

Analysis of Anode Layer Thruster Guard Ring Erosion

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Abstract

The lifetime of the Thruster with Anode Layer (TAL) is limited by the erosion rate of the guard rings that shield the electromagnet pole pieces from ion impingement. In recent investigations performed after several hundred hours of operation, non-uniform erosion patterns have been documented [1,2]. The investigation performed at the Jet Propulsion Laboratory (JPL) showed that the guard rings eroded at higher rates between the positions where both the electromagnets and main propellant inlets are located. Propellant injection uniformity was assessed by measuring the stagnation pressure every 0.5° in the center of the discharge chamber using an impact pressure probe that was located 6.35 mm downstream of the propellant inlets. The results indicate that there was no correlation between propellant distribution and the guard ring erosion pattern. A survey of the thruster magnetic field topology using Hall probes showed that the erosion rates were higher in regions of relatively low magnetic field strength. The mechanism which may be responsible for these observed trends is ion generation near the guard rings where the local electron densities are higher than at the electromagnet positions.

Introduction

Recent interest in Russian Anode Layer Thrusters has grown because they have demonstrated comparable performance to Stationary Plasma Thrusters (SPT) at the same power levels with a smaller size and lower erosion rates. The 1.35 kW TAL has a discharge chamber that is 3/4 the size of the SPT and generates the same amount of thrust. A recent study[2] has shown that the erosion rates of the life-limiting components of the TAL are lower than the SPT. Erosion evaluations have resulted in predicted lifetimes in the range of 5000-10000 hours[3] for TAL's.

Anode Layer Thrusters operate on the same physical principals as the other types of Hall thrusters. They generate an axial electric field between the anode and external cathode and a radial magnetic fields between the inner and outer

electromagnet poles. Because of the crossing electric and magnetic field, the electrons are trapped in the magnetic field and spiral azimuthally towards the anode. In the high density electron region, the configuration of the electric field is governed by the configuration of the magnetic field. Therefore, the configuration of the electric field is controlled by the magnetic field and the electrode geometry.

The lower erosion rates are attributed to the material properties of the thruster components and the position of the acceleration zone. The life-limiting components on the TAL are the electromagnet guard rings. The guard rings are necessary to protect the magnetic system from ion bombardment. SPT's employ a ceramic discharge chamber that protects the electromagnets, while the TAL employs metallic materials which, generally having lower sputter

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yields than conventional extends the thruster lifetime. Later generation TAL's generate an acceleration layer that is external to the thruster, to increase ionization efficiency and lifetime while reducing the risk of spacecraft contamination by reducing the amount of material sputtered from the thruster.

Although the lifetime of the TAL has not been empirically determined, accelerated tests have shown that the thruster has the potential of a longer lifetime than has been displayed by SPT's[2]. Long lifetimes can be achieved by using guard ring materials such as graphite, carbon-carbon, or diamond[3], and by increasing the azimuthal uniformity of mass loss. Significant azimuthal asymmetries in guard ring erosion were observed in a 636 hr. wear test of the D55 TAL. Although mass loss is important, performance degradation and risk of engine failure is a function of the depth of pole erosion, not total mass loss. A more uniform distribution of mass loss will result in slower degradation of the electromagnet poles and therefore, magnetic field and electric field.

The objective of this investigation is to investigate the cause of the erosion non-uniformities measured on the guard rings. This paper presents the erosion patterns that were discovered and explains possible reasons for their existence.

Apparatus and Procedure

The evaluations performed on this thruster include guard ring erosion measurements after the thruster ran for 636 hours on xenon, investigation of the propellant distribution uniformity, and magnetic field mapping.

The Propulsion System

The D55 was purchased by the Jet Propulsion Laboratory from TsNIMASH for the Ballistic Missile Defense Organization. The thruster name is derived from the 55 mm average diameter of the anode. In the back of the thruster there are three inlets from the anode propellant line in the same azimuthal positions as the electromagnets. The guard ring material is stainless steel which artificially accelerate the wear rate. The cathode that was used for the endurance test was fabricated by JPL. It employed a barium oxide

impregnated porous tungsten insert for electron emission. Illustrations of the thruster are shown in figures 1 and 2.

