
Cathode Operating Characteristics

Keeper voltage	12 volts
Keeper current	0.1 amp
Tip power	6 watts
Cathode tip temperature	Starting 1050° C
Vaporizer power	6.5 watts
Mercury flow rate	86 ma equiv.
Anode voltage	40 volts
Anode current	1.6 ampere
Total power	13.7 watts

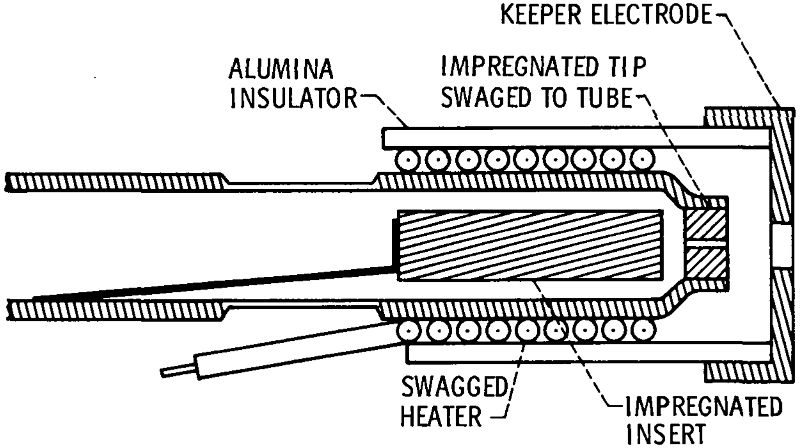


Figure 16. - Neutralizer impregnated insert and tip.

Table 7
Cathode Parameters

Diameter cathode body	3.2 mm
Diameter cathode tip	1.9 mm
Diameter impregnated insert	1.9 mm
Length impregnated insert	7.6 mm
Cathode tip thickness	1.3 mm
Cathode tip orifice	0.25 mm
Tip to keeper spacing	1.5 mm
Keeper orifice diameter	0.76 mm

