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Performance Evaluation and Life Testing of the SPT-100

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ABSTRACT

A cyclic endurance test of the Russian 1.35 kW Stationary Plasma Thruster SPT- 100 is described, The endurance test is scheduled for 6,000 on/off cycles and 5,000 hours of operation at an input power to the thruster of 1.35 kW. Cycles are 50 minutes of thruster on-time and 23 minutes of thruster' off-time, To date 5,000 cycles and 4165 hours of thruster on-time have been completed. Thruster efficiency decreased from 50% to 45% as the thruster aged over the first 1,000 hours; efficiency increased slowly over the next 1,000 hoursand has remained essentially unchanged between 2,000-4,000 hours of operating time, despite considerable erosion of the discharge chamber walls and the downstream face of the thruster. There are no known cases where the thruster failed to start in the cyclic endurance test. The endurance test is being performed under a cooperative program between Space Systems/Loral, JPL, and the Ballistic Missile Defense Organization (BMDO).

INTRODUCTION

Stationary plasma thrusters (SPT) are gridless ion thrusters that were originally developed in the U.S. in the early 1960s.[1-3] Although efforts in the U. S, to develop high thrust efficiencies failed, efforts in the former U.S.S.R. were quite successful; the SPT was successfully developed during the 1960's and 1970's by Morozov[4] and others[5,6] with a unique combination of specific impulse and efficiency. It has been reported that more than 50 SPT-70 thrusters have flown in space, starting with the Meteor I in 1969-1970.[7,8] More recently, 8 SPT-100 thrusters were flown on the Russian GALS communication satellite.[9] Reportedly, all thrusters are performing routine stationkeeping functions,

In 1991 a team of electric propulsion specialists visited the former U.S.S.R. to experimentally evaluate the performance of a 1.35-kW SPT at the Scientific Research Institute of Thermal Processes in Moscow and at "Fakel" Enterprise in Kaliningrad, Russia,[10,11] The evaluation indicated that the actual performance of the thruster appears close to the claimed performance of 50% efficiency at a specific impulse of 1600 s.[11] Studies indicate that for north/south station keeping and Earth orbit raising applications of electric propulsion, the optimum specific impulse is in the range of 1,000-2,000 sec.[12] The combination of the flight heritage of the SPT-70 and the availability of thrusters and thruster data, has led to increased interest in these thrusters by Western spacecraft manufacturers for primary and auxiliary propulsion applications,

Loral is presently flight-qualifying 1.35-kW, SPT-100 thrusters for north/south station keeping and Earth orbit raising applications and plans to provide these thrusters on their spacecraft.[13] At Design Bureau "Fakel", located in Kaliningrad (Baltic coast) a steady-state life test is being performed[14], and performance, plume and EM I/RFI evaluations are being conducted at NASA Lewis Research Center.[15-18] A key aspect of the SPT-100 evaluation program is characterization of the long term operating behavior of the thruster. Typical mission applications of interest require operating times of several thousand hours. Potential use of the thruster for north-south stationkeeping of commercial communication satellites will also require the capability for several thousand on/off cycles. To address these objectives a cyclic endurance testis being performed at JPL under a cooperative program between Space Systems/Loral, JPL (under the JPL Affiliates program) and the BMDO. The endurance testis scheduled for 6,000 on-off cycles and 5,000 hours of operation at an input power of 1.35 kW. A previous paper describes the results of the endurance test for the first 800 cycles.[19] This paper describes the preliminary results of this cyclic endurance test through the first 5,000 cycles.

APPARATUS

The Russian SPT-100 plasma thruster used in this endurance test is shown in Fig, 1. "This thruster as tested comes with two redundant hollow cathodes and a xenon flow control system (XFC) enclosed in a box directly behind the SPT- 100 (Fig. 2). The outer insulator which forms the outside discharge chamber wall is approximately 100,8 mm-dia.

The SPT-100 thruster endurance test is being performed in a 3. 1-m dia. x 5.1-m stainless steel vacuum chamber equipped with three each, 1.2-m diameter helium cryopumps. The minimum no-load tank pressure was observed to be 3,2 x 10-8 Torr. The nominal pumping speed

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for the three pumps combined is 81,000 liters/s on xenon, however the true pump speed on xenon is approximately 50,000 l/s.[19]

The thruster is mounted near one end of the vacuum tank, directly facing a cryopump which is positioned at the other end of the vacuum tank. The discharge chamber surfaces of the SPT thruster consist of insulator materials, and it has been demonstrated that the performance of SPT thrusters can be significantly affected by the deposition of a conducting coating on the insulator.[20] To protect the cryopump and minimize the amount of material sputtered back to the thruster, the facility was lined with graphite, and a graphite beam target was constructed, The beam target consists of 6.4-mm thick graphite panels arranged in a chevron configuration and placed as shown in Ref. 19. Graphite was selected as the target material because of its low sputter yield at the ion energies expected from the SPT.[21] The chevron configuration results in large angles (typically greater than 50 degrees) between the expected ion trajectories and the direction normal to the graphite surface, which may both reduce the graphite sputter rate and reduce the amount of sputtered material directed back towards the thruster. A photograph of the SPT-1OO mounted inside the vacuum chamber is shown in Fig, 2.

Due to the beam divergence characteristics of the SPT- 100, material can be sputtered from the vacuum tank sidewalls and deposited onto the thruster. Therefore the cylindrical side walls of the vacuum chamber were also lined with graphite panels. The graphite beam target panels were baked out at high temperature (approximately 2300 K) prior to installation in order to minimize the potential for hydrocarbon contamination. The side panels, which are subject to a much lower thermal load during thruster operation, were not. Glass slides were placed 21 cm to either side of the SPT thruster such that material back sputtered to the SPT could be quantified and characterized.

Tank pressure was measured using two ion gauges. One gauge tube was mounted directly to the outer wall of vacuum tank; the other tube was mounted inside the vacuum tank, approximately 0.51 m above and 0,58 m behind the SPT-1OO, This tube was calibrated on xenon and nitrogen using a spinning rotor gauge that is traceable to NIST, data from this calibration were used to generate a curve fit that was used to calculate tank pressure.

The propellant system for supplying xenon to the SPT-1OO thruster is described in Ref. 19. The system was constructed from 0.64 -cm-dia stainless-steel tubing that was scrubbed with acetone and alcohol before assembly. Prior to operating the SPT, the propellant system was checked for dew point, hydrocarbon contamination, and particulate contamination.

Pressure was indicated by a capacitance manometer that was calibrated to an accuracy of ±0.25% at 249.94 kPa, the nominal working pressure for the SPT- 100. It should be noted here that the pressure is dropped to the level required by the cathode and discharge chamber within the xenon flow control system (XFC) that is an integral part of the SPT- 100 and is located directly behind it in the vacuum system. Therefore pressure in the propellant tubing is above atmospheric pressure up to the SPT XFC. ‘Any xenon contamination should then be due to contaminants picked up from tubing walls, propellant system components, or the xenon itself, The purity of the xenon used by the SPT was tested from the xenon bottle. Purity data indicate that the specifications (99.999%) were exceeded.

