PERFORMANCE AND QUALIFICATION STATUS OF MULTIMODE STATIONARY PLASMA THRUSTER SPT-140

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Abstract

Qualification test data of Multimode Stationary Plasma Thruster SPT-140 are presented. This test was carried out at FAKEL as part of development model thruster (DM) qualification.

Development and qualification of this thruster at FAKEL is being carried out at FAKEL in a framework of advanced Hall thruster development effort under the program Integrated High Payoff Rocket Propulsion Technology (IHPRPT). Special requirement to the SPT-140 was capability of operation in a wide range of power from 2000 up to 4500 W at efficiency over 55% and life 7200 hours. The thruster was developed on a basis of SPT developed at FAKEL in 1988 and using experience gained in joint efforts with International Space Technology Incorporated (ISTI) in 1996...1997, in which efforts RIAME was a participant. Experience of qualifying the SPT-100 to Western standards was also used.

After revision of customer requirements in late 1997, two development models SPT-140 DM were developed, fabricated and tested in 1998.

DMs were acceptance and qualification tested at FAKEL. Qualification included fire testing with performance parameters monitoring, thruster vector alignment test, plume test, thermovacuum firing test and mechanical test.

Fire test was done at three nominal power levels: 2000, 3000 and 4500 W (discharge current 6.67, 10.0 and 15.0 A, discharge voltage 300 V). Discharge parameters and total Xe flow rate during thruster operation were maintained by test facility power and propellant subsystems. Two vacuum facilities were used in test. One facility was equipped with oil vacuum pumps (pressure down to $7.7 \cdot 10^{-5}$ torr by Xe at current 15 A), and the other with cryogenic Helium vacuum pumps (pressure down to $1.6 \cdot 10^{-5} \ldots 3.2 \cdot 10^{-5}$ torr by Xe at current 6.67...15 A).

The characteristics of the thruster are submitted at acceptance tests and at life tests.

Specific impulse and efficiency were corrected to a pressure level 10^{-6} torr and incorporate total losses in thruster (cathode flow rate and coil power).

Introduction

In 1996 ISTI began funding design and development activities at Fakel and RIAME to develop the SPT-140 thruster to meet the emerging market for higher power, higher efficiency Hall thrusters[1].

Requirements of ISTI Specification at power 4.5 kW are summarized in below:

Thrust	290 mN
Specific Impulse	1770 sec
Discharge Current	15 A
Discharge Voltage	300 V
Flow Rate	16.7 mg/sec
Total Impulse	$4.5 \cdot 10^6$ N-sec +30 % margin
Total Cycles	5895 +30 % margin
Throttling Range	2.0...4.5 kW

Prior to award of the Air Force IHPRPT contract, over ten engineering and laboratory models had been produced and tested at Fakel.

The IHPRPT contract formally began on September 1997.

The IHPRPT program is structured in four phases and three mission application areas to achieve predetermined measurable increases in all rocket technology capabilities. The HPHS program addresses Phase 1 goals for the spacecraft propulsion mission area. The effort will explicitly address the following IHPRPT objectives for the SPT-140 thruster:

Efficiency	≥ 55 %
Operational Life Time	≥7200 Hours.

Since award of the IHPRPT contract Fakel and RIAME have pursued many design changes to components and subsystems to ensure that the

IHPRPT objectives are achieved. As shown in figure 1, the pre-contract SPT-140 engineering model thrusters achieved roughly 50% efficiency.

To increase the efficiency six Engineering Model (EM) model thrusters were designed, fabricated and tested with various configurations of the magnetic path. two variations of anodes. Each modification was tested at a 300 V and 350 V and power levels from 2000 to 5000 W. The result of this works was the EM5 model thruster that achieved 55% efficiency. This configuration was used as the basis of the Demonstration Model (DM1) thruster fabrication.

