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Abstract

Two main cathodes have successfully completed 2800 and 1980 cycles and three neutralizers, 3928, 3050, and 2850 cycles in ongoing cycle life tests of flight-type cathode-isolator-vaporizer and neutralizer-isolator-vaporizer assemblies for the 4.45 mN 8-cm Hg ion thruster system. Each cycle included one hour of cathode operation. Starting and operating conditions simulated those expected in a typical auxiliary propulsion mission duty cycle. This paper presents the cycle life test results and also results of an insert comparison test which led to the selection of a rolled foil insert type for the 8-cm Engineering Model Thruster cathodes.

Introduction

The 4.45 mN (1 mlb) 8-cm mercury ion Engineering Model Thruster (EMT) System presently under development by NASA-LeRC is designed for long term stationkeeping of geosynchronous spacecraft Thruster durability and starting reliability are important requirements for such auxiliary propulsion applications. Design goals for the 8-cm EMT are an operating lifetime of 20,000 hours and 10,000 on-off duty cycles.(1,2)

The cathode-isolator-vaporizer (CIV) and neutralizer-isolator-vaporizer (NIV) assemblies play major roles in ion thruster start-up and operation. As part of the 8-cm EMT development program, LeRC is conducting on going cycle life tests of the CIV and NIV assemblies. The purpose of these tests is to evaluate the efficiency, reliability and durability of flight-type hardware under starting and operating conditions similar to those expected in an auxiliary propulsion mission duty cycle.

The CIVs and NIVs in the cycle life tests were originally designed for use in the 8-cm Structurally Integrated Thruster (SIT-8),(3) which was the predecessor of the 8-cm EMT. The SIT-8 main and neutralizer cathodes were initially intended to operate with alkaline-earth oxide impregnated porous tungsten inserts. However, impregnated inserts used in NIVs were found to produce less than optimum performance in small thrusters. Excessive neutralizer cathode heater powers for starting and operation were required.(4,5) On the other hand, cathode heater power requirements for rolled foil inserts were acceptable. Consequently, rolled foil inserts were chosen for the SIT-8 neutralizer and main cathodes in the cycle life tests and ultimately the EMT cathodes.

This paper presents the results for the first 2800 cycles of one CIV and the first 3050 and 2850 cycles of two NIVs in currently on going cycle life tests. Also presented are the results of a 1980 cycle CIV test and a 3928 cycle NIV test whose terminations were prematurely forced by facility problems. The cathodes were cycled automatically every two hours with one hour operation per cycle. Starting and operating conditions simulated those prescribed for the 4.45 mN EMT. This paper summarizes cathode starting and operating history and presents starting breakdown voltages and operating keeper voltages as a function of number of cycles. The SIT-8 CIV and NIV assemblies differ from the EMT design in some construction details and fabrication procedures. However, the hollow cathodes are identical and the results obtained from the cycle life tests are applicable to the EMT.

Also presented in this paper are the results of a rolled foil insert comparison test whose objective was to determine a suitable insert design for the EMT cathodes. Four NIVs with two insert geometries and two low work function emissive materials were tested. One of the four insert designs was used in the SERT II(6) cathodes and was selected for this test because of a demonstrated restart capability in space flight tests.(7) The evaluation and comparison of the inserts was based on cathode starting and operating performance over 1000 cycles.

Apparatus

CIV and NIV Construction

Figures 1 and 2 show cross-section views of the CIV and NIV assemblies, respectively. The hollow cathodes in both were of similar construction. Details on the cathode body and tip geometry and dimensions are presented in reference 8.

The cathode heaters consisted of 12 turns of 0.25 mm diameter W-26% Rh wire wound over an insulating layer of flame-sprayed Al_2O_3. Covering the heater coil was another layer of flame-sprayed Al_2O_3, over which fit a Ta radiation shield. The room temperature resistances of the cathode heaters were approximately one ohm.

As shown in figures 1 and 2, both the CIV and NIV cathodes used the enclosed keeper electrode configuration. The Ta keeper caps were between 0.25 and 0.37 mm thick at the downstream face and were positioned such that the keeper-to-cathode face spacing was 1.5 mm. The keeper orifice was 2.5 mm in diameter for the CIV and 1.75 mm in diameter for the NIV. The keeper caps were supported by ceramic sleeves to which they were joined by swaging.

Two rolled foil insert geometries and two alkaline-earth oxide emissive materials were used in the insert evaluation test. One insert geometry, hereafter referred to as the "standard" geometry, has been used extensively in the past for 5-cm and 8-cm ion thruster cathodes. Figure 3 shows the dimensions of an unrolled view of the insert. The second insert geometry was similar to that used in the SERT II cathodes.(7) Figure 4 shows the dimensions of both the rolled and unrolled SERT II-type insert. Both inserts were made from 0.0125 mm (0.005 in.) thick Ta foil and had a rectangular section cut from one corner so that when the foil was rolled and placed in the cathode, a cavity was formed upstream to the tip orifice. One main difference between the two insert geometries in the insert comparison test was that the rolled SERT II-

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type insert had many more turns than the standard insert. Another difference was that the wire support was bent over the downstream end and gave the SERT II-type insert a precise spacing of 0.25 mm relative to the cathode tip, a feature the standard geometry did not have.

Of the two emissive materials, one was a triple alkaline-earth carbonate (3-C) consisting of 57.2% $BaCO_3$, 38.8% $SrCO_3$ and 4.0% $CaCO_3$ by weight. The other emissive material (2-C) contained two carbonates, roughly 57% $BaCO_3$ and 43% $SrCO_3$ by weight, and was the same emissive material (R-500) used in the SERT II program.[7] In all cases the foil insert was dipped first in the emissive material and then air-dried before rolling. The inserts in the cycle life test cathodes all had the standard geometry and 2-C emissive material except for the NIV with 2850 cycles whose insert was coated with the 3-C emissive material.

Table I gives some representative steady state CIV and NIV cathode tip temperatures for various cathode heater power levels. These temperatures were determined by means of thermocouples mounted on the cathode tip. The CIV and NIV were mounted in their cycle test configuration with the vaporizer maintained at temperatures corresponding to starting Hg flow rates. The accuracy of the temperature measurements is estimated to be within 10^o C. Starting from cool conditions (20-25^o C) the CIV cathode tip temperature reached 1000^o C in 2 to 3 minutes and the NIV reached 1000^o C in 6 to 7 minutes.

The isolator was not actively a part of the cycle tests. Isolator performances for a CIV and NIV in a 15,000 hour SIT-8 life test are documented in reference 5.

Vacuum Facilities

The 3928 cycle NIV test and the first 1281 cycles of the 2850 cycle CIV test were performed in a 46-cm diameter vacuum bell jar. Figure 5 shows the CIV and NIV test configurations. The bell jar pressure was in the high 10^{-7} to low 10^{-6} torr range during NIV operation and in the mid 10^{-6} torr range during CIV operation. The bell jar pressure with no cathodes operating was in the mid 10^{-7} torr range.

Figure 6 shows the small vacuum tank with six identical test parts where all other CIV and NIV testing was performed. The test ports were 25 cm in diameter and 20-cm long. Figures 7 and 8 show the test configurations for the CIV and NIV, respectively. Port pressures were in the low to mid 10^{-5} torr range during NIV operation and in the low 10^{-4} torr range during CIV operation. The test port pressures with no cathodes operating were in the mid 10^{-6} torr range.

Electrical System

A diagram of the power supply arrangement used in the cathode cycle tests is shown in figure 9. The cathode and vaporizer heater power supplies were line voltage regulated variable voltage transformers with 12 Vac, 10 A rated secondaries. The keeper and collector power supplies were 55 Vdc, 2 A voltage regulated supplies with external constant current controllers. Currents and voltages were read from panel meters with a ±3% rated accuracy. Vaporizer temperatures were measured by means of iron-constantan thermocouples mounted on the vaporizer housing over the porous tungsten plug.

A high voltage pulse applied to the keeper was used for cathode starting.[9] Two slightly different circuits for the blocking diode, shown in figure 9, were used. The pulse ignitors were capable of delivering a pulse of up to 8 kV amplitude every 3-5 seconds. The pulse rise times were in the range of 1.0±0.2 kV per microsecond. The starting keeper voltages used to sustain the discharge after breakdown were 35-40 V. All keeper and collector voltages presented in this paper were measured at the vacuum port terminals and represent voltages applied to the component of interest.

Cam operated timer relays were used to cycle the cathodes automatically every two hours. Figure 10 shows the basic relay and power supply arrangement and cycle sequence. The cycle consisted of 10 minutes preheat, one hour cathode operation and 50 minutes cooldown. At t = 0 minutes, a cam-actuated relay (K1) turned on the cathode and vaporizer heater power supplies. At t = 10 minutes, a second cam-actuated relay (K2) turned on the keeper supply and pulse ignitor. When the keeper discharge ignited, a current meter relay (K3) which sensed keeper current turned the collector supply on, the pulse ignitor off and reduced the cathode and vaporizer heater power levels. Five minutes was allowed for cathode starting, after which the system shutdown if the cathode failed to start. At t = 70 minutes, K1 and K2 opened and the cathode shut down. For CIV operation only, an auxiliary keeper supply, shown in figure 10, provided a higher level of keeper current for starting (360 mA) than was used during operation (60 mA).

Test Procedure

Table II summarizes important physical features of the CIV and NIV cycle life tests, such as number of cycles, facility, emissive material and collector-keeper spacing.

