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# STATUS OF 30-CENTIMETER-DIAMETER MERCURY ION THRUSTER ISOLATOR DEVELOPMENT

by M. A. Mantenieks
Lewis Research Center
Cleveland, Ohio 44135

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M. A. Mantenieks
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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## Abstract

Results are presented of several 30-cm diameter mercury ion thruster isolator life tests that show that the onset and exponential increase of leakage current problems observed in earlier thruster operations and isolator tests have been solved. A 10,006-hour life test of a main isolator-vaporizer operated with no mercury flow at 320° C and 1500 volts was found to have no onset of leakage current during the test. A cathode-isolator-vaporizer (CIV) operated with a mercury discharge at 340° to 360° C and 1200 volts for 18,000 hours, was found to have a small increase ($4.0\times10^{-3}$ μA/hr) of leakage current with time. A 10,000-hour thruster life test at Hughes exhibited no increase of leakage current during the life test. In view of these test results, it is concluded that isolators have been developed which will satisfy 30-cm mercury ion thruster mission requirements.

## Introduction

Several primary propulsion system designs have been proposed which utilize 30-cm mercury bombardment thrusters (refs. 1 to 3). These designs propose the use of a single propellant tank for several thrusters. This approach requires the use of mercury vapor isolators in the propellant lines in order to electrically isolate the high voltage power supplies. The isolator must satisfy a number of requirements: the capability of withstanding about 1200 volts over a wide propellant flow rate range, operation at temperatures comparable to other thruster components (~300° C), and operation over very long time periods (10,000 to 15,000 hr) without excessive leakage current (~1 mA).

Several isolator designs, including the segmented and tortous path concepts, have been proposed and successfully tested for their voltage standoff requirements (refs. 4 to 6). However, until recently, considerable difficulty has been experienced in satisfying the requirements of low leakage current for the time periods of interest of the thruster application. The onset of exponential increase of leakage currents with time after relatively short time periods has been observed in 30-cm thruster operation (ref. 7) and isolator tests (refs. 8 and 9). More satisfactory isolator performance results have been observed in 5- and 8-cm thruster life tests (refs. 10 and 11).

The onset of leakage current in high vacuum, high temperature insulation has not been the unique problem of ion thruster isolators. This phenomena has been observed in thyratrons and voltage regulator tubes (ref. 12) and heater-cathode insulator failures (refs. 13 and 14). The causes of these problems have not been necessarily of the same origin, varying from contamination by sputtered material to metal migration through insulators. What does make the thruster isolator problem unique is the very low leakage current permissible in thruster operation.

This paper will report the results of work performed on the development of isolators for the 30-cm mercury thruster. For reference, a brief description of the criteria for isolator design, fabrication, and operating procedures is also included.

## Isolator Design Criteria

Isolator tests results reported in reference 8 showed that isolator failures occurred within a few hundred hours. Isolator failure will be defined herein as the onset of leakage current which increases exponentially with time. In the past leakage current rates of increase of the order of 1.0 μA/hour have been measured after only several hundred hours of operation. These rates would result in unacceptably large leakage currents during a thruster mission. The leakage current could cause, due to self heating of the isolator, thruster control problems as well as represent an avoidable power loss. The exact impact of leakage current on thruster and power processor operation is beyond the scope of this paper. Therefore, leakage current failure made was conservatively defined as the onset of leakage current which increased exponentially with time.

It was determined that the cause of the leakage current was an external surface contamination, and it could be eliminated by bead blasting the contaminated surface with high purity $Al_2O_3$ beads. Isolator failures were found to have the following characteristics (ref. 8):

(a) The time of onset of the failure mode leakage current was found to be extremely temperature dependent. After the onset of the failure mode leakage current, it was observed to increase exponentially with time at a given isolator temperature. The leakage current rate of increase was also found to increase exponentially with isolator temperature.

(b) Some isolator failures were observed to be directly related to facility failures during which contamination and/or oxidation of isolator components took place.

(c) The surface contamination causing the failure mode leakage current exhibited and semiconductive thin film characteristics. This was shown by the exponential dependence of the leakage current on the reciprocal of the isolator temperature (Arrhenius plot). It was also shown that the isolator leakage current conformed to the theoretical characteristics of thin film formation.

(d) Isolators developed failure mode leakage current in tests in diffusion pumped facilities as well as in a facility free of diffusion pump oil. This behavior indicated that self-contamination was at least partially responsible for the observed isolator leakage current.

Several mechanisms explaining the surface contamination problem were considered. These included: (1) a vaporization-condensation process in which volatile materials may have evaporated from hot sur-

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faces (especially heater leads and isolator shields) and condensed on the isolator surface; (2) sputtering effects arising from the high voltage across the isolator in the presence of outgassed vapors from isolator component materials; (3) chemical reactions which may occur because of possible chemical incompatibility of certain materials in the CIV assembly; and (4) surface migration of conductive impurities on the isolator surface under large temperature and concentration gradients.