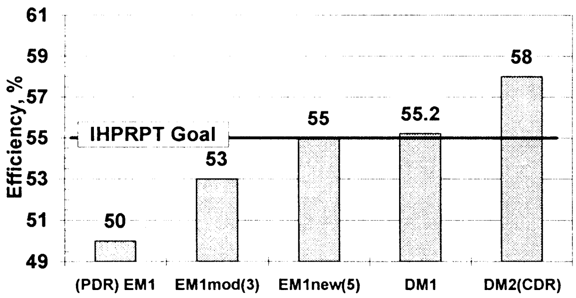

Fig. 1. SPT-140 Efficiency Improvements

The additional improvements gives increase of efficiency up to 58%. The selected optimized configuration has been used in the SPT-140 DM2.

Acceptance and Qualification tests SPT-140 DM2 have been carried out at Fakel.

Now this thruster is tested at life test, which duration should be not less than 1200 hours.

Specification requirements and tests plan

SPT-140DM2 acceptance tests started in December 1998. The matrix of the acceptance tests corresponded to a matrix of the specification and is presented in table 1.

Table 1

	Test
1.	Examination
2.	XFC-140 proof pressure test
3.	XFC-140 leakage test
4.	XFC-140 functioninal test
5.	Reference performance I
6.	Random vibration test (AT)
7.	Thermal Cycling, AT
8.	Thermal balance test
9.	XFC-140 functional test
10.	XFC-140 functional test
11.	Reference performance II
12.	Physical Examination

The levels of mechanical tests and temperatures of thermal cycles at acceptance tests corresponded to the specification. At these tests to evaluate the impact of magnet current variation on the thruster parameters were conducted.

The matrix of the environmental tests corresponded to a matrix of the specification and is presented in table 2.

Table 2

	Test
1.	Acceptance Tests
2.	Sinusoidal vibration
3.	Random vibration test
4.	Shock
5.	Reference performance
6.	Thermal Cycling
7.	SPT-140 and XFC-140 inspection
8.	Reference performance
9.	Thruster Fire Test
10.	Life test

The levels of mechanical tests and temperatures of thermal cycles at environmental tests corresponded to the specification and presented in tables 3...5.

Random Vibration Levels

Table 3

Axis	Frequency range, Hz	Random vibration level, g^2/Hz	RMS acceleration	Test duration min/axis
X,Y,Z	20-125 125-252 252-300 300-900 900-2000	+9 dB/oct 0.130 -12 dB/oct 0.650 -9 dB/oct	13.9	2.0

Sine Vibration Levels

Table 4

Axis	Frequency range, Hz	Acceleration, g (0-peak)	Sweep rate, oct/min
X,Y,Z	5-25.4 25.4-50 50-100	10.0 mm (double amplitude) 18 5.2	2

Shock test parameters: half sine impulse of 0.25 msec duration and 590 g amplitude.

Thermal Environmental by Thermal Vacuum Cycles (QT)

Table 5

	Minimum	Maximum
SPT Temperature (T1)		
Non-Operating	-70	-
Start-Up	-70	-
Operating	-	400
XFC Temperature (Valve)		
Non-Operating	-40	-
Start-Up	-40	90
Operating	-	95

Test Facility & Equipment

All tests, including firing, dynamic environmental, thermal vacuum cycles test, are conducted on test stands EDB Fakel.

Equipment for Firing Tests

Table 6

Stand	71-1-84	71-3-90
Vacuum system	diffusion pumps	Cryogenic pumps
Sise Length, m Diameter, m	 4 1.5	 5 2.5
Pressure at tests, torr (Air) At power of 2.0 kw At power of 4.5 kw	 $\leq 1.4*10^{-4}$ $\leq 2.4*10^{-4}$	 $\leq 1.1*10^{-5}$ $\leq 5,5*10^{-5}$
Assignment	AT, Thermal	AT, Life Test

Stand power supplies were used in both stands for the tests.

