Multi-Mode Thruster with Anode Layer Development Status

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Alexander E. Solodukhin*, Alexander V. Semenkin†, Leonid E. Zakharenkov‡,

Anatoly V. Rusakov§, and Alexander G. Karabadzhak**

Central Research Institute of Machine Building (TsNIIMASH),
Pionerskaya 4, Korolev, Moscow region, Russia 141070,
Phone: (8-495) 513-44-46, Fax: (8-495) 516-59-10

and

Alexander N. Nesterenko††

Experimental Design Bureau "FAKEL",
181 Moskovsky prospect, Kaliningrad 236001 Russia
Phone: (8-4012) 46-16-16, FAX: (8-4012) 53-84-72

Abstract: Thruster with anode layer (TAL) is the Hall type thruster originally developed at TsNIIMASH in 1960th. Multi-Mode TAL concept means the thruster possibility to operate in wide characteristics range. It fully implements advantages of the two-stage TAL scheme. Two-stage scheme allows flexible regulation in unique operation range for Hall thrusters with anode layer. Based on design D-100 (two-stage) and D-55/TAL-WSF (one-stage) new generation multi-mode thruster was developed and thoroughly researched since 1999. Current R&D status of the thruster presented in the paper.

Nomenclature

V_d	=	Discharge voltage (1st Stage)
I_d	=	Discharge current
V_a	=	Acceleration voltage (2nd stage)
I_d	=	Acceleration stage current
V_{sum}	=	Summary Voltage ($V_d + V_a$)
m_a	=	Anode mass flow (Xe)
m_c	=	Cathode mass flow (Xe)
V_{inn}	=	Inner magnet coil voltage
I_{inn}	=	Inner magnet coil current
V_{out}	=	Outer magnet coils voltage
I_{out}	=	Outer magnet coils current

* Group Leader, Electric Propulsion Laboratory, asolodukhin@mtu-net.ru
† Head of Laboratory, Electric Propulsion Laboratory, avs@tse.ru
‡ Deputy Head of Department, Electric Propulsion Laboratory, avs@tse.ru
§ Group Leader, Electric Propulsion Laboratory, avs@tse.ru
** Post-graduate Student, Moscow State University, karabadzhak@mail.ru
†† Senior Scientist, Development Department, fakel@gazinter.net

N	=	Power
V_f	=	Floating potential
I_{sp}	=	Specific impulse
F	=	Thrust
L	=	Discharge channel length
t	=	Time

I. Introduction

TsNIIMASH has a long-term experience of TAL research and development which allowed to develop new generation multi-mode TAL called D-80[1,2,3,4,5,6]. For the purpose of providing long lifetime and wide range characteristics throttle ability D-80 design implemented technical solutions realized in D-55/TAL-WSF (external anode layer) and D-100 (two-stage scheme). Multi-mode thrusters can find application in multifunctional EPS for providing different kinds of missions (e.g. SC orbit raising and station keeping)[7].

Previous investigations resulted in the following:

Several D-80 modifications were experimentally studied at different electrical schemes and operating modes. Effective operating of the one and the same hardware in the wide operating envelope was demonstrated.

- Thrust regulation range: 5…25 G;
- Specific Impulse regulation range: 1200…3200 s;
- Power regulation range: 600…4500 W.

Erosion tests of the multi-mode thruster had been carried out at NASA GRC and TsNIIMASH. Construction elements erosion rates of several thruster modifications with different discharge channel length operating in different modes were obtained.

Current research activity is aimed on continuation of thruster parameters optimization. Thus in the frames of joint development program new test series of multi-mode TAL D-80 samples have been carried out at TsNIIMASH and EDB "FAKEL" facilities.

II. Testing Goals and Objectives

A. Goals and Objectives

Experimental research goals:

1) Multi-mode TAL D-80 testing at EDB "FAKEL" test-qualified facility with cryogenic pumping. Comparison of D-80 characteristics measured in one- and two-stage connection schemes.
2) Erosion testing of D-80 modification with near-zero discharge channel length at TsNIIMASH facility, including special test series aimed on the first stage cathode erosion analysis with help of spectroscopic method.

B. Brief D-80 Design Description

The thruster consists of two main parts:

1) Magnet system.
2) Anode unit.

Magnet system, in turns, consists of following main components:

- mounting flange (#6);
- inner magnet coil with magnetic pole (#3);
- outer magnet coils (#4);
- outer pole piece (#5).

The anode unit is mounted on magnet mounting flange. It includes gas distributing anode (#1), first stage cathode (#2), guard rings (#7), insulators (#8), screen (#9). Anode unit components which are under different potential are isolated from each other with the help of insulators (#8). Magnet system poles are protected from ion sputtering by guard rings (#7).

Mainly radial magnet field is formed between magnet system poles. Voltages from power supplies are applied between the anode, the first stage cathode and channel walls (guard rings), the latter electrically connected with the cathode-neutralizer. Thus discharge with closed drift of electrons in crossed electric and magnet fields is appeared. Propellant entering into the discharge is ionized and accelerated. While operating in two-stage scheme ionization and consequent acceleration are realized in two separate discharges: in the discharge stage (first discharge) almost full propellant ionization occurs, and ions acceleration takes place in the acceleration stage (second discharge).While operating in one-stage scheme voltage is applied only to the second stage, thus ionization and acceleration happen in one discharge.

The thruster characteristics detailed study confirmed that the thruster can operate as well in one-stage scheme typical for modern Hall thrusters as in two-stage scheme. The change from one scheme to another does not require the thruster design modification and can be accomplished by power supply scheme change.

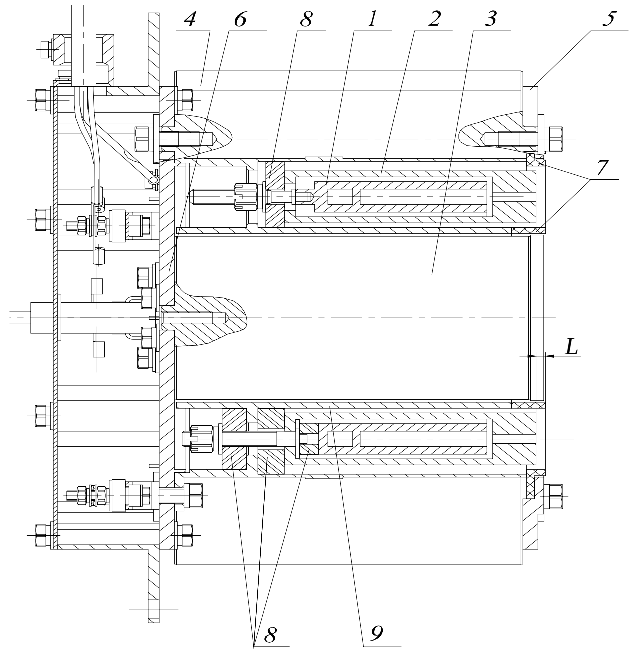


Figure 1. D-80 principle design scheme.

D-80 modification with discharge channel length L ~ 1.8 mm was tested at EDB "FAKEL", while for erosion testing in TsNIIMASH discharge channel length was sharply decreased down to L ~ 0.2 mm.

III. Test Procedure

A. Facility and Hardware Description

Photos of D-80 at EDB "FAKEL" and TsNIIMASH facility are presented in Fig. 2 and Fig. 3 correspondingly. For testing at EDB "FAKEL" facility cathode-neutralizer KN-3B was utilized while for testing at TsNIIMASH laboratory multi-purpose cathode-neutralizer with discharge current up to 10 amperes was used.

Figure 2. D-80 prepared for testing at EDB "FAKEL" facility.

Figure 3. D-80 photo at TsNIIMASH facility.

1. EDB "FAKEL" facility

The facility contains two cylindrical compartments of 2.5 m diameter each (see Fig.4). The length of cylindrical part of the fire compartment, where the thruster is installed, is 5 m and its volume is about 30 m^3. Volume of maintenance compartment is about 15 m^3. Compartments are combined with help of 1.2 m diameter branch pipe. There are two cryogenic pumps at the end of the fire compartment. Their pumping speed is about 110 000 liters per second (estimated for air). Tank pressure for considered D-80 modes was not more than 6×10^{-5} torr (not corrected for Xe). There is thermal screen realized as a shutter in front of cryogenic pumps meant for defense from thruster plasma plume. The thruster was mounted at the thrust arm located at maintenance compartment.

Plume divergence measurements are realized by multigrid probe mounted at tilting device. Ion current angular distribution was taken at one meter distance from the thruster. To cut off the electron component, the first grid potential was -20 V and to cut off thermal ions the collector potential was +20 V.

