Operating Envelopes of Thrusters with Anode Layer

Semenkin A.V., Tverdokhlebov S.O., Garkusha V.I., Kochergin A.V., Chislov G.O., Shumkin B.V., Solodukhin A.V., Zakharenkov L.E.

ABSTRACT

The operational envelopes of present-generation xenon thrusters with an anode layer (TALs) on thrust, specific impulse and power consumption have been analyzed in the paper. The data about the characteristic tendencies in changes of a plume focusing, lifetime and oscillations arising in a discharge circuit of a thruster at a variation of operational modes have been represented.

INTRODUCTION

Growing application of EP systems for different mission results in enhancement of the thruster's required characteristics as compared with the present ones, and also in multimode thrusters operation.

The requirements to an electric thruster appear rather conflicting:

- a high thrust is necessary for an orbit rising,
- and a high specific impulse allowing reducing of the propellant mass - for a long-duration station keeping.

The power consumption can vary up to an order of magnitude.

By virtue of the said, it is reasonable to analyze not only some working points for present-generation thrusters with anode layer (TALs), but also the whole area of parameters which can be covered by every thruster.

In general case, it is necessary to analyze a number of parameters describing an electric thruster and determining its operating envelope:

- thrust characteristic (thrust, specific impulse, power consumption),
- parameters of a plasma plume generated by a thruster (angular divergence, power spectrum),
- generated electromagnetic disturbances,
- lifetime.

There is a rather full information about thrust characteristics for electric thrusters, so it is sensible to start an analysis of operating envelopes just from these ones.

GENERAL FACTORS DETERMINING A THRUSTER'S OPERATING ENVELOPE

Several physical factors can determine the boundaries of effective range for thrust, specific impulse and power consumption:

The bottom value of specific impulse (discharge voltage) is determined by a thruster jump into an abnormal mode followed by a stepwise loss of efficiency and generation of heavy oscillations in the discharge [1]. The value of discharge voltage corresponding to this boundary depends on design features of a thruster, conditions of tests and density of an ion current in the discharge zone. The typical values of boundary voltage are 100...300 V, and for some given thruster the boundary moves into the higher voltage area at increase of the density of a propellant flow in the discharge zone.

Every thruster has its inherent minimum mass flow rate value. Mass flow decreasing lower this value leads to decreasing of ionization probability in the discharge zone. In one's turn, it leads to rapid reduction of thruster efficiency [1]. For xenon thrusters the characteristic density for the flow of propellant should be more than 0.1 A/cm^2. The flow rate of a propellant, discharge current and thrust for Hall-effect thrusters have linear relations. So, the bottom of a flow rate determines the low bound for discharge current and thrust.

A set of bottom bounds for a propellant flow rate and a discharge voltage determines the minimum power, thrust and specific impulse, which can be performed by a thruster.

The upper bound is connected, first of all, to thermal condition of a construction. At a first approximation, the quantity of energy emitted into a construction, is proportional to

$$(1-\eta)\cdot I_d \cdot V_d,$$

where η - the efficiency of a thruster.

Depending on design features of a thruster some of its elements can be the most critical. E.g., the overheat of a thruster can be connected to the loss of magnetic properties at heating of magnetic core elements above the Curie's point or, for example, to the anode melting.

The main heat release in a design is determined by the electrons flow on the thruster's anode and depends on two values - of an electron current and of the energy of electrons. The latter, in its turn, depends not only on the value of applied voltage, but from a lot of factors including oscillations, the portion of electrons energy spent on ionization of atoms of a propellant, etc. Therefore, the upper bound for power consumption for any thruster is not a constant, and varies at an operational mode variation. The highest applied voltage and maximum power during operation at low flow rates near to the threshold of effective ionization can appear lower than the ones for high flow rates and, correspondingly, high ionization efficiency of a propellant in a thruster's discharge.

In general case, there can be a number of parameters limiting the upper bound for the discharge voltage, propellant flow rate and power consumption of a thruster. For example, an insulation resistance which can limit applied voltage, etc. However, for all TALs analyzed below the later has no practical importance, as the effective range boundaries for a thrust, power and specific impulse depends only on the three criterions discussed above:

- the boundary for a thruster jump into an abnormal mode;
- the minimum flow rate of a propellant, ensuring effective ionization;
- a construction thermal condition.

Any point inside the operating envelope of a thruster can be realized. However, just some cases can have a particular importance for practical use:

- capabilities of a mode variation at a constant power;
- the maximum possible change of a thruster's power;
- thrust (power) variation at a specified specific impulse;
- the maximum thrust for a specified power;
- the maximum specific impulse for a specified power.

The listed cases reflect the most probable conditions of electric propulsion applications on a space craft (S/C) to solve the typical missions:

- orbit rising or an interplanetary transfer;
- long-term station keeping;
- deorbiting after the end of life or due to malfunctions (e.g., loss of power in the power supply system of S/C).

The appropriate isolines and the working points are represented in the thrusters operating envelope below and in the tables of operating parameters for every thruster.

TAL OPERATING ENVELOPES

The nomenclature set of thrusters with anode layer, created by TsNIIMash, and their technical characteristics are presented in **Table 1**[2].

Representative characteristics and operating envelopes of these thruster are given in Tables 2…6 and Figures 1…6 [3], [4], [5], [6], [7], [8], [9].

The represented data allow to say that each TAL from the current assortment can be considered as a multimode thruster ensuring regulation of thrust, specific impulse in a rather broad range.

