THE RESULTS OF 7000-HOUR SPT-100 LIFE TESTING
EDB "FAKEL", Kaliningrad, Russia

ABSTRACT

This report discusses the results of testing of the Stationary Plasma Thruster SPT-100, accomplished at EDB "FAKEL". The life testing was part of SPT-100 thruster qualification to Western standards. Total accumulated time of operation was 7008 hours. The thruster was tested at nominal discharge power level of 1350 W (discharge current $I_p = 4.5$ A, discharge voltage $U_p = 300$ V). The change relative to nominal value of current did not exceed 0.1 A and discharge voltage - 2 V. The discharge parameters were maintained by facility power supply. Total xenon flow rate was $5.5 \pm 0.1$ mg/s and was provided by facility's xenon supply system. Life testing was conducted on a cryogenic pumping system equipped facility. Testing consisted of consequent 8 hours long firings with K1 or K2 cathode operational with 10-15 min pauses between. During the entire testing thruster did not come into contact with air, vacuum chamber was not opened. Testing demonstrated stability of thruster performance. Thrust ($F$) was 78-84 mN at average of 80.61 mN. Specific impulse (Isp) was 1400-1600 s, efficiency ($n$) - 0.43-0.47. Total impulse exceeded $2 \times 10^6$ Ns. Erosion of exit portion of the acceleration channel did not result in controlled parameter change, which have been controlled, which have been controlled before and after life test. Thruster and cathodes are still operational. Testing is going on.

INTRODUCTION

SPT-100 is a stationary plasma thruster with closed electron drift (Hall thruster). By this time over 60 SPT M70 have been flown (power 660 W and thrust 0.4 N), some of which are still operating /1, 2/. "FAKEL" developed a new thruster M100 for north-south station-keeping of GALS geostationary spacecraft, delivering 1350 W power and 0.8 N thrust /3/. This thruster is qualified to Russian standards and is currently being flight tested since January, 1994, on board of GALS spacecraft.

The performance of this thruster attracted foreign customers, one of them is SS/Loral. Qualification (final development) of SPT-100 thruster, which is analog to M100 thruster, to Western standards is closing to end as part of "FAKEL" and SS/L effort /4/. SPT-100 thrusters passed demonstration test and plume investigation test at FAKEL in 1991-92 /5, 6/, and test sequence at NASA Lewis Research Center, Jet Propulsion Laboratory (JPL) and in For Collins, Kaufman and Robinson Inc. /7-11/. In 199 the same thruster SPT-100 successfully accomplishes life test at JPL /12/. During this test one cathod operated during 5000 hours and 6000 cycles. This report presents the results of SPT-100 life test a "FAKEL", during which 7008 hours of operation wer totalled.

SPT-100 is pictured in Fig.1. The thruster consists of: anode assembly with discharge chamber (out side channel diameter - 100 mm, channel width 15.5 mm), magnetic assembly and propellant supply system; two cathodes-neutralisers xenon flow regulator (XFC).

Fig. 1. Thruster unit view.

EQUIPMENT

The thruster was tested in vacuum chamber wit cryogenic pump system. General diagram of vacuum facility and layout of principal items (thrust stand thruster, mass-spectrometer, titan shields) is in Fig. 2. Vacuum system employs neon and helium pumps (N1 N4). One neon pump was used for testing (Ne), providing the temperature of liquid neon cooled cryopane of 27 °K. The facility has total 6 neon cryogenic pumps providing total pumping capability 40 mg/s Xe a dynamic pressure no greater than $2 \times 10^{-4}$ torr by air. One neon pump was used for test, which has capabil
Ity to pump N2, O2, H2O as well as Xe. To pump Ne, He, H2, four turbomolecular pumps (TMP) were used at initial test phase. These pumps were consequently overridden by helium cryosorption pumps with cryopanel temperature 14-24 K. TMP pumps override provided better Ne, He and H2 pumping and eliminate oil vapor (carburized hydrogen) from vacuum chamber ambient. Cryogenic pumps need to regenerate each 400-500 hours.

Ionization sensors, which were installed at different locations in vacuum chamber (BP1-BP3, BP4H) monitored the vacuum. Sensor life was limited to 400-500 hours, besides, there was no possibility to replace them without opening vacuum tank, hence beginning at hour 3081 vacuum was monitored by BP4H sensor with vacuum valve, which could be replaced from time to time. During life test static vacuum did not exceed $5 \times 10^{-6}$ torr, and dynamic vacuum - $5 \times 10^{-3}$ torr by Xe.

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Facility's propellant supply system was equipped for testing, which consisted of Xe bottle, high pressure reducer, receiver, flow rate transducer and interfacing pipelines. 40 liter receiver served to compensate for the Xe pressure change at flow rate transducer to enhance the stability of transducer readings.

Thermal sensor MDR, developed at "FAKE" was used for flow rate monitoring in flow rate measurement system (FMS), which sensor was sensitive to ambient temperature variation and was replaced at hour 1318 with RRG sensor, which provided better performance. Each 2 hours during testing "0" of FMS was tested and each 150 hours (weekly) flow rate transducer was tested by volumetric method. Besides, temp was weight calibrated from time to time, to the same results as other techniques.

