NASA Technical Memorandum 79287

Hg ION THRUSTER COMPONENT TESTING

(NASA-TM-79287) Hg ION THRUSTER COMPONENT TESTING (NASA) 15 p HC A02/MF A01 CSCL 21C
N80-13159

Unclas
G3/20 46231

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Prepared for the
Fourteenth International Conference on Electric Propulsion
sponsored by the American Institute of Aeronautics and Astronautics
and Deutsche Gesselschaft fur Luft- und Raumfahrt
Princeton, New Jersey, October 30-November 1, 1979

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ABSTRACT

Cathodes, isolators, and vaporizers are critical components in determining the performance and lifetime of mercury ion thrusters. The results of life tests of several of these components are reported. A 30-cm thruster CIV test in a bell jar has successfully accumulated over 26 000 hours. The cathode has undergone 65 restarts during the life test without requiring any appreciable increases in starting power. Recently, all restarts have been achieved with only the 44 volt keeper supply with no change required in the starting power. Another ongoing 30-cm Hg thruster cathode test has successfully passed the 10 000 hour mark. A solid-insert, 8-cm thruster cathode has accumulated over 4 000 hours of thruster operation. All starts have been achieved without the use of a high voltage ignitor. The results of this test indicate that the solid impregnated insert is a viable neutralizer cathode for the 8-cm thruster.

INTRODUCTION

Electron bombardment thrusters have been under development to provide both auxiliary and primary propulsion functions for a large variety of space missions. In general, the missions proposed for these thrusters require lifetimes of up to about 15 000 hours (Ref. 1). Thruster design verification requires life tests of durations of the order of the time anticipated in space applications. The life time and reliability of electron bombardment thruster are significantly dependent upon the performance of several critical components. These components include cathodes, vaporizers, and isolators. Cathode performance is critical to overall thruster performance and control. In addition cathode starting requirements must be compatible with power processor requirements. Vaporizers must be capable of long term operation with no significant variation on flow conductance in order to assure that the thruster remains within thermal and electrical control envelopes. Finally, propellant isolators must be capable of withstanding the ion accelerating voltage in order that the present thruster system grounding design remains viable.

Life tests of various 8 and 30 cm thruster components have been conducted at Lewis Research Center (Refs. 2 to 7) as well as elsewhere (Refs. 8 and 9). This report will update results from a 30-cm Cathode-Isolator-Vaporizer (CIV)

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test that has accumulated over 26 000 hours. Also described will be another 30-cm Cathode-Vaporizer (CV) life test which has operated for over 10 000 hours. Operating characteristics of a 30-cm main cathode vaporizer will be described and recommendation for appropriate acceptance tests are offered based on these test results.

Recently, the inserts of the 8-cm thruster were changed from the rolled foil to the solid impregnated ty [illegible] A test of a neutralizer cathode with a hollow solid insert operating on a [illegible]m thruster has accumulated over 4000 hours. The performance characteristics of such a cathode will be described. The results of these tests and those conducted elsewhere (Ref. 10) resulted in the final thermal design configuration of the 8-cm neutralizer cathode.

APPARATUS AND PROCEDURE

Some of the component test conditions have been described in previous reports and the reader is referred to the specific report for more detail.

30-cm Cathode-Isolator-Vaporizer (CIV) Test

The description of the 30-cm CIV cathode and its performance up to 18 000 hours of operation was reported in Ref. 5 (cathode #3). The isolator-vaporizer description and performance were given in Ref. 6. After 22 600 hours a crack appeared in the tantalum body, believed to be due to mechanical and thermal stresses from a swaged fitting connecting the cathode to the isolator. The tantalum body was also weakened by embrittlement from exposures to high pressure caused by many facility malfunctions. The original hollow cylindrical insert was placed into a new cathode body of the present EMT design. The first cathode body had an 0.76 mm orifice and a radiation fin with a collar. The replaced cathode body has a 0.75 mm orifice with a 1.75 cm fin with no collar. The insert in the original configuration was recessed 0.95 cm from the tip. In the second cathode body the insert was placed adjacent to the tip.