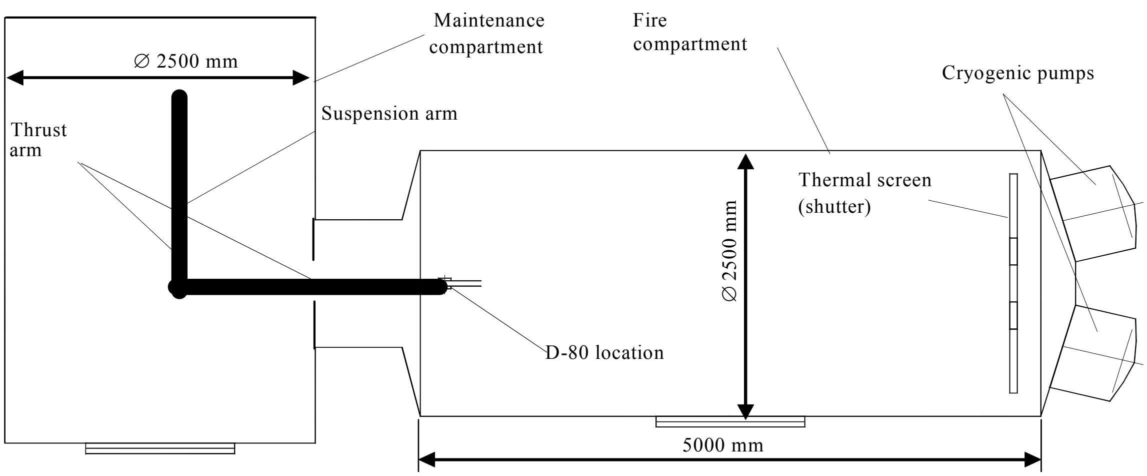


Figure 4. EDB "FAKEL" test facility scheme.

2. TsNIIMASH facility

TsNIIMASH vacuum chambers of 5 cubic meters equipped with 5 oil diffusion pumps and with forvacuum mechanical pumps was used to run the thruster. The general view of the test facility with measuring equipment is shown in Figure 6. Vacuum tank is equipped with power supply and xenon management systems and measurement equipment. Vacuum system had provided tank pressure no more than 2×10^{-4} torr (not corrected for Xe) for all tested D-80 modes. The test facility had a quartz window where spectrometric equipment was mounted, it was used for measurements of the discharge plasma electron temperature and thruster erosion rate variation.

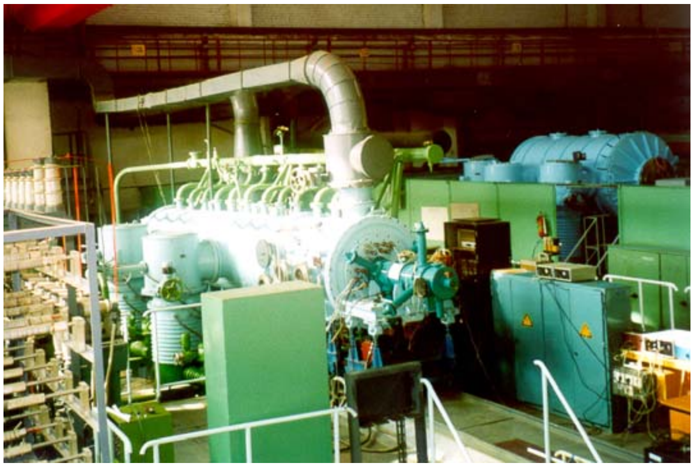


Figure 5. TsNIIMASH facility photo.

3. *General info of power supplies used and measurement accuracy*

For D-80 testing commercially available power supplies were used. Their characteristics are given in Table 1. Measurement accuracy of parameters is given in Table 2.

Table 1. Power supplies characteristics.

Circuit	Voltage range, V	Current range, A	Control accuracy	Additional information
The first stage	0…500	0…25	1% ±1 V	Constant-voltage
The second stage	0…1000	0…25	1% ±1 V	Constant-voltage
Inner magnet coil	0…30	0…6	1% ±0.01 A	Constant-current
Outer magnet coils	0…30	0…6	1% ±0.01 A	Constant-current

Table 2. Accuracy characteristics of measurement equipments.

Measured parameter	Sign	Measurement range	Accuracy
Thrust, G	F	0…15	2.5%
First stage voltage, V	U_d	0…500	0.5%
First stage current, A	I_d	0…10	0.5%
Second stage voltage, V	U_a	0…1000	0.5%
Second stage current, A	I_a	0…10	0.5%
Anode flow rate of xenon, mg/s	m_a	0…6	3%
Cathode flow rate of xenon, mg/s	m_c	0…0.6	3%
Inner magnet coil current, A	I_{inn}	0…6	0.5%
Inner magnet coil voltage, V	V_{inn}	0…30	0.5%
Outer magnet coils current, A	I_{out}	0…6	0.5%
Outer magnet coils voltage, V	V_{out}	0….30	0.5%
Floating potential, V	V_f	0…30	0.5%
Vacuum chamber pressure, torr	P_c	$10^{-6}…10^{-4}$	60%
Thruster elements temperature, °C	$T_1…T_4$	0…400	3%
Ion current density angle distribution, μA/cm^2	$j_i(\beta)$	5…2000	10%

B. Testing Program

1. *At the EDB "FAKEL" facility*

D-80 multimode two-stage thruster was tested in one-stage and two-stage and FE connection schemes. Four distinctive mass flow rates of the thruster operating envelope were chosen: 3.0, 3.5 (relatively low mass flow rate values) and 4.0, 4.7 mg/s (average mass flow rate values). Maximal summary voltage was limited by stable operating in one-stage scheme (900 V). For two-stage scheme the first stage voltage value was constant ~ 125 V. Magnet coils was optimized by minimum acceleration stage current criterion. Cathode mass flow rate value was constant ~ 0.4 mg/s. Especial test series aimed on thruster parameters optimization (I_{sp} and Efficiency) by changing cathode mass flow rate value (0.1…0.4 mg/s) was made. Thruster thermal characteristics was measured in one-stage scheme (700 V, 4.25 A). In one- and two-stage schemes (low voltage and high voltage modes) ion current angular distributions were taken.

2. *At the TsNIIMASH facility*

Before erosion testing parameters of D-80 modifications with different discharge channel length (L~6 mm, L~1.8 mm and L~0.2 mm) were compared. Erosion testing of D-80 modification with discharge channel L~0.2 mm was carried out in two-stage scheme and high voltage mode. Erosion tests of new modification were carried out. Total testing time was about 100 hours. Since in two-stage connection scheme and high voltage mode there was maximal erosion this mode were chosen for erosion testing. For erosion tests acceleration guard rings made of stainless steel were used. Stainless steel erosion rate is significantly higher than erosion rate of pyrolitic graphite, which is generally used for the thruster parts under the ion sputtering.

The guard ring material replacement was repeatedly proved before for the erosion test acceleration[8]. Stainless steel erosion rate can be converted to pyrolitic graphite erosion rate with the help of experimental coefficients obtained for this pair of materials and energy of xenon ions corresponding to the thruster operating modes. Ratio between the erosion rates of stainless steel and graphite is usually in the range of 5…7. Guard rings material does not influence on the other thruster characteristics that was repeatedly proved by dedicated experiments on D-80. During the testing the erosion rate variation was also controlled by spectroscopic method[9]. Material replacement method was also utilized during special testing series aimed on the first stage cathodes erosion rate measurement by spectroscopic equipment. Usually first stage cathodes are made of the same material as guard rings (pyrolitic graphite). To measure the first stage cathode erosion rate graphite was replaced by molybdenum.

IV. Results and Discussion

A. Analysis of experimental data obtained at EDB "FAKEL" facility.

1. Comparison of characteristics obtained in one- and two-stage schemes

D-80 characteristics obtained at one and two-stage schemes are presented in Fig. 6-10. As one can see volt-ampere characteristics (Fig. 6) and correspondingly power vs. summary voltage characteristics (Fig. 7) are almost the same. While thrust (Fig. 8), specific impulse (Fig. 9) and efficiency (Fig.10) characteristics are different. Two-stage scheme is preferable. Two-stage scheme characteristics values (thrust, specific impulse and efficiency) exceed one-stage characteristics values. The largest values difference was measured at lowest mass flow rate (3 mg/s). So for this mass flow rate ion current density angular distribution was investigated (Fig. 10). Distributions for one-stage scheme modes (300 V, 400 V and 700 V discharge voltage values) and for two-stage scheme modes (first stage voltage 125 V and 300 V, 600 V, 700 V second stage voltage values).