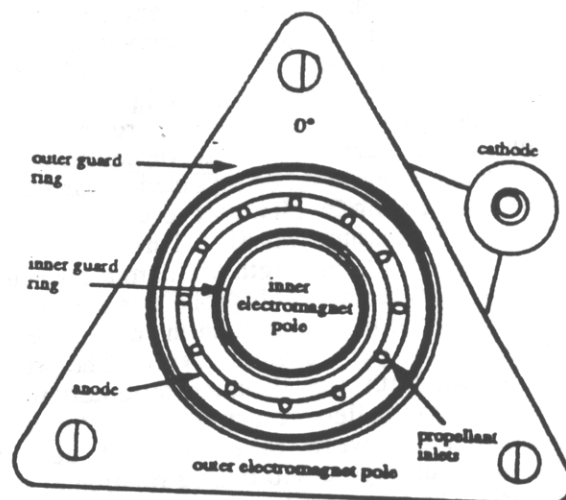


Figure 1. The face of the D55. The electromagnets are located at the vertices of the triangle.

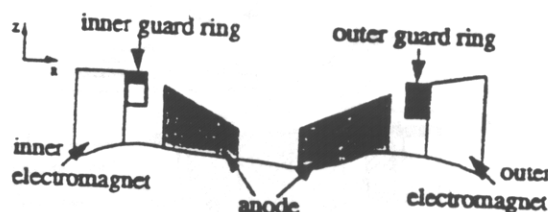


Figure 2. A diagram showing the position of the guard rings. The dark area of the rings are presented in figures 6 and 7, showing the erosion profile after 636 hours.

The Wear Test

A 636 hour wear test was performed on the D55 at 1.35 kW at the JPL to evaluate the performance degradation with time and the erosion rates of the thruster components. The performance of the thruster did not change over the duration of the test despite the erosion of the electromagnets and guard rings. The thruster efficiency remained at 48% with 1600 s specific impulse.

The Erosion Measurements

The position of the surface relative to the center of the inner electromagnet surface height was measured using a microscope with a digital focal length readout. The measurements were made every 10° at the inner and outer edges and the

center of the guard rings. The instrument was accurate to ± 0.025 mm.

Propellant Distribution Measurements

The propellant distribution was analyzed at the University of Michigan Plasmadynamics and Electric Propulsion Laboratory (PEPL). The propellant uniformity was assessed by measuring the total gas stagnation pressure within a cylindrical impact probe since variations in the flow uniformity should be reflected in variations in the local anode chamber pressure. The background pressure was $8E-5$ Torr. The probe consisted of a 12 cm length of 3.2 mm diameter stainless steel tubing. This probe was positioned in the center of the anode with the probe inlet 7 mm above the gas distribution ring. The probe was fixed, with the thruster mounted to a computer-controlled rotary table. Pressure measurements were taken in $1/2$ degree increments through a 360 degree rotation of the thruster. The set up is shown below as fig. 3.

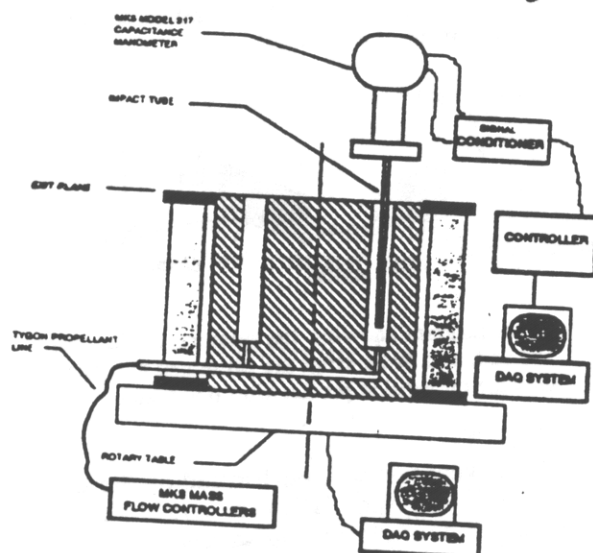


Figure 3. The experimental set-up for the propellant distribution analysis.