After consideration of all the observed isolator test results, it was concluded that vaporization-condensation process was the most likely cause for most of the isolator contamination problem.

Because of the conclusions stated above the following design, fabrication procedures, and operation changes were implemented in the isolators used in the tests reported here as well as in the isolators of the Engineering Model (EM) thrusters:

(a) Materials that contain high vapor pressure elements such as cadmium, zinc, sulphur, and phosphorus as well as materials that form relatively volatile metal oxides such as W, Mo, Cr, and Cu were eliminated wherever possible from the vicinity of the isolator. Also sources of silver were eliminated in order that surface migration across the isolator be avoided (ref. 15).

(b) The isolator shadow shields were redesigned and hot heater terminals were repositioned so that contamination from other thruster or CIV components was minimized.

(c) Spotwelding and other fabrication techniques which could cause local melting and evaporation of metals or formation of metal oxides, were eliminated.

(d) Nickel plating was applied to all metallic isolator components including the exposed copper braze joints and the Kovar end caps, in order to minimize oxidation.

(e) The surfaces of the alumina body of the isolator were ground before isolator assembly and were bead blasted with high purity $Al_2O_3$ beads after assembly to insure a clean isolator surface in the finished assembly.

(f) It was recommended that isolators be operated at lowest possible temperature (without mercury condensation taking place) and low ambient pressures in order to minimize the oxidation and evaporation of isolator components.

## Apparatus

A brief description will follow of the apparatus and facilities used for the life tests of a Main Isolator Vaporizer (MIV) assembly, Cathode Isolator Vaporizer (CIV) assembly, and two thrusters used in thruster life tests (refs. 16 and 17).

### Cathode-Isolator-Vaporizer Assembly

The CIV used in the life test is shown in figure 1. This design is similar to the CIV's used in the so-called "400 series" 30-cm diameter thrusters, one of which was used in the life test reported by Collett (ref. 7).

The isolator was of a segmented design, consisting of seven short alumina chambers (ref. 5). The chambers were separated by optically dense screens in a manner such that the applied voltage between any screens was below the Paschen minimum voltage (~300 volts) (see appendix). The Kovar end flanges were copper brazed to the metalized alumina. The stainless steel shadow shields protected the exterior surface of the isolator from the ambient particle flux. They were nickel plated and attached mechanically with straps to the nickel plated Kovar end flanges.

The hollow tantalum cathode was fabricated with a thoriated tungsten tip and had an alumina flame sprayed Nichrome heater mounted near the tip. The cathode tip had a radiation fin to provide correct cathode temperature during thruster operation and a tantalum foil wrapped around the tip and heater to improve the cathode starting capability. A 0.53×0.25×2.5-cm porous barium oxide impregnated tungsten hollow cylinder insert was installed inside the hollow cathode and recessed 0.95 cm from the tip. Tungsten wool was placed in the hollow cathode body so that plasma diffusion and radiation from the cathode discharge did not impair the proper functioning of the isolator.

The vaporizer of the CIV consisted of a 0.45-cm diameter porous tungsten plug, electron beam welded to the tantalum tube. The flow of the propellant through the plug was determined by its temperature, which was governed by the power applied to a heater wrapped around the outside of the vaporizer housing.

The CIV's used on the Engineering Model (EM) "900 series" (ref. 17) 30-cm diameter thrusters and the "700 series" thrusters (ref. 18) differs from the one "400 series" described above, in that the isolator and vaporizer are separated from the cathode by a heated feed tube. This allows the isolator to operate at a lower temperature and by reducing the thermal feedback from the cathode, it improved the thermal control of the vaporizer. Also, a larger isolator similar to that of the main isolator was incorporated in the EM CIV.

The CIV test was conducted in a 30-cm diameter port on the 7.6×18.3 m vacuum facility at Lewis Research Center. The main vacuum tank operated with hydrocarbon oil diffusion pumps. A liquid nitrogen trap was installed in the ports' roughing pump line. A grounded partially opaque shield was installed in the port as seen in figure 2. This shield protected the isolator from the cathode discharge plasma and from the particle flux existing in the main vacuum facility. Because of the required shielding the pressure in the port during operation was ~$5\times10^{-5}$ torr.

The port was prepared to meet the requirements outlined in the Design Criteria Section. Thus, all high vapor pressure materials such as silver solder, solder flux, cadmium plated electrical connectors, brass flanges, etc. were eliminated. High temperature electrical feedthroughs and thermocouple connectors were used. Aluminum wires were used for electrical connections in order to avoid the possibility of contamination by oxides if copper wires were used.

An electrical schematic of the CIV test is shown in figure 2. Power supplies required were:

discharge supply keeper supply, ignitor, high voltage supply and heater supplies for the cathode tip, isolator, and vaporizer. There was no control loop on the vaporizer heater supply. The cathode end of of the isolator was mounted on an electrical standoff and held at ground potential. The vaporizer end of the isolator was biased negatively by the high voltage D.C. power supply. This configuration simulated the voltage gradient in a thruster. The temperatures of the isolator at both end caps, vaporizer and cathode tip were monitored during the test. The collector was a perforated molybdenum disc. Provisions were present for automatic shutdown for the cathode and high voltage if a pressure rise to $>10^{-4}$ torr occurred in the main tank.