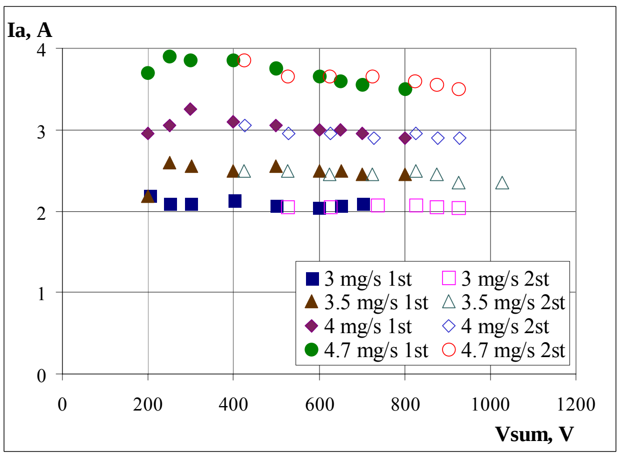


Figure 7. Volt-ampere characteristics.

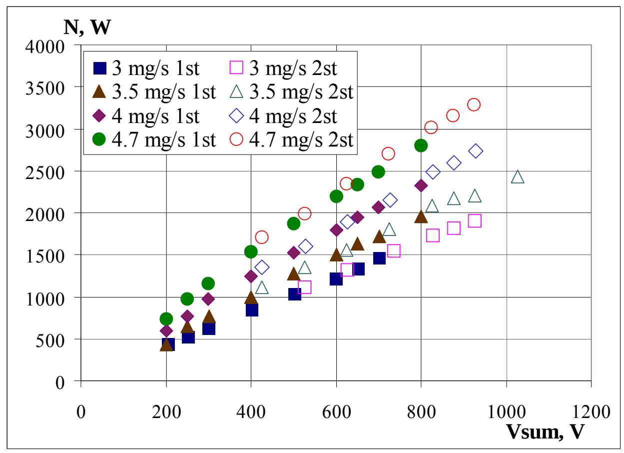


Figure 8. Power versus summary voltage.

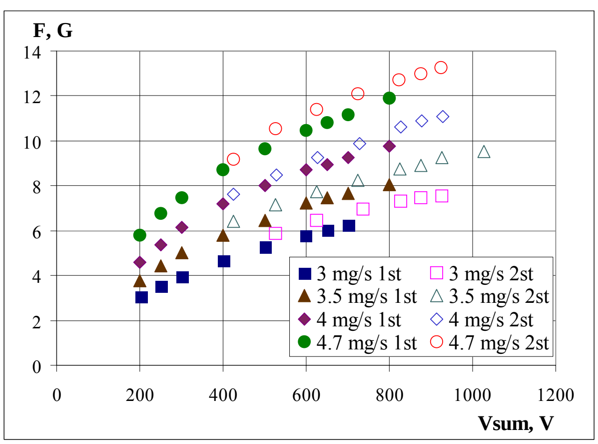


Figure 6. Thrust versus summary voltage.

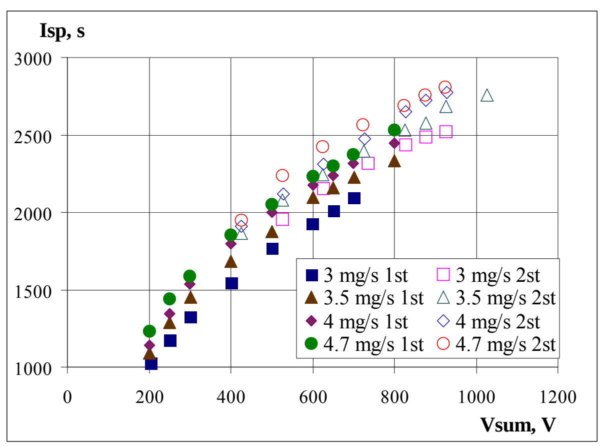


Figure 9. Specific impulse versus summary voltage.

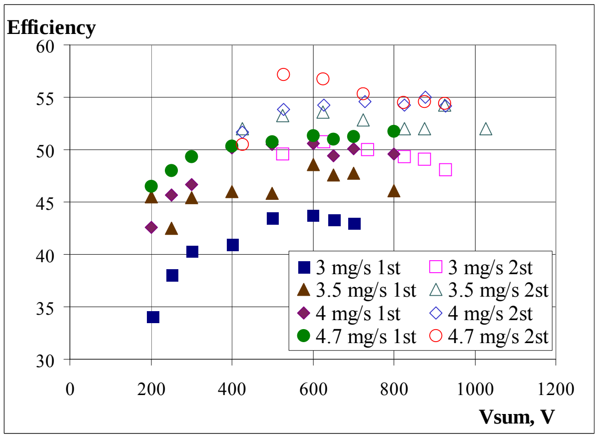


Figure 11. Efficiency versus summary voltage.

Figure 10 illustrates that plume divergence for one-stage scheme modes bigger than for two-stage scheme modes. Obtained experimental data was calculated and for two-stage scheme modes (first stage voltage 125 V and 600 V, 700 V second stage voltage values) full angle of plume divergence determined by 90% of ion current was lesser than 60 degree.

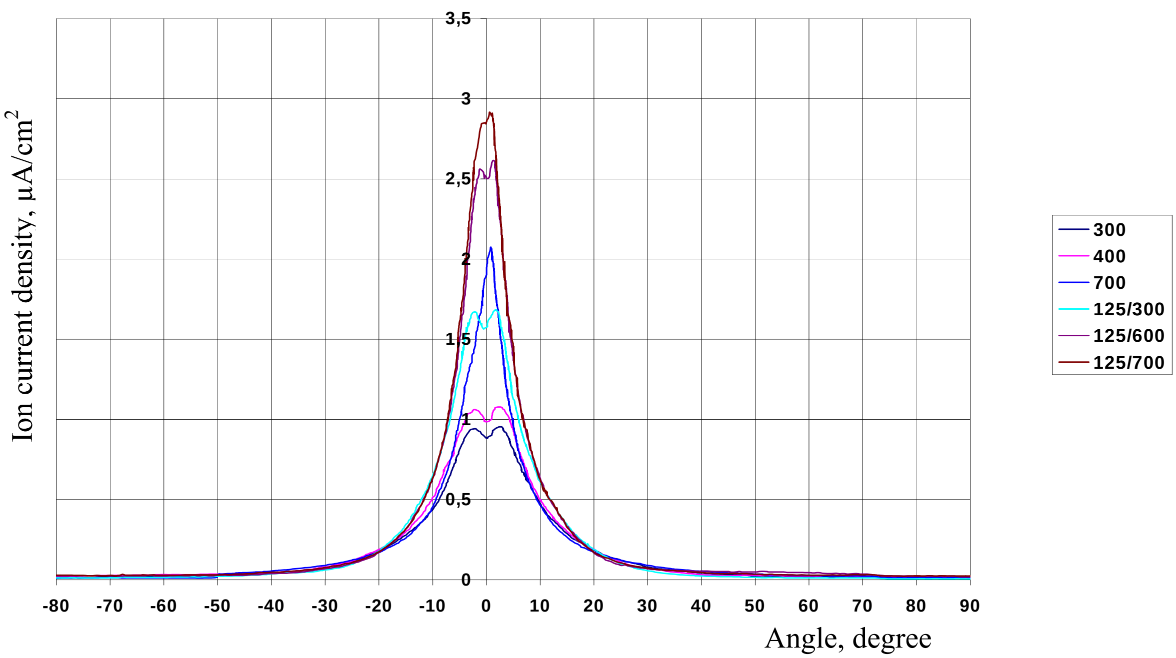


Figure 10. D-80 ion current density angular distribution.

2. Results of thermal test.

To verify thermal properties of D-80 design the thruster was stationary operated at one-stage scheme mode during two and half of an hour with following parameters:

– Discharge voltage 700 V;
– Discharge current 4.25 A;
– Power 3000 W.

Magnet coils current values were optimized by criteria of discharge current minimum and were not changed during the testing. The thruster characteristics were stable (see Table 3), thermal equilibrium condition was determined by measured construction elements temperatures and magnet coils circuit voltages.