The thruster anode and ion beam were electrically simulated by means of collector anodes. For the CIV with 1980 cycles (CIV-2), the collector anode was a solid 2.5-cm diameter Ta disc. In all other cases the collector anode was a 3-cm square stainless steel screen. The collector-keeper spacing was adjusted to give a voltage of 35-40 V for the CIVs and 10-20 V for the NIVs. The spacing was 3.5 cm for all four NIVs in the insert evaluation test.

The starting and operating conditions, presented in Table III, were generally the same for both the cycle life tests and the insert comparison test. These values were essentially those prescribed for the 4.45 mN EMT. The EMT values, where different, are shown in parentheses. There were times when other than 25 w cathode heater power was used for starting and will be reported under Results and Discussion. The Hg flow rate of 80 mA for main cathode operation corresponds to a 90% discharge chamber utilization with 72 mA beam current.

All CIVs and NIVs were new at the beginning of the cycle tests. Careful handling procedures were followed to keep the cathodes clean and dust-free. The same insert activation procedure, summarized in

Table IV, was followed for the initial start of each cathode. Flow rates were determined by measuring the time rate of change of the Hg column height in a precision bore capillary tube. Flow rates for cathode starting and operation during the cycle tests were inferred from the corresponding vaporizer temperatures. After the initial activation of the cathodes, exposure to atmosphere of the cathodes was avoided when possible, although occasionally necessitated by facility failures. If exposed to atmosphere, the insert was first reconditioned by following the pre-start procedure given in Table IV before resuming the cycle test.

Results and Discussion

Cycle Life Tests

A general summary of the cycle life test results will be presented first and then be followed by a somewhat more detailed discussion of the individual life test results in the following order: (1) CIV-1 and CIV-2, (2) NIV-1 and (3) NIV-2 and NIV-3. The more detailed results are generally limited to breakdown voltages required for cathode starting and the keeper voltage during operation. Discussion will include general trends over the cycle life tests and those events which were observed to either influence or cause departures from the general trends. Cathode starting breakdown voltages and keeper voltages were selected for presentation because increases in these two voltages are indicators of insert degradation such as a decrease in activity or depletion of low work function emissive material.[10,11] Insert degradation strongly impacts cathode starting capability and lifetime. The design goal for the EMT is a maximum pulse amplitude of 5 kV. The cathodes must be capable of starting within this limit throughout their cycle life.

General Results

Table V summarizes the cycle life test results and shows the ranges of tip heater power, breakdown voltage and keeper and collector voltages. With the exception of the NIV-3 collector voltage, which exceeded the EMT design goal of 20 V or less for the neutralizer-beam coupling voltage, all other voltages were within limits acceptable for EMT operation. The cathode heater power required for each cathode start was 25 W or less. All other parameters such as keeper and collector currents and Hg flow rates were at the EMT levels as shown in Table III. No abnormalities were observed during the initial activation and start of any of the cathodes. All starting failures were traceable to equipment failure. Ignition of the discharges was observed to generally occur within 10-15 seconds after the pulse ignitor was turned on.

As mentioned previously, terminations of the cycle life testing of CIV-2 (1980 cycles) and NIV-1 (3928 cycles) were facility related. In the case of CIV-2, cathode performance became unstable after a leak in the feed system caused a depletion of Hg in the feed lines and the admission of air into the operating cathode. Testing of NIV-1 was discontinued when the cathode no longer started within acceptable limits following relocation from the vacuum bell jar to the multiport test facility.

Keeper (V_K) and collector (V_C) voltages were always measured during the last 15 minutes of cathode operation in the CIV cycle and during the last 30 minutes of cathode operation in the NIV cycle, after near thermal equilibrium conditions were reached. Changes in these parameters over a large number of cycles, therefore, represented changes in the cathode condition with the cycle transient effects minimized. Figures 11 and 12 are typical examples of the variation of V_K and V_C during cathode operation for CIV-1 (cycle 2719) and NIV-2 (cycle 2920), respectively. These figures show the CIV sufficiently close to thermal equilibrium after 45 minutes, and the NIV, with less thermal mass, sufficiently close to thermal equilibrium after 30 minutes. At the beginning of each cycle, the CIV and NIV vaporizer temperatures were usually 65-70° C and 40-45° C, respectively, in the multiport facility and averaged 5-10° lower for CIV-1 and NIV-1 in the vacuum bell jar.

CIV Cycle Life Tests

Figures 13 and 14 are plots of breakdown voltage (BDV) and keeper voltage (V_K), respectively, versus number of cycles for CIV-1 and CIV-2. The first observation to be made is the general trend toward increasing BDV and V_K. Such increases usually indicate insert degradation, part of which may occur naturally and part from exposure of the insert to an adverse environment. For both CIVs, however, the BDV remained well within the acceptable limits.

Those occurrences where there was an interruption of the normal cycling procedure, (e.g., facility shutdowns) are referred to in this paper as "events". Table VI summarizes the events and their effects on cathode performance for CIV-1 and CIV-2. Only those events which significantly influenced performance, represented by solid symbols in figures 13 and 14, will be discussed.

For the first 1281 cycles, which were performed in the vacuum bell jar facility, CIV-1 did not require a high voltage pulse for starting. The 35-40 Vdc keeper supply voltage sufficed. During this period, V_K rose from an initial value of 7 V to slightly above 14 V. The first time a pulse was required (400 V) was in cycle 1282 after CIV-1 was exposed to atmosphere during transfer to the multiport vacuum tank. The keeper voltage increased by about 1 V. In cycle 2249, CIV-1 BDV increased significantly to 1.8 kV after being exposed to approximately 1 torr during a long facility shutdown. In subsequent cycles BDV decreased to around 1.3 kV.

Cycle 429 was the first cycle where a pulse (200 V) was observed to be required for starting CIV-2. Two events occurred in the cycle history of CIV-2 which resulted in observable increases in BDV. In cycle 753, following exposure to atmosphere, BDV increased to 1 kV and shortly thereafter to 1.5 kV. Similarly, in cycle 1909, after exposure to 1 torr during a long facility shutdown, BDV increased to 1.8 kV. In both instances, the increase in V_K was either small or negligible. Cycle 774 was preceded by first an exposure to atmosphere and then 16 hours of continuous operation. The resulting effect, a decrease in BDV to 450 V and in V_K to 13.2 V, was an apparent reactivation of the insert. After about 300 cycles (774 to 1075) the BDV returned to its previous high of 1.5 kV whereas V_K rose to only 15.5 V, which was well below its previous high of 18 V.

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NIV-1 Cycle Life Test

NIV-1 was the first flight-type neutralizer to undergo a life test with a large number of cycles (3928) and consequently some of the test conditions were of an experimental nature. Figure 15 is a plot of breakdown voltage (BDV) vs. cycles. As figure 15 shows, the BDV underwent numerous fluctuations and ranged from a low of 120 V to a high of 5 kV. The plotted points generally represent maximum and minimum values of BDV. A large number of intermediate measured values are not shown. The symbols correspond to significant events during the cycle test which impacted starting and operating performance.

NIV-1 was the only cycle life test cathode where the cathode heater power (P_{NH}) was less than 25 W during start-up. The maximum P_{NH} applied during initial activation of the insert was 20 W. The diamond symbols in figure 15 correspond to increases in P_{NH}. Table VII presents periods of operation at each level of P_{NH} and corresponding values of BDV. The cycle test began with P_{NH} = 21 W, the minimum value for which BDV was less than 5 kV. As the cycle test proceeded, P_{NH} was increased in increments of 1 W to a maximum of 25 W in cycle 1466. Each increase was intended to reduce BDV and usually succeeded although sometimes temporarily. As figure 15 shows, after cycle 1466, P_{NH} = 25 W was generally effective in holding BDV below 2.5 kV except for 4 peaks corresponding to facility shutdowns. If one disregards these peaks, BDV shows a generally increasing trend from a low of 120 V in cycle 1728 up to 2.3 kV in cycle 2742.

Twelve facility shutdowns, summarized in Table VIII, occurred during the NIV-1 cycle life test and resulted in either direct exposure to atmosphere or to pressures in the 10-1000 millitorr range. Six of these occurrences are indicated by the circle symbols in figure 15 (cycles 60, 98, 2111, 2150, 2323 and 2823) and can be directly correlated with peaks in BDV. The four BDV peaks in cycle 2111, 2150, 2323 and 2823 themselves show a trend towards more difficult starting, culminating in a BDV greater than 5 kV after cycle 3928 when NIV-1 was exposed to atmosphere during transfer between facilities.

On three occasions during the NIV-1 cycle life test, the cathode was operated continuously (at EMT conditions) for times longer than the normal cycle time of one hour. These events are summarized in Table VIII and are indicated by the triangle symbols in figure 15. The first period of continuous cathode operation lasted 22 hours and occurred after cycle 2867, when the BDV was observed to have remained high (> 4 kV) 45 cycles after the exposure to atmosphere preceding cycle 2822. The result was a decrease in BDV in the next cycle (2868) to 700 V - a dramatic improvement in starting capability. The second time occurred after cycle 2918 when NIV-1 was exposed to atmosphere four times. In between each exposure, the cathode was restarted but not cycled. After the fourth exposure, the cathode was operated continuously for 118 hours. When cyclic operation was resumed (cycle 2919), the BDV was observed to have decreased to 300 V. Over the next 500 cycles, the BDV then increased to a high of 2.2 kV (cycle 3422). The third time occurred after cycle 3592 when NIV-1 was intentionally operated continuously for 24 hours in order to observe the effect on starting capability. The results were positive - the BDV was reduced to 300 V although it did rise to 1.6 kV about 150 cycles later.