MIV Test

The main isolator was designed similarly to the cathode isolator above, except it was larger in order to accommodate the higher mass flows required. (The "900 series" EM thruster has two isolators of this size.) The design changes incorporated in the MIV to meet the low isolator leakage requirements were similar to those made in the CIV. These have been presented in the Design Criteria Section.

The MIV test was conducted in a cryogenically pumped bell jar, therefore eliminating the possibility of contamination of the isolator surface with diffusion or roughing pump oil. The pressure in the bell jar was maintained at $\sim 1\times10^{-6}$ torr. The test was conducted with no mercury flow, therefore only two heater supplies, one on each end of the isolator, and a high voltage supply were required. Temperatures of each end cap of the isolator were monitored during the test.

Thruster Life Tests

The 10,000-hour thruster life test (ref. 16) was conducted with a "700 series", 30-cm diameter thruster having a CIV and MIV incorporating the modifications in the Design Criteria Section. The present on going life test (ref. 17) is of a "900 series" thruster.

## Results and Discussion

MIV Test

As pointed out in reference 8, tests in a cryogenically pumped bell jar (pump oil free environment) indicated an isolator failure due to self-contamination and not necessarily due to the test facility environment. The history of a typical failure of a MIV isolator observed in this bell jar previous to the use of design modifications discussed previously is shown by a curve in figure 3. To confirm the self-contamination hypothesis an MIV with all the changes was tested in the same bell jar. Since the earlier failures occurred with no mercury flow through the isolator, none was used in the MIV test.

The MIV test operating conditions are given in table I. The end cap temperatures were 310° and 330° C and the applied voltage was 1500 volts. These isolator temperature and voltage operating conditions were more severe than those of a thruster (265° C and 1100 volts, respectively), therefore, providing an accelerated life test.

The initial current of the isolator was 0.1 μA at 1500 volts, which corresponds to approximately the bulk conductivity of the alumina in the isolator. There was no increase of this current in the 10,000 hours of operation (fig. 3) at which time this test was terminated. During this time period the isolator test underwent 17 shutdowns during which pressure increases of up to about $1\times10^{-4}$ torr range occurred. These shutdowns had no apparent detrimental effects on the isolator performance. After the test the isolator was inspected and, as expected, was found to be in excellent condition.

Therefore, it may be concluded that the external leakage current source has been identified as self contamination, probably due to the evaporation-condensation mechanism discussed before, and that the implemented design changes have corrected the failure mode leakage current problem.

CIV Test

The MIV test just discussed showed that the external isolator leakage current problem was primarily a self contamination effect. It remained to be shown that the internal integrity of the isolator could be sustained during actual operating conditions with a mercury flow and discharge. Therefore a CIV test was conducted and again at more severe operating conditions than those found in a normally operating thruster. Successful operation at these conditions would ensure considerable margin for thruster operation.

The operating conditions of the CIV are shown in table I. The operating isolator temperatures ranged from 320° to 360° C (depending on the discharge current and vaporizer temperature), as compared to 265° C found in a normally operating thruster. In the cathode preheat periods, temperatures of the isolator reached as high as 400° C. During operation the applied voltage was 1200 volts, and the discharge current ranged from 7 to 12 amps with corresponding discharge voltages of 11.5 to 20 volts. The mercury flow rate was held nearly constant at about 180 mA. Keeper current was maintained at 0.5 ampere and about 9.5 volts.

The cathode performance including discharge and keeper conditions and tip temperature appear in reference 19. The leakage current history of the 18,000 test and the corresponding isolator and vaporizer temperatures during the test are shown in figure 4. The initial isolator leakage current of 1. μA indicated that some surface contamination could have been present before the lifetest. However, as shown later the indicated leakage current may also have been due to contaminated high voltage feedthroughs, leakage across power supply isolation insulators, or discharge plasma leakage. However, it was concluded in reference 8 that higher than normal initial leakage currents due to some isolator contamination did not necessarily contribute to early onset of exponential increases of the isolator leakage current, so this initial leakage current was not a matter of major concern.

From figure 4 it can be seen that the leakage current slowly increased for approximately the first 1100 hours at an average rate of about $2.2\times10^{-3}$ μA/hour. A sudden drop of leakage current at about 1130 hours was due to cleaning of all insulators on the port flange feedthroughs and the floating power supplies. At about the same time the isolator thermocouple malfunctioned. From about 1130 to 2400 hours on the test the average leakage current increase with time was about $6.7\times10^{-3}$ μA/hour. The vaporizer thermocouple reading indicated that the increase may have been associated with a slightly higher isolator-vaporizer temperature.