Facility power supply, wired as shown in Fig. 1, provided power for testing. Testing at "FAKEL" allowed to select optimal configuration of electric circuit, hence beginning at hour 360, with inductance L=0.35 mH instead of 15 mH capacitor of C=6 μF instead of 2 μF. Between

![General diagram of vacuum facility](image-url)

**Fig. 2. General diagram of vacuum facility**
3600 and 4200 power was provided by Power Processing Unit (PPU) developed at SS/Loral. To measure root mean square oscillations of discharge current, current transformers I1 and I2 were used.

![Electrical test diagram](image)

**Fig. 3. Electrical test diagram.**

The composition of propellant used during testing is described in Table 1. The propellant cleanliness was provided by facility preparation techniques.

<table>
<thead>
<tr>
<th>Состав рабочего тела, ppm</th>
<th>Время работы, ч</th>
<th>0...300</th>
<th>300...7008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe</td>
<td></td>
<td>99.990</td>
<td>99.999</td>
</tr>
<tr>
<td>O₂</td>
<td></td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>H₂O</td>
<td></td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>CO₂</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CH₄</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Kr</td>
<td></td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Ar</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CF₄</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N₂</td>
<td></td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>H₂</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Testing proceeded in 8 hour cycles with 10 minute pauses, and with longer pauses up to several days long due to specific technical and management issues. While replacing vacuum equipment, vacuum tank was filled with dry nitrogen to pressure over atmospheric.

**LIFE TEST RESULTS**

**Thrust**

The thrust behavior during life testing is shown in Fig. 4 and can be divided into three principal sections:

- first - thrust decrease during first 100-200 hours of testing by 3-5 mN;
- second - thrust stabilization after 600 hours at 78-80 mN;
- third - thrust increase by 1-2 mN after 1500 hours and stabilization till 7000 hours.

Similar thrust variation by value and by time was observed during SPT-100 test at JPL /9/. Average thrust within 7008 hours of life testing was 80.6 mN at 1350 W power.

![Thrust during life test](image)

**Fig. 4. SPT-100 thrust during life test.**

After long pauses test continued with some thrust increase up to 82 mN and gradual thrust drop to 80-8 mN. The difference in thrust between two consequent firings at minutes of operation 15 and 60 is indicate in Fig. 5 and 6.

![Absolute thrust difference between two subsequent firings at minute of operation 15](image)

**Fig. 5. Absolute thrust difference between two consequent firings at minute of operation 15.**

![Absolute thrust difference between two consequent firings at minute of operation 60](image)

**Fig. 6. Absolute thrust difference between two consequent firings at minute of operation 60.**
As mean value of thrust difference between consequent firings during life testing was close to zero (less than 0.1 mN), absolute thrust difference was used in analysis.

Mean absolute value of thrust difference in two consequent firings at minute 15 after start was 0.44 mN. Maximal absolute thrust difference at minute 15 was 6.86 mN.

Mean thrust difference in two consequent firings 1 hour after start was 0.45 mN. Maximal absolute thrust difference at minute 60 was 3.33 mN.

**Flow rate**

Total flow rate in thruster (anode and cathode) was 5.2-5.9 mg/s and it is shown in Fig. 7.

![Fig. 7. SPT-100 flow rate during life testing.](image)

**Total impulse**

The thruster totalled 1'000'000 Ns in 3483 hours. Total impulse was 1'500'000 Ns (margin 150% for required design life) was achieved at hour 5191. At hour 6892 total impulse 2'000'000 Ns was achieved, that corresponds to double the requirement according to customer Specification.

**Specific and integral parameters**

Specific power, specific impulse and efficiency changes were respectively 16-17.5 W/mN, no less than 1450 s and no less than 43%.

**Current and voltage oscillations**

The root mean square value of discharge voltage (U) oscillations measurement results within life are shown in Fig. 8. Oscillation increase within hours from 4300 till 4400 occurred due to that filter used capacitor of 4 uF instead of 6 uF after transient from PPU to facility system.

Beginning at hour 1866 root mean square oscillations of discharge current were measured in anode circuit as shown in Fig. 8. The results of current oscillations measurements are shown in Fig. 9.

![Fig. 8. Root mean square oscillations of discharge voltage.](image)

**Fig. 9. Root mean square oscillations of discharge current.**

The current oscillations frequency and amplitude measurements at different locations (Fig. 3), beginning at hour 1500, provided the following results:

1. $I_1 = 2.0...7.00 \ A, f = 28...35 \ kHz$;
2. $I_2 = 0.1...0.13 \ A, f = 28...35 \ kHz$.  

**Testing after life test**

Having accumulated 7000 hours, SPT-100 underwent tests to check up and compare the thruster performance before and after life testing.

Thruster components condition (electrical parameters, thruster erosion, etc.) and test equipment and vacuum facility condition were investigated as well.