The isolator was of the usual segmented design, consisting of seven short alumina chambers. The vaporizer consisted of a 0.45 cm diameter porous tungsten plug and the propellant flow was controlled by the temperature of the vaporizer plug. This test along with the other 30-cm component tests described herein were conducted in 30-cm diameter ports in the 7.6x18.3 m vacuum facility operating at a nominal pressure of 1 to 5×10^{-6} torr.

30-cm Cathode-Vaporizer (CV) Test

The description of this cathode and its performance up to 3000 hours was reported in Ref. 5 (cathode #5). The cathode body essentially had the same dimensions as the replacement cathode in the CIV test described above. The insert was located even with the cathode tip.

30-cm Vaporizer Tests

The vaporizers tested were the standard EMT vaporizer attached to an isolator. The porous tungsten plug dimensions were: 0.451 cm diameter and 0.117 cm long. Provisions were made so that the mercury propellant line could be pressurized up to 120 psia with nitrogen gas.

8-cm Neutralizer Cathode Test with Hollow Cylindrical Insert

The neutralizer was that of an EMT design (Refs. 11 and 12) except that the rolled foil insert was replaced by a hollow cylindrical insert made of the same porous tungsten and emission material as the 30-cm cathode inserts. The insert was 1.25 cm long with an O.D. and I.D. of 0.23 and 0.12 cm, respectively, and was placed even with the cathode tip. The neutralizer assembly and the 8-cm thruster on which it was operated are described in Ref. 13.

The following conditioning procedure was found to result in repeatable cathode restarts after atmospheric exposure: (1) preheat at low temperature (550° C) for 3-4 hours, (2) cool down for 1/2 an hour, (3) preheat for one hour at approximately 1050° C, (4) cool down for 1/2 an hour, and (5) preheat for 1/2 hour at approximately 1050° C. Following this procedure, the cathode ignition was attempted by applying vaporizer and keeper voltage supplies (without the high voltage ignitor). If the cathode would not start then tip heater power was increased in small increments over 5-10 minute intervals until ignition was obtained. If the cathode was restarted after a facility shutdown, ignition was initiated with step #5. The cathode temperature was monitored by a thermocouple on the tip of the cathode.

The test was conducted in a 1.5x6.1 m vacuum facility in which the pressure was maintained between 1 to 5×10^{-6} torr.

RESULTS AND DISCUSSION

30-cm Cathode-Isolator-Vaporizer (CIV) Test

The CIV test was initiated on July 5, 1973 and has been operated intermittantly since that time. The performance of the cathode, isolator, and vaporizer over the test period will be described separately below.

Cathode performance. - Figure 1 shows the keeper voltage with time over the 26 600 hours of operation. The operating conditions of the cathode were: keeper current 0.5 A, mercury propellant flow rate 160-180 mA, and discharge current generally between 10.5-11.5 A, except during the first 6000 hours when the discharge current was varied for different intervals of time between 7 and 12 A.

The keeper voltage is a sensitive indicator of cathode performance and any variations in cathode geometry or insert effectiveness during operation is directly reflected by the keeper voltage. It is evident from Fig. 1, that no degradation of this cathode has taken place. The changes in keeper voltage during the first 6000 hours are associated with changes of discharge current and mercury flow rate. Smaller changes in keeper voltage between 6000 and 22 600 hours can be attributed to changes in pressure in the facility and the many facility failures during the course of the life test. (Automatic shutdown of the test was initiated when the pressure reached 5×10^{-5} torr in the facility.) Small variations in keeper voltage have been observed with facility pressure changes also by Ref. 8.

After a facility failure at about 22 600 hours in the test a longitudinal crack in the cathode body was discovered. It is surmised that this crack developed because of tantalum embrittlement during a facility failure and the physical or thermal stresses on the cathode body due to the swaged fitting used to attach the cathode to the isolator body. Because it was considered that the insert of the cathode is the most critical component of the cathode, the cathode body was replaced with one constructed of the present design and the test continued with the same insert. Because the new cathode body did not have a radiation collar as the previous configuration and the insert was not recessed, the cathode temperature increased from about 970° to 1030° C during steady state operation and the keeper voltage was reduced by approximately 2 volts. A similar decrease of keeper voltage was observed by Ref. 5 when the insert was moved adjacent to the tip.