At 2400 hours, the discharge power supply malfunctioned and probably overheated the cathode and isolator and a shutdown took place. After repairs to the power supply, a restarting of the cathode discharge, the keeper voltage and cathode tip temperature exhibited abnormal conditions for some time, which indicated that during this shutdown, also the cathode was adversely affected. From this startup at 2400 hours until the 3950-hour mark the leakage current increased with time at a faster rate of about $56\times10^{-3}$ μA/hour with no increase indicated on the isolator temperature during that time period. This sudden increase of leakage current rate is attributed to the abnormal shutdown caused by the faulty power supply.

After 3950 hours in the test, the isolator was removed, the surface was bead blasted, and a new shadow shield made from tantalum was installed. The leakage current after the bead blasting was reduced to about 2 μA at 350° C, which was slightly higher than at the beginning of the test. This leakage could have indicated a slight degradation of the internal structure of the isolator.

From 3950 to 8150 hours the leakage current increase with time averaged only about $1.2\times10^{-3}$ μA/hour at an average isolator temperature of about 330° C. A unique phenomenon, not observed on previous isolator tests, was first observed on the isolator leakage current after the shutdown at the 5010-hour point. The leakage current on restarting was found to have decreased considerably from the value measured before the shutdown. Later it was determined that these leakage current decreases were only associated with shutdowns in which the CIV was exposed to atmospheric conditions. Therefore, this phenomenon is assumed to be associated with the oxidation of the thin film responsible for the leakage current. However, this phenomenon is not well understood at this time. The leakage current reduction after a shutdown involving atmospheric exposure appeared to depend on the temperature required during preheat to restart the cathode. It was observed that the magnitude of the decrease in leakage current after a shutdown increased with increasing isolator temperature reached during startup. After such a decrease the leakage current increased with time at an accelerated rate for a while until the previous normal rate was attained.

At the 8150-hour mark, the plasma sprayed cathode tip heater burned out. Because heaters as originally fabricated cannot be replaced on cathodes, a makeshift heater was installed by wrapping several windings of heater material around the cathode tip in order that the isolator test might be continued. Additional heat shielding around the cathode tip was added to assist cathode startup. This change resulted in a higher operating temperature (~360° C) of the isolator. This, in turn, resulted in a somewhat higher average leakage current increase with time of about $3.9\times10^{-3}$ μA/hour.

At 16,260 hours it was decided to bead blast the exterior of the isolator surface in order to determine if any deterioration had occurred on the inside of the isolator. Af... the bead blasting the the isolator it was also nec...sary to replace the heater and heat shielding. The leakage current after this operation did not return to the 2 μA value which was measured after the previous bead blading operation at 3950 hours but rather decreased only to 12.5 μA. This result, however, was somewhat obscured by the fact that the cathode did not operate normally for some time after the restart, resulting in abnormally high insolator temperatures compared with the operation before the shutdown at 8150 hours. Two explanations are possible for the observed remaining leakage current after the bead blasting operation at 16,258 hours: either the cleaning operation was not entirely successful in removing all of the outside isolator contamination or the observed leakage current after the shutdown was an internal isolator phenomenon.

It is of interest to compare the plots of the voltage vs. leakage current and of the leakage current vs. the reciprocal of the isolator temperature for times before and after the cleaning operation at 16,258 hours. Figure 5 shows that after the cleaning operation the previously observed sudden transition in the V-I plot occurring at around 1000 volts disappeared. The reason for the transition is not understood. Current-voltage plots found in reference 8 exhibited ohmic behavior with some exceptions at very high voltages, and the deviation observed from ohmic behavior was gradual, not like the transition observed in figure 5. A gradual deviation is consistent with thin film behavior found in literature.

Figure 6 shows the leakage current as a function of the reciprocal of the isolator temperature plot at various times of the test. The data taken after the isolator cleaning showed the same characteristics as observed before the cleaning. The characteristic activation energy of a semiconductor was found to decrease with time between 2099 and 16,258 hours as was observed in similar plots in reference 8. Again these observed characteristics are found to be consistent with thin film semiconductor behavior.

Thus, in general, the observed behavior of the CIV leakage current was similar to that found in the early isolator tests of reference 8, except that the average leakage current increase with time was reduced significantly in the present test with the implementation of the described design changes. For example, the average increase with time found in the present test was about $3.9\times10^{-3}$ μA/hour at an average isolator temperature of about 350° C. At the same temperature, average leakage current increases with time of up to 4 μA/hour were measured in the insolator tests of reference 8. The maximum average leakage current increase with time measured during the present test (not considering the catastrophic shutdown occurrence) was $6.7\times10^{-3}$ μA/hour. This rate of increase would result in a leakage current of 134 μA after 20,000 hours of operation, which is well within the 1 μA requirement established for isolator performance. Since the CIV isolator temperature in a normally operating thruster is considerably lower (265° C) than the 350° C average in the CIV test, the increase in the isolator leakage current with time should also be significantly lower. From the exponential leakage current dependence upon the reciprocal of the isolator temperature (ref. 8) a decrease of 65° C in isolator temperature was estimated to result in a decrease in the leakage current by at least a factor of 30.