The pressure sensor was an MKS model 317 Capacitance Manometer with a full scale output of 1 Torr and a sensor zero of 1×10^{-5} Torr. The signal from this sensor was amplified, filtered, and analyzed using a Macintosh-controlled National Instruments digital data acquisition system.

Magnetic Field Measurements

The topology of the magnetic field was determined at the Jet Propulsion Laboratory using stationary Hall probes and rotating thruster beneath them. Measurements were taken every 4° at the positions noted by the intersections of the grid lines shown in fig. 5.

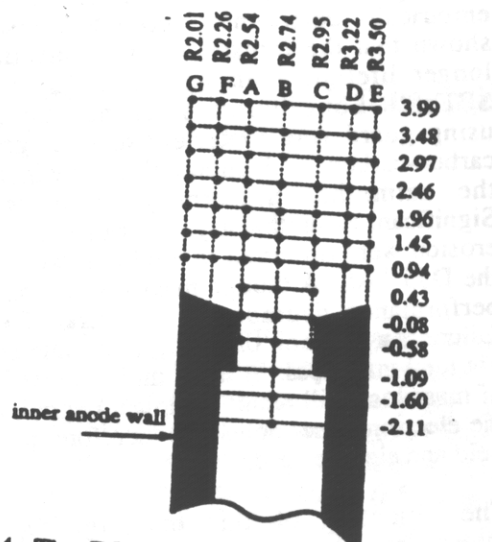


Figure 4. The D55 anode with the positions of the magnetic field measurements noted by the dots. The axial positions are given in centimeters and the radial positions are noted by a letter (A-G) and the corresponding radial position with respect to the axis of the inner electromagnet.

Results

The results included in this paper are guard ring erosion measurements from an earlier investigation[2], discharge chamber pressure measurements, and radial magnetic field measurements.

The TAL erosion depth measurements are shown in figures 5 & 6. The depth plotted is the height of the guard ring surface with respect to the initial height of the rings. Only the positions of the electromagnets are noted on the graphs, however, these three positions are also the locations of the three propellant inlets in the back of the gas distributor. Between the three propellant injection holes and the twelve holes that feed the propellant into the discharge chamber there is a series of plena to improve propellant distribution uniformity.

Figures 5a and 5b display a pattern that corresponds to a greater erosion between the electromagnets for the outer edge of the inner guard ring at position R1.74. At the two other radial positions the pattern is almost reversed, with surface heights that are higher than were originally measured. The measurements imply that some of the material eroded off of the outer edge of the inner guard ring was then deposited on the inner edge. The rough texture of the stainless steel surface near the inner edge is characteristic of sputtered material that was redeposited.

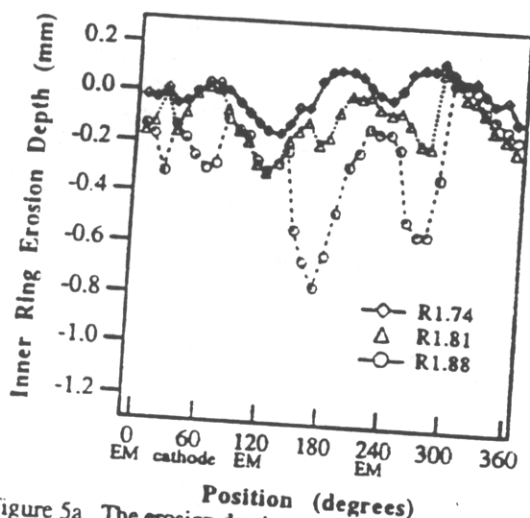


Figure 5a. The erosion depth measured on the inner guard ring at the three radial positions noted on the graph. The radial positions are given in centimeters.

