AIAA. 151447

CSA

AIAA-94-3010

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30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference
June 27-29, 1994 / Indianapolis, IN

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Performance and endurance testing of ti **1.35 kW** thruster with anode layer **(TAL)** developed at the Central Research Institute of Machine Building (TsNIIMASH) *is* described. The **TAL** evaluated herein Is designated the **D-$5** and **is** characterized by an external acceleration zone to maximize engine life. Performance measurements indicate that the D-55 performance is comparable **to** that of **the SPT-100** for operation at **1.35 kW.** A 636 hour accelerated wear **test** was performed to **assess the** thruster service life capability. For this test the TsNIIMASH cathode **was** replaced by a cathode fabricated at JPL to eliminate concerns over cathode durability since the primary objective was to evaluate the discharge chamber erosion characteristics. Post **test examination** indicated **that the** volume **of** material removed over the course of **the wear** test was approximately an order of magnitude less than for the SPT-100 over **the same** operating duration. Most **of** the **engine** erosion takes place on guard **rings which protect** the **magnetic circuit** pole **pieces** from erosion. Changing this ring material from stainless steel **to a** more sputter-resistant material, such **as** graphite, will further reduce the erosion rate and yield engine life times estimated to be greater than **5,000** hours.

Introduction

Hall thrusters have generated a great deal of interest world-wide since the introduction of the Russian stationary plasma thruster, SPT-100, to the West **at** the beginning of this **decade.** Performance evaluations [1,2] and **on-going** endurance tests [3,4] continue to support claims that the SPT-100 thruster is a robust device with excellent operating characteristics. A different type **of** Hall thruster, the thruster with anode layer (TAL), also developed **in**

Russia, has performance characteristics which are comparable **to** those of the stationary plasma thruster [5]. **For** the **same** power level, however, the TAL discharge chamber is physically smaller than that **of** the **SPT.** The **D-55 TAL,** for example, has a nominal operating power level of **1.35** kW and a characteristic discharge chamber diameter **of** only **75 mm** or approximately **3/4** of the characteristic dimension of the 100 mm diameter 1.35-kW, SPT-100. Never-the-less, **in** spite of **the** increased thrust density corresponding *to* its small physical size, there is reason to believe that the TAL with "external layer" **may** have erosion characteristics superior **to** *the* **SPT.**

For this **reason the** Ballistic Missile Defense Organization **(BMDO)**has sponsored **a** program to evaluate the performance, erosion characteristics and integration issues associated with the anode layer

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thruster [6]. The program is being executed primarily by **NASA** Lewis Research Center (LeRC) **and** the Jet Propulsion Laboratory (JPL) in cooperation with the Central Research Institute for Machine Building **(TsNIIMASH)** in Kaliningrad (Moscow region), Russia. Performance testing and evaluation **of** integration **issues** are **being performed** at LeRC [7], while performance and endurance testing is being done at **JPL. Two** types of anode layer thrusters were purchased from TsNIIMASH, the 1.35 kW **D-55 and** the 4.5 kW D-100. This paper describes the performance and endurance testing of the **D-55** TAL at JPL.

Historical Background

The physical principle of the thruster with anode layer was first proposed by A. V Zharinov more than 30 years ago [8,9,10]. Work **at TsNIIMASH** in the early 1960s under his guidance emphasized understanding the fundamental physics of anode layer thruster operation. Members of Zharinov's team included Bvgeny Lyapin, V. **S.** Erofeev, M. A. Abdukhanov, and Yu. **S.** Popov. The **TAL** research at **TsNIIMASH** was part **of** a larger program to investigate a wide variety of plasma accelerators under the supervision of S. D. Grishin.

Early development of the anode layer thruster concentrated on the double-stage thruster **[11,12]** The first stage in this thruster is a low voltage discharge with closed Hall current **used** for ion generation. In the second stage of the engine the ions **are** accelerated **by** the electric field of the anode layer produced in the transverse magnetic field. Such engines were designed for application to Solar System exploration spacecraft and have specific impulses **ranging** from 2,000 to 8,000 s.

By the end of the 1960s a double-stage **TAL** using bismuth as the propellant had been operated at up to 100 kW with a specific impulse of 8,000 s and a total efficiency of close to 0.8 [12,13]. Wear tests of a few hundred to a thousand hours indicated an engine lifetime of a few thousand hours [14]. Cesium **and** xenon propellant were also investigated.

By the 1970s, thruster development had outpaced the availability of high power levels in space and the program **was** redirected to emphasize the development of low **(~1** kW) and medium (~10 kW) power level thrusters operating on rare gases (especially xenon). Research efforts centered on the development of a single-stage anode layer thruster [15,16], and also on understanding the thruster dynamic characteristics [17,18,19] and service life capabilities [16,20]. The product of this effort was

the high efficiency, single-stage anode layer thruster [20,21].

To achieve long thruster lifetimes, one of the principal innovations was the development of the TAL with external layer in which the ion production **and** ion acceleration **regions** actually exist just downstream of the exit plane of the thruster. This configuration greatly reduces the flux of energetic ions to thruster surfaces thereby significantly reducing the erosion of those surfaces.

Apparatus and Procedure

The single-stage, **D-55 TAL,** shown in Fig. 1, consists of an annular discharge chamber in which the anode electrode extends **nearly to** the exit plane of the thruster **as** suggested in **Fig. 2.** In **a** fashion similar to the SPT, **a** radial magnetic field is established across the annular discharge chamber through the **use** of electromagnets. The strength of the magnetic field is sufficient to magnetize the electrons but not the ions. **Tailoring** of the magnetic field is accomplished through **a** proprietary design which concentrates the magnetic **flux** density in the region of space just beyond the anode. This in **turn** establishes most of the anode to cathode voltage difference in this region, which is roughly half of the axial length of that in the SPT-100.