A thermal mass flow meter was used to measure propellant flow rate. The flow meter was calibrated on both nitrogen and xenon by the manufacturer using a primary calibration standard, and at JPL using a bubble volumeter. The nitrogen calibration performed at JPL agrees with the primary standard calibration to within 1 % for all flow rates tested. The bubble volumeter data on xenon were curve fit and the curve fit was incorporated into the SPT data acquisition and control program.

A xenon recovery system is used to recover and store xenon consumed by the SPT- 100. The recovery system is used in the event of a cryopump failure or when 3000 liters of xenon have been consumed. A mechanical pump in the recovery system pumps the xenon out of the vacuum tank and into a holding tank chilled with liquid nitrogen; the vacuum tank is pumped by the recovery system pump to less than 0.4 Torr pressure. Oil traps prevent recovery system pump oil from entering the vacuum tank.

A probe rake, consisting of 25 Faraday probes of diameter 2.3 cm, mounted on a semicircular arc 2.4 m ‘in diameter was used to examine the thruster exhaust plume. The probe buttons were biased to -23 volts when used to measure the plume shape. The probe rake was positioned such that the thruster is at the center of the semicircular arc; the axes of the rake were aligned with the plane formed by the outer insulator of the SPT-100 such that the rake can be pivoted around a line normal to the thruster axis, This configuration enables complete hemispherical profiles of the exhaust plume to be obtained. When the probe rake is not in use, a motor rotates the rake to a position of approximately 90 degrees with respect to the thruster axis.

The SPT-1OO is mounted to an inverted pendulum style thrust stand of the type developed at NASA LeRC;[22] in this design, thrust is indicated by a linear voltage displacement transducer (LVDT). The thrust stand is surrounded by a water-cooled housing to minimize temperature effects on the measured thrust; the housing can be seen just below the SPT-1OO in Fig. 2. The thrust stand inclination is adjusted continuously by computer to improve the accuracy of the thrust measurement over extended test times. Thrust stand calibrations are performed in-situ throughout the life test in the vacuum chamber using a set of weights deployed with a motor. Normally 15 or more calibrations are performed in order to obtain a large enough sampling for statistical analyses, Statistical analyses of the calibration data was also used to determine the thrust stand inclination. Repeatability of the calibrations were normally 1.0% or better.

The thruster is operated with a bread board power conditioning unit (PCU) developed by Space Systems/Loral. Preliminary data imply that the bread board PPU is approximately 93% efficient. The SPT-100 discharge. current and magnetic field current are adjusted by supplying the appropriate voltage input signal to the PCU. The PCU output voltage is fixed at approximately 300 V. Propellant flow rate was controlled by the SPT-100 flow control unit which is part of the thruster; the mass flow rate was determined by the discharge current setting. The PCU was turned on and off by supplying the appropriate digital voltage pulse to the PCU. Once the engine parameters were adjusted and the PCU was turned on, the SPT-100 thruster was started and operated automatically by the bread board PCU. The PCU sequencing is described in Table. 1.

Table 1. Power Conditioning Unit Sequencing

Time sec	Action
0	PCU start command received from computer
10	Cathode heater, capillary current, magnetic field current on
170	Cathode igniter voltage applied; cathode heater off.
171	SPT achieves 1.5 A discharge; run time clock started, begin on-phase
180	SPT achieves 4.5 A discharge
3180	SPT turned off by stop command issued by computer; begin off-phase
4380	PCU start command received from computer for next cycle

Steady-state thruster operation, start-up and shutdown sequencing are controlled by a PC based data acquisition (DAC) system. This system also monitors the vacuum facility enabling unattended operation. A total of 56 channels that include thrust, xenon mass flow rate, anode voltage and current, floating voltage, magnet current, cathode heater current, thermothrottle current, SPT inlet xenon pressure, tank pressure and various other facility components are monitored and recorded as a function of time. The data are averaged and the averaged values are displayed on a monitor screen. The data are recorded on the computer hard disc drive every 60 seconds, and printed every 120 seconds,

The computer is responsible for issuing the PCU start and stop commands. If certain engine or facility parameters exceed specifications, the computer sends the PCU stop command to the PCU, opens a relay between the PCU and its power source, and activates a telephone dialing machine (autodialer). The computer sends a change-of-state signal every 15 seconds to an electronic timer (heartbeat box); in the event of a computer failure, the timer activates a series of relays to turn off PCU power, xenon flow, and activates the autodialer.

The data acquisition program averages and stores PCU telemetry for discharge current, cathode heater current, capillary current, discharge voltage, floating voltage and flow rate. PCU telemetry for various SPT-100 currents were calibrated to values obtained from calibrated current shunts, The discharge current calibration was determined using a voltmeter which averages the direct-current value of the discharge current shunt voltage drop over a period of four seconds. Oscillations in the discharge current were obtained with an inductive probe placed on the discharge current cable close to the vacuum tank feedthrough. The discharge voltage ripple was measured at the vacuum tank feedthrough as well, using a combination inductive/Hall effect probe, Cabling length between the feedthrough and SPT is approximately 6 m. After cycle 663 of the cyclic life test the RMS value of the discharge current was measured using a true RMS voltmeter.

The thruster was photographed (from an off-axis view) periodically through a window in the vacuum system to document the condition of the thruster. Insulator thicknesses are determined from photographs by measuring the ratio of insulator width to the length of the outer edge of the outer insulator or inner edge of the inner insulator. An off-axis view of the SPT-100 is shown in Fig. 3. The SPT-100 can be seen operating in the endurance test facility in Fig. 4.

PROCEDURE

The SPT-100 was purged with argon when the mechanical pumps were used to pump the vacuum tank from atmosphere to 50 mTorr; as of this writing the SPT-100 life test thruster has not been exposed to atmosphere since it was installed on June 22, 1993. The SPT-100 is operated only if the vacuum tank pressure indicated by the calibrated ion gauge reads below 2×10^{-7} Torr. During a facility shutdown (cryopumps off) the SPT-100 is purged with xenon.

A cycle is defined as any time the thruster achieves a discharge current of >1.5 A. The first 25 cycles of the life test were used to test the data acquisition and control program, the facility, and the probe rake; in these cycles the thruster was operated for varying time periods, from less than one minute to over 60 minutes, and at varying discharge currents.

The computer performs the task of starting and stopping the thruster, taking data, and monitoring the facility. Life test cycles are nominally 50 minutes on and 20 minutes off, with an additional three minutes for cathode pre-heating. Oscilloscope traces of current oscillations in the discharge current and a.c. ripple in the discharge voltage are obtained approximately every 10 cycles. Approximately every 200 hours the life test was interrupted for a short period of time 10 photograph the thruster, measure flow meter zero drift, and to re-calibrate the thrust stand (T/S). Approximately every 200 hours a probe scan was obtained using the probe rake.