Figure 16 is a plot of keeper voltage (V_K) vs. number of cycles for NIV-1, NIV-2 and NIV-3 (NIV-2 and NIV-3 are discussed later). Overall, V_K for NIV-1 followed an increasing trend as the cycle test progressed, increasing by about 4 V from near 16 V to near 20 V. The exposures to atmosphere or pressures of 10-1000 millitorr had no observable effect on V_K. Continuous operation of the cathode had only a slight effect on V_K, lowering it by about 0.5 V in each of the last two occurrences (cycles 2919 and 3593 in figure 16). After cycle 2919, V_K increased over the next 400 cycles to a high of 20.3 V (cycle 3305). After cycle 3593, V_K remained about the same for the duration of the test (330 additional cycles).

Continuous operation of the cathode appeared to have a more pronounced effect on starting capability than on keeper voltage but was not always successful in reducing the BDV to 5 kV or less. This was the case after cycle 3928 when NIV-1 was exposed to atmosphere during transfer between facilities. Several hundred hours of continuous operation failed to reduce BDV below 5 kV, even with 30 W of cathode heater power.

NIV-2 and NIV-3 Cycle Life Tests

The first 1000 cycles of the NIV-2 and NIV-3 cycle life tests were part of the insert comparison test and will be covered in more detail in that section.

Figure 16 shows keeper voltage V_K vs. cycles for NIV-2 and NIV-3. Contrary to expectation, V_K for NIV-2 (circled symbols) increased only during the first 1000 cycles and then generally decreased over the remainder of the test. After a high of 18.7 V in cycle 72, V_K for NIV-3 (triangular symbols) decreased to a low of 13.8 V in cycle 930 and then gradually drifted upward until cycle 2674 (solid triangles in fig. 16). At that time the keeper current was increased from 0.5 to 0.6 A in order to reduce collector voltage below 20 V. The effect on V_K was an increase of approximately 1 V.

Figure 17 is a plot of breakdown voltage (BVD) vs. cycles for NIV-2 and NIV-3. The general trend was towards increasing BDV. The NIV-2 cathode started without a pulse in the first 172 cycles. In cycle 173 the BDV was 300 V and increased to 2.3 kV after 3050 cycles. On the other hand NIV-3 required a high voltage pulse from the beginning (1 kV). The lowest observed BDV for NIV-3 was 0.5 kV between cycles 90 and 101. After 2850 cycles, the BDV for NIV-3 was 2.8 kV.

The exposures to atmosphere or pressures of 10-1000 millitorr and the occurrences of continuous cathode operation for NIV-2 and NIV-3 are summarized in Table IX. NIV-2 was exposed a total of 12 times during the 3050 cycles including 8 times during the first 1000 hours. Two of the other 4 exposures were observed to be followed by increases in BDV and are indicated by solid circles in figure 17 (cycles 2165 and 2870). The BDV in both cases continued to increase reaching peaks of 1.8 kV (cycle 2260) and 2.3 kV (cycle 3050). Preceding cycle 2594, NIV-2 was exposed to 20-30 millitorr during a facility shutdown and then operated continuously for 17 hours. The result was a substantial drop in BDV (400 V) and V_K (13.8 V). This event is indicated by solid circles in figures 16 and 17.

As a result of facility shutdowns, NIV-3 was exposed six times to pressures in the 10-1000 millitorr range. These events are summarized in Table IX. Three of the exposures were followed by increases in BDV (see cycles 1196, 2030 and 2674 represented by solid triangles in figure 17). After the cycle 2458 exposure, the NIV-3 cathode was operated continuously for 30 hours. The result was a decrease in BDV (from greater than 2.5 kV down to 800 V) as indicated by the solid triangle at cycle 2460 in figure 17. There was no change in V_K. As in the case of NIV-1 (prior to the facility transfer), continuous cathode operation was successful in reducing the BDV and thereby improving the starting capability for NIV-2 and NIV-3. Only in the case of NIV-2, however, was V_K also lowered.

Insert Comparison Test

For the insert comparison test, the following items were made as identical as possible: NIV construction, test geometry, test environment, electronics, starting and operating procedures, Hg flow rates, keeper and collector anode discharge currents, and initial insert activation procedure. It was assumed that any failure to meet starting and operating requirements could then be ascribed to the insert, unless demonstrated otherwise.

Three of the cathodes began the cycle test simultaneously, the intent being that any facility shutdowns would occur after the same number of cycles. The one exception was NIV-2 which commenced cycling about 135 cycles sooner. NIV-2 was exposed to atmosphere 6 times during the first 76 cycles for the purpose of adjusting the collector anode position. These early exposures did not observably affect NIV-2 performance and therefore did not handicap the insert for comparison purposes. In fact, the NIV-2 cathode started without a pulse through cycle 172 and was the only cathode in the insert comparison test which began the test without requiring a pulse for starting.

A general summary of the insert comparison test results will be presented first and then be followed by more detailed results for (1) NIV-2 and NIV-3 with the standard insert geometry and (2) NIV-4 and NIV-5 with the SERT II-type insert geometry. As reported earlier, NIV-2 and NIV-3 were also part of the cycle life tests.

General Results

The insert comparison was based on starting and operating performance over 1000 cycles. The Hg flow rates and discharge currents were set at the levels prescribed for EMT operation. As the test proceeded, three parameters emerged as useful as comparison criteria - the breakdown voltage (BDV) and cathode heater power (P_{NH}) required for starting and the collector anode voltage (V_C) during operation. The keeper voltage was found not to be a useful comparison criterion in this test.

Table X summarizes the results of the insert comparison test. NIV-2 with the standard insert geometry and 2-C emissive material was the only neutralizer which satisfied all three comparison criteria, viz, BDV $\leq$ 5 kV, P_{NH} = 25 W and $V_C \leq$ 20 V. NIV-4 and NIV-5 with the SERT II-type insert geometry required more than the recommended EMT cathode starting levels of P_{NH} = 25 W and BDV $\leq$ 5 kV. NIV-3 with the standard insert geometry and 3-C emissive material operated at greater than the recommended limit of 20 V collector voltage.

On the basis of these results the standard insert geometry and the 2-C emissive material (8-10 mg) were selected for the 8-cm EMT cathode design. This decision was reinforced by the fact that a neutralizer with a similar insert (NIV-1) had already performed satisfactorily for 3400 cycles.

NIV-2 and NIV-3

Figure 18 is a plot of BDV vs. cycles for NIV-2 and NIV-3 for the 1000 cycle insert comparison test. As mentioned previously, NIV-2 started without a pulse for the first 172 cycles. The maximum BDV observed during the 1000 cycle test was 700 V. In contrast NIV-3 required a pulse from the beginning and the maximum BDV observed was 2.2 kV between cycles 592 and 691, after which the BDV dropped to 1.2 kV or less for the duration of the test. The solid symbols in figure 16 correspond to a facility shutdown during which the cathodes were exposed to a pressure around 1 torr. No effect on starting capability was observed. At no time during the 1000 cycle insert evaluation test did NIV-2 or NIV-3 fail to start. Using BDV as a measure of starting capability, NIV-2 was clearly superior to NIV-3, although the BDV for the latter was still within the 5 kV EMT limit.

The keeper voltages (V_{NK}) for NIV-2 and NIV-3 for the 1000 cycle insert evaluation test are shown in figure 16 which was referred to previously. V_{NK} for NIV-2 was around 17 V in the beginning and increased to around 19 V after 1000 cycles. V_{NK} for NIV-3 was initially 15 V, peaked at 19 V between cycles 72 and 82 and then dropped to around 14 V after 1000 cycles. After 1000 cycles NIV-3 had a 2.5 V lower V_{NK} than NIV-2. Although not a part of the insert comparison test, the cycle life test results showed V_{NK} for both cathodes about equal at 14 V by cycle 2500.

Figure 19 shows the collector anode voltages (V_C) vs. cycles for NIV-2 and NIV-3. V_C for NIV-2 was 11 V in cycle 77 (final adjustment of collector spacing) and gradually increased to around 16 V after 1000 cycles. In contrast, V_C for NIV-3 was as high as 73 V in cycle 82 and was greater than 20 V over most of the 1000 cycle test, rising from a low of 17 V in cycle 90 to close to 40 V in cycle 1000. The solid symbols correspond to the facility shutdown mentioned previously which had no observable effect on V_C.

Figure 20 is a plot of V_C vs. neutralizer keeper current (J_{NK}) for NIV-2 and NIV-3 after 1000 cycles. V_C for NIV-3 was much more sensitive to the level of J_{NK}. A J_{NK} of 0.58 was required to reduce V_C to 20 V or less and exceeded the 0.5 A EMT specification.

NIV-4 and NIV-5

Figure 21 is a plot of BDV vs. cycles for NIV-4. The solid circle represents the one time when NIV-4 was exposed to atmosphere (after cycle 85). The BDV subsequently increased to 8 kV over the next 25 cycles. Between cycle 153 and 166 a BDV of 5 kV was observed but then returned to 8 kV. Increasing P_{NH} to 26 W (after cycle 250) did not affect BDV. Between cycles 693 and 733, P_{NH} was increased in 1 W increments up to 32 W until BDV was

5 kV or less, where it remained until the end of the 1000 cycle test. NIV-4 failed to start once (cycle 513) during the 1000 cycle test.