Temperature measured by thermocouples at following construction elements:

– Outer pole piece – 280 °C;

Table 3. Thermal testing characteristics

t	I_a	V_a	m_a	F	V_f	I_{out}	V_{out}	I_{inn}	V_{inn}	Eff.	I_{sp}	N
min	A	V	mg/s	G	V	A	V	A	V	%	s	W
20	4.25	701	5.34	12.98	17.9	0.76	6.5	1.01	6.55	51.0	2431	2991
40	4.23	700	5.34	13.04	16.7	0.76	6.65	1.01	6.55	51.7	2442	2973
60	4.22	700	5.34	13.12	16.0	0.77	6.9	1.03	6.80	52.5	2457	2966
90	4.22	700	5.34	13.11	17.2	0.75	7.0	1.01	6.95	52.4	2455	2966
120	4.22	700	5.34	13.18	17.0	0.75	7.1	1.03	7.05	53.0	2468	2967
140	4.23	700	5.34	13.20	16.9	0.75	7.1	1.01	7.05	53.0	2472	2973

- Outer magnet coil core – 208 °C;
- Inner magnet coil core – 220 °C;
- Mounting flange – 196 °C.

Resulting temperatures showed that the thruster was "cold", and it can be operated in modes with discharge power 4000…5000 W.

More detailed two-stage TAL thermal investigations results are given in this conference paper[10].

3. *Thruster specific impulse and efficiency optimization by cathode mass flow rate changing.*

Results of thruster parameters optimization by cathode mass flow changing are given in Fig. 12-15. One-stage low voltage mode and two-stage high voltage mode were considered. As one can see for one-stage low voltage mode optimal cathode mass flow rate value was within range 0.2…0.4 mg/s. While for two-stage high voltage mode minimal cathode mass flow rate value (0.1 mg/s) was preferred.

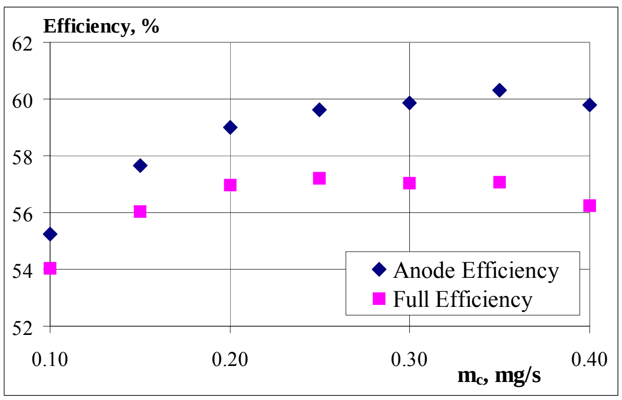


Figure 12. Efficiency vs. cathode mass flow rate, one-stage scheme low voltage mode.

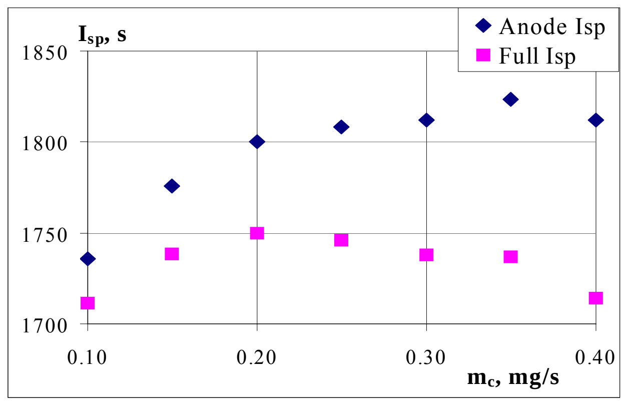


Figure 15. I_{sp} vs. cathode mass flow rate, one-stage scheme low voltage mode.

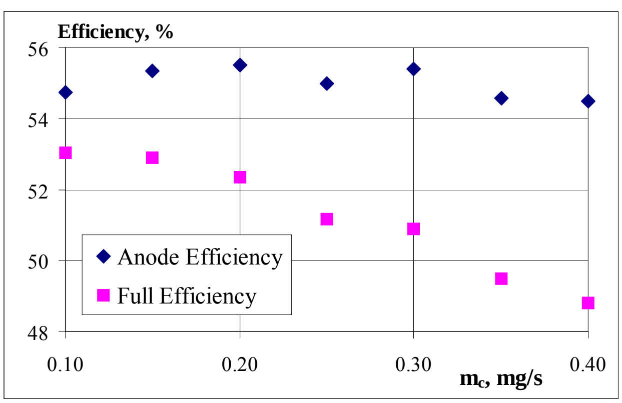


Figure 14. Efficiency vs. cathode mass flow rate, two-stage scheme high voltage mode.

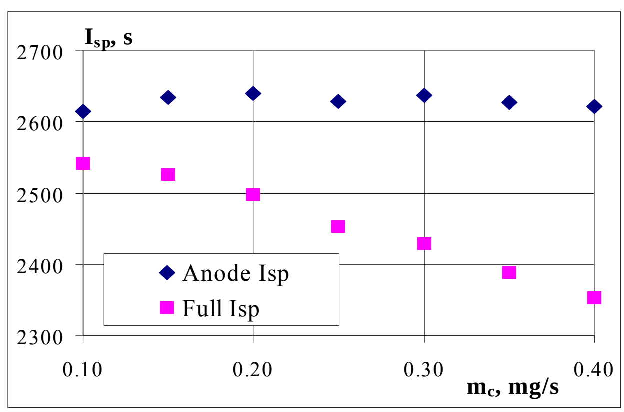


Figure 13. I_{sp} vs. cathode mass flow rate, two-stage scheme high voltage mode.

B. Analysis of erosion tests data obtained at TsNIIMASH facility.

1. Brief description of previously obtained erosion tests results.

To provide multi-mode TAL lifetime several objectives should be investigated:

1) To investigate the thruster construction elements dependence of connection scheme (one- or two-stage) and operating mode (low- or high voltage).
2) To prove the possibility of significant construction elements erosion rate decreasing by discharge channel length reduction (at the same time saving the thrust efficiency).

As a result the final thruster design should be chosen and the lifetime should be proven. There are several ways to provide required lifetime:

– Construction elements manufacturing from sputter resistant materials;
– Construction elements thickness increasing;
– Scheme with external anode layer realizing by discharge channel length L decreasing (see Fig. 1).

The last way is the most effective it practically allows to exclude construction elements direct sputtering by ion flux. External anode layer scheme was demonstrated in D-55[11] (TAL-WSF) and TAL-110[12] design.

Two-stage xenon TAL lifetime research activity began in the frames of D-80 erosion testing in NASA GRC. The first modification of D-80 with L ~ 3 mm was tested in one-stage connection scheme and V_d= 700 V, I_d= 4 A mode. Total testing time was 1200 hours. After every 300 hours the thruster discharge channel profiles were taken. Results are given in the table 4 and figure 16.

As one can see, erosion of magnet system poles began in the range of 600…900 hours. In spite of magnet system poles erosion thrust value was not changed. Average thrust value was 118 mN and data spread was about ±2% that is within thrust measurement accuracy.

Table 4. Thruster elements volume erosion rate mm^3 per hour

Hours	0-300	300-600	600-900	900-1200
Inner Guard Ring	1.06	0.41	0.24	0.18
Outer Guard Ring	1.76	1.19	0.67	0.4
Inner pole piece	0.1	0	0.07	0.26
Outer pole piece	0	0.12	0.48	1.18

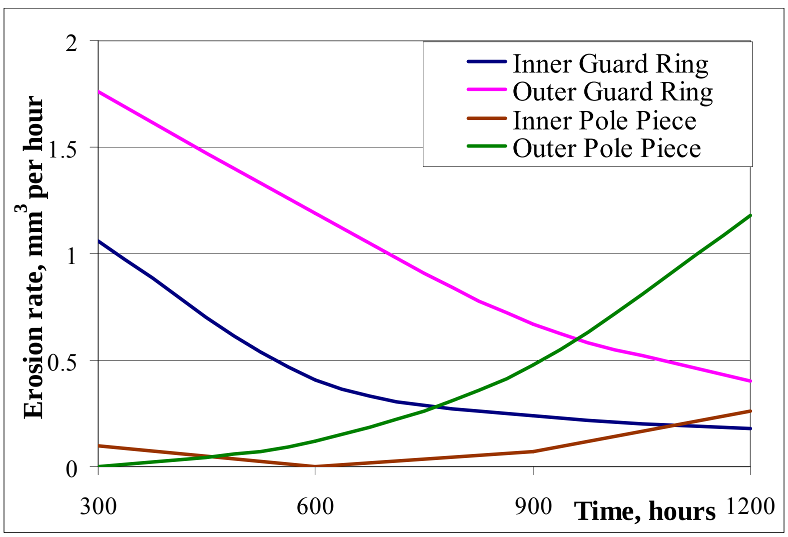


Figure 16. Volume erosion rate versus operating time.