RESULTS AND DISCUSSION

The SPT- 100 has completed 5,000 starts and 4165 hours of operation; of these, 86 cycles totaling 26.64 hours were not operated for the standard 50 minutes because of testing requirements, computer/facility failures, operator error, or to computer-commanded shutdowns. All shutdowns have occurred due to facility/hardware failures, PCU or PCU power input failures, operator errors, or computer software failures, There. have never been any shutdowns required due to SPT operation- in all cycles the SPT has always started and performed to its nominal operating condition of 1.35 kW.

A glow in the non-operating cathode was observed in cycle 1 and all subsequent cycles. The glow may be due 10 a propellant leak in the SPT XFC. This SPT-100 thruster utilizes a propellant system with no absolute flow shut-off to the unused cathode,[23] a design feature present in newer SPT thrusters, The cathode glow occasionally flickers on engine start-up and periodically disappears completely for approximately 3 seconds before reappearing. The glow in the unused cathode is visible in a photograph (Fig. 5) of the SPT- 100 in operation. The brightness of the glow may have decreased with time.

Starting with cycle 26 theSPT-100 was cycled for 50 minutes on and 20 minutes off, with 3 minutes for cathode pm-heating. Four cycles were "double-booked) so the total actual number of cycles reported herein should be incremented by 4 (after C822). In 85 of the 5,000 cycles accumulated to date the thruster was operated for less than the usual 50 minutes for a variety of reasons, The shutdowns are categorized in Table 11,

During cycle 93 a software error resulted in operation of the SPT thruster for approximatel y 30 minutes without sufficient xenon flow; no data for this cycle were printed or stored. The software error was corrected and tested during cycles 94-97. Cycle 4657 was operated for 5.6 hours due to a computer/software error, During most of this cycle the thruster operating characteristics were not monitored and data were not stored by the computer. The thruster was operating at nominal values of discharge voltage and discharge current when the problem was discovered.

20 shutdowns were due to cryopump failures. Most of the shutdowns were commanded by computer when a cryopump began to fail and vacuum tank pressure exceeded 0.013 Pa; tank pressure did not exceed 0.04 Pa during these failures. In two of the failures the computer commanded the cryopumps off and tank pressure approached 0.1 Pa for a short time; the partial pressure was mostly xenon evaporating off of the pump surfaces, Xenon flow through the SPT was maintained when a cryopump was turned off, and tank pressure never exceed 0.1 Pa.

Table 11, Test/shutdown descriptions

Shutdown Description	Number of Shutdowns
Cycle stopped, thruster emitting sparks	2
Cryopump failures	20
PCU/PCU input power supply failures	18
Power grid transients	2
Operator errors	6
Computer/DAC errors or hardware failures	7
Thruster/t)AC testing	30
TOTAL	8S

TEST DATA FOR CYCLES 26-5000

Engine parameters such as efficiency, discharge current and voltage, etc., for cycles 26-5,000 are shown in Figs. 6-9. The data represent values for 242 individual Cycles. Data through cycle 2,000 were calculated by averaging computer data for the last ten minutes of each cycle. Discharge current and voltage data obtained using voltmeters are more consistent compared to data obtained from the data acquisition system, because the DAC or the PCU telemetry are affected by thruster operation, Therefore after cycle 2,000 values for discharge current and voltage read from voltmeters were used in Figs, 6-9.

Thruster data were analyzed to determine cycle-to-cycle changes in thruster operating characteristics. Thrust was determined by subtracting the LVDT voltage four minutes after the SPT was turned off from the LVDT voltage obtained from the ten-minute average, and multiplying by the appropriate thrust stand calibration factor. Efficiency and specific impulse were calculated using the values for thrust, mass flow rate, and engine power, averaged for the last 10 minutes of the cycle.

Large variations in thruster parameters such as floating voltage and thrust occurred in the first 900 hours of thruster operation, In most of the cycles the variations were induced by applying supplementary current to the magnet coils to investigate thruster performance- and oscillations in the discharge current and voltage. Most of the variations in thruster performance evident in other cycles are related directly to the fact that when the thruster is shut off for more than a few hours and then restarted, for a few cycles following the start discharge current and thrust increase, and current/voltage oscillations decrease. This behavior has been observed repeatedly, including those times when the tank pressure did not exceed 10-5 Pa.

Discharge Voltage

The decrease in discharge voltage between run hours 1S0-900 was due to failures of one of the PCU discharge supply modules; without all modules functioning the engine discharge loaded down the PCU and the output voltage dropped. All modules became functional after run hour 1400, Due to noise in the DAC voltage measurements after run hour *2000* were obtained from voltmeters.

Mass Flow Rate and Discharge Current

Mass flow increased 3% and discharge current decreased 1% between run hour 8-4,000. The thermal mass flow meter calibration drifted approximately 1% between run hour O-1 ,740; in the data presented in Figs. 6-9, the mass flow indicated by the flow meter was adjusted with the assumption that the drift rate was uniform between run hour 0-1,740, Variations in discharge current are due in part to shifts in PCU telemetry output,

Thrust Measurements

Thrust measurements are obtained from an inverted-pendulum thrust stand, In-situ calibrations were performed periodically to obtain the thrust stand calibrations shown in Fig. 10. In Fig. 11 the voltage difference of the LVDT is plotted as a function of time for the three masses used for the calibrations. To increase repeatability of the thrust measurements the thrust stand platform which supports the SPT-100 was wiggled for five or ten seconds during calibrations and at the start and end of each cycle Typically, calibrations are better than one percent. LVDT drift in the thruster off-phase was studied; for all thrust measurements 30 mV was subtracted from the LVDT voltage difference between the on and off phases to account for LVDT drift, Thrust stand tilt values for the on and off phases were also recorded; if the tilt varied between the on and off phases, a correction factor to the LVDT voltage difference was applied to account for changes in LVDT voltage due to differences in thrust stand inclination.

Until approximately run hour 2,600 the LVDT voltage difference exhibited a predictable change over time (Fig. 10); On January 17, 1994, about 10 minutes after cycle 2,674 (run hour 2122, 14) ended, a magnitude 6,9 earthquake struck Los Angeles. As a result of the severe shaking the LVDT off-phase voltage 13%; in addition, it was no longer possible to obtain thrust stand calibrations of the second of three weights; it is possible that the second mass slipped on the chain holding the weights and is in the wrong position for a calibration.

This scenario should not affect the calibrations of the other two masses. It will be noted here, however, that after the earthquake the LVDT voltage difference over time reversed its direction and began to increase in magnitude (Fig. 11). Severe shaking from the earthquake may have changed the spring constant of the thrust stand system. Calibrations have continued to have standard deviations of less than 1.25%.

Efficiency and Specific Impulse

Between run hours 1-1,000 thrust and efficiency decreased, then increased between run hour 1,0002,000. Since approximately run hour 2,500 thruster performance has not changed significantly, except between run hours 2,650-2,850, where thrust increased by approximately 3 mN; it is not understood how or why the thrust increase occurred, but analyses of the computer data indicate that the thrust for most of these cycles was greater than normal. These data are surprising; however, the general shape of the efficiency vs time curve shown in Fig. 9 matches well with the data obtained from a steady-state life test being performed in Russia[14] at the Design Bureau Fakel. Quantitatively, the thrust measured at JPL is approximately two mN greater than thrust measurements obtained at Fakel. Theoretical analyses of the thrust increase with time will be presented in Ref. 14.