Figure 22 is a plot of BDV vs. cycles for NIV-5 which showed an even poorer starting capability than NIV-4. NIV-5 required a high BDV (4 kV) from the beginning and failed to start 14 times (cycles 32, 227, 320, 444, 521, 600, 610, 766, 960, 961, 968, 972, 989 and 1000 as indicated by the arrows in figure 22). NIV-5 was exposed to higher pressure (1 torr) only once after which the BDV rose to 8 kV, (cycle 85 indicated by the solid triangles in figure 22). After cycle 644, P_{NH} was increased with the intent of reducing the BDV. A cathode heater power of 34 W was required to bring BDV below 5 kV (cycle 778, 4 kV). Over the next 180 cycles, the BDV rose to 8 kV and the cathode eventually failed to start in cycles 960 and 961. NIV-5 was then operated continuously for 77 hours, which resulted in a dramatic reduction in the BDV (4 kV) and P_{NH} (25 W). Within a few cycles, however, the BDV increased to 8 kV and even a cathode heater power of 34 W did not reduce BDV below this level.

In spite of poor starting capability, NIV-4 and NIV-5 operated quite acceptably. As Table X shows, keeper and collector voltages were relatively low. V_{NK} for NIV-4 peaked at 16.8 V in cycle 47, dropped to 15 V in cycle 83 and was 13 to 15 V for the remainder of the 1000 cycles. V_{NK} for NIV-5 was only 13 to 14 V for the entire test.

Concluding Remarks

Two main cathodes have successfully completed 2800 and 1980 cycles and three neutralizers have successfully completed 3928, 3050 and 2850 cycles in ongoing cycle life tests, during which the cathodes satisfied the starting and operating requirements for the 4.45 mN 8-cm EMT system. These are the first long duration tests of flight-type hardware where cyclic operation of the cathodes realistically simulated that expected in a typical auxiliary propulsion mission duty cycle. The primary conclusion is that the 2800 cycle CIV test and the 3928 and 3050 cycle NIV tests have demonstrated a capability of meeting the starting and operating requirements for an 8 to 10 year mission requiring one thruster start per day.

The general trends toward increasing breakdown voltage and keeper voltage as shown by the cycle life test results indicate insert degradation. However, none of the cycle life tests were free from exposure of the cathodes to probable contamination by non-spacelike conditions. It is not possible to state quantitatively how much these exposures may have accelerated the degradation effects.

Finally, a rolled foil insert comparison test, based on the starting and operating performance of 4 NIVs over 1000 cycles, resulted in a choice of insert geometry and low work function emissive material for the 8-cm EMT cathodes. The cycle life test results reported in this paper demonstrate that this insert is capable of performing satisfactorily for 3000-4000 cycles. Further cycle life testing is required to demonstrate its adequacy to meet the 8-cm EMT design goal of 10,000 on-off duty cycles.

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TABLE 1. - REPRESENTATIVE CIV AND NIV CATHODE TIP TEMPERATURES FOR VARIOUS CATHODE HEATER POWER LEVELS

Cathode heater power, W	Cathode tip temperatures, °C	
	CIV	NIV
20	990	900
25	1095	1000
30	----	1065
35	----	1115

TABLE II. - SUMMARY OF IMPORTANT PHYSICAL FEATURES OF CIV AND NIV

CYCLE LIFE TESTS

(All cathodes listed here had the standard insert geometry)

Cathode	Cycles	Facility	Low work function emissive material	Collector-keeper spacing, cm
CIV-1	1-1281	Vac. B.J.	3-C (8-10 mg)	2.5
	1282-2800	Multiport Vac. tank		3.0
CIV-2	1980	Multiport Vac. Tank	3-C (8-10 mg)	3.3
NIV-1	3928	Vac. B.J.	3-C (8-10 mg)	0.6
NIV-2	3050	Multiport Vac. tank	3-C (8-10 mg)	3.5
NIV-3	2850	Multiport Vac. tank	2-C (46 mg)	3.5

TABLE III. - CYCLE TEST STARTING AND OPERATING CONDITIONS

(EMT specifications, where different, are shown in parentheses)

	CIV		NIV	
	Start	Operate	Start	Operate
Tip heater power, W	25±0.5	0	25±0.5	0
Hg flow rate, mA	80±2 (100±2)	80±2	22±2	6±1
Keeper voltage, V	37±3 (45)	----------	37±3 (45)	----------
Keeper current, A	0.36±0.05	0.06±0.005	0.5±0.05	0.5±0.05
Discharge current, A	----------	0.5±0.05	----------	0.072±0.005

TABLE IV. - SUMMARY OF INSERT ACTIVATION PROCEDURE

FOR FIRST CATHODE START

Pre-start procedure	
0-75 min	Tip heat increased 5 W every 15 minutes up to 25 W maximum
75-120 min.	Vaporizer turned on - Hg flow rates for starting established
120 min.	Keeper and pulser supplies turned on
Post-start procedure	
0-20 hr	Cathode operated at 0.5 A keeper current and 5 W tip heat - Hg flow rates for operation established
After 20 hr	Cathodes operated for at least one hour at EMT conditions

TABLE V. - SUMMARY OF CYCLE LIFE TEST RESULTS

Cathode	Cycles	Start-up		Operation	
		Tip heater power, W	Breakdown voltage, kV	Keeper voltage, V	Collector voltage, V
CIV-1*	1-1281	25	No pulse	7-14.2	37-40
	1282-2800		0.2-1.8	15-20.2	36-38
CIV-2	1980	25	No pulse to 1.8	13-18	36-40
NIV-1	3928	21-25	0.1-5	15.5-21	11-17
NIV-2*	3050	25	No pulse to 2.3	13.8-19.2	11-17
NIV-3*	2850	25	0.5-2.8	13.8-18.7	17-73

*On going cycle life tests

TABLE VI. - SUMMARY OF EVENTS IN THE CIV-1 AND CIV-2 CYCLE LIFE TESTS

(See figures 13 and 14)

	Cycle	Event	Effect	
			BDV	V_K
CIV-1	1282	Exposure to atmosphere	Went from no pulse to 400 V	1 V increase
	2249	Exposure to 10-1000 millitorr	700 V increase	1 V increase
	83,155,1929 2585	Exposure to 10-1000 millitorr	None	None
CIV-2	753	Exposure to atmosphere	300 V increase followed by 500 V increase	None
	774	Preceded by exposure to atmospheres and then by 16 hours continuous operation	2 kV decrease lasted 300 cycles	5 V decrease -2 V increase over next 100 cycles
	1909	Exposure to 10-1000 millitorr	300 V increase	<1 V increase
	40,158,1816	Exposure to 10-1000 millitorr	None	None

TABLE VII. - SUMMARY OF TIP HEATER POWERS (P_{NH}) AND

BREAKDOWN VOLTAGES (BDV) FOR NIV-1

Cycles	PNH (W)	BDV (kV)		
		Min.	Max.	Typical
1-60	21	1.8	4.5*	2.0
61-246	22	0.3	4.0	1.0-1.5
247-765	23	0.8	5.0	2.5-3.5
766-1465	24	1.0	5.0	1.8-3.5
1466-3928	25	0.12	5.0*	0.5-2.0

*Followed exposure to atmosphere

TABLE VIII. - SUMMARY OF EVENTS IN NIV-1 CYCLE LIFE TEST

Cycle	Event	Effect
60,98,2111,2150, 2323,2823	Exposure to atmosphere or 10-1000 millitorr	BDV increased - see fig. 15 No observed change in V_K
333,1315	Exposure to 10-1000 millitorr	None
2868	Preceded by 22 hr of continuous operation	BDV decreased from >4 kV to 700 V. No change in V_K
2919	Preceded by (1) 4 exposures to atmosphere between which cathode was started but not cycled and then (2) 118 hrs of continuous cathode operation	BDV decreased to 300 V V_K reduced by 0.5 V
3593	Preceded by 24 hrs of continuous cathode operation	BDV reduced from 2 kV to 300 V. V_K reduced by 0.5 V

TABLE IX. - SUMMARY OF EVENTS IN THE NIV-2 AND NIV-3 CYCLE LIFE TESTS

	Cycle	Event	Effect
NIV-2	9,32,56,66,75,76, 161,210,2029	Exposure to atmosphere or 10-1000 millitorr	None
	2165,2870	Exposure to 10-1000 millitorr	BDV increased - see Fig. 17 no change in V_K
	2594	Preceded by (1) exposure to 20-30 millitorr and then (2) 17 hours continuous operation	BDV decreased from >1.5 kV to 400 V V_K decreased by about 1 V
NIV-3	85,2137	Exposure to 10-1000 millitorr	None
	1196,2030,2674	Exposure to 10-1000 millitorr	BDV increased - see Fig. 17 no change in V_K
	2460	Preceded by (1) exposure to 20-30 millitorr and then (2) 30 hrs of continuous operation	BDV reduced from >2.5 kV to 800 V no change in V_K

TABLE X. - SUMMARY OF RESULTS FOR INSERT COMPARISON TEST (1000 CYCLES)

Cathode	Insert geometry	Emissive coating	Coating weight, mg	Maximum breakdown voltage, kV	Tip heater power, W	Keeper voltage V	Collector voltage, V
NIV-2	Standard	2-C	8-10	0.7	25	17-19	11-16
NIV-3	Standard	3-C	46	2.2	25	14-19	17-73
NIV-4	SERT II type	2-C	8.4	8.0	25-32	13-17	13-14
NIV-5	SERT II type	3-C	8.9	8.0	25-34	13-14	11-12