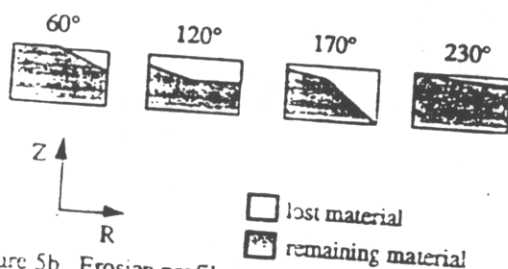


Figure 5b. Erosion profiles on the inner guard ring at the noted azimuthal positions in figure 5a.

Figures 6a and 6b show that the stainless steel was eroded off of the outer guard ring at a much higher rate than on the inner ring. The sinusoidal pattern has erosion maxima in the positions between the propellant inlets and electromagnets. The inner edge of the outer ring

eroded to a maximum depth of 1.26 mm because the guard ring is flush with the surface of the anode at this depth. This shadowing effect by the anode prevented further erosion of that edge of the ring; however, the middle of the ring continues to be eroded beyond the limiting depth set by the anode surface. The only positions where the erosion depth in the middle of the ring exceeds the inner edge erosion depth are those where the inner edge was eroded to the height of the anode, at 70°, 190°, and 290°.

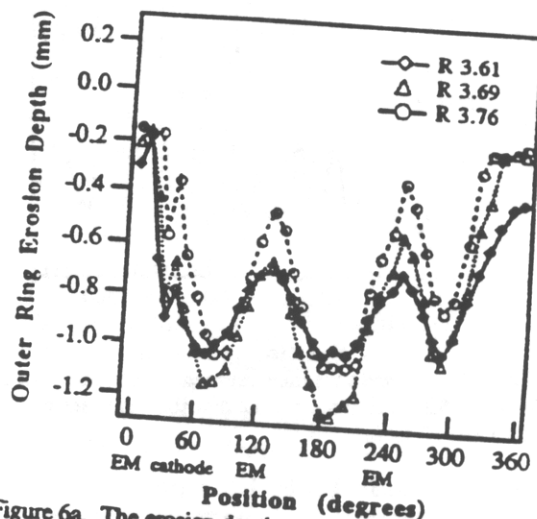


Figure 6a. The erosion depth measured on the outer guard ring at the three radial positions noted on the graph. The radial positions are given in centimeters.

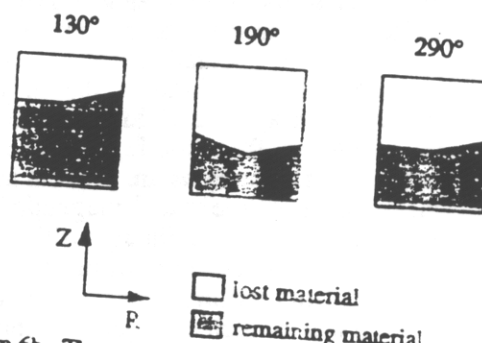


Figure 6b. The erosion profiles at the noted azimuthal positions in fig. 6a.

Flow Measurements

The measurements taken to evaluate the uniformity of the propellant are presented in fig. 7. The twelve peaks correspond to the positions of the propellant inlets. The data show no correlation between the pattern etched in the

guard rings and the mean value of the pressure. There seems to be no pattern in the pressure distribution. Although there are fluctuations in the pressure, the fluctuations measured at both flow rates are different. From the data obtained, it seems that the erosion patterns were not caused by propellant fluctuations.