Discharge Current Oscillations and Voltage Ripple

Oscillations in discharge current and voltage are shown in Figs. 12-15, The probes used to measure discharge current and voltage oscillations were positioned close to the vacuum tank feedthrough. There is approximately 6 m of cable length between the tank feedthrough and the thruster.

In Ref. 19 reduced current and voltage oscillation amplitudes were associated with improved thruster performance. Initially, discharge. current oscillation amplitudes were generally less than 2 A p-p, and voltage ripple less than 2.5 V p-p, By cycle 1,100 (run time 887 hrs) current oscillation amplitudes up to 10A p-p, and up to 15 V p-p ripple in the discharge voltage could be found. Oscillation amplitudes began to decrease at approximately cycle 2,500 (2,043 hrs run time); on cycle 5,000 current oscillation amplitudes were 6 A p-p maximum and 7 volts p-p for the discharge voltage.

Insulator Erosion

Erosion of the discharge chamber insulator surfaces was documented photographically and is plotted in Fig, 16 as a function of run time. The photographs indicate that by app. run hour 1,200 the edge of the outer insulator was eroded completely away; by run hour 2,600 the downstream face of the SPT-100 was being eroded by ion bombardment because the outer insulator was worn flush with the thruster surface. The inner insulator has been reduced in thickness to

17% of the original thickness. Preliminary results indicate an erosion rate that is approximately the same as reported in Ref. 24, except for data obtained at JPL on the inner insulator at run hour 4,000. Thruster performance continues to be very acceptable despite the extreme wear of the insulators and the downstream face of the thruster.

Wear characteristics of the SPT-100 arc shown in Figs. 17-22, The dark material on certain locations of the SPT-100 may be uneroded deposits of graphite sputtered from the graphite beam target. The unused cathode (bottom cathode) has eroded considerably. The orifice of the functioning cathode has increased in diameter and is evolving into an ellipsoid with one end, the side facing away from the SPT- 100, eroding the most.

CONCLUSIONS

An endurance test of an SPT-1OO is scheduled for 6,000 on/off cycles and 5,000 hours of operation at an input power of 1.35 kW. The endurance test was initiated July 1, 1993 and has accumulated 4,165 hours of operation and 5,000 on/off cycles as of this writing. The nominal cycle duration is 50 minutes on and 23 minutes off, including nearly **three minutes of cathode preheat** time. Thruster efficiency decreased, from 49% to 44% as the thruster aged; thruster efficiency increased and has remained relatively constant after approximately 2,000 hours of operating time.

Variations in thruster performance from cycle to cycle appear related primarily to the whether or not the thruster was not operated for any significant time; this phenomena appears unrelated to tank pressure during the off-phase. The insulators forming [he discharge chamber have been heavily eroded, as has the downstream face of the insulator. Current and voltage oscillations increased, then decreased 6 A p-p maximum at cycle 5,000.

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Fig. 1. New SPT-1OO as tested.

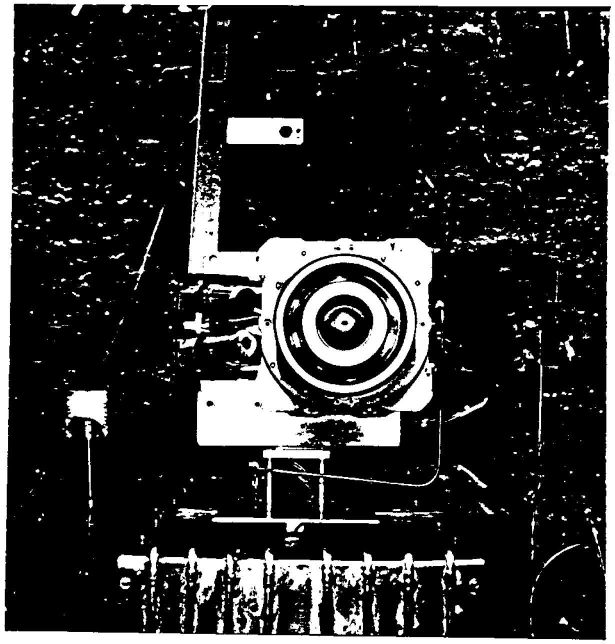

Fig. 2. SPT-1OO installed on water-cooled thrust stand.

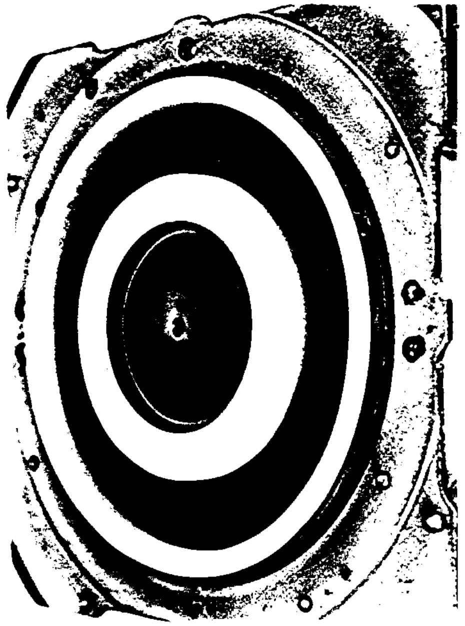

Fig. 3. New SPT-100 form off-axis view.

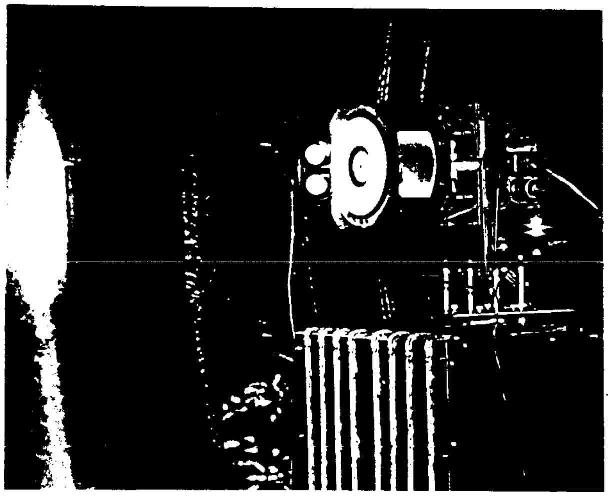

Fig. 4. SPT-100 in operating in the JPL life test facility.