For multi-mode thruster it is needed to investigate erosion rate in whole thruster operating range. Thus the second erosion tests series was aimed for studying erosion rate characteristics dependence from the thruster connection scheme and operating mode.

In comparison with the thruster tested at NASA GRC the next version of D-80 thruster was modified using the previous experimental experience and results of the first erosion tests. The main difference between them is the discharge channel length. The length was reduced from 3 mm down to 1.8 mm to prove the feasibility erosion rate decreasing in comparison with base design. Another difference is the material of guard rings. As it was mentioned above, for erosion tests acceleration guard rings made of stainless steel were used.

Erosion characteristics in one- and two-stage schemes low and high voltage modes were compared:

1) One-stage scheme, High voltage mode.
2) Two-stage scheme, High voltage mode.
3) One-stage scheme, Low voltage mode.

Concrete operating parameters for every mode were chosen in accordance with the following thoughts:

– To compare with NASA GRC erosion tests results one-stage high voltage mode

– To make easier results comparison input power should be equal in all modes.

– At high voltage modes summary voltage applied should be at least twice as much voltage applied at low voltage mode.

Selected parameters are given in Table 5.

Obtained data of stainless steel guard ring erosion rates with help of coefficients were recalculated for pyrolitic graphite (see Table 6). Data analysis showed:

1) Erosion characteristics in one-stage scheme in low voltage mode accurate within to measurement error coincided with ones of D-55 and TAL-110 in comparable modes. One-stage scheme, High voltage mode.
2) Erosion rate in high voltage modes significantly exceeded one in low voltage in spite of the fact that the input power was the same in all modes.

Since D-80 erosion rate in low voltage mode coincides with erosion rates of D-55 and TAL-110 thrusters in comparable modes all previous experience of one-stage thruster lifetime providing is also fully applicable for D-80. It means that the D-80 lifetime equal to 5000…10000 hours in low voltage mode can be provided.

The same order of erosion rate magnitude obtained at NASA GRC and at TsNIIMASH data proves its significant growing due to voltage doubling, i.e. the growing can not be explained by specific character of the tests. On the other hand, the discharge channel length reducing allowed to decrease erosion rate as compared with the previous thruster version (see Table 4, column 0-300 and Table 6). There is a possibility of further design optimization to provide required lifetime in high voltage modes.

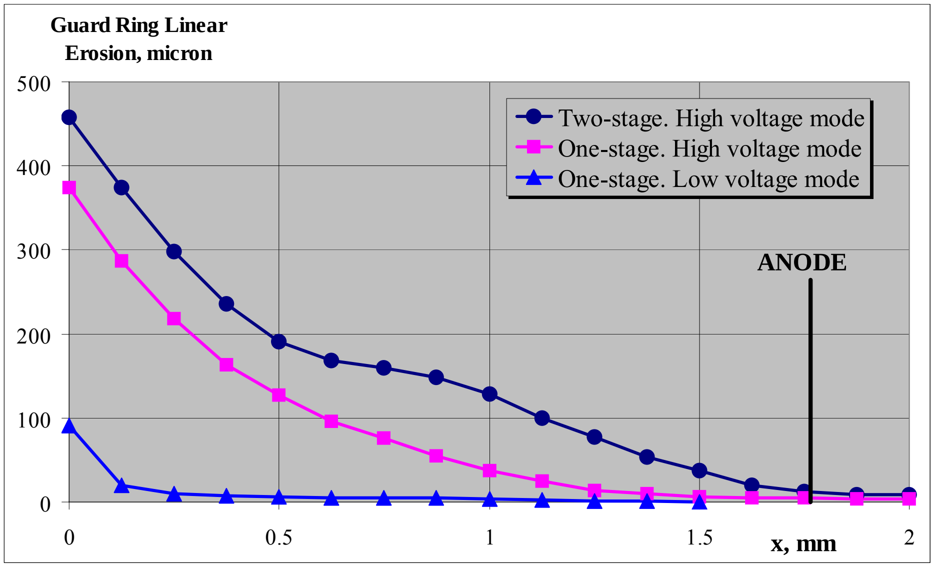
Table 5. Thruster parameters in tested modes/schemes.

MODE/ PARAMETER	One-stage, High voltage	Two-stage, High voltage	One-stage, Low voltage
m_a, mg/s	4.7 ± 0.1	4.7 ± 0.1	7.95 ± 0.1
V_d, V	705 ± 5	125 ± 5	355 ± 5
I_d, A	4.1 ± 0.1	4.4 ± 0.1	7.8 ± 0.1
V_a, V	—//—	575 ± 5	—//—
I_a, A	—//—	4.0 ± 0.1	—//—
N, W	2891 ± 91	2851 ± 112	2770 ± 75
F, mN	114…123	124…128	161…169

Table 6. Thruster elements volume erosion rate mm^3 per hour

Mode/ Thruster Part	Two-stage, High voltage	One-stage, High voltage	One-stage, Low voltage
Inner Guard Ring	0.58	0.36	0.04
Outer Guard Ring	0.51	0.3	0.04
Inner pole piece	--//--	--//--	--//--
Outer pole piece	--//--	--//--	--//--

Note: stainless steel erosion rate values are recalculated for pyrolitic graphite.



2. *Testing of new modification of D-80.*

In order to decrease erosion rate significantly it was decided to reduce the discharge channel length down to 0.2 mm. Before the erosion testing discharge channel length influence on the thruster parameters was determined. Several D-80 modifications with different L (6 mm, 1.8 mm 0.2 mm) were tested at mass flow rate ~ 3.5 mg/s (see Fig. 18 and Fig. 19).

Modification with L = 6 mm provided the most efficient operation, but in aggregate with largest erosion rate. Modification with L = 0.2 mm showed acceptable characteristics, its thrust parameters are almost coincide with parameters of modification with L = 1.8 mm, which was tested earlier.

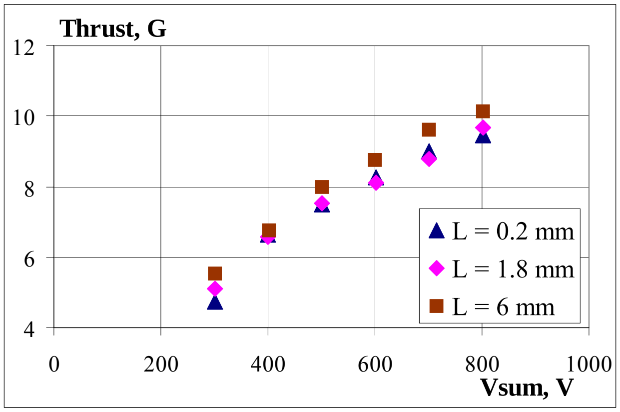


Figure 18. Thrust versus summary voltage.

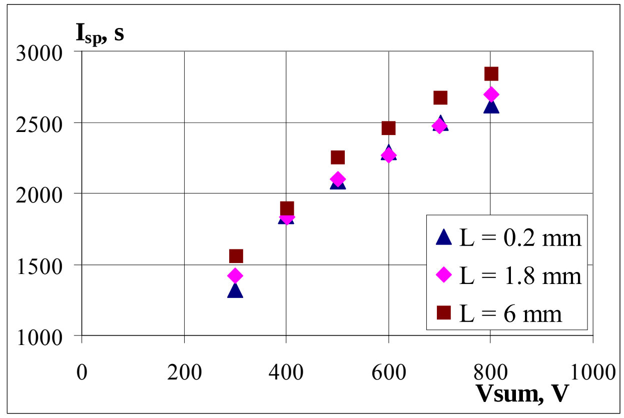


Figure 19. Specific impulse versus summary voltage.

Since in two-stage connection scheme and high voltage mode there was maximal erosion rate value, this mode was chosen for erosion testing. Total firing time of the new modification erosion testing was about 100 hours.

The thruster characteristics changing during the erosion testing are given in Table 7 and Figures 20-22 (voltages, currents and thrust). Characteristics values measurements were taken every hour.

Table 7. Thruster parameters during erosion testing.