Thruster Life-Time Tests

Ultimately, the isolator has to perform satisfactorily in thruster tests and a thruster lifetest is required to judge its performance. One such test (ref. 16), during which the thruster was operated for 10,000 hours, was conducted at the following conditions as shown in table I: main isolator temperature of about 275° C, cathode isolator temperature of 260° C, beam current average of 1.4 amps (1.75 max), and screen voltage across the isolator of 1100 volts. The current measured during the test was on the order of 0.1 μA and no increase was observed during the test. After the test, examination of the isolators revealed them to be in excellent condition (ref. 16).

Another life test of the "900 series" thruster (ref. 17) is presently being operated at a 2.0-amp beam level and therefore at a slightly higher isolator temperature tha in the earlier thruster test. After 4100 hours of operation in this test, no increase in the leakage current has been observed. Thus it appears that the isolator leakage current phenomenon experienced in early thruster and isolator tests has been identified and that suitable modifications have been implemented to correct the problem.

Summary and Conclusions

In order to eliminate surface leakage current problems found during earlier thruster and isolator tests, several modifications in isolator design, fabrication techniques, and operation (suggested in ref. 8) were implemented in the Engineering Model isolators and several life tests were performed and reported herein. The isolator tests performed were: a 10,000-hour test of a MIV operated without mercury vapor or discharge, a 18,000-hour test of a "400 series" CIV (partially modified) operated with mercury vapor and a discharge, and two thruster life tests (refs. 16 and 17).

The MIV test was operated at ~330° C and an applied voltage of 1500 volts, temperature and voltage conditions which were much more demanding than those found on a normally operating thruster. There was no increase of current measured during the life test above the 0.1 μA current measured at the beginning of the test, which is approximately the bulk conductance of the isolator. This test demonstrated that the previously observed surface leakage current due to self-contamination has been eliminated by the implemented isolator design and fabrication modifications.

The CIV test was operated at an isolator temperature of 320° to 360° C and with 1200 volts across the isolator with mercury vapor flow and a discharge simulating thruster operation. Again the test conditions were more severe than found in an operating thruster. An average leakage current increase with time of ~$3.9\times10^{-3}$ μA/hour was observed over approximately the final 14,000 hours of the test. The source of the leakage current in the CIV test is not certain. Cleaning of the isolator surface early in the test reduced the leakage current to 2 μA. However, a cleaning at 16,260 hours reduced the leakage current to 12.5 μA, which may indicate that some internal isolator leakage may have developed. The observed average leakage current increase of about $4.0\times10^{-3}$ μA/hour over major portion of the test is well within the established isolator performance requirements. Because the CIV isolator was operated at a considerably higher temperature than found in normal thruster operation, the leakage current rate of increase observed would be much higher than those expected under normal operating conditions.

The isolator performance in the 10,000-hour life test (ref. 16) and the present ongoing test (ref. 17) has confirmed that the modifications implented have solved the isolator leakage problem, since during the 10,000-hour test and after 4100 hours of the ongoing test neither the cathode or main isolators have experienced any measurable increase of leakage current. Therefore it is felt that the leakage current problem experienced in earlier thruster and isolator tests has been identified and design, fabrication, and operation modifications implemented have corrected the problem.

Appendix - Paschen Breakdown in Mercury Vapor

For reference, breakdown characteristics of mercury vapor and a brief description of isolator design considerations will follow.

The mercury vapor isolator requirements include the capability of withstanding high voltage (~1100 volts) over a wide range of mass flow rate through the isolator. The large variation of mass flow rate during thruster operation results in large variations of pressure (0 to 50 torr) over which the isolator must be able to stand off the high voltage. To achieve the standoff requirements, in the segmented type of isolator, the isolator body is divided in a number of short chambers of equal lengths by optically dense screens in a manner such that the total applied voltage is in principal divided equally among the chambers and the voltage between adjacent screens is thus held below the Paschen minimum. The minimum breakdown voltage of mercury vapor has been found to be

$$V_{min} = 282 + 20(D/d) \text{ volts (ref. (20))}$$

where:

D diameter of electrodes

d electrode gap distance

This value of breakdown voltage is in good agreement with minimums of other measured Paschen curves (refs. 21 to 23) shown in figure 7. The analytical models proposed for the Paschen minimum, however, do not offer such agreement in the literature (refs. 24 and 25) because of various assumptions used in treating breakdowns resulting from effects of secondary electrons, surface charge, insulation flashover, space charge, and magnetic fields.