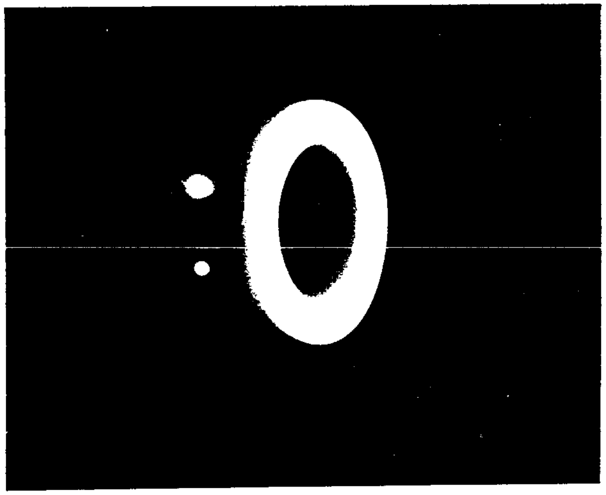

Fig. 5. Unused (bottom) cathode glow.

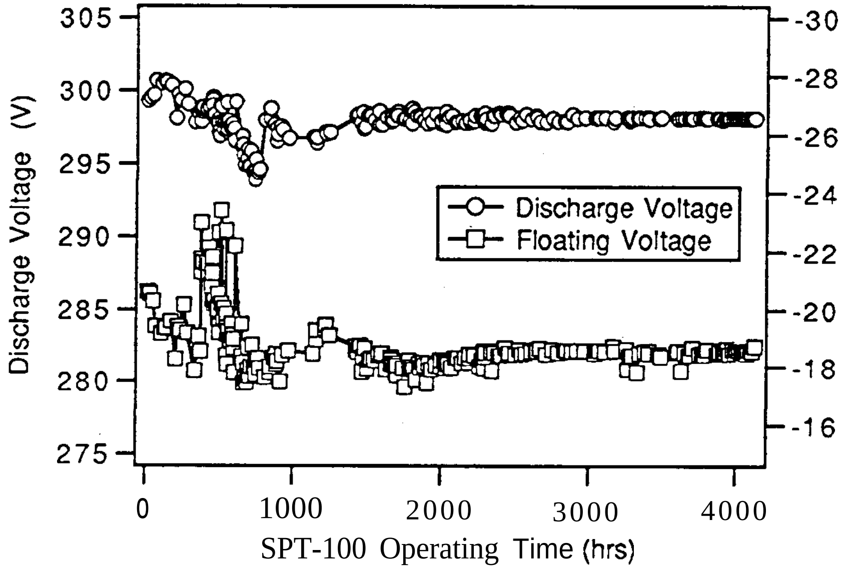

Fig. 6. Discharge and floating voltage for the SPT-100 cyclic endurance test.

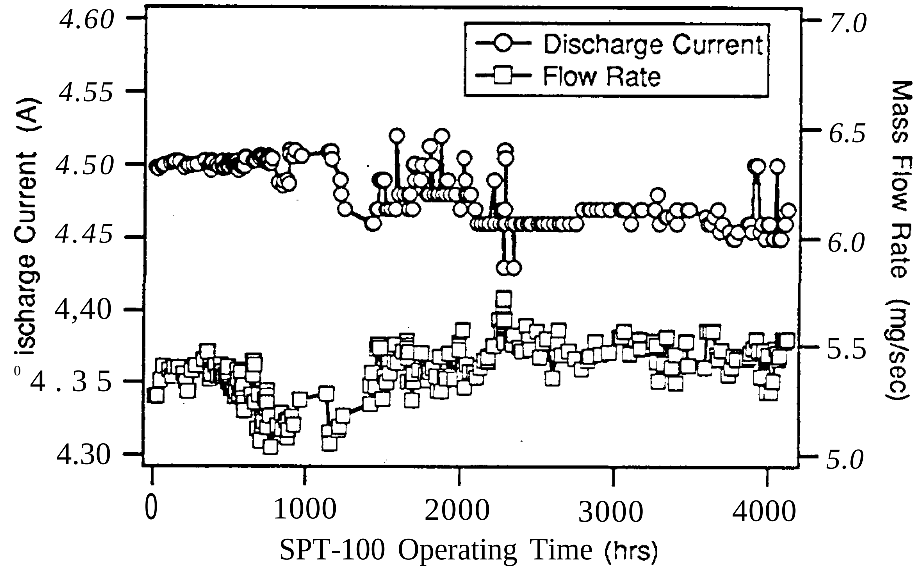

Fig. 7. Discharge current and mass flow rate for the SPT-100 cyclic

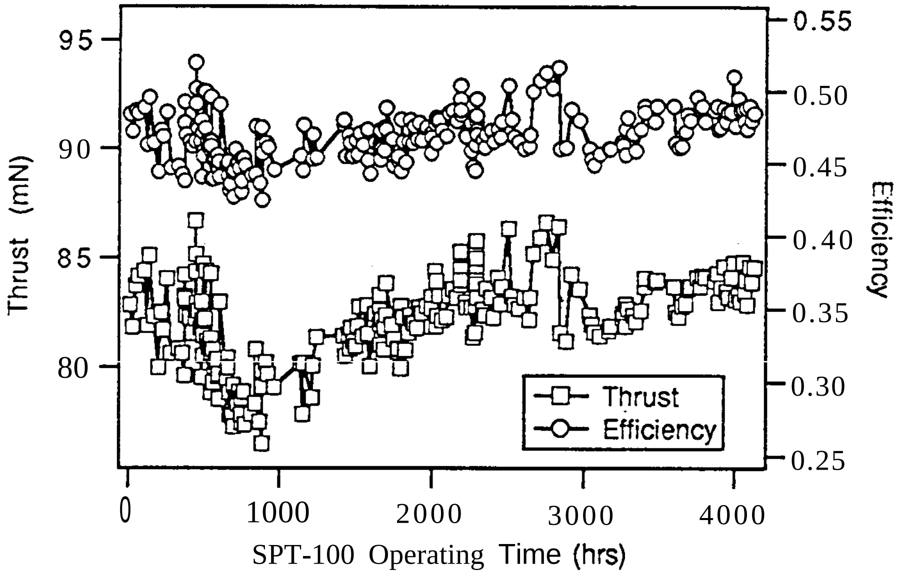

Fig. 8. Thrust and efficiency for the SPT-100 cyclic endurance test.