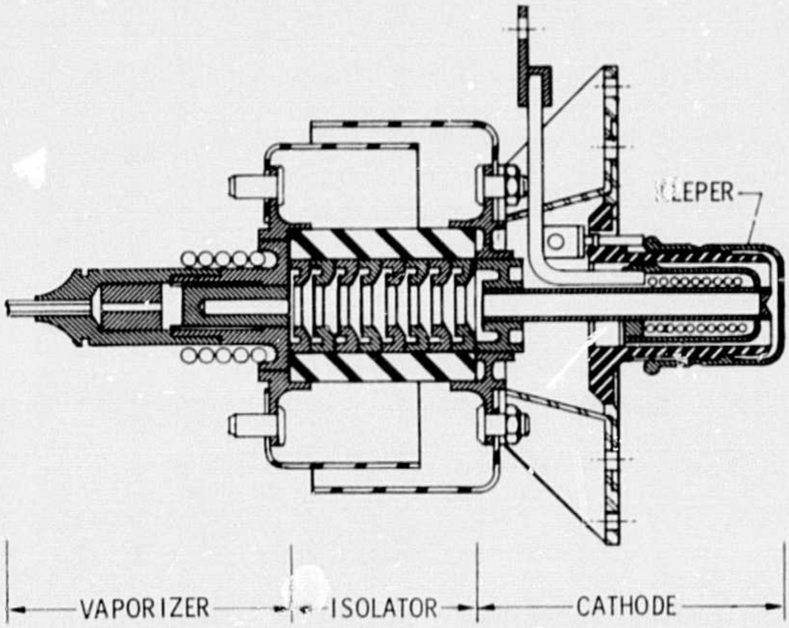

Figure 1. - Cross-section view of CIV assembly.

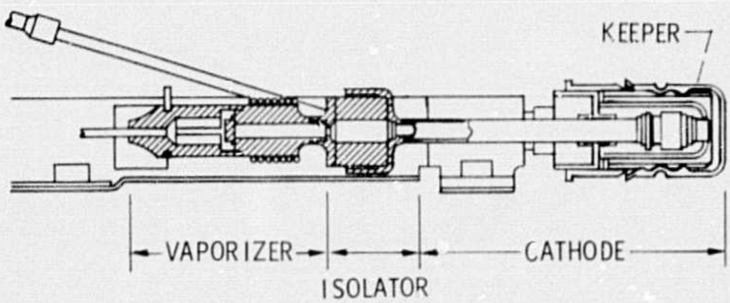

Figure 2. - Cross-section view of NIV assembly.

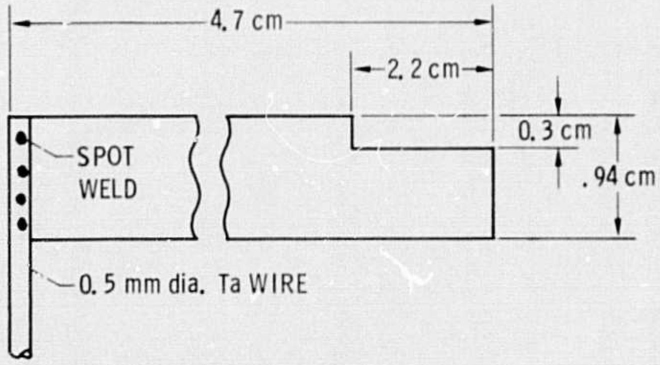

Figure 3. - Unrolled view of standard insert.

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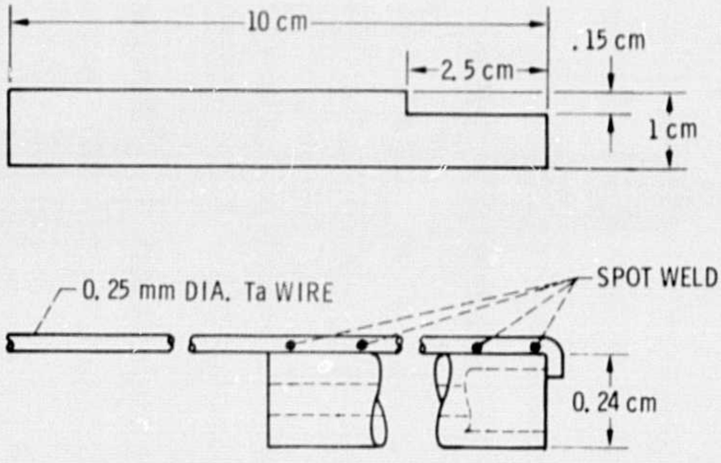

Figure 4. - Rolled and unrolled views of SERT II-type insert.

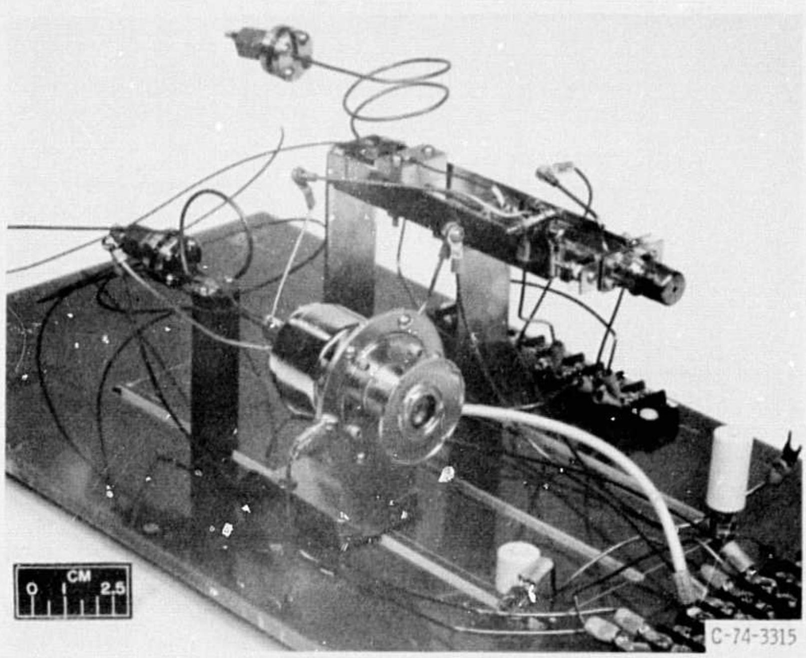

Figure 5. - CIV-1 and NIV-1 test configuration in vacuum bell jar.

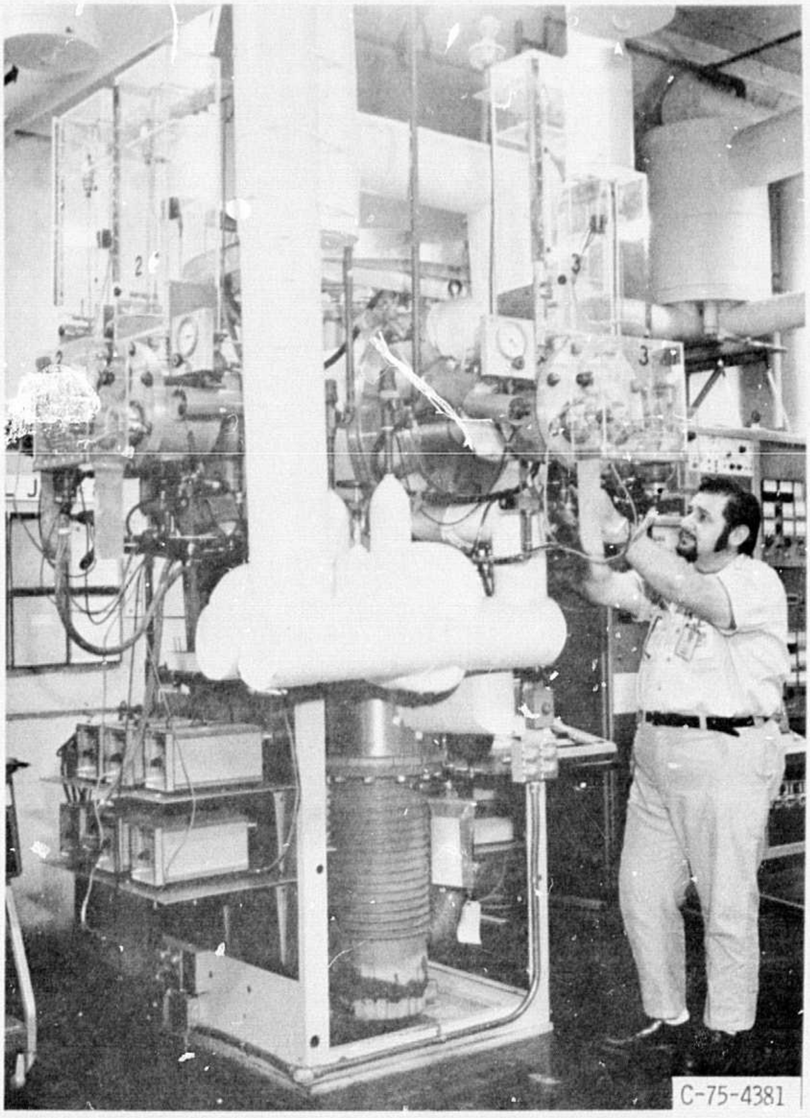

Figure 6. - Multiport (6) vacuum tank.