The tests were conducted in compliance with programs and procedures used for other types of SPT, and with procedures specially developed for tests SPT-140

Standard and special measuring equipment is used For measurements and control of parameters

Thrust and flow measurement system subject to frequent calibration.

Calculation of the efficiency incorporate total losses in thruster (cathode flow rate and magnet coils power).

Calculation of the specific parameters (specific impulse and efficiency) was conducted accounting for vacuum chamber pressure correction[2]. Correction formula for mass flow rate to the thruster (Mt):

$$M_t = M_m + M_{add}$$

where M_m is the total mass flow to the thruster through XFC-140. M_{add} is a mass flow correction for vacuum chamber pressure. This correction was calculated using the formula

$$Madd = A_p * P_{vc}$$

where,

Ap is the correction factor;

Pvc is the vacuum chamber pressure in torr measured by a transducer calibrated for air.

Thrust at the discharge powers of 4.5 and 3.0 kW was measured in the same measurement range: 0-40 grams. Thrust at the discharge power 2.0 kW was measured at 0-20 measurement range.

Mass flow at the discharge powers of 4.5 and 3.0 kW was measured in the measurement range of 0-20 mg/sec, and 0-10 mg/sec at the discharge power of 2.0 kW.

Control points were assigned to decrease the efficiency measurement error in acceptance tests procedures at reference performance. Metrological parameters of the thrust measurement devise and mass flow meter were tested in the control point after the tests (control calibration and correction of the «zero» temperature drift were conducted). Efficiency measurement error did not exceed ±1.4% in the control point at the discharge power of 4.5 kW.

Test Results

Firing Test Results

Table 7 give the results obtained on SPT-140 DM2 at Reference Performance 1

Test Results at Reference Performance I

Table 7

Discharge Voltage, Ud, V	300	300	300
Discharge Current, Id, A	15	10	6.67
Thrust, F, mN	302	198	130
Specific Impulse, sec (corrected)	1827	1710	1615

The parameters of the thruster on cathodes K1 and K2 practically are identical. Thruster in compliance with specification requirements for thrust, mass flow rate, specific impulse and efficiency at the discharge powers from 2.0 kW to 4.5 kW.

Like all SPT models, the function of thrust vs discharge current is linear for SPT-140 DM2; that is, it is proportional to the discharge current. This fact is illustrated in Figure 2.

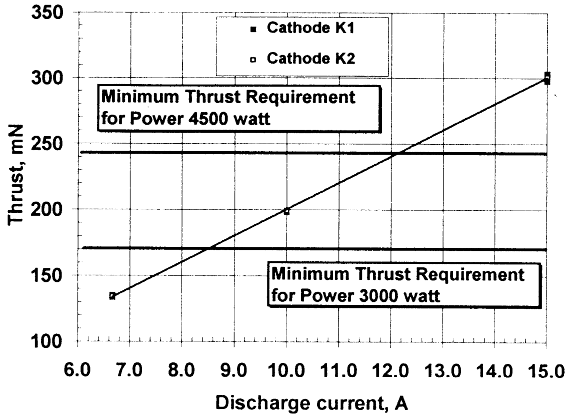

Fig. 2. Thrust versus discharge current

Reference Performance after Thermal Cycling (before Life Test)

Table 8

Discharge Voltage, Ud, V	300	300	300
Discharge Current, Id, A	15	10	6.67
Thrust, mN	291	194	128
Specific Impulse, sec (corrected)	1805	1701	1599

After the environmental tests of a qualifying level the thruster has saved of the characteristics.

Magnet impact

Tests to evaluate the impact of magnet current change on thrust and specific parameters were conducted with model SPT-140 DM2. The outcomes of tests show, that the thruster SPT-140 tolerates magnet current variation in a wide range.

Figure 3 present thrust efficiency vs. magnet coils current.