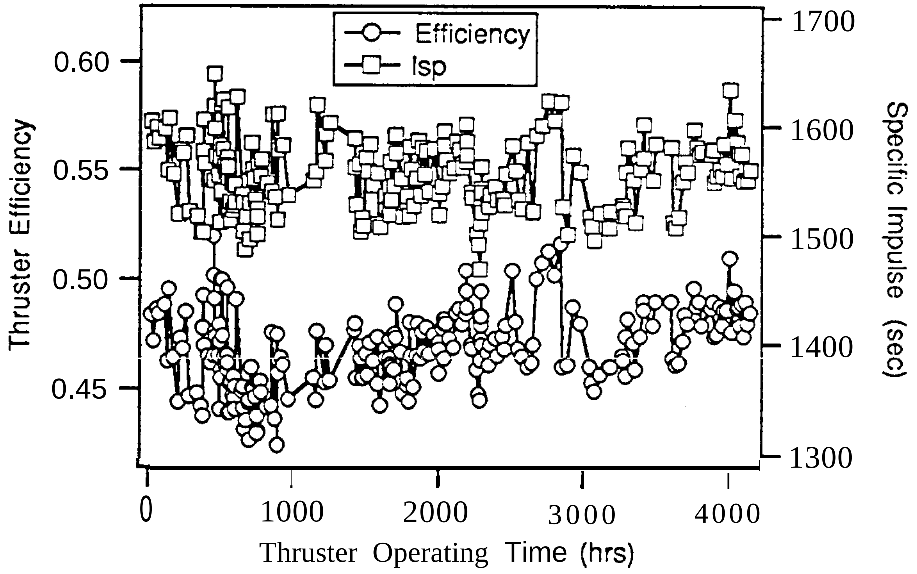

Fig. 9. Efficiency and Isp for the SPT-100 cyclic endurance test.

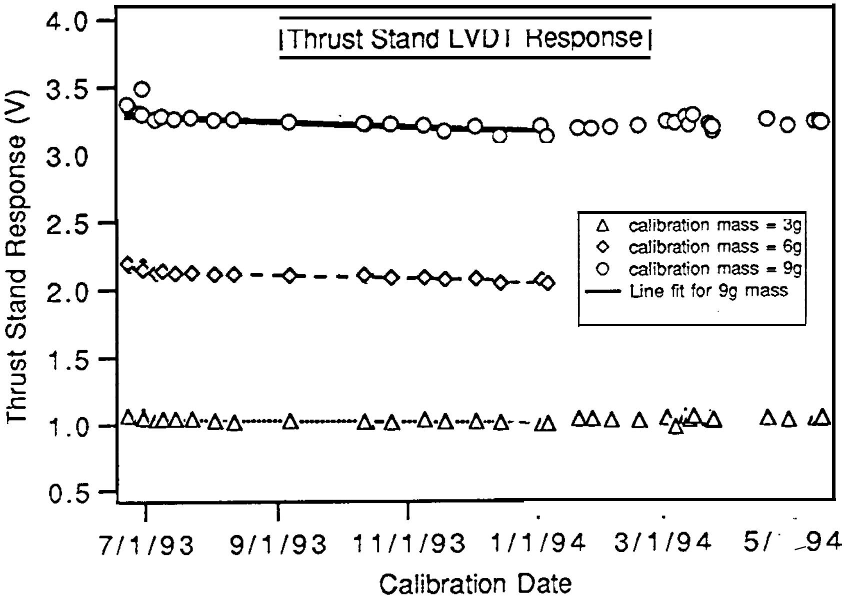

Fig. 10. Thrust stand response vs time.

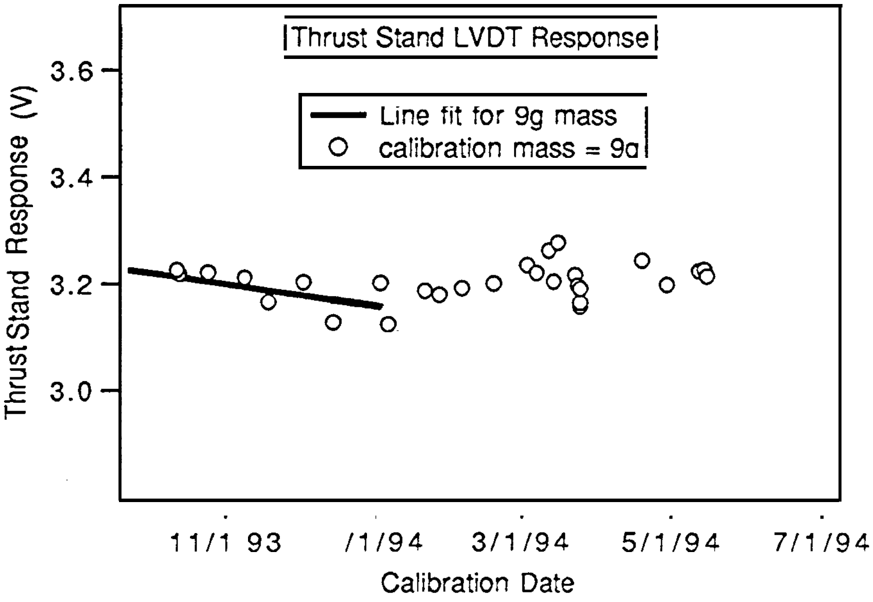

Fig. 11. Thrust stand response before and after the earthquake

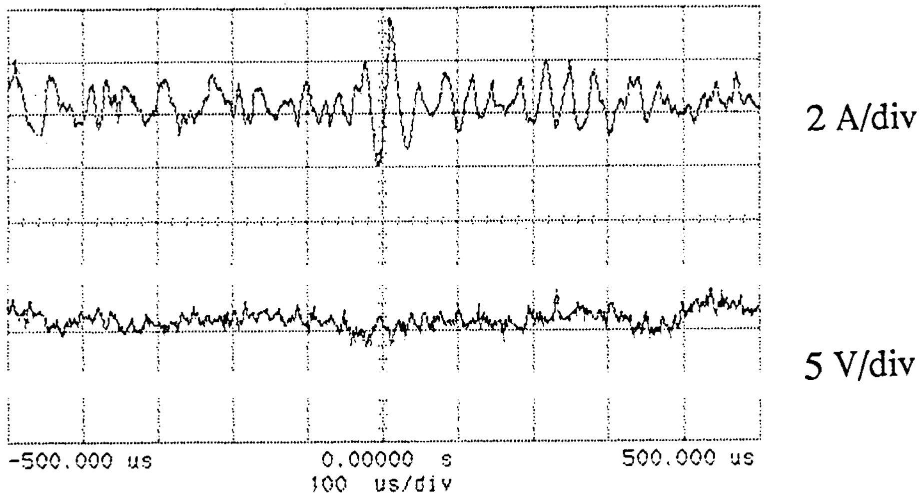

Fig. 12. Current and voltage oscillations for cycle 78.

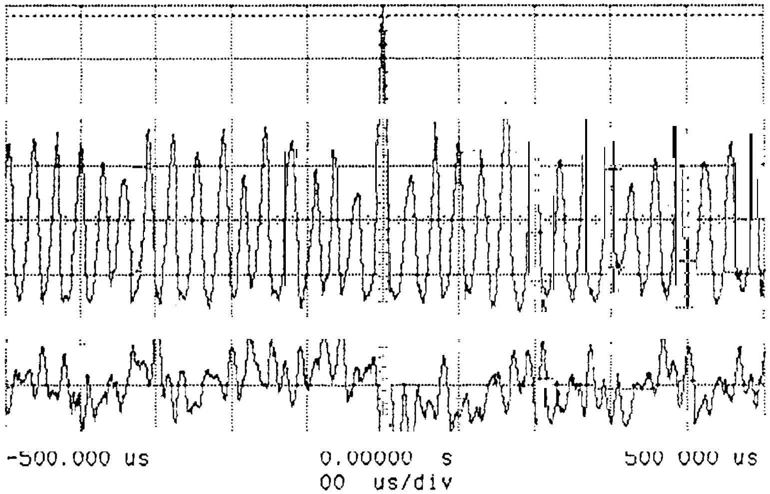

Fig. 13. Current and voltage oscillations for cycle 1100.