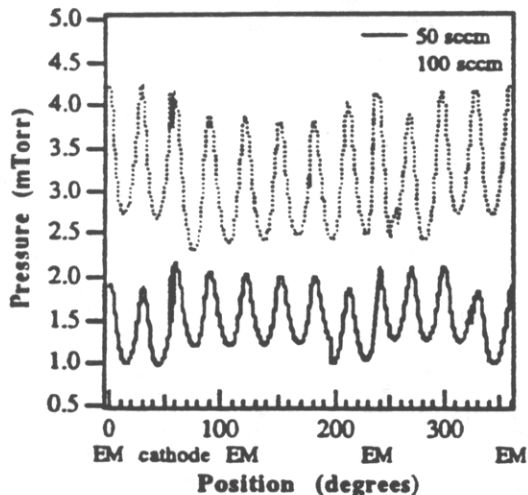


Figure 7. The pressure measurements taken inside of the anode at 6.25 mm from the 12 distribution holes at 100 sccm and 50 sccm.

The Magnetic Field Measurements

The measurements of the radial magnetic field taken in azimuthal sweeps show that the generated field is non-uniform. Figures 9 and 10 show the fluctuations in the magnetic field at a few positions compared to the erosion pattern. The magnitude of the fluctuations decreased with distance from the exit plane of the thruster, therefore, a few magnetic field measurement sweeps were shown from the regions near the guard rings. The fluctuations are as great as 8% of the maximum positive radial magnetic field strength and 170% of the maximum positive axial field strength. This paper focuses on the radial magnetic field fluctuations because the radial magnetic field has a much stronger influence on the configuration of the electric field than the axial magnetic field.

The dips in the magnetic field are intensified in the regions where there are larger gaps between the magnetic poles and the anode. The Hall probe was centered in the anode, however, the anode is not exactly on center with the thruster and the inner electromagnet. Both the field dips

and the anode placement together show correlation with the erosion patterns. The general tendency was that lower magnetic field strengths were associated with higher erosion rates.

Figure 8 shows the magnetic field at position B.43 because at positions closer to the inner guard ring there is a 6% single dip in the field at 168°. This large fluctuation in the magnetic field strength is generated by the gap between the inner electromagnet and the anode. The actual field fluctuations at the ring surface might be different.

The pattern etched in the inner guard ring does not follow any of the magnetic field patterns that were measured as well as the outer ring followed E.94 (fig 8). However, the general tendency to higher erosion rates between the outer electromagnet positions for the outer edge of the ring is consistent. It is believed that the pattern etched in the ring follows the magnetic field topology in the region closer to the inner ring and anode. Because of the size of the probes that were used, the closest position that could be evaluated was G.94, however, it is possible that the majority of the ions were not coming from this region, but further upstream.

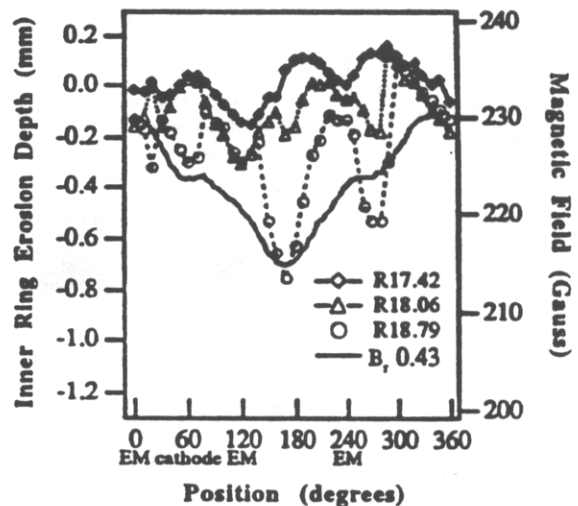


Figure 8. A comparison of the inner guard ring erosion to the azimuthal magnetic field variations at the position B.43 that is illustrated in figure 5.

Figure 9 shows how the erosion pattern etched on the outer guard ring matches the magnetic field non-uniformity. Since the erosion pattern follows the configuration of the magnetic field in

position E 94 ions might have originated near the position. In the weak magnetic field regions the guard rings were eroded to a pattern that implies that radially directed ions sputtered the material off of the ring until the anode shadowed the inner edge of the ring. As the erosion pattern and electric field near the ring evolved, it is possible that the ions were accelerated from positions further downstream of the anode.