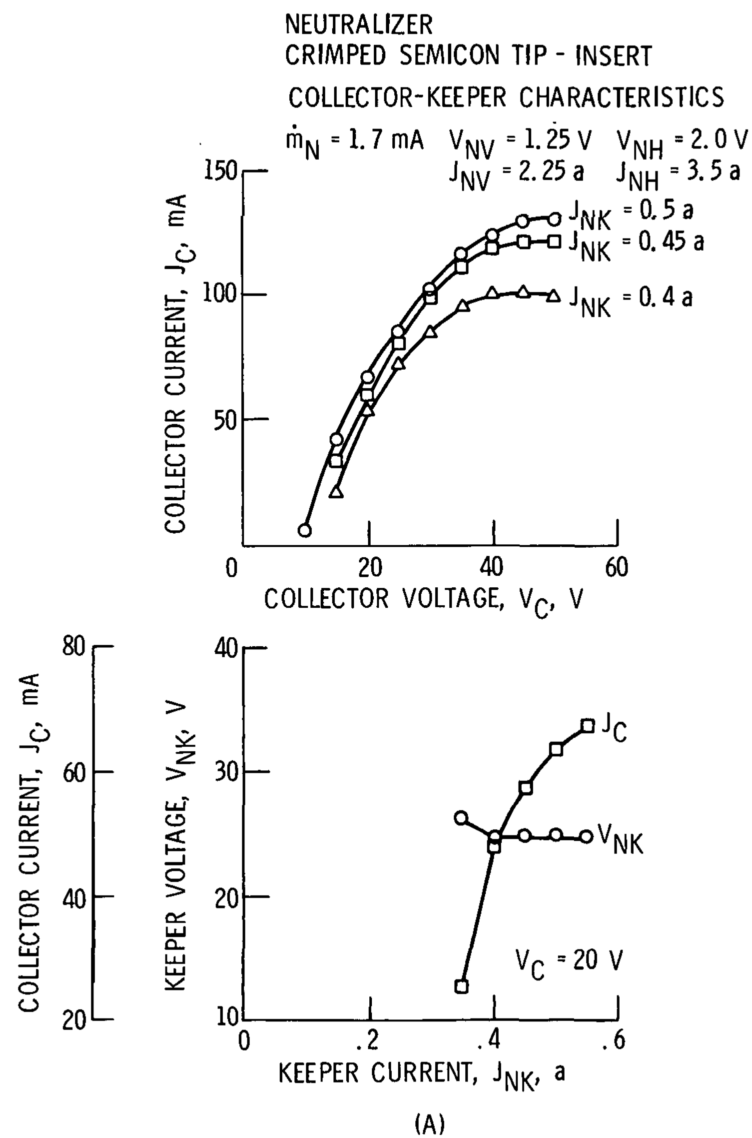
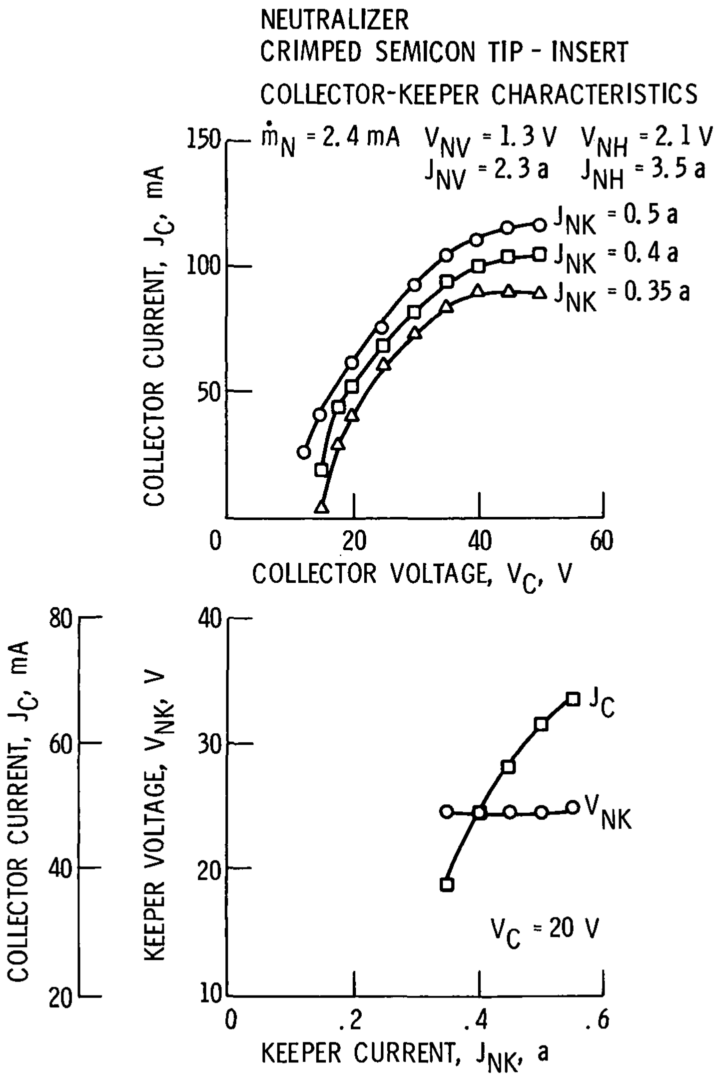
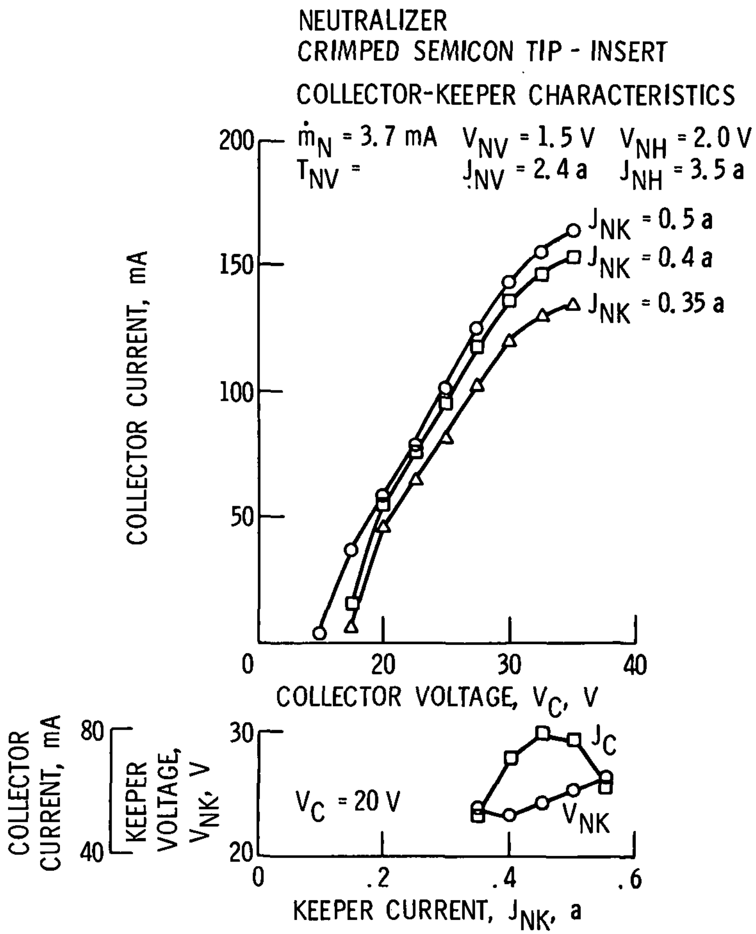