An external cathode is used to supply electrons to the discharge chamber, as well as neutralize the ion beam. During normal operation most of the applied voltage difference between the anode and the cathode appears in a relatively thin layer adjacent to the anode. In the modern version of the single-stage **TAL,** this layer exists just downstream of the exit plane of the thruster and the thruster is **referred** to as a TAL with external layer. **By** positioning the ionization and acceleration zone downstream of the discharge chamber walls, erosion of the thruster is minimized.

Surrounding the OD of the anode is a guard ring (see Fig. 2) designed to protect the steel magnetic circuit pole piece from ion sputtering. **A** similar guard **ring** is positioned inside the ID of the anode. The separation between the guard rings, which are **at** cathode potential, and the anode is approximately 0.97 **mm** for the outer ring and **1.14** mm for the inner one. A possible failure mechanism for the thruster is shorting of the anode to the guard ring by a flake of sputter deposited material. **In** the thruster **tested at** JPL the guard rings were fabricated from stainless steel. It is recognized that substitution of a more sputter-resistant material, such as graphite, would substantially increase the thruster life. The use of

stainless steel in the thruster for the endurance test results in an accelerated erosion test in that the erosion characteristics obtained over a relative short time with stainless steel should be representative of much longer operation with graphite.

The heaterless cathode consists of a LaB_6 emitter in a tantalum tube, A starter electrode positioned adjacent to the cathode is used only during startup. Little effort has been expended at TsNIIMASH in the development and optimization of hollow cathodes since this technology already exists at other Russian organizations (Fakel Design Bureau for example, makers of the SPT-100 hollow cathodes).

The D-55 laboratory model thruster also did not come with a flow splitter or flow control hardware, so independent control of the main and cathode flow rates was accomplished manually.

Test Facility

AH testing of the D-55 thruster was performed in a 2.4-m dia. x 5-m stainless steel vacuum chamber equipped with oil diffusion pumps, with an effective pumping speed on xenon of approximately 14,000 L/s. A radiation cooled, graphite beam target was positioned at the end of the vacuum chamber opposite the thruster. In addition, the side walls of the chamber were also lined in graphite to minimize the rate of material back-sputtered to the thruster.

A laboratory propellant feed system was assembled and carefully leaked checked. The micrometer valves controlling the main and cathode flow rates are positioned inside the vacuum chamber. The xenon feed pressure is dropped across the micrometer valves from 200 kPa (29 psig) to a few torr or less for the engine. Since the feed pressure is above atmospheric pressure, this arrangement guarantees that no air can ieak into the propellant feed system. Rotary vacuum feed throughs are used to adjust the micrometer valves from outside the vacuum chamber.

A schematic diagram of the power supply configuration is shown in Fig. 3, Laboratory power supplies are used for all functions. The main run supply is a 12-kW, custom Spellman high voltage supply. Laboratory power supplies were used for both the cathode tip heater and for the cathode starter. A data acquisition and control system using LabView software and National Instruments hardware was used to record the operating data and permit unattended operation.

Thruster performance was measured using a modified' version of the inverted pendulum type thrust stand developed at NASA LeRC [22] Thrust stand calibrations are performed in situ and under computer control. Generally 40 to 80 calibrations are performed autonomously in order to obtain a large enough sampling for statistical analyses. Repeatability of the calibrations were normally 0.6% or better. During thruster operation, the thrust stand inclination is corrected every 3 s by the computer. To get the most accurate thrust measurements it is necessary to shut off the thruster. The thrust is determined by the difference in thrust stand LVDT signals with the thruster on and off, This approach minimizes any effects due to long term thrust stand zero drifts. In the course of the wear test the thruster was shut off approximately once every 24 hours to get an accurate thrust measurement.

JPL Cathode

Engine performance was measured with two different cathodes, the LaB_6 cathode from TsNIIMASH and a cathode fabricated at JPL. The JPL cathode consists of a 6.4-mm diameter molybdenum tube with a barium oxide impregnated porous tungsten insert. A 2% thoriated tungsten orifice plate, with an orifice diameter of 1.3 mm is eiectron-beam welded to the downstream end. A tantalum-sheathed tantalum heater wire is wrapped around the molybdenum tube to form the tip heater. An "enclosed keeper" starter electrode made of graphite surrounds the cathode. The endurance test was performed with the JPL cathode.

Performance Results

Engine efficiency as a function of input power is given in Fig. 4 These data suggest an engine performance which is comparable to that of the SPT-100 thruster.

Endurance Test

To investigate the erosion characteristics and evaluate the prospects for achieving a useful service life of several thousand hours, a 500 hour wear test at 1.35 kW was planned. At the completion of 500 hours the engine was operating so well that it was decided to continue the test. A photograph of the D-55 taken during the wear test is shown in Fig. 5. The glowing regions evident in this photograph are believed to be sputter deposits on the anode. The extent of these glowing regions grew steadily over the duration of the wear test. The thruster performed reliability for most of the wear test. On two cycles, however, a high current transient

exceeding **20 A** occurred causing the discharge to extinguish and terminating the cycle.

The test was terminated after 636 hours of operation when the thrust stand tilt mechanism failed. Without the ability to accurately measure the thmst it **was** decided **to** terminate the **test and** examine the condition of the thruster. The post-test condition of the thruster is shown in Figs. 6 and 7. The erosion of discharge chamber components is difficult to see both in this photograph and on the actual hardware.

Performance History

The thrust, discharge voltage, discharge current, **mass** flow rate **and** floating voltage **are** given in Fig. 8 as a function of time over the wear test. The floating voltage is the potential difference between the cathode and facility ground. The engine/power supply combination is operated ungrounded as indicated in Fig. 3. The data in Fig. 8 indicate essentially no change in the engine performance over the wear test. The scatter in the data over the first 20 hours was due to changes in operating conditions as the thruster performance envelope was explored.