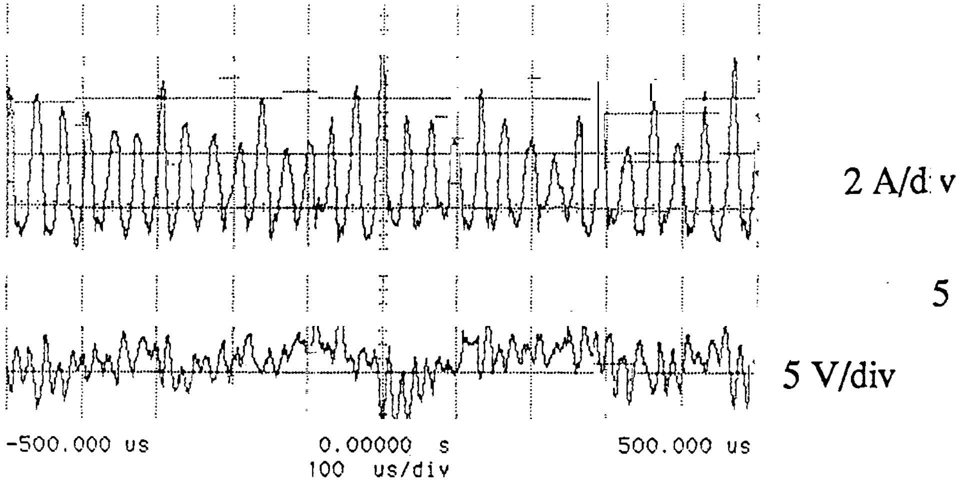

Fig. 14. Current and voltage oscillations for cycle 2527.

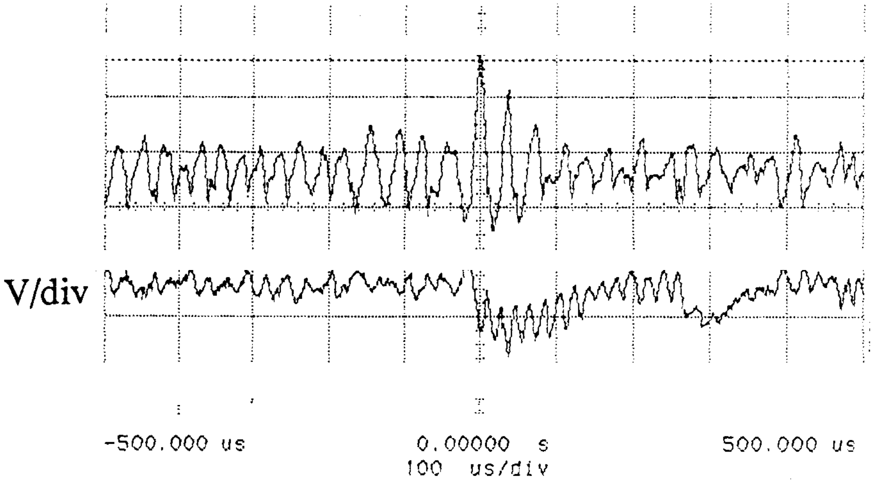

Fig. 15. Current and voltage oscillations for cycle 5000.

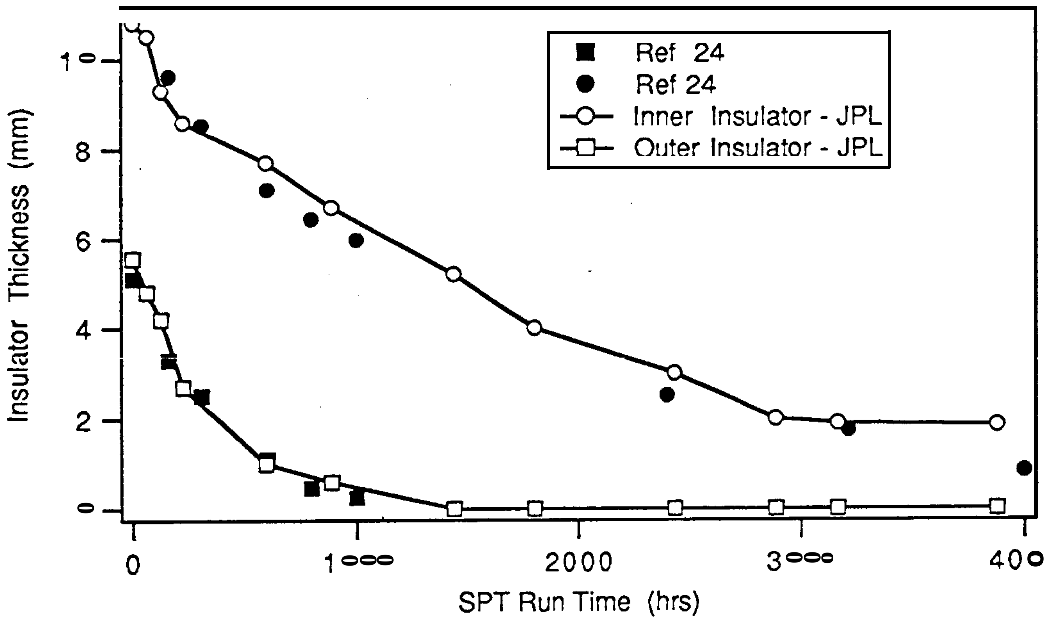

Fig. 16. Insulator erosion as a function of SPT-100 operating time.

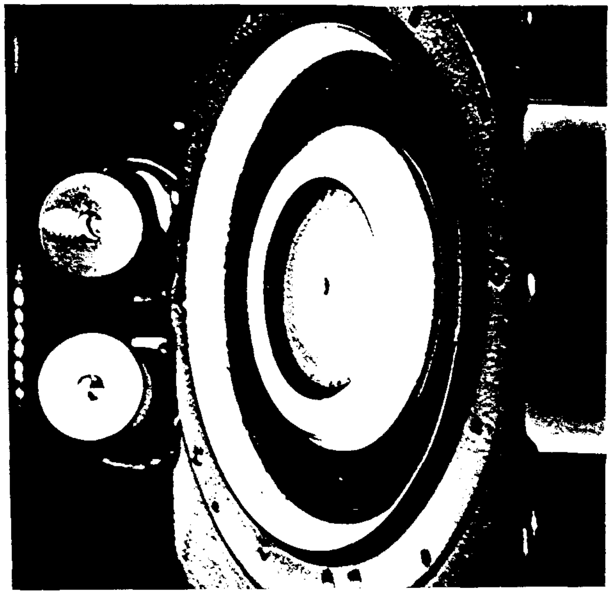

Fig. 17. SPT-1OO after 1100 cycles and 887 hours of operating time at 1.35 kW.