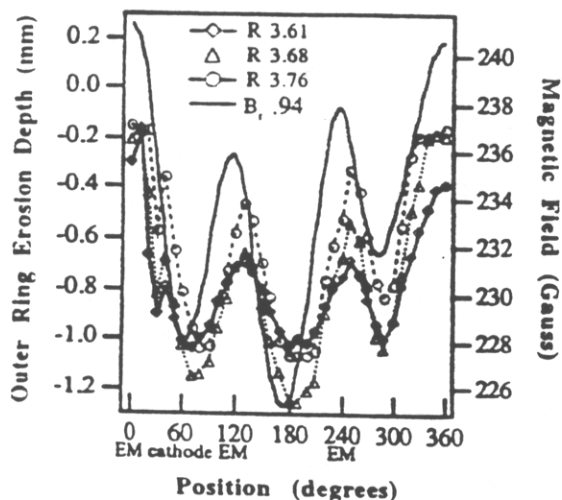


Figure 9. A comparison of the outer guard ring erosion to the azimuthal magnetic field variations at E .94.

The results of this investigation imply that the non-uniform erosion patterns are generated from magnetic field non-uniformities because of the strong correlation between the erosion and magnetic field measurements. In the region very close to the anode, the radial electric fields are greater than the axial electric fields. If ionization occurs in these regions, the ions will be accelerated radially into the guard rings. In the weak field regions where the magnetic field fluctuations are as great as 7% of the field strength, the diffusion coefficient for electrons across the magnetic field will increase by 15%. The electrons will choose this path of less

resistance to the anode creating electron densities very close to the anode that are greater than in the regions near the electromagnets. Consequently, the ionization rates will also be higher in these regions. Ions created in these near-anode regions, where the radial electric fields are greater than the axial electric fields, will be accelerated to the guard rings.

The erosion patterns created on both of the rings are indicative of etching caused by radially accelerated ions. It is possible to see the effect of these ions much better on the outer ring where the erosion rate was much higher. In the weak magnetic field regions, the guard ring was sputtered by the ions until it was flush with the anode, indicating that the ions were accelerated out radially. The erosion rates near the outer electromagnets are much greater than the erosion rates near the inner electromagnet because the magnetic field strength is about half that near the inner electromagnet, shown in fig.10. The radial magnetic field gradients near the inner ring are double those near the outer ring, therefore, the axial field strengths are much stronger there. For an ion to be accelerated into the inner guard ring, it would have to originate much closer to the ring than would be required by an ion being accelerated into the outer ring. Since it is much more difficult for the electrons to diffuse through the inner magnetic field region, the erosion rate of the inner ring should be much lower. This conclusion was supported by the data.

It is also possible that the erosion non-uniformities are caused by ion focusing into the regions between the electromagnets. The ions are being focused by either the strong magnetic fields or local electric fields. If the ionization rates are higher at the electromagnets and the beam is more divergent, the low energy ions generated near the anode will be directed to the guard ring regions between the electromagnets by an electric field with a Larmour radius on the order of a few centimeters.