Discharge Oscillations

Oscillations in the discharge current and **voltage** were recorded **for** each cycle using a digital oscilloscope. The **data** in Figs. 9a,b&c were taken near the end of cycles 95 (run hour 25.9) and 126 (run hour 600). The discharge oscillations were measured in two different ways, and both are presented here. In the first way the "average" **mode** of the oscilloscope generates **a** trace by averaging 12 separate traces. In the second way, the "high resolution" mode was used to provide single-sweep traces. The high resolution mode results for cycle 126 are given in Fig. 9a and the corresponding average mode trace in Fig. 9c. The high resolution mode indicates slightly larger peak current oscillations (note the scale change between Figs. 9b&c).

The oscilloscope traces clearly indicate that there was no substantial change in current and voltage oscillations from the start **to** the end of the wear test **(as** seen by comparing Figs. 9a&b). Current oscillations approached 9 **A** peak-to-peak, a level similar to that measured with the **SPT-100** thruster, but voltage oscillations *are* almost **non-existent.**

Beam profiles were measured using a single Faraday button probe mounted to **a** motorized arm which could swing the probe through an arc 0.86 m in radius from the thruster. *The* Faraday probe surface was covered with plasma sprayed tungsten to minimize secondary electron emission effects. **A** comparison of beam profiles taken at cycles of 95 and 128 is given in Fig. 10. These data indicate essentially no change in the beam shape over the course of the wear test. Since essentially no significant erosion of the magnetic circuit pole pieces occurred during this test, the shape and strength of the magnetic field should not have changed, which is consistent with a constant beam current density profile,

Erosion Results

During the 636 hours that the thruster was run, a dark gray material was deposited on the anode. Material analysis by EDAX indicated that the primary elements of the deposits are the constituents of stainless steel, carbon, molybdenum and xenon. The carbon is most likely backsputtered material from the graphite beam target **and** the stainless steel is probably from the guard **rings.** The xenon is obviously trapped propellant and the molybdenum is from the anode and was found only on the side of the deposits adjacent to the anode surface. **The** deposits were greatest on the anode **and barely** noticeable on the other thruster components. The maximum thickness of the deposited material was 11 μm. The entire anode appeared to be covered by a layer of this material except for an area of about 242 mm^2 on the **back** wall of the anode located near the position of **the** cathode. In this region, the anode seemed to be covered with a thin oxide layer, giving the **material** a discolored appearance.

Erosion of the inner and outer guard rings **was** caused by **ion** sputtering, which resulted in modifying the shape of the ring **covers** (Figs. 11). The erosion depth in the direction parallel to the thruster axis of the outer **guard** ring is given in Fig. **12** as a function of clock angle (see Fig. 7 for the definition of zero degrees) for three different radial distances from the thruster axis. These erosion data appear to have a roughly sinusoidal shape with the minimum erosion depths occurring at the clock angles corresponding to the locations of the electromagnets, The maximum measured erosion depth on the outer **guard** ring was **1.25** mm (49.6 **mils).**

Similar erosion depth measurements for the inner guard ring are given in Fig. 13 also for three radial positions on the ring. The erosion depth typically vanes from zero to 0.25 mm, with a maximum measured depth of 0.75 mm (29.7 mils).

The total volume of material eroded from the inner and outer guard rings was estimated to be 0.3 cm^3. Using a density of stainless steel of 7.75 g/cm^3 results in a mass loss estimate of 2.5 g. If graphite had been used instead, the mass loss would have been approximately 1 g (assuming the same volume of material removed) and it would have taken nearly 4,000 hours to remove this material.

Conclusions

A thruster with anode layer (TAL) having an average discharge chamber diameter of 55 mm was tested on both a TsNIIMASH and U.S. hollow cathode. The performance of the D-55 anode layer thruster appears to be comparable to that of the SPT-100 thruster. A total of 636 hours of operation were accumulated on the D-55 before the test was terminated due to a failure of the thrust stand tilt control mechanism. No change in discharge current and voltage amplitudes, exhaust beam current density profile or engine performance was observed over this time. The components showing the most wear were the inner and outer ring magnet covers that serve to protect the electromagnets. The erosion data appear to have a roughly sinusoidal shape with the minimum erosion depths usually occurring at the clock angles corresponding to the locations of the electromagnets. Replacement of the stainless steel magnet covers used in the thruster tested with a more sputter resistant material should result in an engine with a useful service lifetime of greater than 5,000 hours.