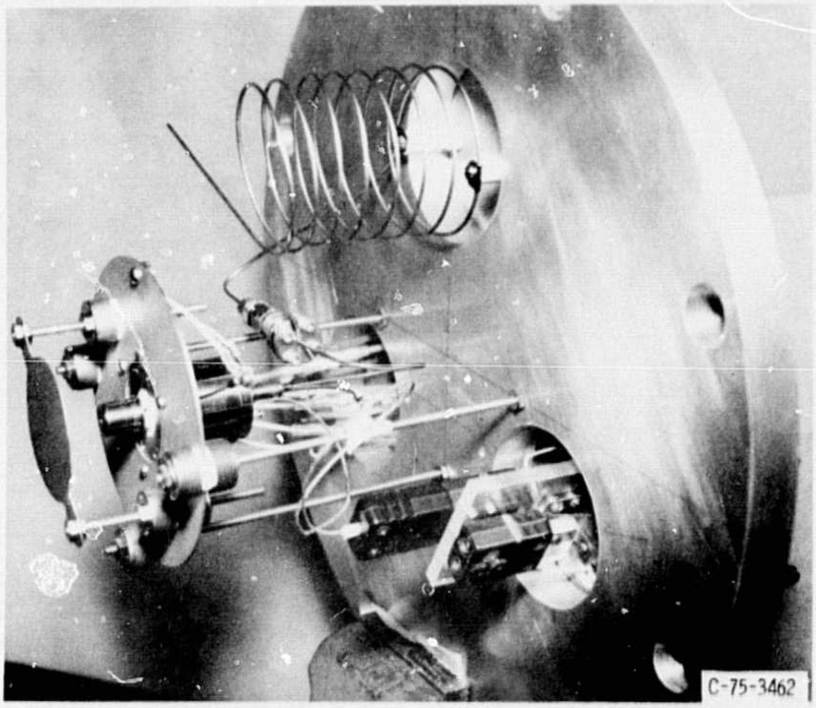

Figure 7. - CIV test configuration in multiport vacuum tank.

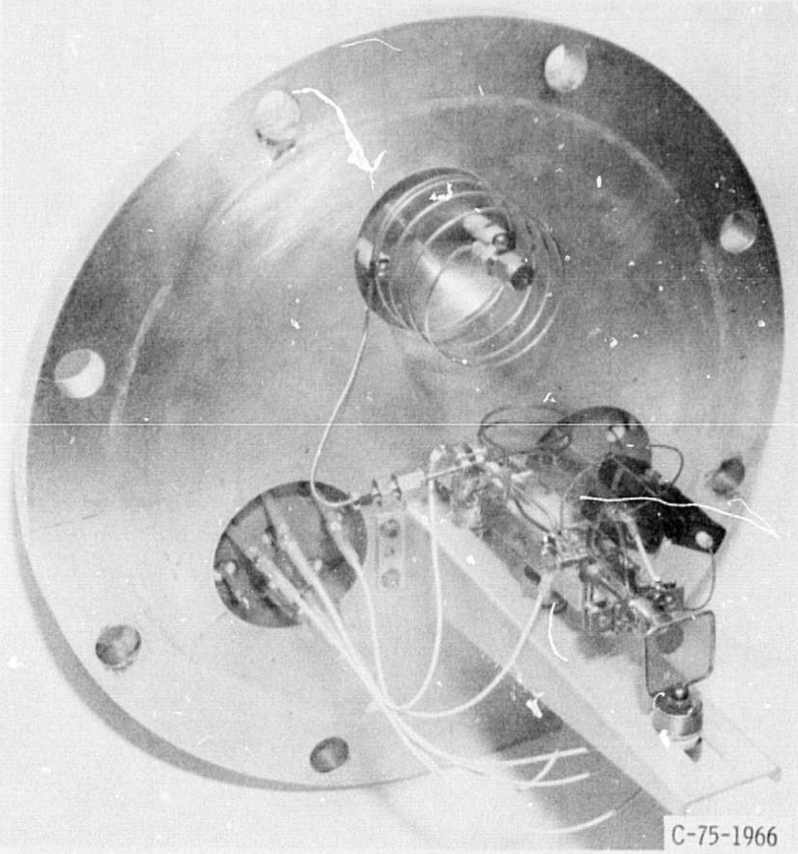

Figure 8. - NIV test configuration in multiport vacuum tank.

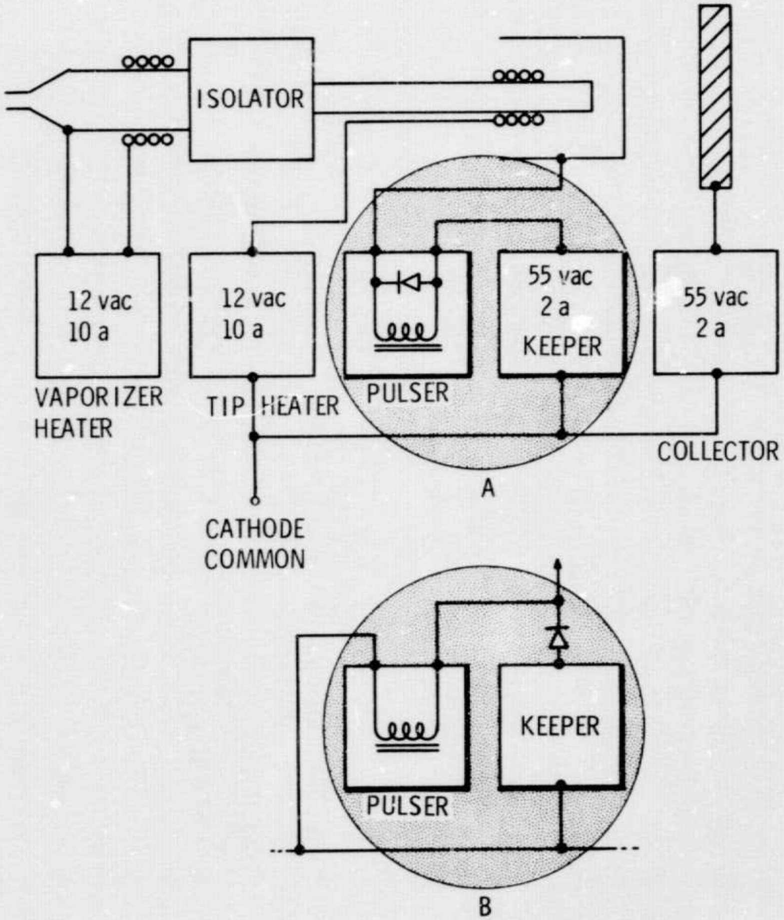

Figure 9. - Power supply arrangement for cathode cycle tests with two blocking diode positions - (A) multiport vacuum tank cycle tests and (B) vacuum bell jar cycle tests.

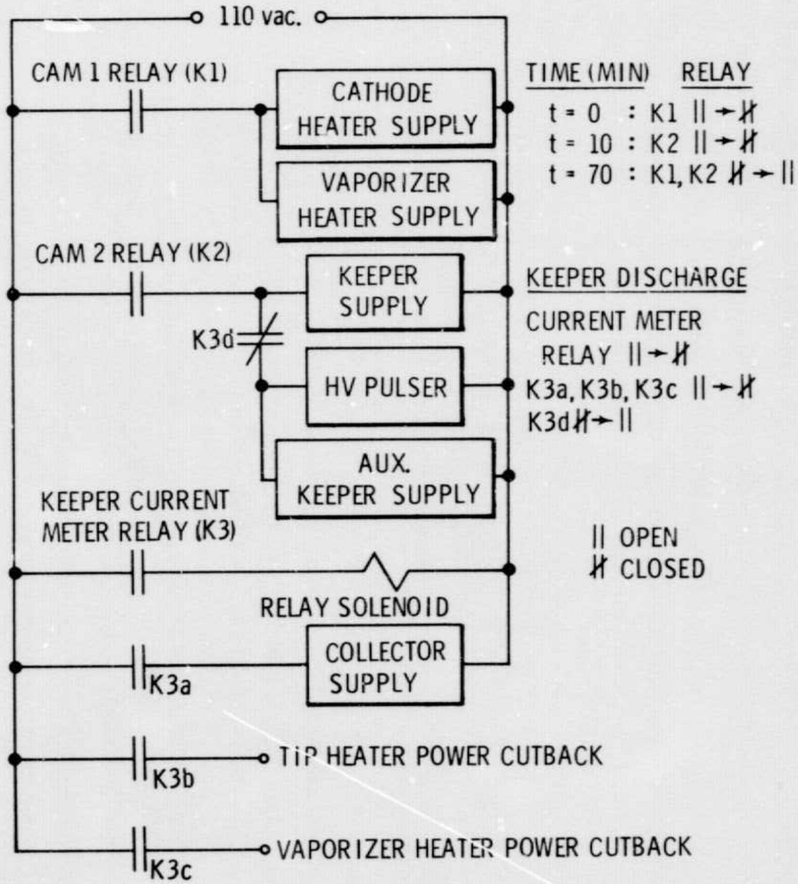

Figure 10. - Schematic showing relay and power supply arrangement and cycle sequence.