Another important cathode performance characteristic is its starting capability. Figure 2 shows the required starting temperatures of the cathode tip during the life test and shows that no significant trends in starting temperature occurred during the test. All starting temperatures are below those where excessive removal of low work function material occurs (Ref. 5).

It is significant to note that all starts after 25 144 hours were attained with only the open circuit keeper voltage of 44 volts without the 400 volt ignitor used in the cathode ignition procedure for the first segment of the test. These data indicate that it may be possible to eliminate the high voltage starter section which is presently included in both the neutralizer and main cathode keeper power supplies.

Isolator. - As reported in Ref. 6, the average rate of increase of $\sim 4\times10^{-3}$ μA/hr of leakage current during the time from 4000 to 11 000 hours was well within the established isolator performance requirements. The average rate of increase of leakage current from 18 000 to 22 600 hours was approximately 7×10^{-3} μA/hr. The isolator was operating at a slightly higher temperature during this segment of the test and because the rate of increase of leakage current has been found to be very sensitive to the isolator operating temperature (Ref. 14), this increase is not considered to be significant. The leakage current was found to be predominantly due to the contamination of the outside surface of the alumina body.

Numerous times during the later stages of the test, the high voltage supply was "tripped," indicating a sudden surge of leakage current or a breakdown. This was believed to be due to high pressure excursions in the bell jar because of facility malfunctions. Because of these recurring facility problems the application of the high voltage across the isolator was not continued after 22 600 hours. There have been no increases in isolator leakage current observed during life tests of 30-cm mercury ion thrusters (Refs. 15 and 16). The probable reason for this fact is that inside a thruster the isolator surface is better shielded from the facility environment and that the operating temperature of an isolator inside a thruster is considerably lower (~250° C) than the temperature in the bell jar test (~360° C). Because of the sensitivity of the rate of increase of leakage current to its operating temperature, it has been recommended to keep the isolator temperature as cool as possible during all phases of thruster operation (Ref. 14).

<u>Vaporizer</u>. - The flow conductance of the vaporizer has been monitored during the 26 000 hour test which has taken almost 6 years to complete. Figure 3 shows the flow calibration of the mass flow rate as a function of the vaporizer temperature at the beginning of the test and after 26 600 hours of operation. It is evident that the performance of the vaporizer has not been changed during the life test.

30-cm Cathode-Vaporizer (CV) Test

Figure 4 shows the keeper voltage of a 30-cm cathode as a function of time which has accumulated 10 000 hours. The cathode operating conditions were: discharge current of 10.0-10.5 A during the first 500 hours and 11.0 A, thereafter, discharge voltage of 12-14 volts and a mercury flow rate of approximately 140 mA. Similar to the test described before, the performance of this cathode has not degraded over the accumulated test time.

The cathode was restarted 25 times. However, because of a partial short circuit between heater elements, sufficient heat could not be supplied to the cathode for starting without an ignitor. The heater limited the tip temperature to only 960° C. This temperature was below the 1000°-1050° C required to start the CIV test cathode without an ignitor. Cathode starting conditions exhibited no significant degradation. Starting tip power for the first 5000 hours was from 65-77 watts; whereas, 79-87 watts were required to start during the next 5000 hours. The small increase is not considered to be significant considering the detrimental effects encountered during the many facility breakdowns.

For both cathodes tested the starting temperature was slightly higher than the normal operating temperature of the cathode tip.

30-cm Vaporizer Acceptance Tests

Thruster tests (Ref. 16) and subsequent vaporizer tests have shown that certain vaporizers exhibit changes of conductance with time at pressures considerably less than their cold intrusion pressure. Three vaporizes have been tested and typical results will be presented.