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Anode Layer Thruster-55
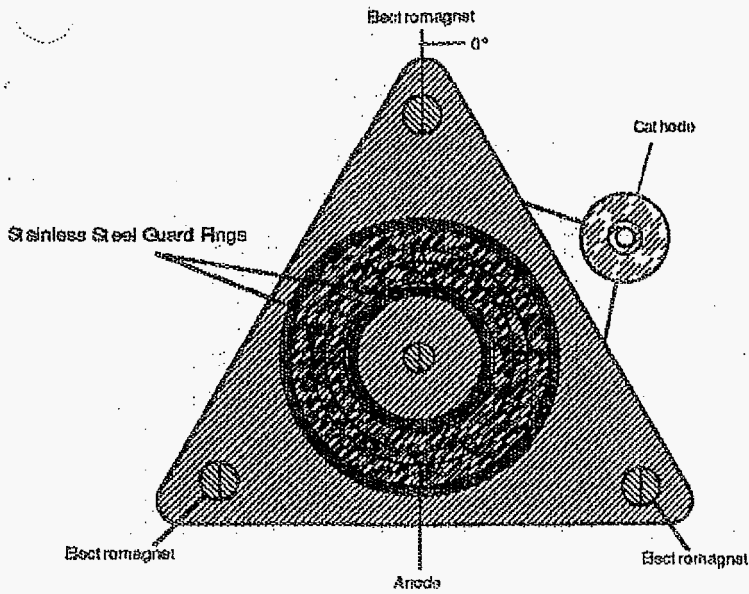
Fig. 1(a). Anode Layer Thruster schematic.
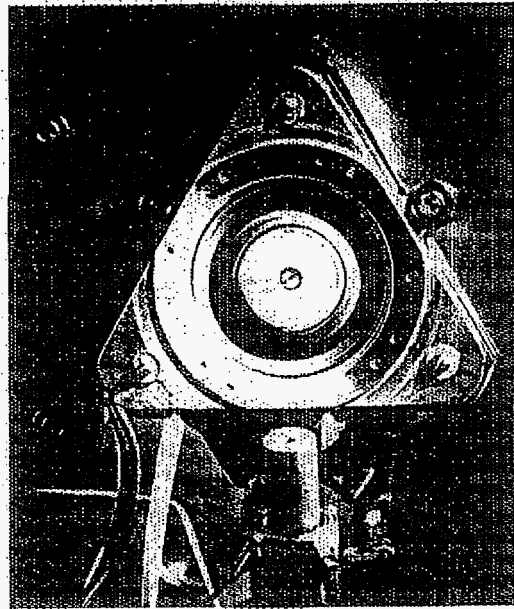
Fig. 1(b). Pre-test photograph with the JPL cathode.
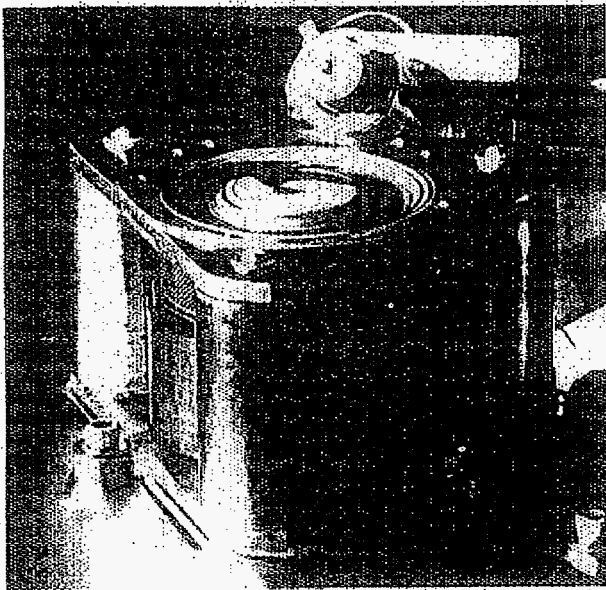
Fig. 1(c). Pre-test photograph with the JPL cathode.

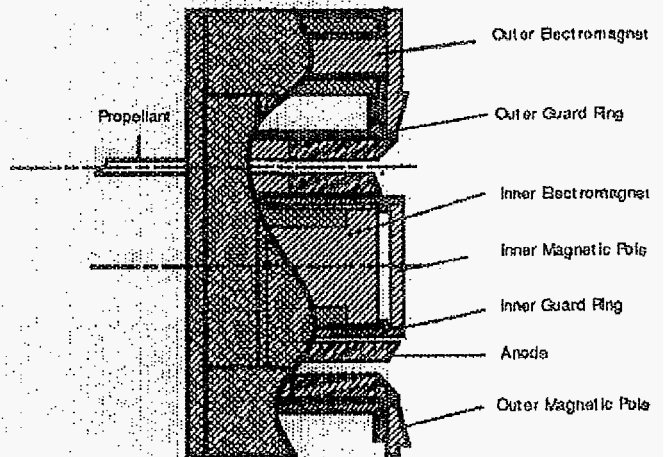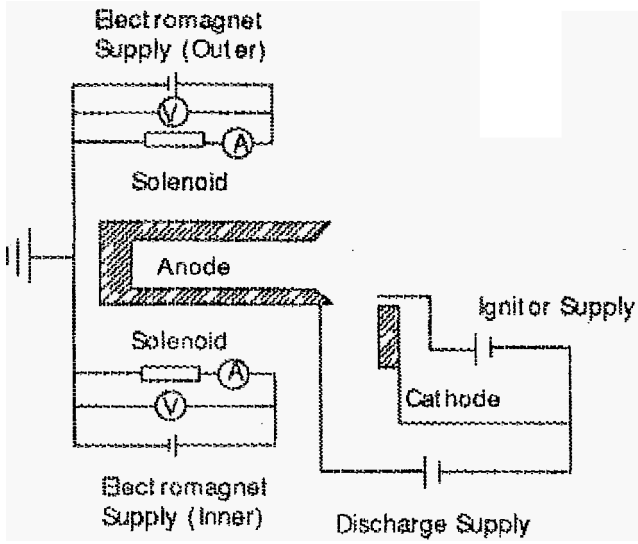

Fig. 2 Cross-section schematic of the D-55.