Parameter	Range of measured values
m_a, mg/s	4.6 ± 0.1
V_d, V	125…128
I_d, A	4.1…4.2
V_a, V	575…580
I_a, A	3.83…4.0
N, W	2730…2810
F, G	11.75…12.19

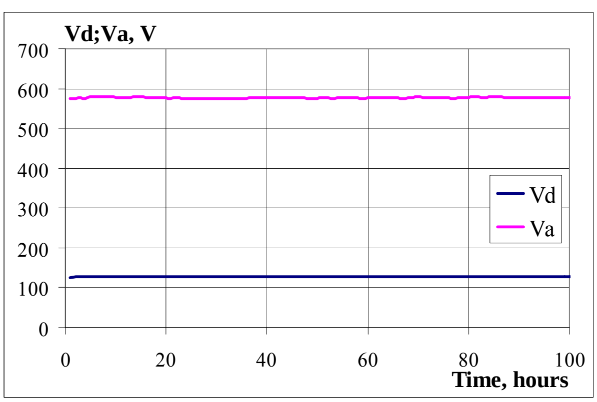


Figure 21. Voltages changing during the 100 hours of erosion testing.

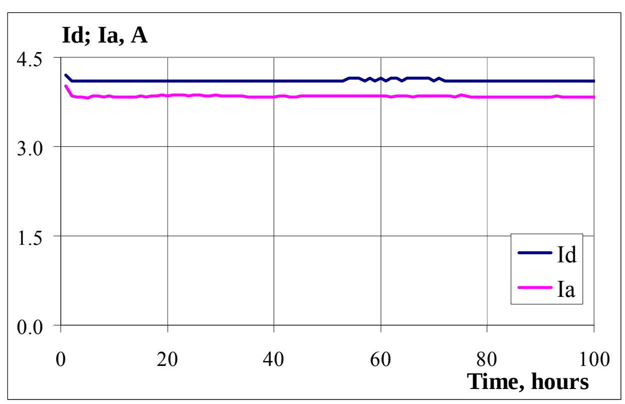


Figure 20. Currents changing during the 100 hours of erosion testing.

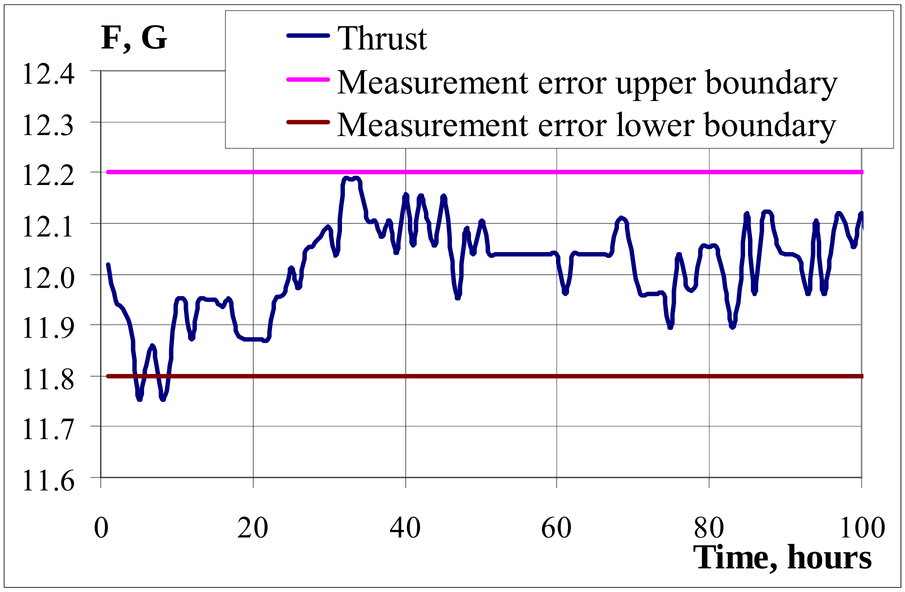


Figure 22. Thrust changing during 100 hours of erosion testing.

Analysis of measured parameters showed that the thruster was stable during testing. Thrust changing was within accuracy measurements range.

Before and after testing thruster parts were weighed. Their eroded mass values are given in Table 8

Table 8. Mass of thruster parts eroded material

Thruster part	Material	Eroded mass, g
Inner Pole Guard Ring	Stainless Steel	0.36
Outer Pole Guard Ring	Stainless Steel	0.73
Inner Pole Piece	Permendur	0.04
Outer Pole Piece	Permendur	0.63

Table 9. Average erosion rate of D-80 different modifications parts, mm^3 per hour.

	One-stage scheme, high voltage mode			Two-stage scheme, high voltage mode	
Thruster part	3 mm 0-300 h	3 mm 900-1200 h	1.8 mm 0-30 h	1.8 mm 0-30 h	0.2 mm 0-100 h
Inner Pole Guard Ring	1.06	0.18	0.36	0.51	0.08
Outer Pole Guard Ring	1.76	0.4	0.3	0.58	0.17
Inner Pole Piece	0.1	0.26	--//--	--//--	0.05
Outer Pole Piece	0	1.18	--//--	--//--	0.81

Note: stainless steel erosion rate values for 1.8 mm and 0.2 mm modifications are recalculated for pyrolitic graphite.

Obtained results showed that D-80 with near-zero discharge channel length (L ~ 0.2 mm) has significantly lower erosion rate. In comparison with L~1.8 mm and L~3 mm modifications it is in five and in ten times lesser correspondingly. Thruster photos taken before and after erosion testing are given in Appendix. During testing cathode was located at 6 o'clock position (see Fig. 3).

At the detail thruster inspection following effects were revealed:

1) Discharge channel erosion azimuthal inhomogeneity. For example there are no traces of erosion in significant section of thruster discharge channel (from six to nine o'clock sector). And there is maximum level of erosion in opposite section (from twelve to three o'clock).

2) Clear dependence between small-scale chips of the first stage cathodes and erosion traces in the guard rings is defined. The first stage cathode parts made of pyrolitic graphite were chipped at the manufacturing stage, typical chip size is about 0.2 mm.

So in spite the fact that absolute values of erosion rate were minimal, azimuthal inhomogeneity of erosion rate and local intensification of erosion may be a problem for flight hardware with 10000 hours of lifetime development. Revealed effects should be investigated in detail.

Similar discharge channel erosion azimuthal inhomogeneity was observed earlier during TAL-110 testing at JPL. The most probably it was connected with cathode operating mode and its location. However this local erosion intensification was not appeared in all testing series, for example it was absent during 1000 hours testing at TsNIIMASH. Luck of data does not allow to state exact criteria for thruster operating mode controlling and for prediction of local zone with erosion intensification appearing.

Spectroscopic method could help to obtain data needed for discharge channel erosion azimuthal inhomogeneity analysis, for that spectra at several different discharge channel sections should be taken. Unfortunately during last erosion testing spectra of whole thruster discharge was measured. This measurement only showed that summary erosion rate of both guard rings was almost constant during the testing time.

At the end of the 100 hours testing, spectra in different operating modes were measured. Results are given in Figure 23. Thruster mass flow rate was constant as well as magnet coils currents, only summary voltage and power were changed. Of course data binding between obtained spectra and erosion mass was made for mode with summary voltage ~ 700 V (see Table 7).

Another test series directed for the erosion of the first stage cathode was carried out. For this graphite first stage

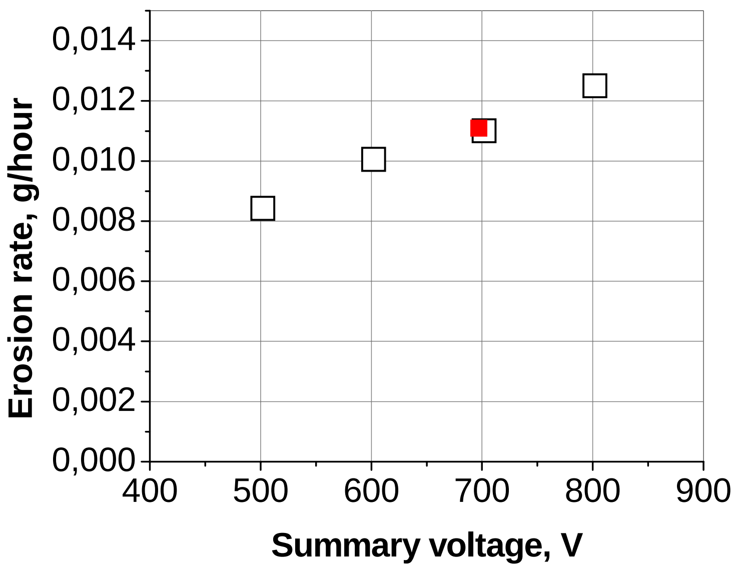


Figure 23. Erosion rate versus summary voltage.

cathode parts were replaced by molybdenum ones. To make sure that change of the material does not influence on thruster characteristics comparison test was carried out (see Figure 24 and 25).