In order to determine the operating limits of a vaporizer, the intrusion pressure was measured as a function of vaporizer temperature. The data for the three vaporizers tested are shown in Fig. 5. As the temperature of the vaporizer was increased from room temperature to the normal operating temperature of about 300° C, a reduction of up to 25% of the intrusion pressure was measured. These results are similar to those obtained by Ref. 17. The difference of the intrustion pressure of the three vaporizers is not considered to be significant.

A bakeout procedure was followed which results in the vaporizer returning to its original flow calibration after an intrusion (Ref. 17). The vaporizers were then subjected to various pressures and the mass flow rate at a given pressure was measured as a function of time. Typical results of two of the vaporizers are seen in Figs. 6 and 7 (Ref. 18). The conductance of vaporizer #1 changed in tests at two pressures over a period of about 150 hours and then reached a steady value. These changes occurred at pressures considerably below the intrusion condition shown in Fig. 5. The conductance of vaporizer #2 did not vary until the conditions of intrusion shown in Fig. 5 were approached. Vaporizer #3 exhibited characteristics close to those of vaporizer #2. The reason for the differences in performance are not known at this time. Hair line cracks in the vaporizer may be one possible explanation. The data in Figs. 6 and 7 indicate that more than a cold intrusion test is necessary to verify vaporizer design. It appears that each vaporizer may have to be subjected to a pressurized 100-150 hour test to verify that it meets the required pressure limits imposed by anticipated propellant tank operating pressures.

8-cm Neutralizer Cathode Test

Performance characteristics. - Solid impregnated porous tungsten inserts have been incorporated in a 15 000 hour life test of an 8-cm thruster (Ref. 9). The inserts used in this test were solid, cylindrical in shape and recessed from the cathode tip. It was found that the main cathode operated properly during the life test at a keeper voltage between 13-14 volts. However, for stable cathode operation the neutralizer required 7.2 watts of power for most of the test duration. Even with the addition of the heater power, the neutralizer floating potentials and keeper voltage were quite high at about 30-40 and ~20 volts, respectively. Because of imposed power limitation at that time, the solid insert was not believed to be a viable alternative to the rolled foil insert. This insert type did not require any tip heat during steady state operation.

Due to subsequent tests in which inconsistant cathode performance was observed while using the rolled foil insert, and the excellent results obtained by the solid insert in the 30-cm thruster program, the use of the solid insert again was proposed for the 8-cm thruster. The experience gained from the 30-cm cathode program suggested changes which led to improved performance of the 8-cm neutralizer cathode. To achieve the improvement, the cathode tip-insert recess was eliminated and a hollow insert was used instead of a solid one. The performance characteristics of such a cathode are shown in Fig. 8 where the neutralizer keeper voltage and floating potential are plotted as a function of mercury flow rate for various keeper current values. The cathode tip temperature is noted at each data point. The minimum keeper voltage appears to be at a mass flow rate between 8-12 mA. This flow rate is well beyond that required for minimum cathode tip erosion (Ref. 20). The minimum voltage of 19 to 20 volts observed in this best is comparable with the keeper voltage of the 15 000 hour test with 7.2 watts applied. More significant improvement is seen in the neutralizer floating potential. At a keeper current of 0.6 A a floating potential of only 13 volts was measured, compared to the 30-40 volts observed in the life test. Figure 8 shows that increasing the keeper current resulted in considerable reductions in the neutralizer floating potential whereas, the effect on keeper voltage was minimal.

These characteristics demonstrated that a neutralizer cathode with a solid hollow cylindrical insert could operate stably without the addition of tip heat power. The observed keeper voltage of approximately 19 volts was still considered to be marginal. Therefore, some minor changes were made to improve the thermal design of the cathode (Ref. 10).

The keeper voltage of the neutralizer cathode is shown in Fig. 9 as a function of time for over 4000 hours. No evidence of cathode degradation is seen from this data.

The required starting heater power of the cathode with only the 44 volt keeper supply is shown in Fig. 10. The required power increased from approximately 25 to 35 watts during the first 2000 hours, and no significant increase observed after that time. Somewhat disconcerting are the relatively high starting temperatures of this cathode. Whereas the 30-cm cathode starting temperatures ranged from 950° to 1050° C, this cathode required up to 1220° C. It should be noted that starting voltage of the keeper supply of the 30-cm CIV test was approximately 10 volts higher then the 8-cm supply. Therefore, the exact reason for the different starting temperature requirements are not known at this time.