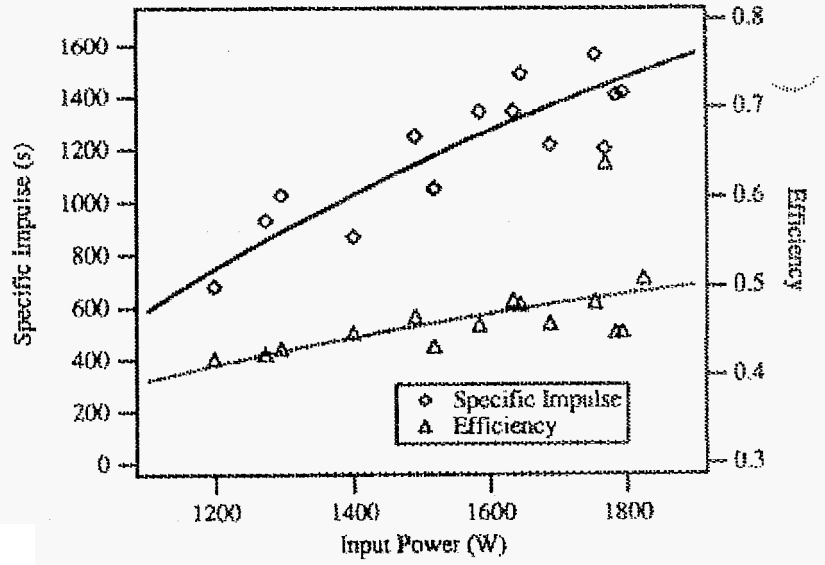Fig. 3 Power supply system schematic

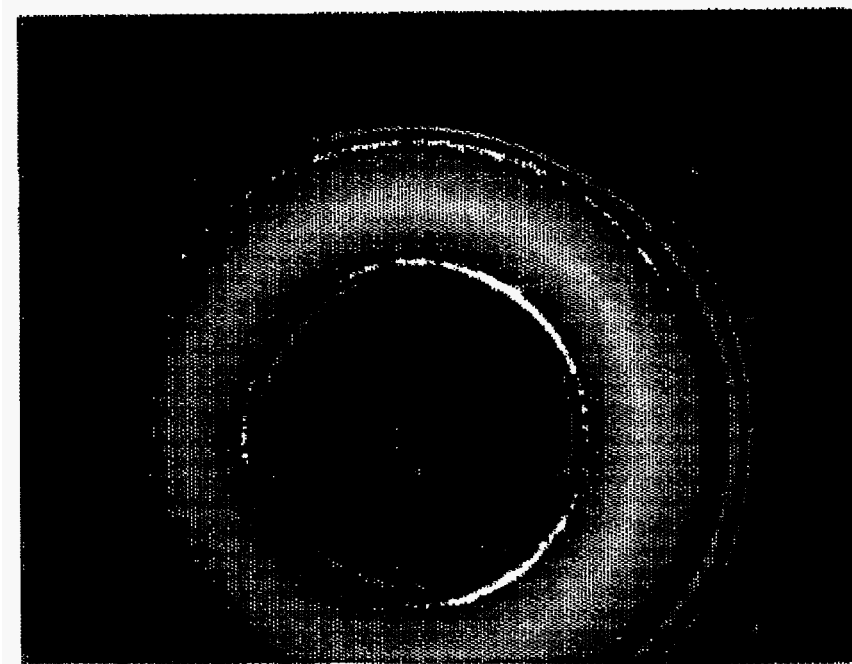Fig. 4 Specifc impulse and engine efficiency vs. input power (with JPL cathode).
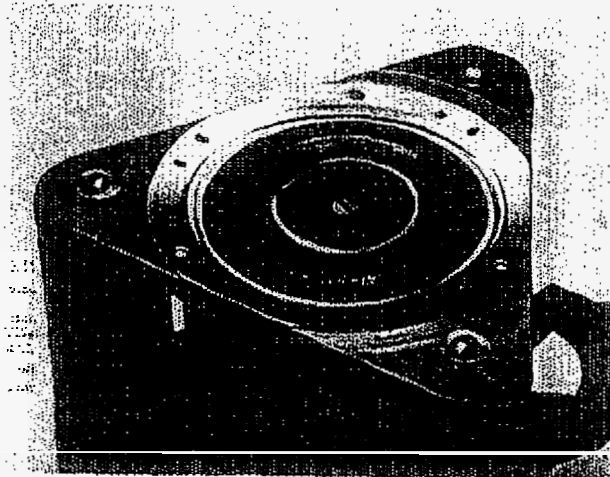

Fig, 5 The D-55 in operation.

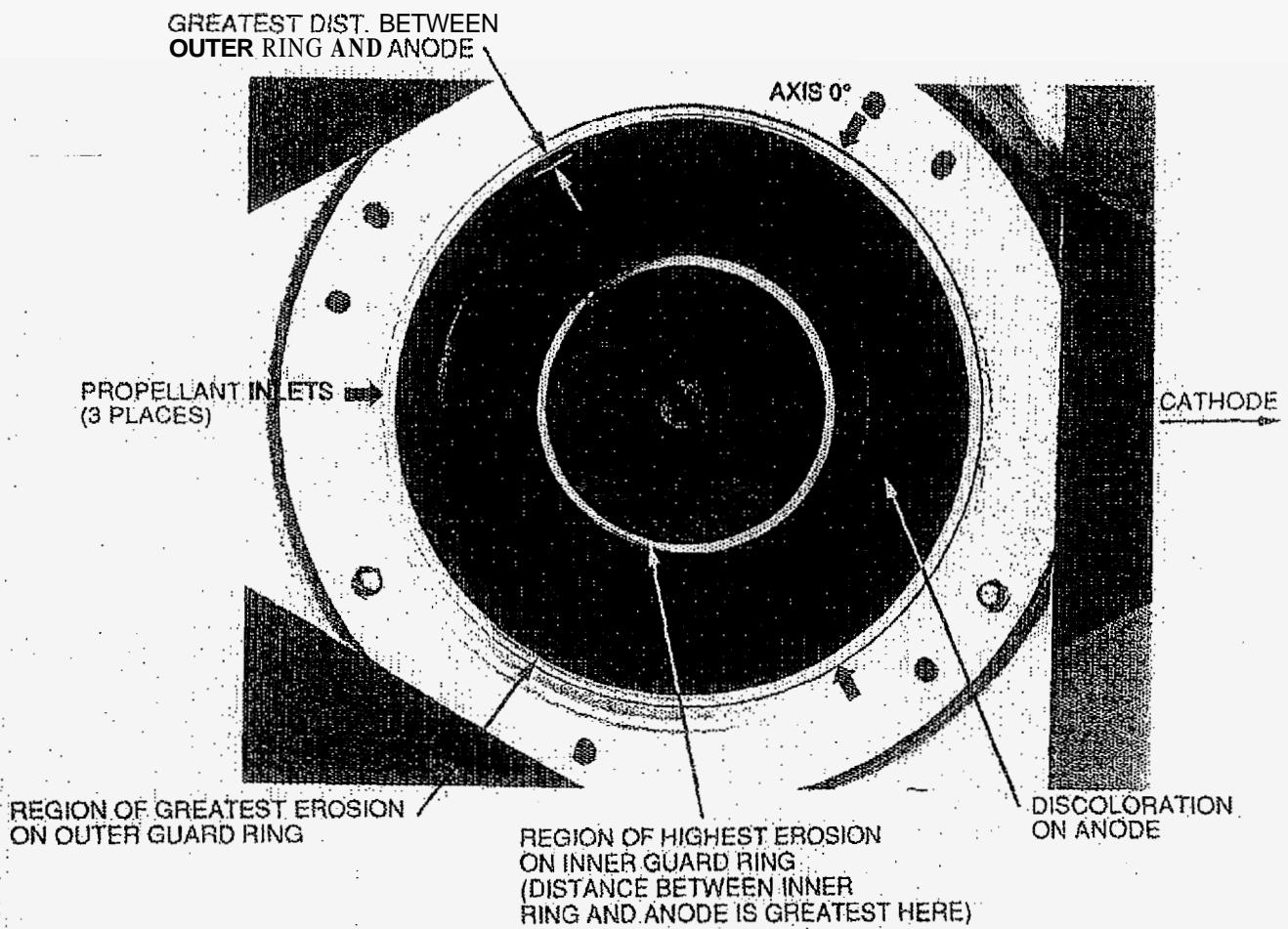Fig. 6 Post wear test condition of the D-55 discharge chamber.