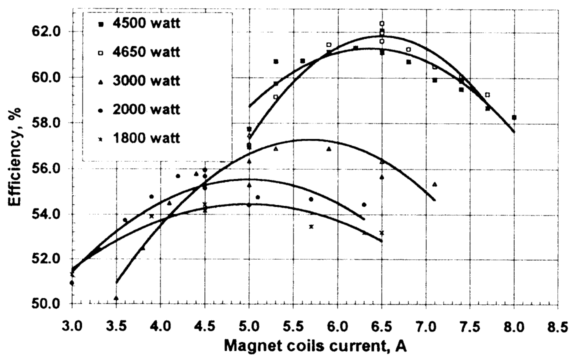

Fig. 3. Efficiency versus magnet coils current

Thrust Vector Measurement

Work related to the development of thrust vector control procedure was conducted during DM1 tests. Test results demonstrated that thrust vector measurements may be conducted at the discharge power of 2.0 kW. Thrust vector non-alignment angle remains the same at various powers.

A series of control procedures related to providing a small angle value of thrust misalignment were developed during SPT-100 manufacturing process. These procedures were also used during SPT-140 DM2 manufacturing. The use of these procedures allowed to forecast a small thrust vector non-alignment value during SPT-140DM2 manufacturing phase. Direct tests confirm that thrust vector non-alignment angle not more 45'.

Figure 4 present thrust vector non-alignment angle in two mutually perpendicular positions vs. operating time at AT. Component β - angle in axial plane between the cathodes, component α - angle in the plane formed by the intersection of the module axis and component β.

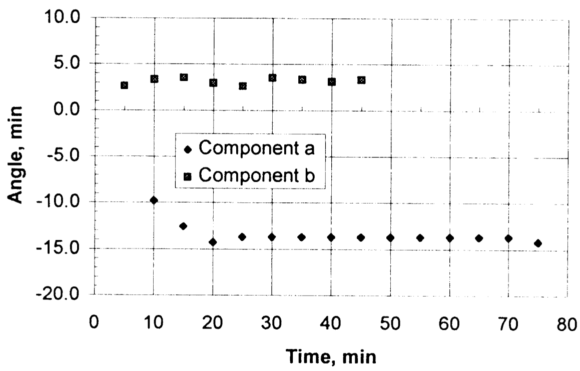

Fig. 4. Thrust vector non-alignment angle in two mutually perpendicular positions vs. operating time at AT

Thermal Cycling tests

At qualifying thermal cycles is made till 10 cycles at maximum and minimum temperature. The scheme of thermocouples location on the thruster (T1, T2, T4, T6) is shown on a figure 5. The XFC's thermocouples were installed on valves (T_{valv1}, T_{valv2}) and mounting plate (T_{XFC}). Temperature T_{sc} is the temperature on the test fixtures. Temperature fluctuation of the SPT-140 anode block XFC during one QT cycle is presented in Figure 6.

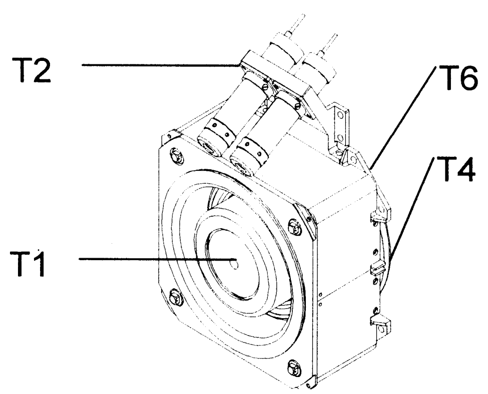

Fig. 5. Temperature transducer location on the thruster SPT-140 at AT and QT

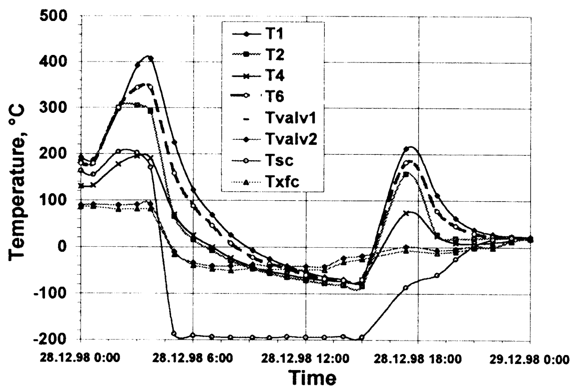

Fig. 6. Temperature fluctuation of the SPT-140 anode and cathode blocks, XFC and screen at QT thermal cycling

At thermal cycles minimum temperature on valves made -43 °C, maximum temperature + 98 °C.