Test procedure was the following. Thruster was operated in two-stage scheme, mass flow rate was constant (4.7 mg/s), second stage voltage was also constant (500 V). The first stage voltage was varied within range 0…200 V. Typical thruster characteristics (currents and efficiency) versus discharge voltage are given in Figure 26 for reference. Normalized erosion rate values measured by spectroscopic method are given in Figure 27. Strong nonlinear dependence between erosion rate and the first stage voltage can be seen and it can not be explained by sputtering coefficient changing versus xenon ion energy, since molybdenum sputtering coefficient characteristic versus xenon ion energy has a linear behavior. More likely with the first stage voltage increasing xenon ionization zone has shifted. Nevertheless detail research of this issue is planned.

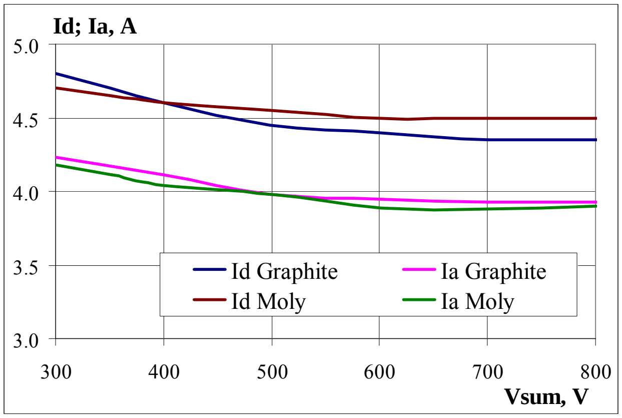


Figure 24. The first and the second stages currents vs. summary voltage, graphite and moly modifications.

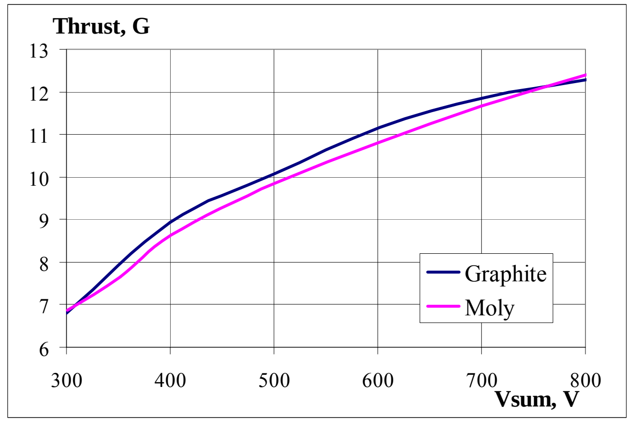


Figure 25. Thrust vs. summary voltage, graphite and moly modifications.

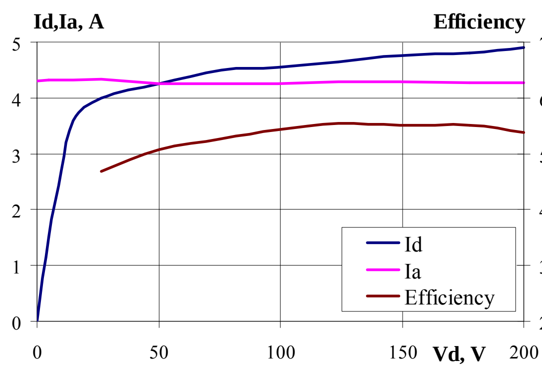


Figure 26. The first and the second stages currents and efficiency vs. the first stage voltage.

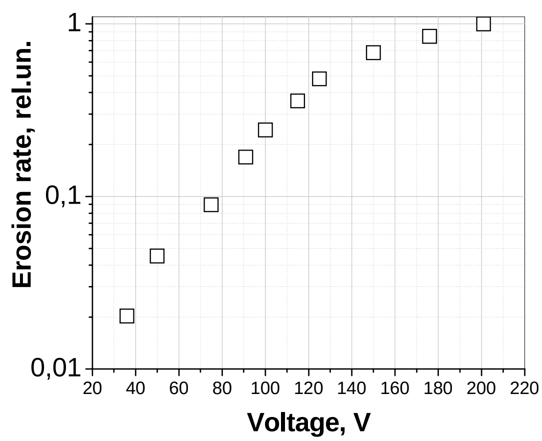


Figure 27. Erosion rate versus the first stage voltage.

V. Conclusion

Parametric testing of multi-mode TAL D-80 was carried out at EDB "FAKEL" facility. The thruster characteristics in one- and two-stage are measured. Analysis of the D-80 parameters shows that two-stage scheme is preferred for given mass flow rates (3.0, 3.5, 4.0 and 4.7 mg/s). Minimal plume divergence value was also measured in two-stage scheme, full angle of plume divergence determined by 90% of ion current was lesser than 60 degree. Cathode mass flow rate influence on the thruster parameters was investigated.

In order to increase the thruster lifetime erosion testing of new D-80 modification with near-zero discharge channel length (L=0.2 mm) was carried out. During erosion tests the thruster characteristics were stable, thrust fluctuation was within accuracy range of measurement equipment. In comparison with previous modification the construction elements erosion rate values were significantly decreased, however some new effects were revealed.

The first stage cathode parts erosion rate values were measured with help of spectroscopic method. It allows optimizing thruster operating mode taking into account the first stage parts lifetime.

Multi-mode TAL lifetime investigations and further thruster design optimization will be continued.

Appendix

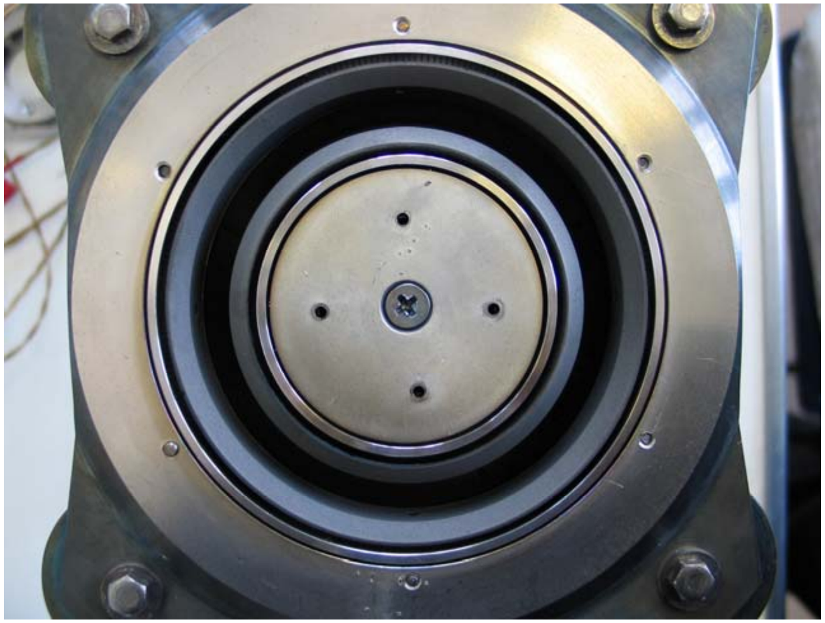


Figure 29. Before erosion testing, top view.

Figure 28. After erosion testing, top view.

Figure 30. Before erosion testing, 12 o'clock, camera location 3 o'clock.

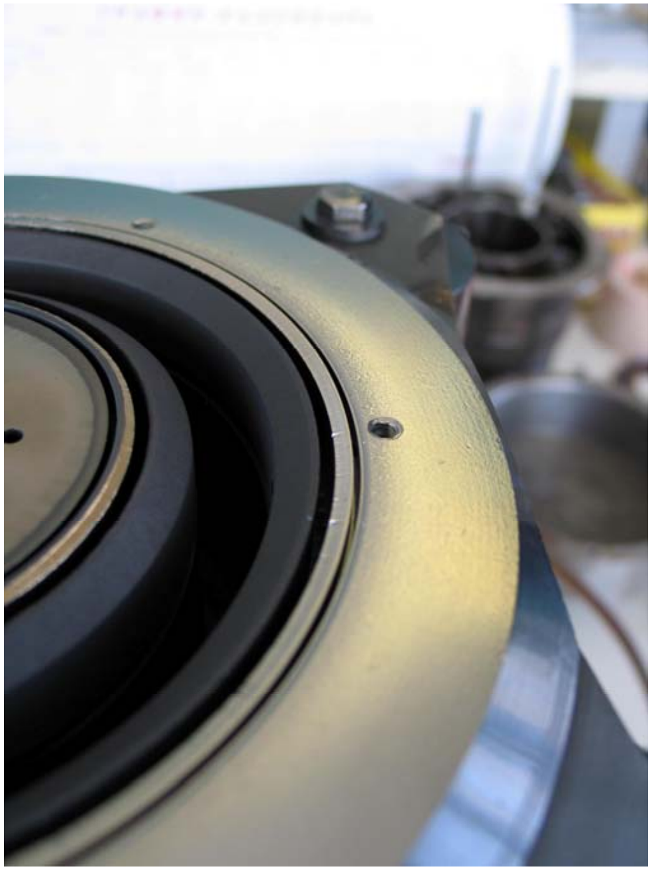


Figure 31. After erosion testing, 12 o'clock, camera location 3 o'clock.