GREATEST DIST. BETWEEN
OUTER RING AND ANODE

AXIS 0°

PROPELLANT INLETS
(3 PLACES)

CATHODE

REGION OF GREATEST EROSION
ON OUTER GUARD RING

REGION OF HIGHEST EROSION
ON INNER GUARD RING
(DISTANCE BETWEEN INNER
RING AND ANODE IS GREATEST HERE)

DISCOLORATION
ON ANODE

Fig. 7 Details of the D-55 erosion geometry.

9
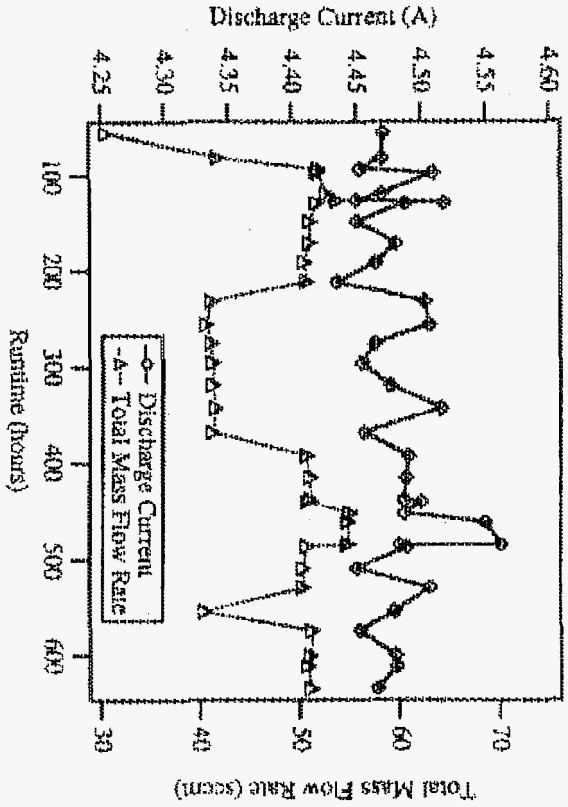
Fig. 8(a). Discharge current and mass flow rate for wear test cycles 94-128.
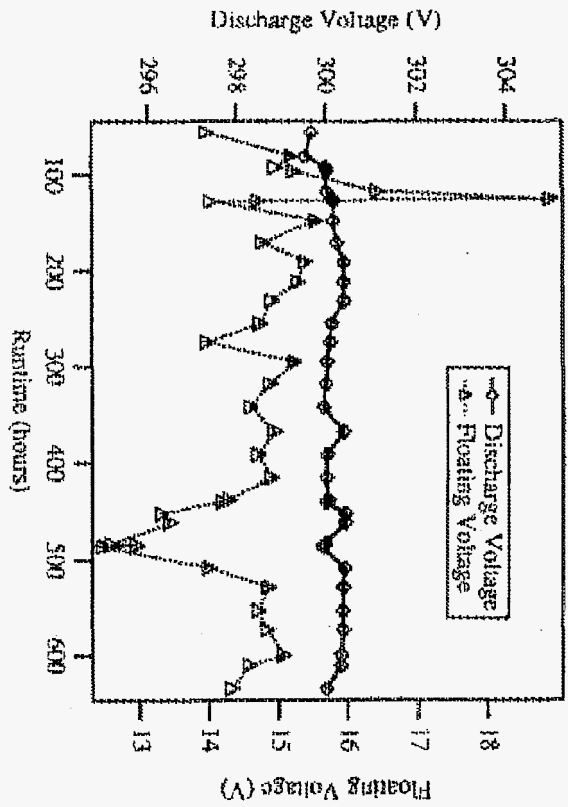
Fig. 8(b). Discharge voltage and floating voltage for wear test cycles 94-128.
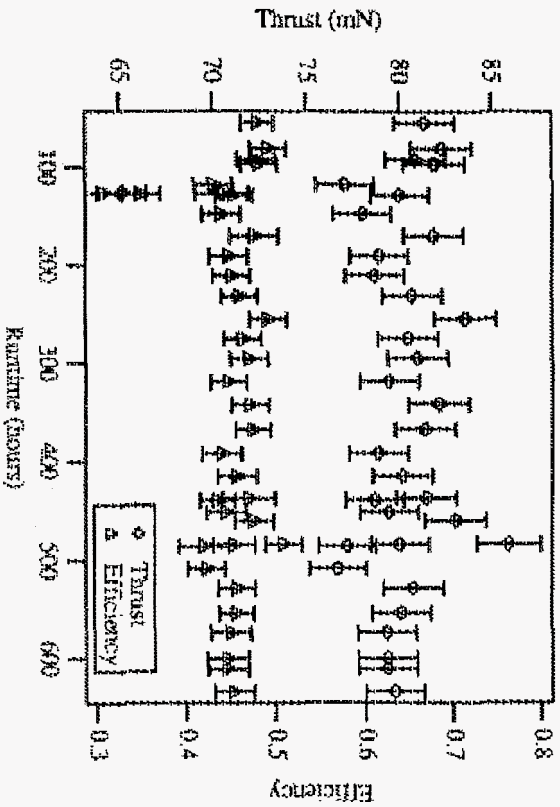
Fig. 8(c). Thrust and engine efficiency for wear test cycles 94-128.
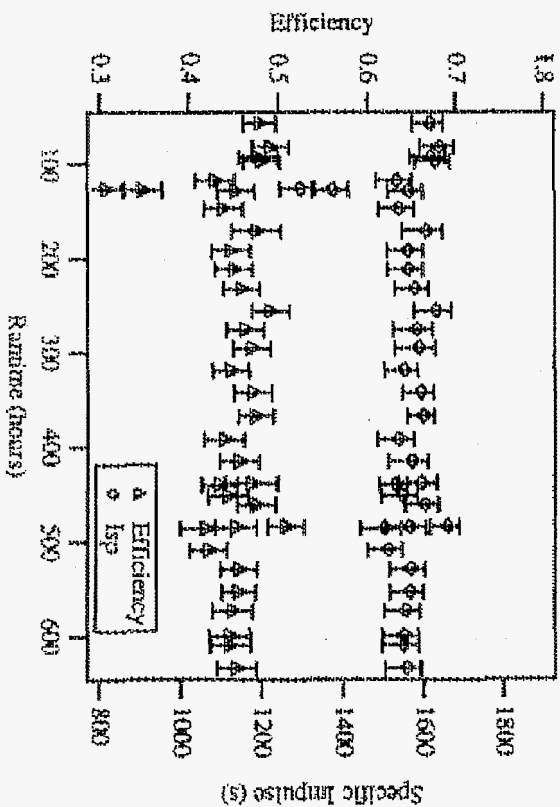
Fig. 8(d). Engine Efficiency and specific impulse for wear test cycles 94-128.
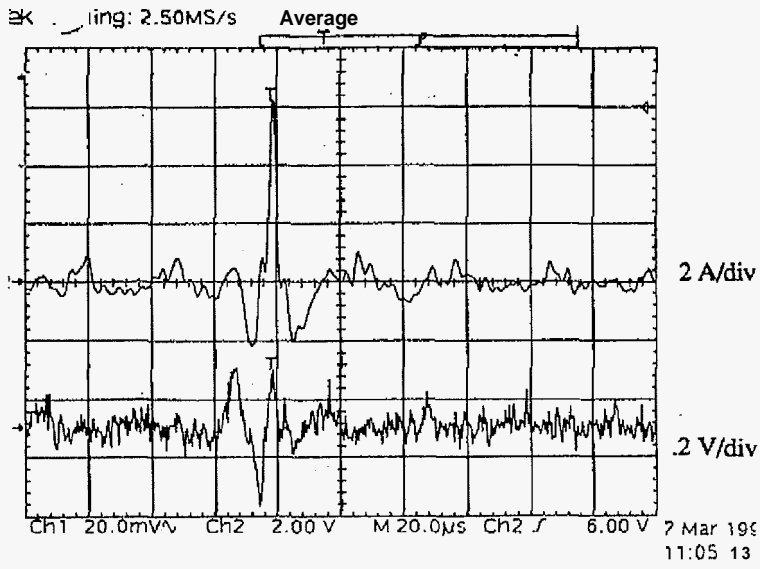
Fig. 9(a). Oscilloscope trace from cycle **95**