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TABLE I. - OPERATING CONDITIONS OF VARIOUS TESTS

| | MIV | CIV | Thruster life tests | |
|---|---|---|---|---|
| | | | 10,000 hours (ref. 16) | Present (ref. 17) |
| Average temperature (°C) | 320 | 320-<br>360 | CIV - 250<br>MIV - 270 | CIV - 265<br>MIV - 285 |
| Applied voltage (V) | 1500 | 1200 | 1100 | 1100 |
| Mercury flow and discharge | None | Yes | Yes | Yes |

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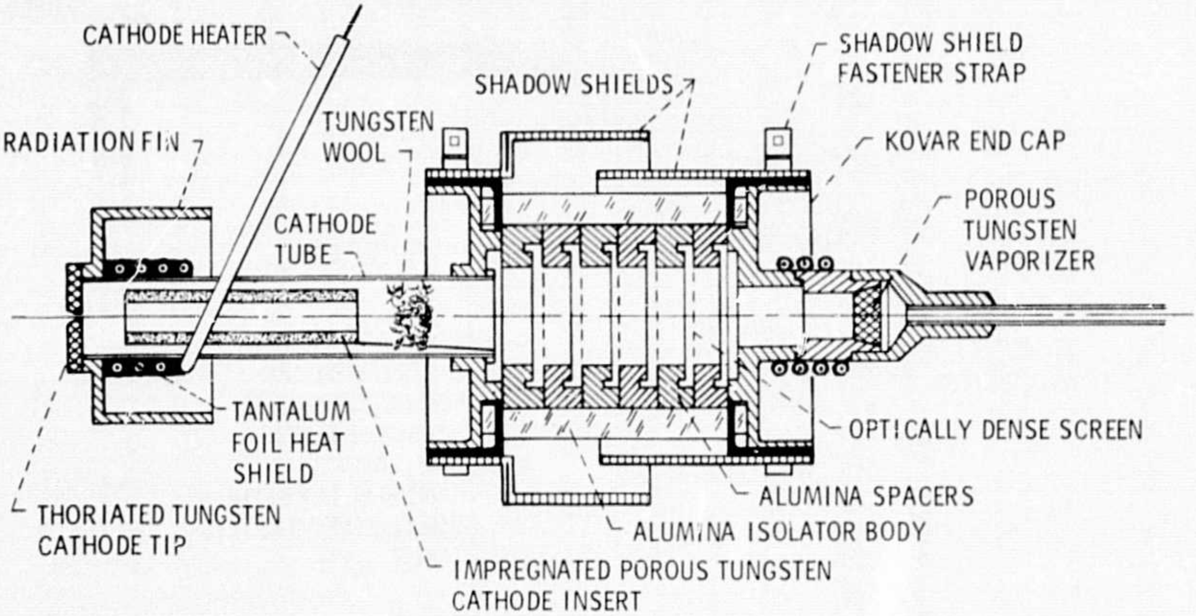


Figure 1. - Cathode-Isolator-Vaporizer (CIV) assembly.

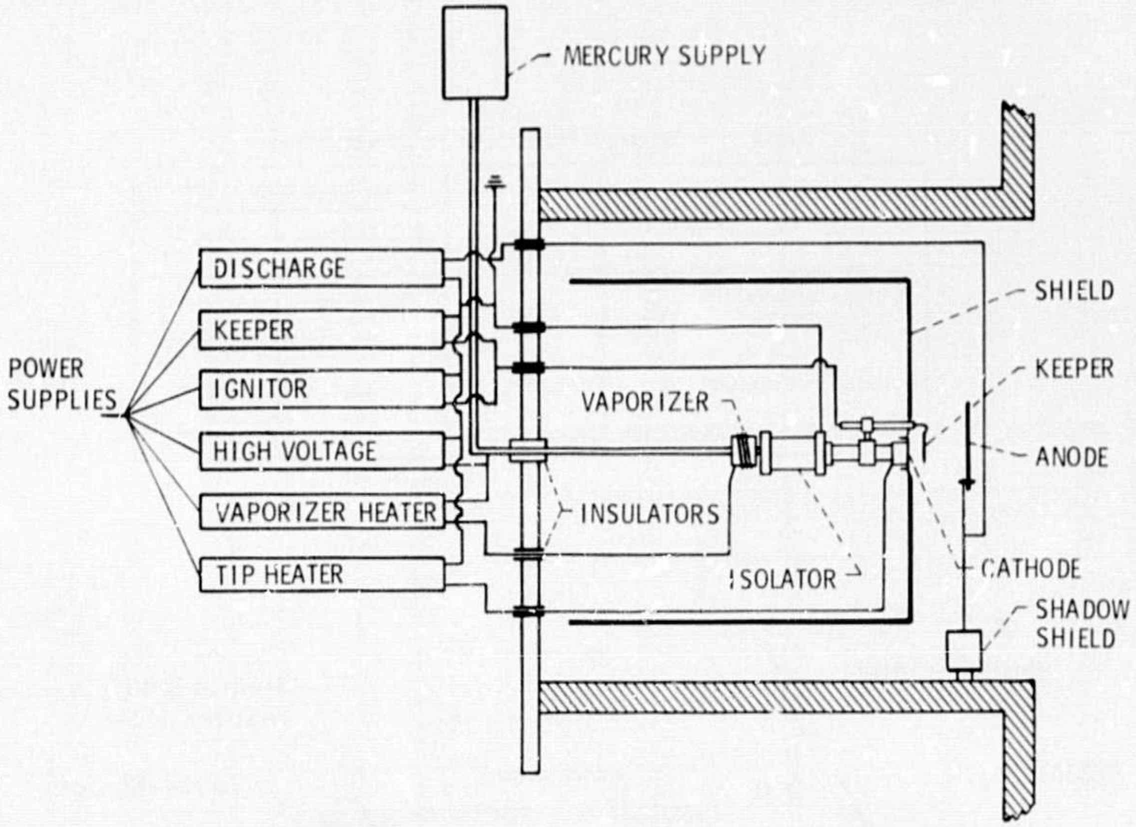


Figure 2. - Schematic of CIV test in 30 inch port.