Based on the promising results obtained in this study and elsewhere (Ref. 10), it was decided to replace the rolled foil insert with the solid hollow cylindrical insert for both cathodes of the 8-cm thruster. Also the high voltage (5000 V) ignitor was eliminated from the Power Processor and a high voltage section of 460 volts was substituted in the keeper supply to take its place.

CONCLUSIONS

Results of several 30-cm component life-tests as well performance of an 8-cm neutralizer cathode with a hollow cylindrical insert are reported herein. Two 30-cm cathode tests have accumulated up to 26 000 and 10 000 hours without any apparent degradation in performance. (A cathode body had to be replaced in one of the tests after 22 700 hours.) Starting of the 26 600 hour 30-cm Cathode-Isolator-Vaporizer test was achieved recently without the high voltage ignitor after six years of intermittent testing using the conventional high voltage ignition. No additional heater power was required to achieve the low voltage starts. Isolator and vaporizer performance was found to be satisfactory during the 26 600 hour test. Satisfactory results were also obtained from the 30-cm Cathode-Vaporizer test. No degradation of the cathode was observed from the keeper voltage characteristics or starting tip heater requirements during the 10 000 hour test.

30-cm vaporizer tests results are reported which have indicated a necessity of an additional pressurized time acceptance test to determine if a vaporizer is capable of operation at a given pressure without a change in its flow conductance.

An 8-cm neutralizer cathode with a hollow cylindrical insert was tested on a thruster and its performance characteristics presented. It was shown that similar to the 30-cm cathodes, the solid insert cathode is a viable cathode for the 8-cm thruster. A life test of the cathode over 4000 hours, with starting achieved with a low voltage keeper supply, showed no deterioration in its performance.

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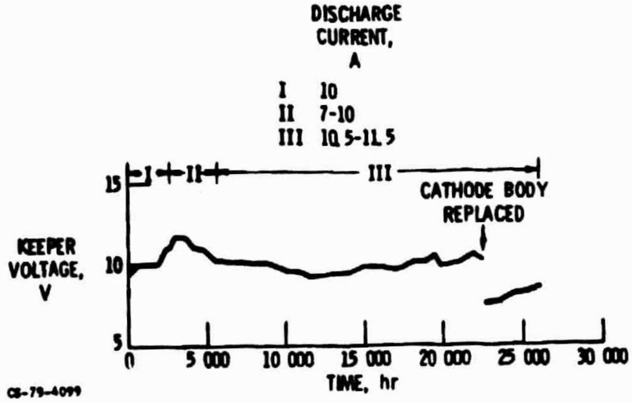

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Figure 1. - Keeper voltage vs time of 30-cm CIV test.

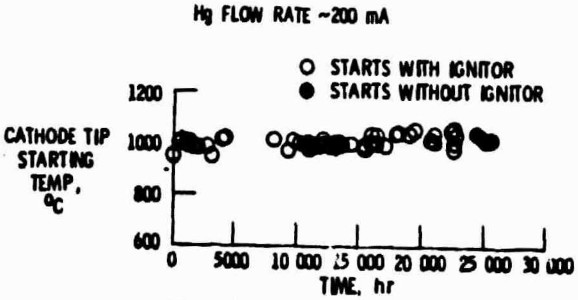

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Figure 2. - Cathode tip starting temperature vs time of 30-cm CIV test.

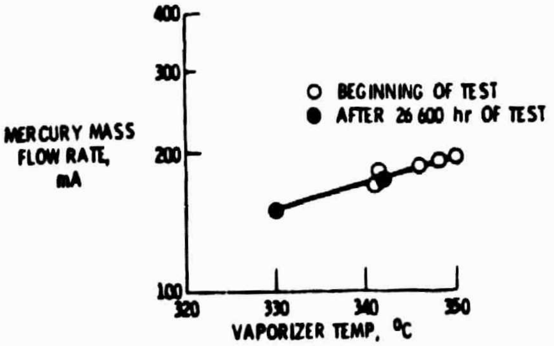

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Figure 3. - Calibration of 30 cm CIV test vaporizer.