Figure 17. - Collector and keeper voltage-current characteristics measured at mercury flow rates of 1.7, 2.4, 3.7, and 6.7 mA.



(B)

Figure 17. - Continued.



(C)

Figure 17. - Continued.

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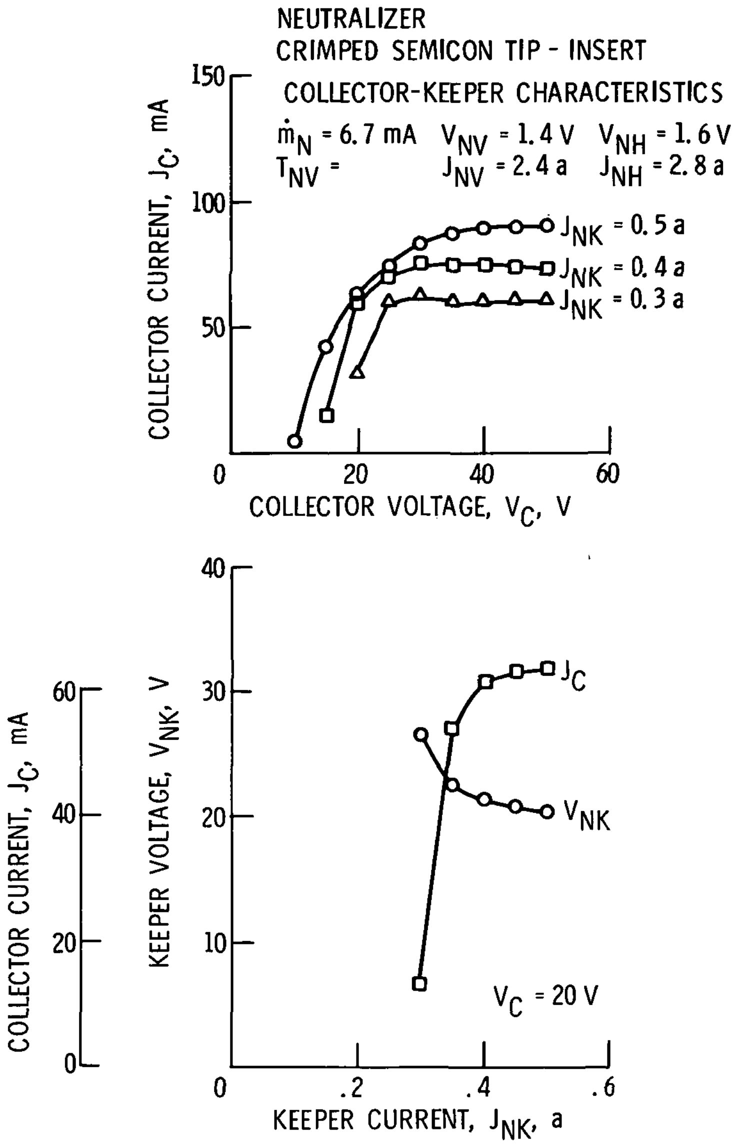

(D)

Figure 17. - Concluded.