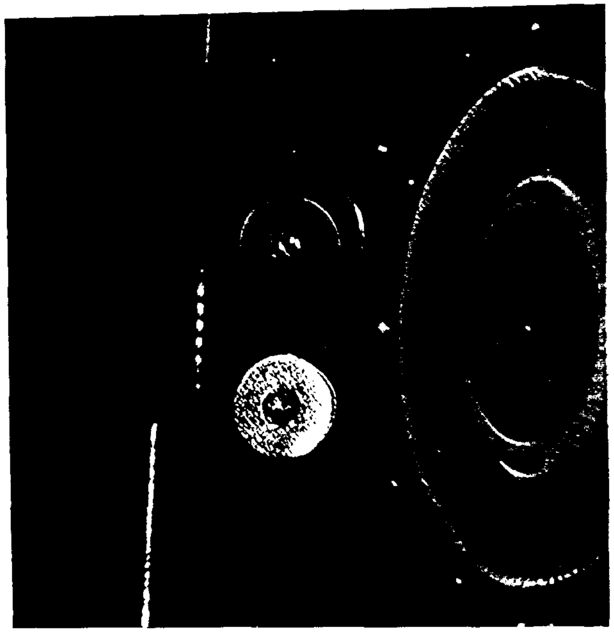

Fig. 18. SPT.-1OO after 2200 cycles and 1795 hours of operating time at 1.35 kW.

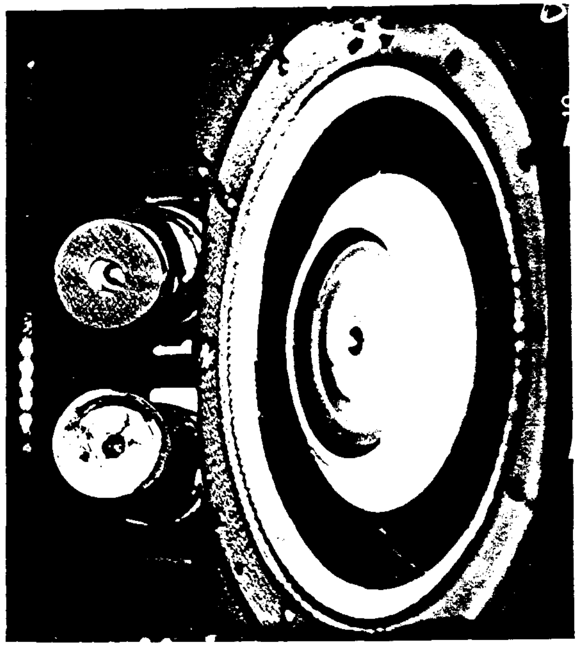

Fig. 19. SPT-1OO after 3816 cycles and 3169 of operating time at 1.35 kW.

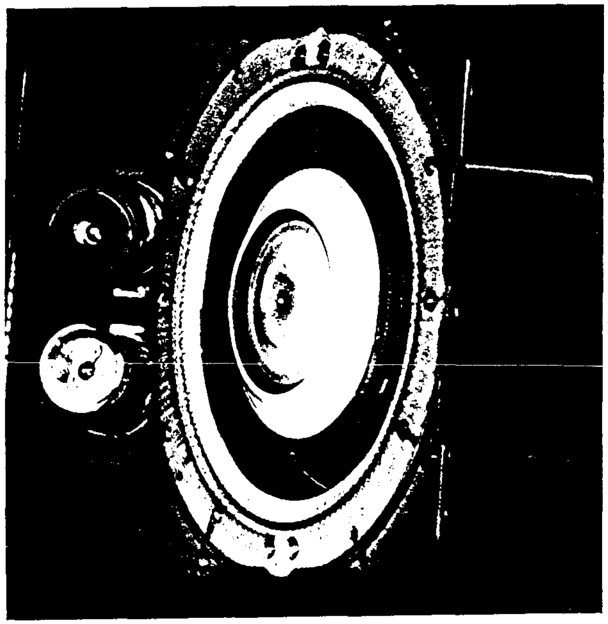

Fig. 20. SPT-1OO after 3816 cycles and 3169 hours of operating time at 1.35 kW.

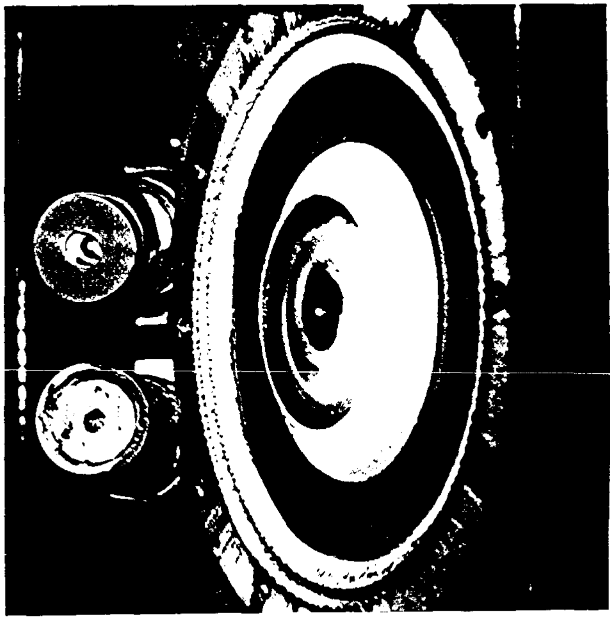

Fig. 21. SPT-1OO after 4701 cycles and 3879 hours of operating time at 1.35 kW.

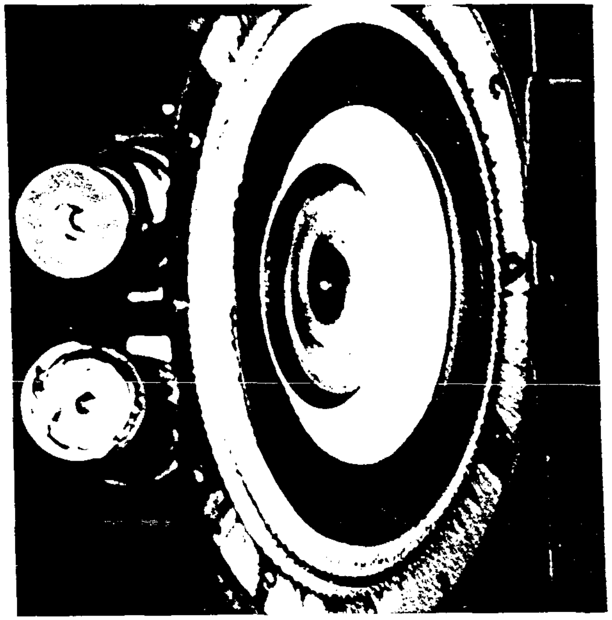

Fig. 22. SPT-100 after 4710 cycles and 387 of operating time at 1.35 kW.