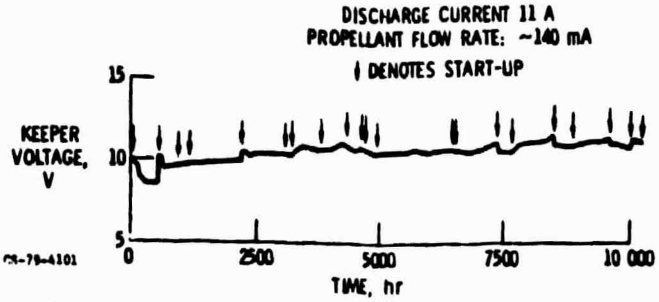

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Figure 4. - Keeper voltage vs time of 30-cm thruster cathode.

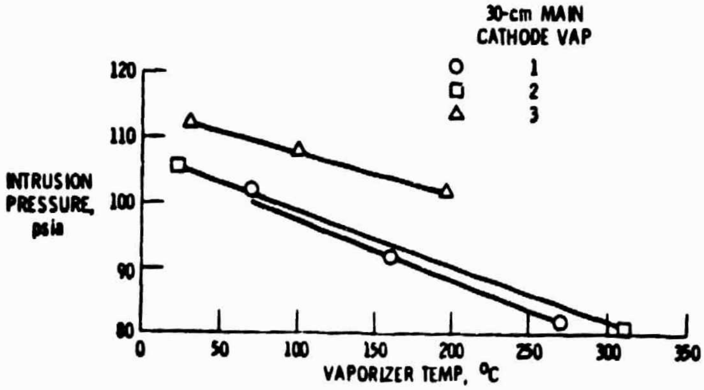

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Figure 5. - Intrusion pressure as function of vaporizer temperature.

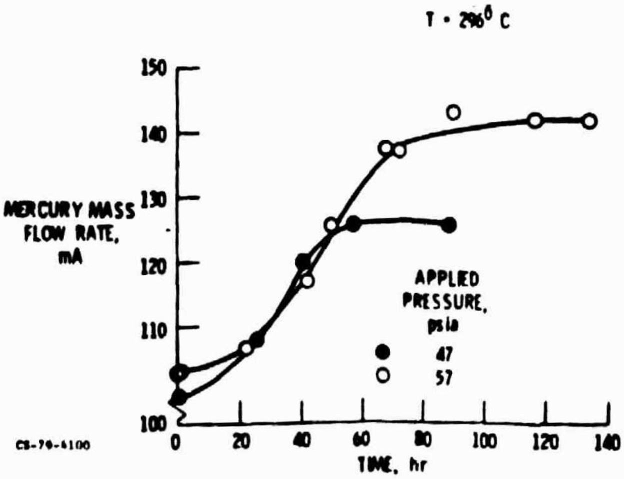

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Figure 6. - Mercury mass flow rate as function of time of 30-cm main cathode vaporizer No. 1 (ref. 18).

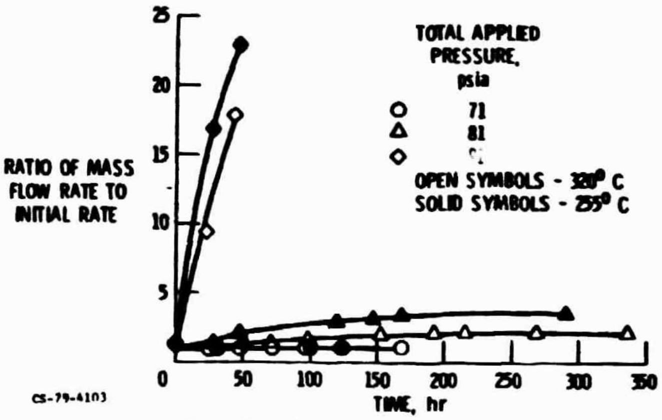

Figure 7. - Change of conductance with time of 30-cm main vaporizer No. 2.