**Check results**

Thruster performance in discharge current rang 4.0-5.0 A with both cathodes before life test and after 7000 hours was similar and summarized in Table 2.
Table 2

<table>
<thead>
<tr>
<th>Катод</th>
<th>До ресурсных испытаний</th>
<th>После 7000 часов</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>82.70 мГ</td>
<td>82.49 мГ</td>
</tr>
<tr>
<td>K2</td>
<td>81.73 мГ</td>
<td>81.57 мГ</td>
</tr>
</tbody>
</table>

Testing after 7000 hours did not reveal the thruster performance variation with bias coil current. Electrical parameters of thruster, bias coils and XFS were maintained. The impedance decrease in circuit "Cathode ignitor - Housing" was due to deposition of conductive layer on ignitor isolator inside vacuum tank.

Physical condition of thruster

The view of thruster after accumulation of 7000 hours is pictured in Fig. 10.

Fig. 10. Thruster view after life testing

Thruster surface at discharge chamber exit and on sides was coated by a layer with metallic shine. Deposited layer on bias coils was partially peeled. Spectral analysis of deposit samples revealed its composition of aluminum, magnesium and titan. These elements are products of titan screen and aluminum alloy screens sputtering, which are located in vacuum tank within thruster plume impingement zone.

Thruster erosion

The erosion zones on outside and inside walls of discharge chamber isolator are seen in Fig. 11 and 12. The erosion zone surface structure is typical for SPTs, having accumulated large operation time /13/.

Fig. 11. Erosion walls of discharge chamber

The erosion zone surface structure is typical for SPTs, having accumulated large operation time /13/.

Typical erosion profiles on inside and outside walls are shown respectively in Fig. 15 and 16. Outside wall profile shows two curves: 1 - on "peaks", 2 on "valley". The inside wall erosion chart is more smooth and does not have distinct local "peaks" and "valleys" as outside wall and thruster with less accumulated operation do. Outer magnetic pole has characteristic notches, continuing from the outside isolator (fig. 12). After 7000 hours at this erosion grade thrust change was observed. Total volume of sputter isolator material, as estimated by typical erosion profiles, was 16.81 cm$^3$ for outside wall and 7.57 cm$^3$ for inside wall.

Fig. 12. Outer magnetic pole erosion

After 1000 hours of testing the discharge chamber erosion speed decreases in 10 times and then re
mains almost constant /6/, that is shown in Fig. 15. The analysis indicates that inside wall erosion speed in SPT-100 No 02 (4100 hours in oil vacuum) SPT-100 (at JPL in cryogenic vacuum) and SPT-10 (7008 hours in cryogenic vacuum) are almost the same.

During above tests there was not revealed a significant change of thruster erosion with environment gas composition, pressure and dimensions of vacuum tank variation /9, 10, 14/, and erosion is primarily determined by physical processes in the thruster.

Cathode-neutraliser condition

Surface of both cathodes (Fig. 16), including igniters isolators, are coated with sputtered material from vacuum facility screens, as chemical analysis of deposit indicates.

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Fig. 13. Inside wall erosion in M100 thruster (4100 hours) and in SPT-100 (7008 hours).

Fig. 14. Outside wall erosion in M100 thruster (4100 hours) and in SPT-100 (7008 hours).

Fig. 15. Comparative speeds of erosion in three thrusters.

Erosion on both cathodes-neutralisers looks almost the same. The observed erosion on both cathodes neutralisers was similar to what was observed at JPL while testing the SPT-100 thruster. Similarity of erosion on cathode, which was not operating during testing with other cathode operating, observed in both tests indicates the same nature of such phenomenon. The dynamic change of physical condition of non-operating cathode-neutraliser while other cathode-neutraliser is operating is discussed in /12/. In about 3100 hour of operation on K1 cathode (K1 cathode was used in a major portion of operation at JPL while K2 was off the exit portion of K2 cathode ignitor actually disappeared at JPL.

At “FAKEL” the thruster was tested by consequent switching between cathodes K1 and K2. During such cycling each cathode was off half the life test duration while another was operating. Thus, both cath
odes after 7000 hours had to erode similar to cathode K2 of the thruster SPT100 (JPL).

One probable cause why the ignitor of K2 cathode at JPL and cathode-neutraliser at "FAKEL" is galvanic (electric) connection between the cathode-neutraliser K1 and K2 along cathode circuitry and ignitor circuitry respectively.

Vacuum tank equipment condition
All vacuum tank components within the thruster plume impingement zone were eroded. In shadow areas sputtered material was deposited. Results of chemical and spectral analysis of sputtered material, collected from vacuum tank and thruster, showed that major contribution was by chemical compounds of vacuum tank components, louvers and screens of vacuum pumps.

CONCLUSION

SPT-100 had operated 7008 hours at 1350 W power without entering in contact with air.

Thruster performance before and after life testing is the same.

The thruster discharge chamber erosion is similar to erosion of other SPT-100 thrusters.

Erosion of cathode-neutraliser ignitors after 7000 hours is similar to erosion of spare cathode at JPL /12/. To define the spare cathode ignitor erosion during life testing and to decrease erosion the investigation is being carried out, which results will provide ideas about upgrading the thruster design.

SPT-100 life testing is going on.

LITERATURE

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