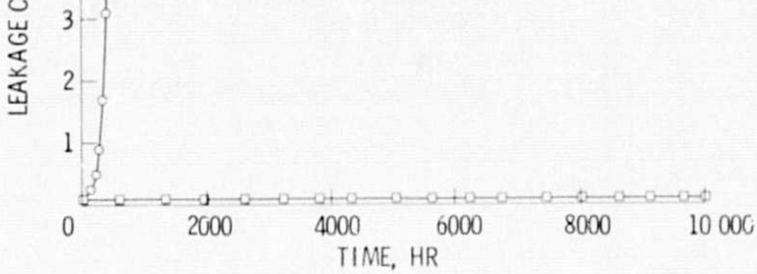


Figure 3. - Leakage current with time of MIV test.

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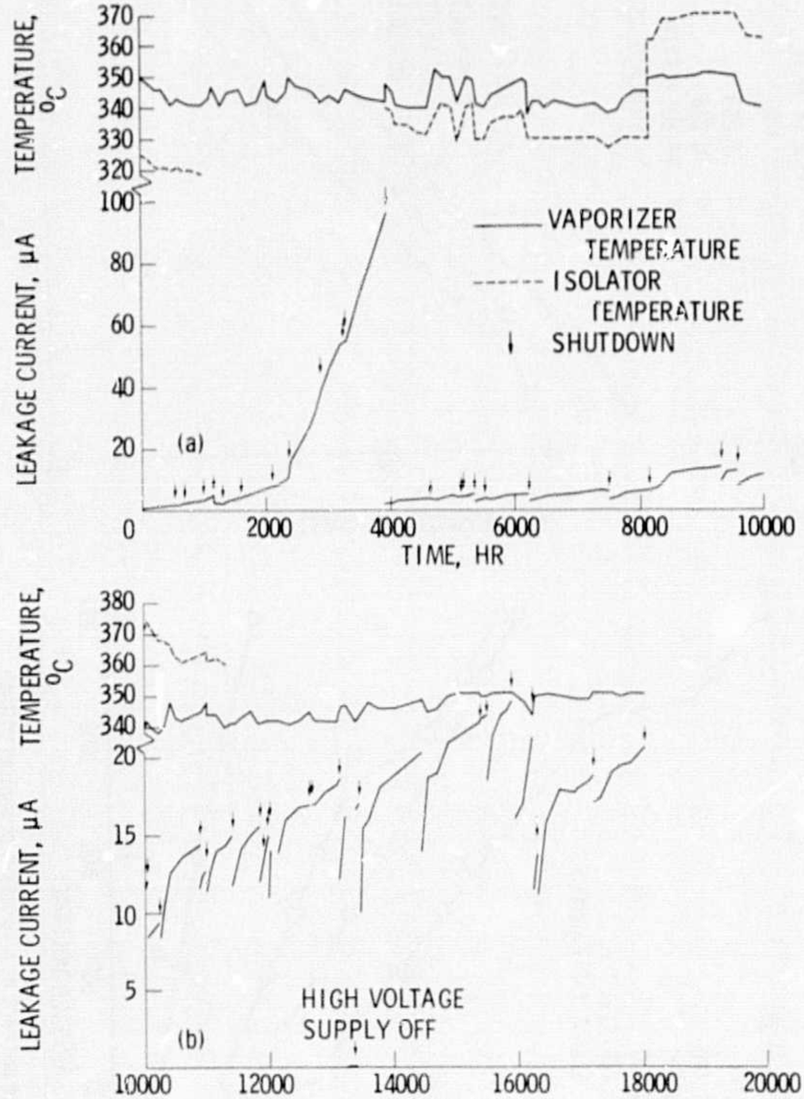


Figure 4. - Leakage current with time of CIV endurance test.