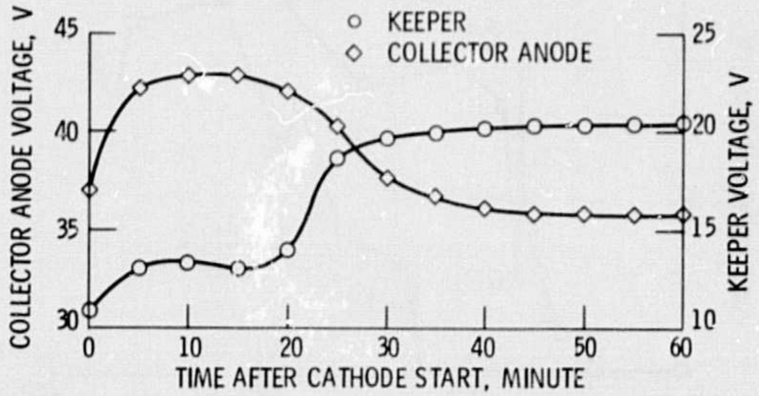

Figure 11. - Collector and keeper voltage profiles for CIV-1 cathode operation during cycle number 2719.

E-8842

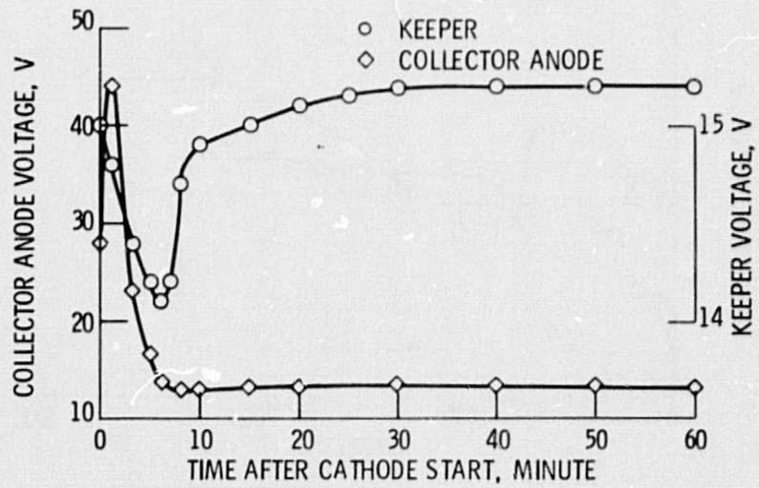

Figure 12. - Collector and keeper voltage profiles for NIV-2 cathode operation during cycle number 2970.

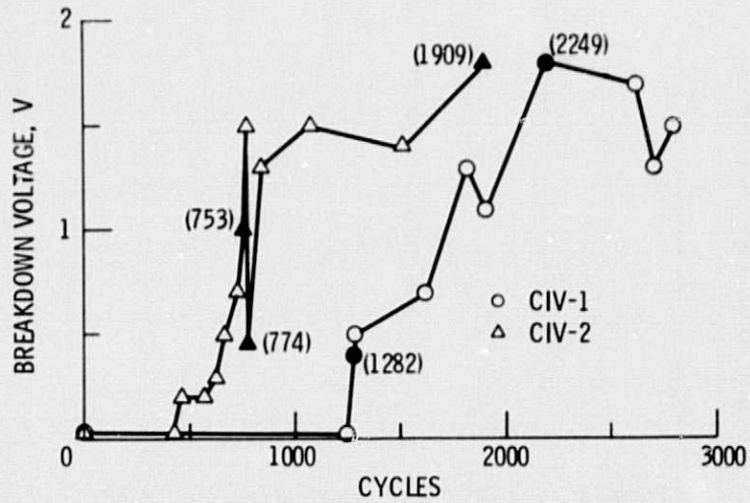

Figure 13. - Breakdown voltage versus number of cycles for CIV-1 and CIV-2. Solid symbols indicate events significantly affecting performance. (See Table VI.)

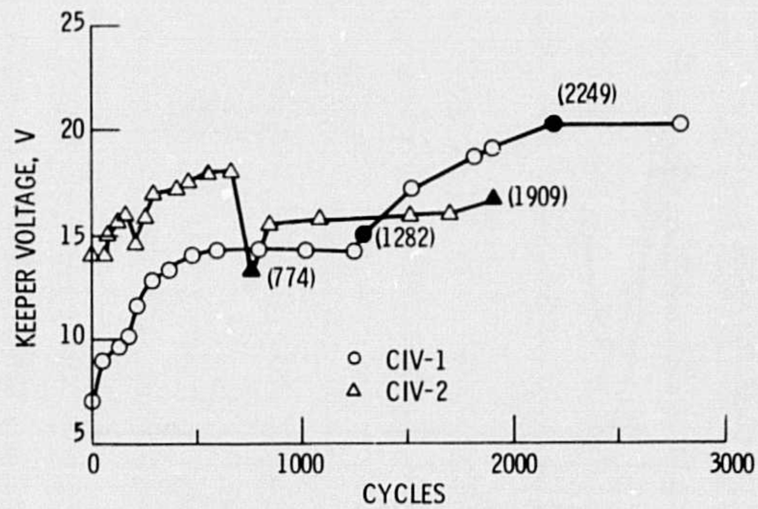

Figure 14. - Keeper voltage versus number of cycles for CIV-1 and CIV-2. Solid symbols indicate events significantly affecting performance. (See Table VI.)

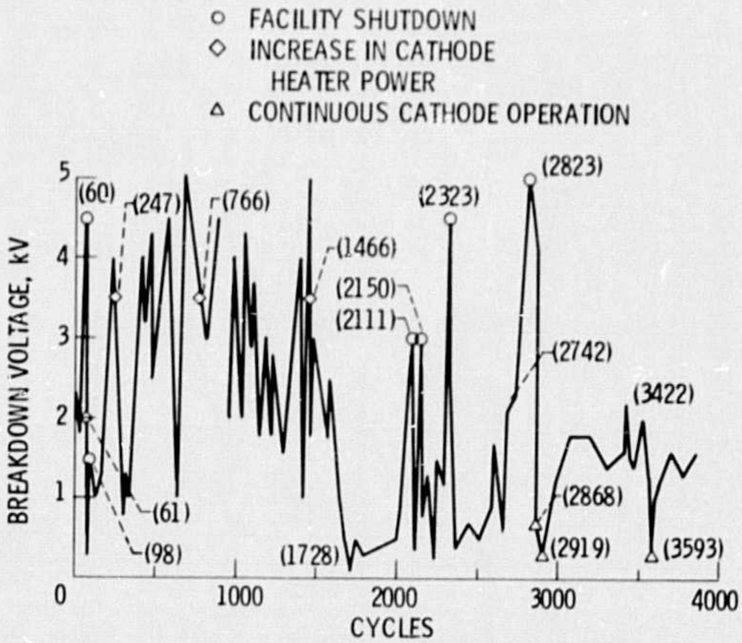

Figure 15. - Breakdown voltage versus number of cycles for NIV-1.

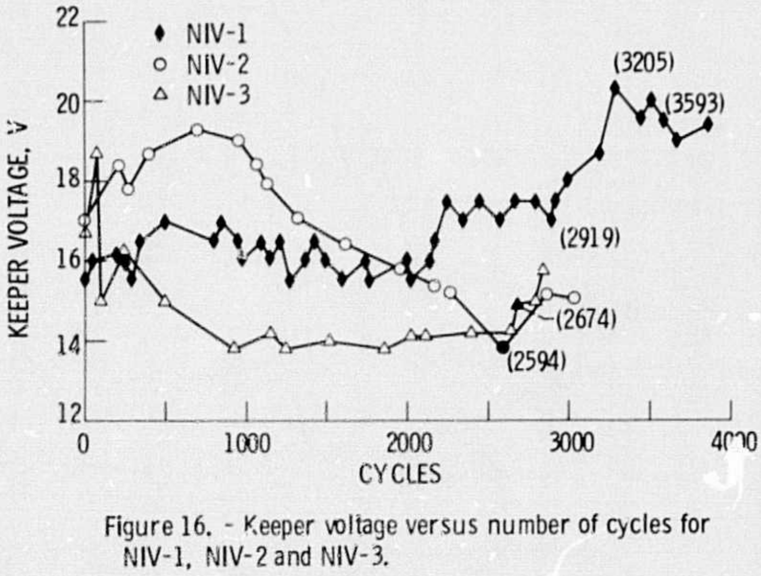

Figure 16. - Keeper voltage versus number of cycles for NIV-1, NIV-2 and NIV-3.

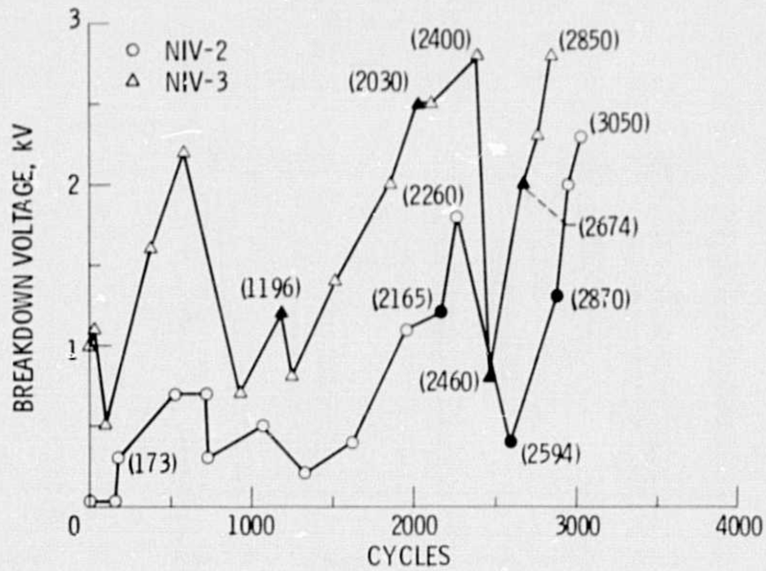

Figure 17. - Breakdown voltage versus number of cycles for NIV-2 and NIV-3 for cycle life test.