At temperatures on the cathode -84 °C of nonconformance in parameters of start-up of the cathode were not.

Life Test

After a full cycle of environmental tests at the end of February, 1999 are begun life test.

The view of a SPT-140 DM2 thruster before life tests is presented at a Figure 7.

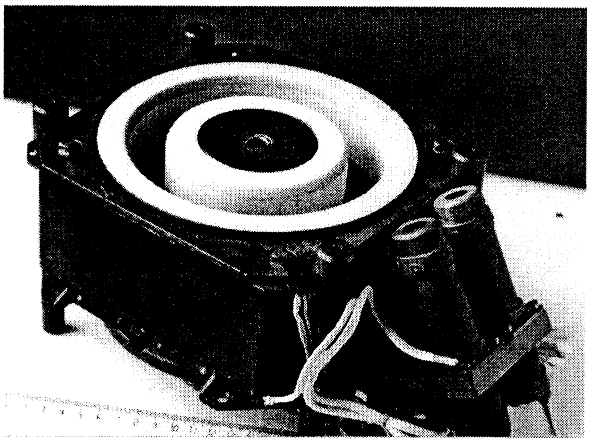

Fig. 7. SPT-140 DM2 before life test

On a moment of writing of the article the operating time on the thruster has made more than 1000 hours. Dynamics of the thruster parameters is presented on figures 8...10.

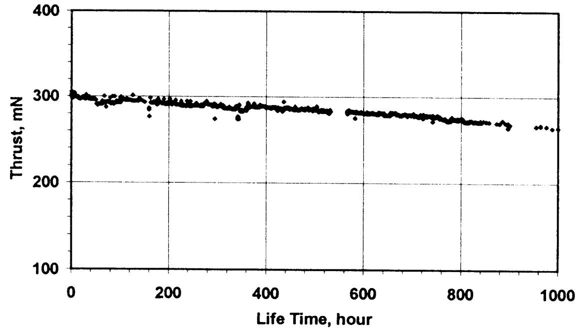

Fig. 8. SPT-140 DM2 thrust vs. lifetime

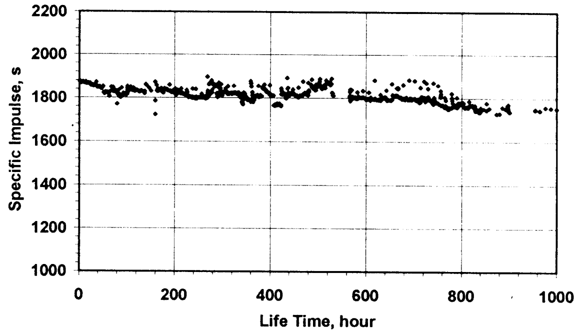

Fig. 9. SPT-140 DM2 specific impulse vs. lifetime

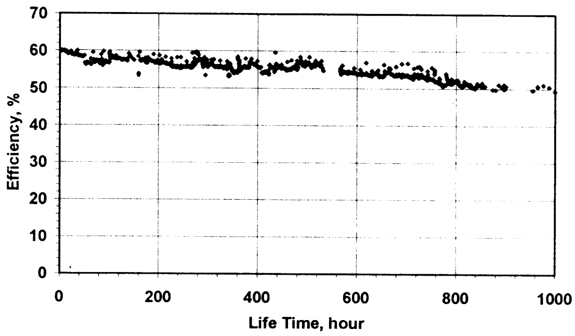

Fig. 10. SPT-140 DM2 efficiency vs. lifetime

Dynamics of the parameters for the thruster SPT-140 DM2 is similar to dynamics for the thruster SPT-100[3, 4]. Now of life test is continued.