taken **just** before engine shutdown.
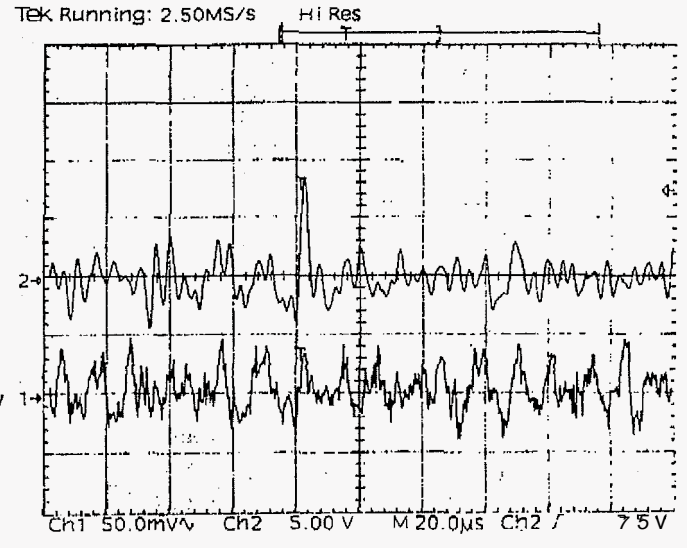
Fig. 9(b). Oscilloscope trace **from cycle** 126