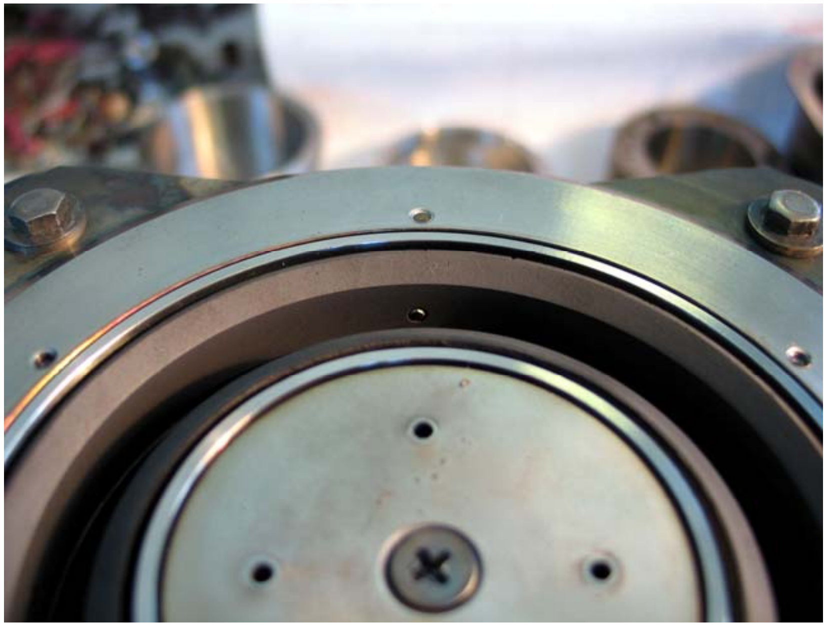


Figure 32. Before erosion testing, 12 o'clock, camera location 6 o'clock.

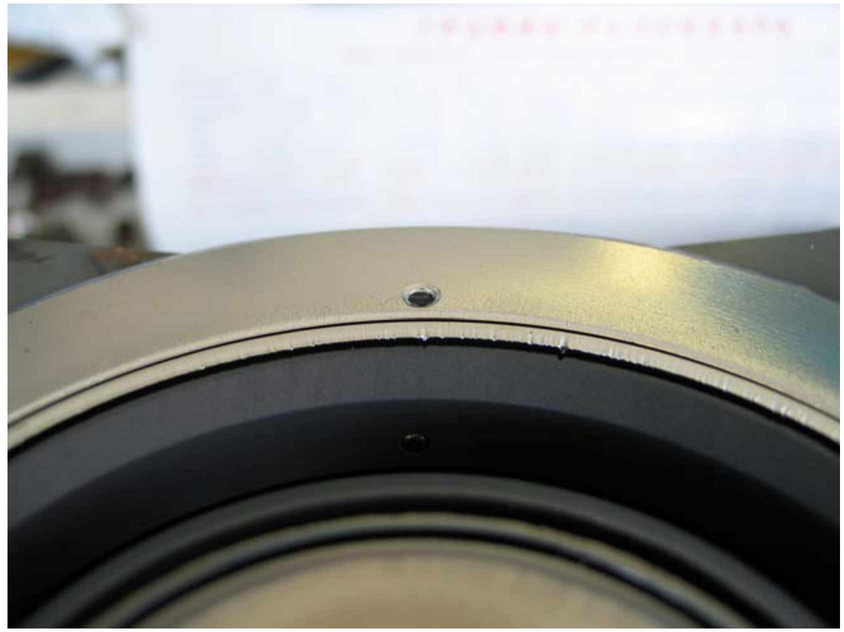


Figure 33. After erosion testing, 12 o'clock, camera location 6 o'clock.

Figure 35. Before erosion testing, 6 o'clock, camera location 3 o'clock.

Figure 34. After erosion testing, 6 o'clock, camera location 3 o'clock.

Figure 36. Before erosion testing, 12 o'clock, camera location 6 o'clock.

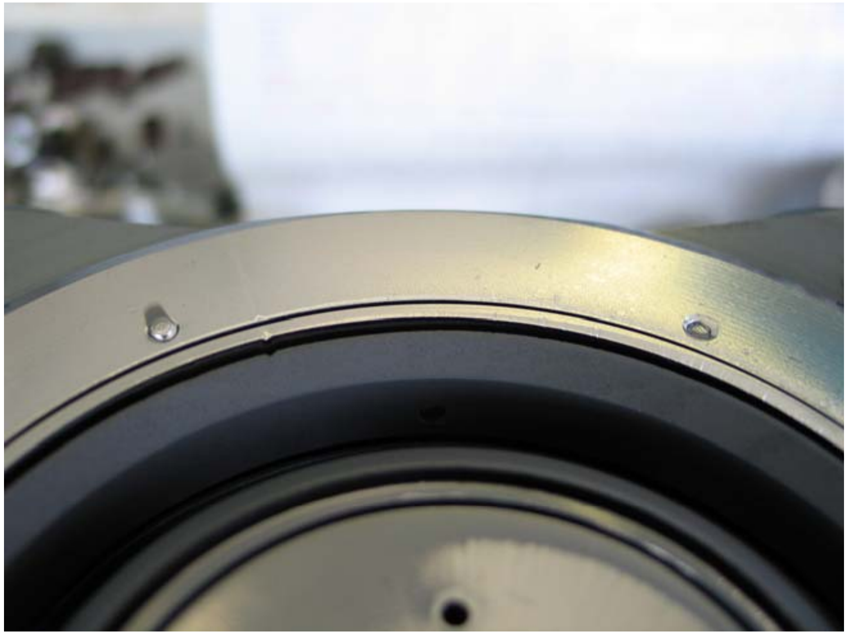


Figure 37. After erosion testing, 9 o'clock, camera location 3 o'clock.

Figure 38. Before erosion testing, 3 o'clock, camera location at 6 o'clock.

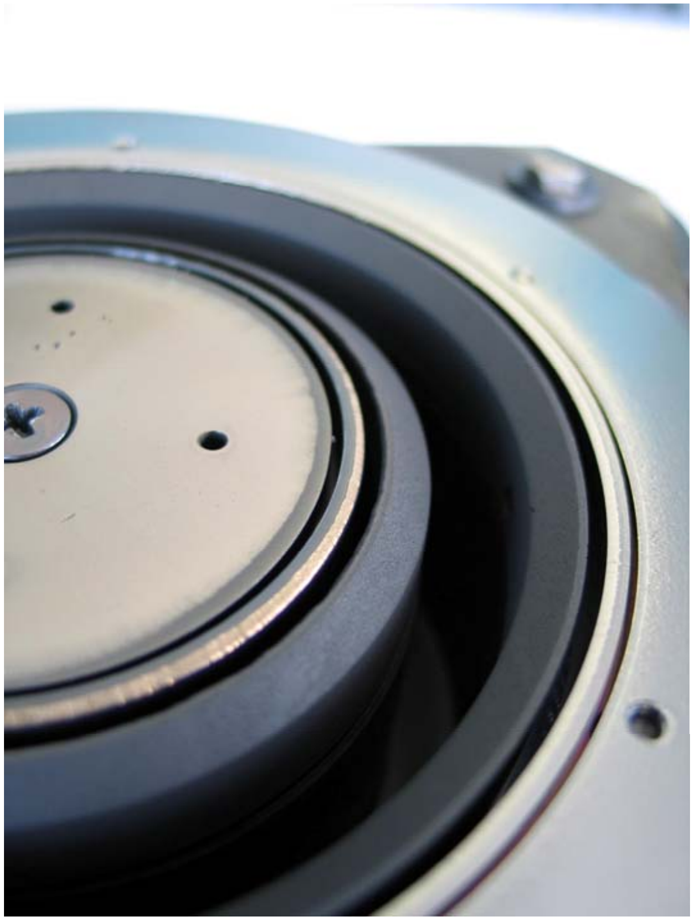


Figure 39. After erosion testing, 3 o'clock, camera location at 6 o'clock.

Acknowledgments

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