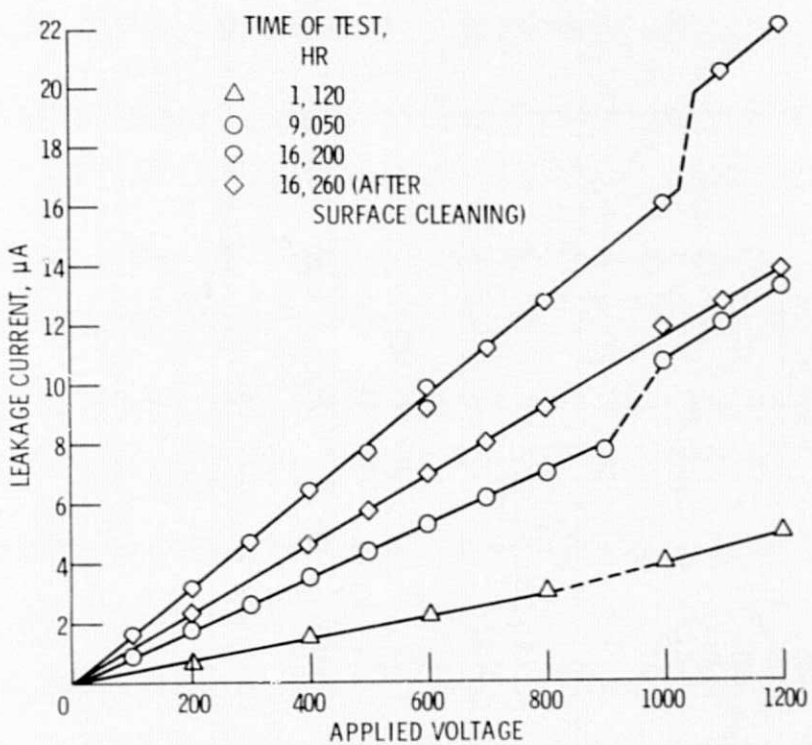


Figure 5. - Leakage current as a function of applied voltage.

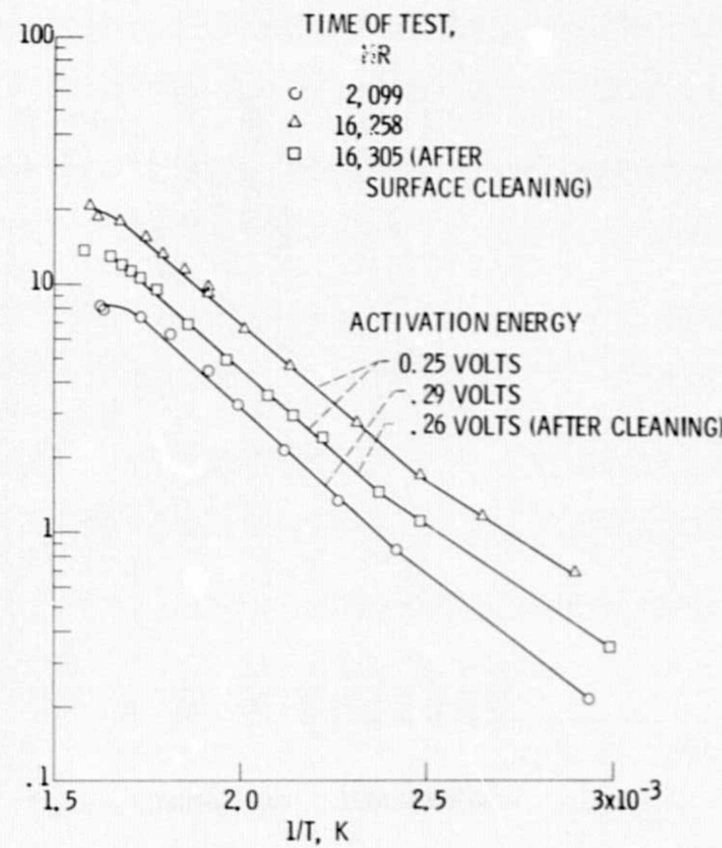


Figure 6. - Leakage current as a function of reciprocal isolator temperature.

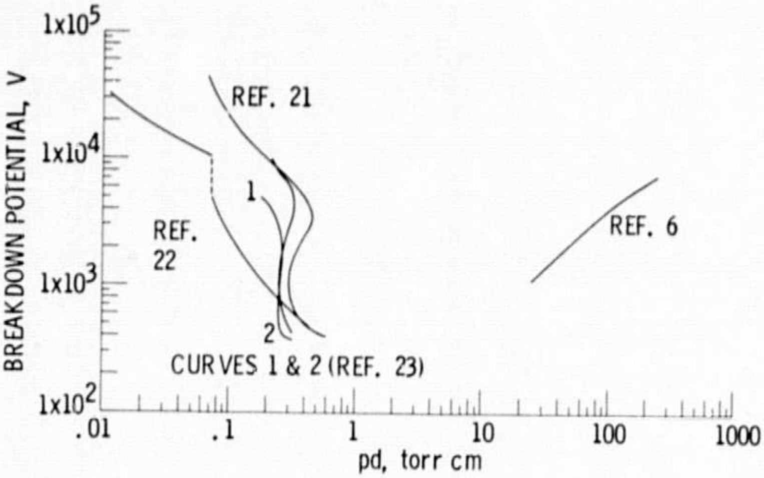


Figure 7. - Paschen curve for mercury vapor (pressures corrected to $0^0$ C).

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