taken just before engine **shutdown.**
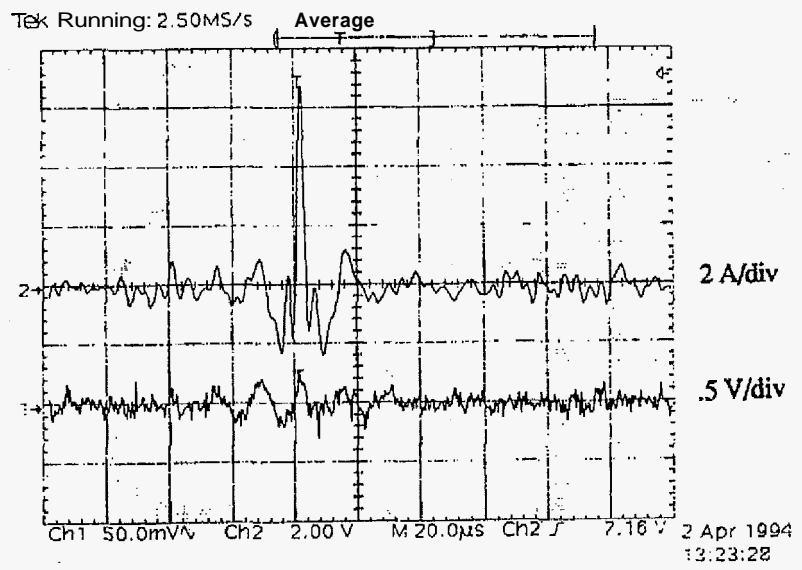
Fig. 9(c). Oscilloscope trace **from cycle** 126
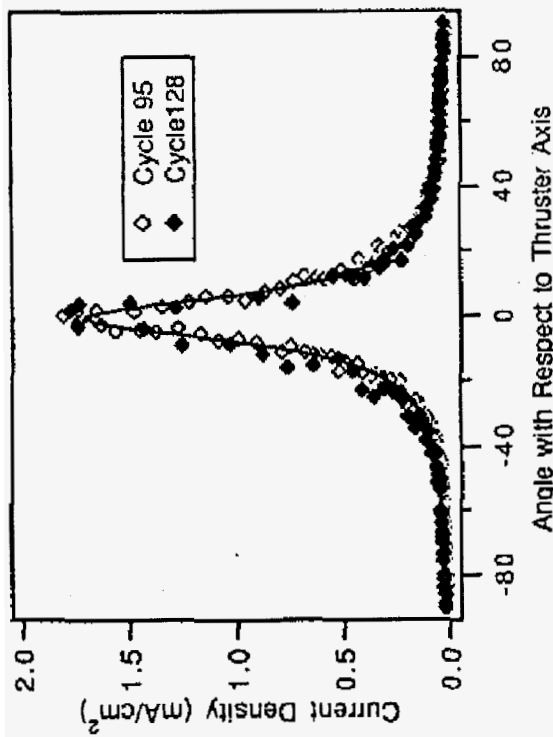**taken just** before **engine shutdown.**

11

Fig. 10 Comparison of exhaust beam current density profile 1-m downstream of the thruster after 81 and 634 hours of operation
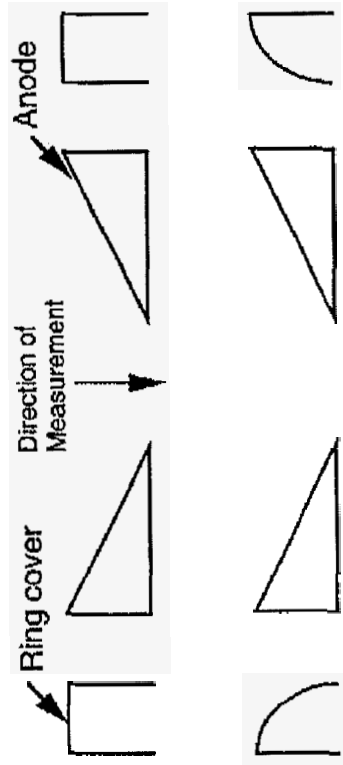

Fig. 11. Schematic diagram of the ring covers before (top) and after (bottom) the 636-hr wear test.
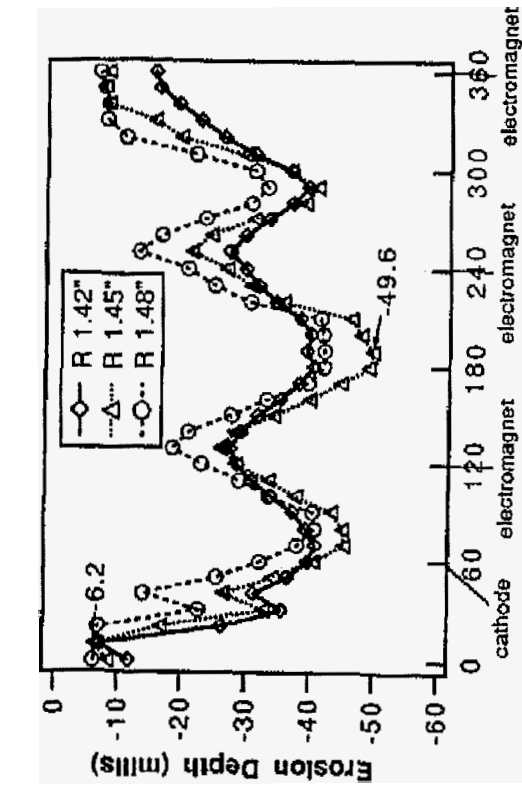

Fig. 12. Erosion depth measurements on the outer guard ring as a function of clock angle and radial distance.
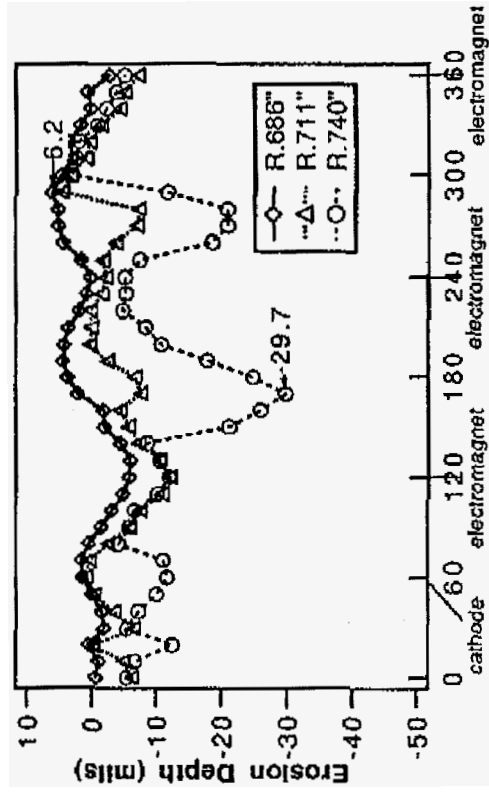

Fig. 13. Erosion depth measurements on the inner guard ring as a function of clock angle and radial distance.