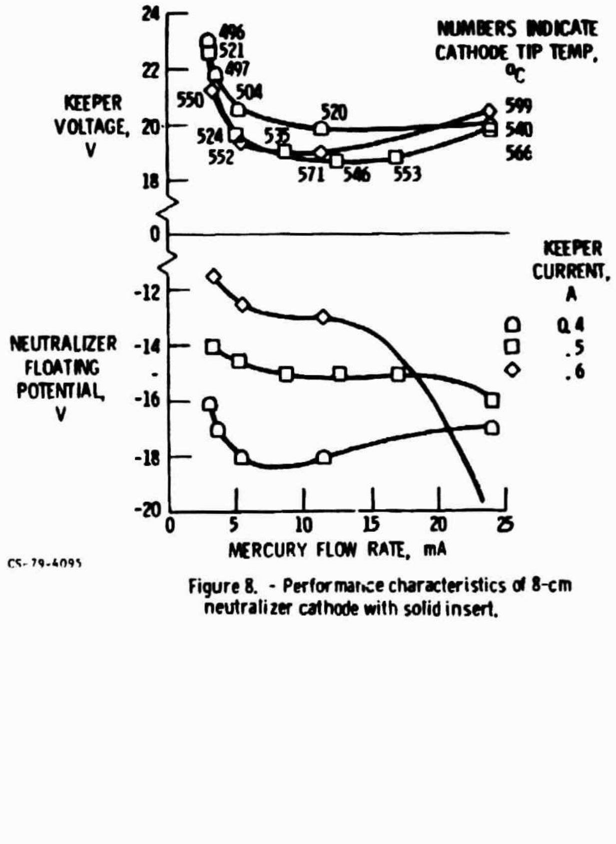

Figure 8. - Performance characteristics of 8-cm neutralizer cathode with solid insert.

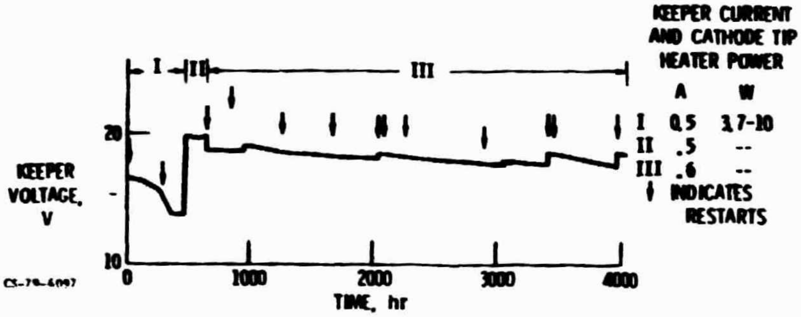

Figure 9. - Keeper voltage vs. time of 8-cm neutralizer cathode with solid insert.

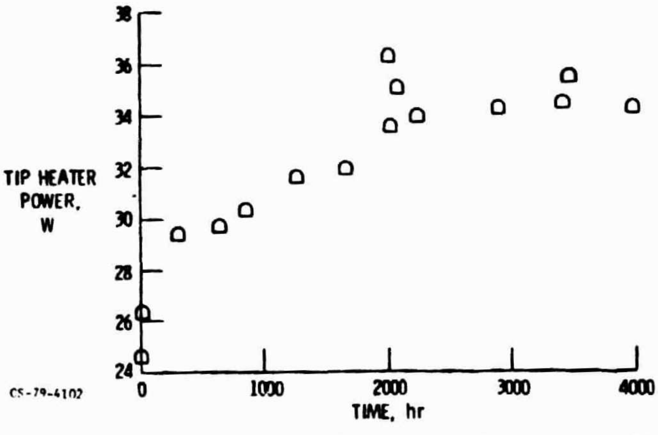

Figure 10. - Cathode tip heater power required to start with 33V. Keeper supply vs. time of a 8-cm neutralizer cathode with solid insert.