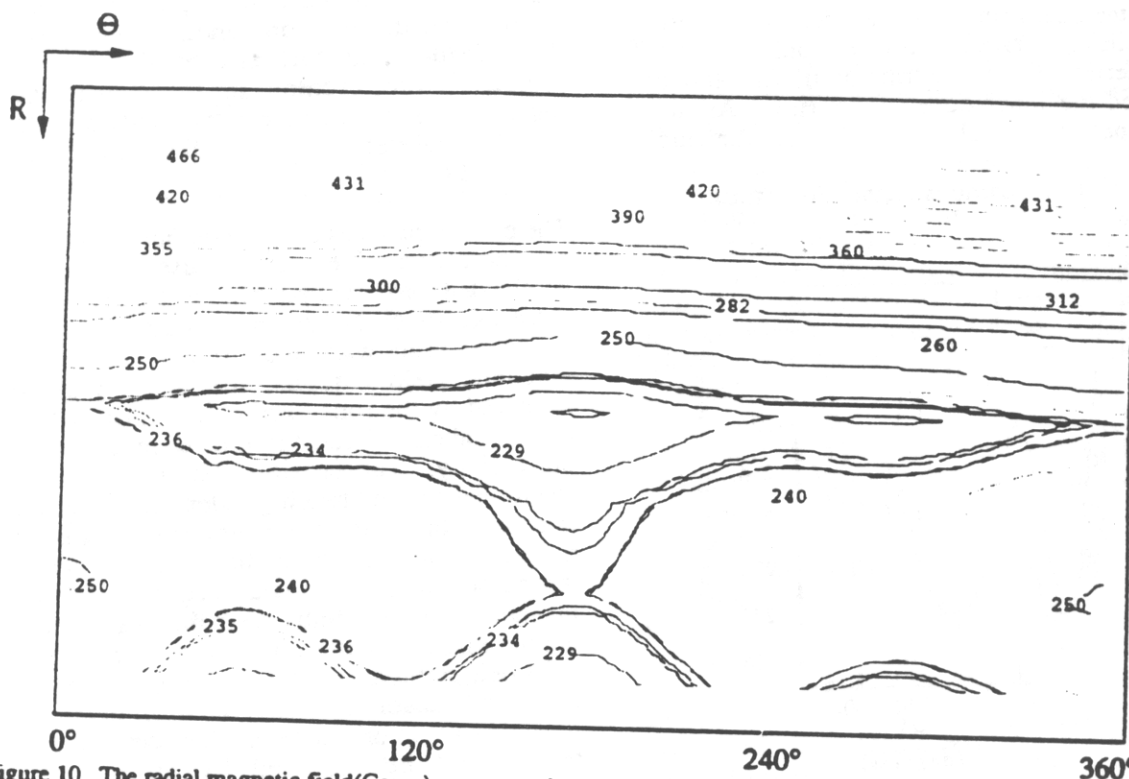


Figure 10. The radial magnetic field(Gauss) contours taken in the .94 plane shown in fig. 4.

In addition to the radial electric fields generated by the anode-guard ring potential, there could be nonuniform ambipolar electric fields that are focusing the ions into the guard rings. Where the neutral particle flow expands out the anode through a larger angle, the locally generated ions will be closer to the strong radial electric field regions where the ions are accelerated into the guard rings. This study proved that there was no correlation between the position of the rear propellant rear injectors and erosion pattern. However, the pressure measurements were performed near the back wall of the anode, only evaluating the propellant distribution in these regions. It is also possible that the gas jets are expanding differently out of the anode in different regions creating azimuthal non-uniform ionization rates.

Conclusion

Two possible explanations for the non-uniform guard ring erosion patterns generated on the D55

after 636 hours were investigated: propellant distribution non-uniformities, and magnetic field non-uniformities. The azimuthal pressure measurements in the anode showed that there was no correlation between the pressure fluctuations in the radial magnetic field in the azimuthal sweeps. The erosion rates were higher between the electromagnets where there were dips in the magnetic field. It is believed that the erosion pattern is caused by local radial electric fields, amplified in the regions where there were the magnetic field dips, that accelerate ions into the guard rings.

Several investigations can be carried out to investigate this theory further. Plasma potential measurements could be performed to determine the true structure of the electric field. Flow visualization can be done with a plasma discharge using an electron gun and CCD camera to determine if the radial neutral particle density gradients exist. Spectroscopic methods could be employed to determine ion velocities in the near anode region. Another accelerated life test could

be performed with periodic evaluation of the guard ring surface profiles to determine the evolution of the guard ring erosion profiles.

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