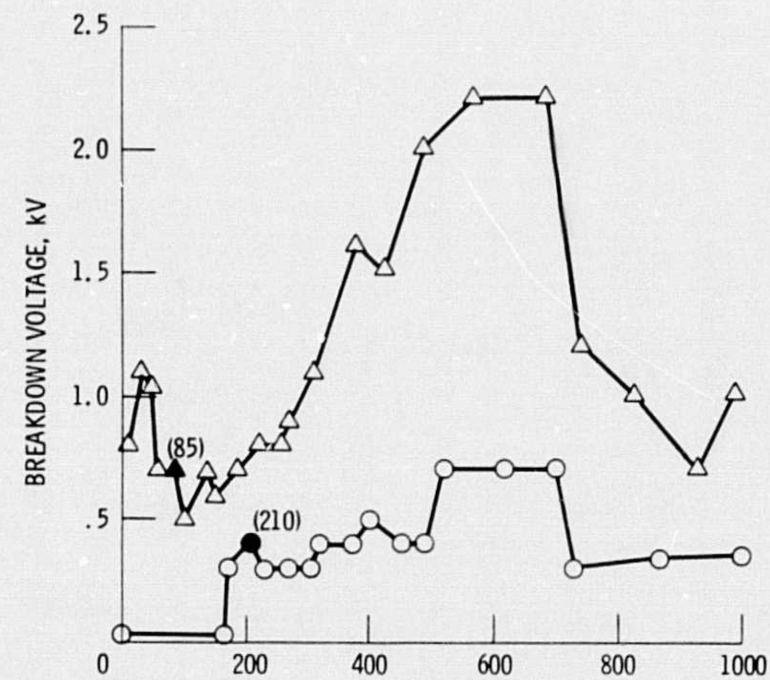

Figure 18. - Breakdown voltage versus number of cycles for NIV-2 and NIV-3 for 1000 cycle insert evaluation test. Solid symbols correspond to a facility shutdown.

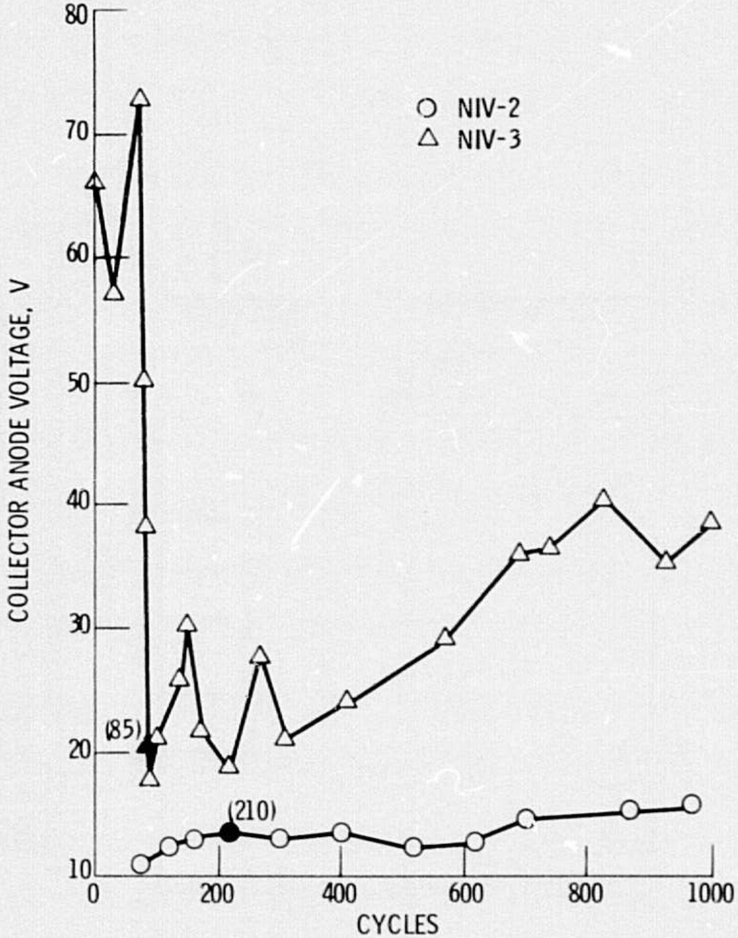

Figure 19. - Collector anode voltage versus cycles for NIV-2 and NIV-3.

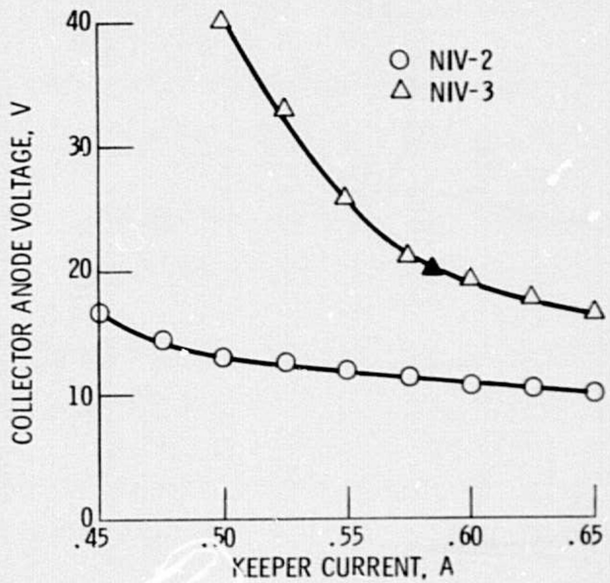

Figure 20. - Collector anode voltage versus keeper current for NIV-2 and NIV-3 after 1000 cycles at 72 mA collector current and 6 mA Hg flow.

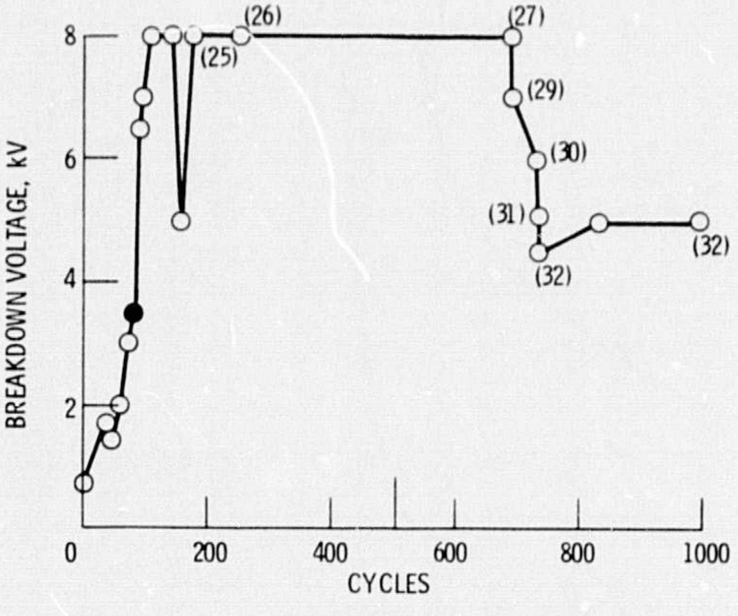

Figure 21. - Breakdown voltage versus cycles for NIV-4. Numbers in parentheses are tip heater powers (w). Solid symbol corresponds to facility shutdown.

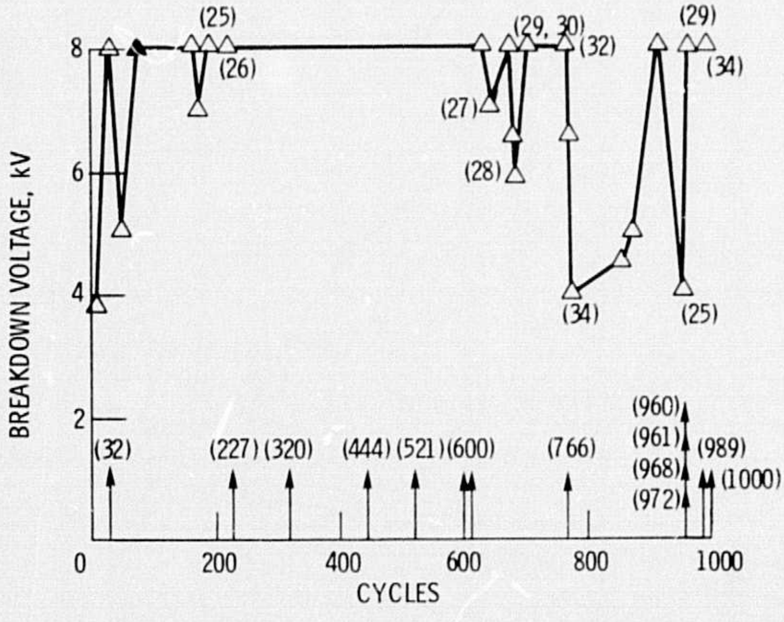

Figure 22. - Breakdown voltage versus number of cycles for NIV-5. Numbers in parentheses are tip heater powers (w). Solid symbol corresponds to facility shutdown. Arrows indicate failures to start.