Life Forecast

A function of operating life value (τ) vs. thruster parameters (discharge current (Id), discharge voltage (Ud), discharge chamber insulator dimensions (D), insulator erosion rate (Cv), insulator temperature (Ti) and efficiency (η) was used for the SPT-140 life forecast:

$$\tau = f(Id, Ud, D, Cv, Ti, \eta) \quad (1)$$

This function was calculated using results of life test of SPT's. Results of SPT-100 direct tests (7500 hours) were used for SPT-140 operating life calculation.

In compliance with function 1 thruster operating time of the SPT-140 is not less 6300 hours of operation at 4.5 kW.

Function 1 was used for the erosion forecast at the isolator edge (on external and internal walls of insulator).

During life test the measurements on edge the chamber were executed. Fig. 11 and 12 present curves for the isolator exit plane erosion vs. life time and the forecast dimensions.

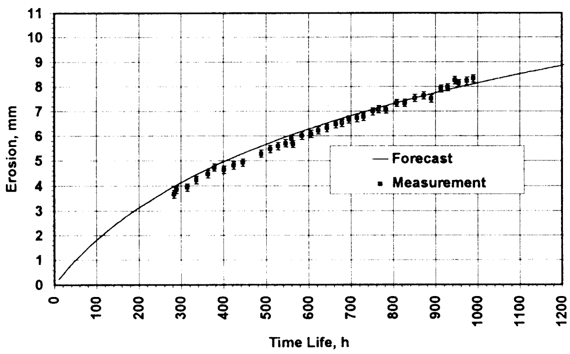

Fig. 11. Erosion evolution on the edge of the external wall

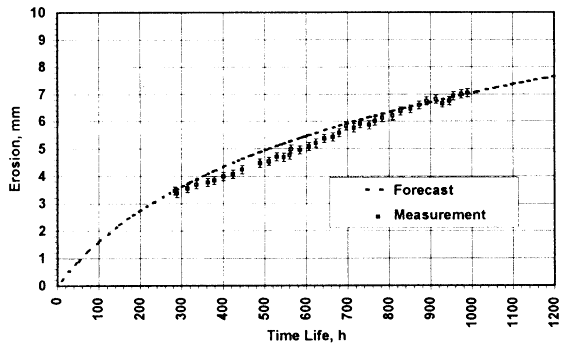

Fig. 12. Erosion evolution on the edge of the internal wall

Thus this results demonstrated that forecast for operating life is in compliance with direct measurements.

Conclusion

The SPT-140 thruster is qualified on IHPRPT Requirements and ISTI Specification.

Thruster design is in compliance with the requirements for thrust, Xe mass flow rate, specific impulse, specific power and efficiency.

The lifetime demonstrated is 1000 hours of activation with improved specific impulse and efficiency. Life test is continued.

References

[1] D. Manzella, et. al, "Performance Evaluation of the SPT-140", IEPC-97-059, 25th International Electric Propulsion Conference, Cleveland, 1997.

[2] M. Day, V. Kim H. Kufman, K. Kozubsky, et al. "Facility Effects on SPT Thruster Testing", IEPC-93-093, 23rd International Electric Propulsion Conference, Seattle, Washington, 1993.

[3] B. Arkhipov, et al, "The Results of 7000 Hour SPT100 Life Testing", IEPC-95-039, 24th International Electric Propulsion Conference, Moscow, Russia, 1995.

[4] C. Garner, J. Brophy, J. Polk, L. Pless, "Cyclic Endurance Test of a SPT100 Stationary Plasma Thruster."3nd Russian-German Conference on Electric Propulsion Engines and Their Technical applications. July 19-23, 1994. Stuttgart, Germany.