In Figure 7 the operating envelopes of thrusters are shown in one diagram. One can see that for the present-generation thrusters due to the overlap of ranges there is practically no "blanks". In the range of thrusts of 100... 200 mN - which at present can be of the greatest practical interest with regard to geostationary S/C orbit adjustment and station keeping - the specified value of thrust cannot be provided by only thruster, but at the least by two different ones. The selection of a configuration version can be based on additional criterions: the mass of construction, life time, specific impulse, etc.

The minimum specific impulse for all thrusters lies close to 1000 s and corresponds to the voltage (approximately the same for all the engines) of the jump in an abnormal mode.

The maximum achievable specific impulse grows with the increase of type-dimensions. It can be explained by the fact that the dimensional increase of a thruster widens the capabilities ensuring a thruster's thermal condition and specific power per square unit of its exit section.

Against the single-stage configurations, application of a two-stage configuration (D-80) allows a sufficient expanding of the operating envelope into the area of high specific impulses.

It should be noticed that the test programs for D55 and D110 configurations did not plan a detail investigation of boundary modes. So, in future, in accordance with the new obtained data the said ranges can be updated.

Table 1

Thruster	Power, kW	Specific impulse, s	Efficiency, %	Thrust, mN	Propellant
D-38 & D-38M	0,2…1,5	$(13…28)\cdot10^2$	50…70	25…100	Xe
D-55	0,8…2,5	$(13,5…27)\cdot10^2$	55	40…120	Xe
D–80 (two stage)	0,7…5,6	$(10…33,5)\cdot10^2$	60…70	50…250	Xe
D-100-I	1,3…7,5	$(14,5…28)\cdot10^2$	60	80…340	Xe
D-100-II (two stage)	3,5…15	$(18…42,5)\cdot10^2$	65	80…650	Xe
D-110	0,6…4,5	$(10…25)\cdot10^2$	50…60	50…240	Xe
D-150	4,5…17,5	$(15…31)\cdot10^2$	60	20…800	Xe
TM-50 (two stage)	20…50	$(30…70)\cdot10^2$	70…75	1000…1500	Xe

Table 2. D-38M operating parameters.

Operating Point	ma	Vd	Id	F	N	Isp	Efficiency
	Mg/s	V	amps	mN	watts	s	
Minimum Power Level	0.62	148	0.50	4.12	74	692	0.18
Power Level 100 W							
High Isp	0.62	200	0.55	5.1	110	862	0.19
High Thrust	1.11	102	1.07	7.3	109	680	0.22
Power Level 160 W							
High Isp	0.62	301	0.55	6.7	165	1027	0.22
High Thrust	1.03	150	1.07	9.8	161	993	0.29
Power Level 200 W							
High Isp	0.88	250	0.88	11.4	220	1336	0.33
High Thrust	1.93	95	2.23	12.9	212	699	0.21
Power Level 300 W							
High Isp	1.01	300	1.00	15.1	300	1546	0.37
High Thrust	2.27	124	2.7	21.5	335	982	0.30

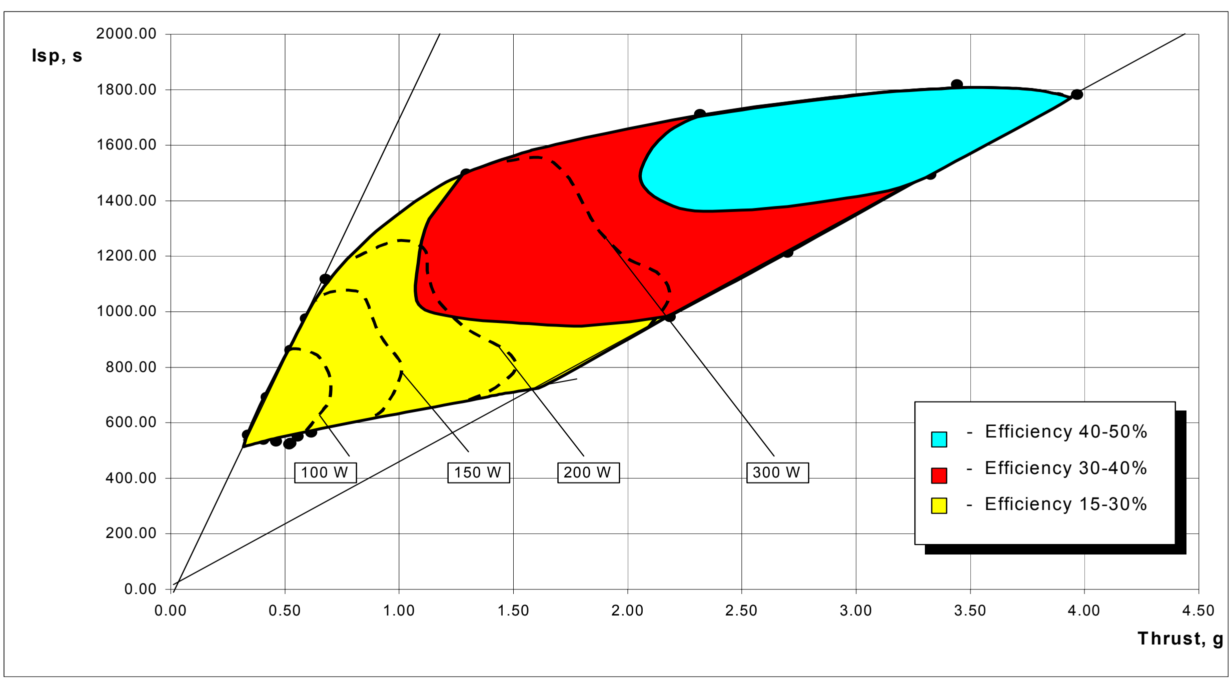

Figure 1. D-38M performance range divided into zones in accordance with thruster efficiency.

Table 3. D-55, TAL-WSF operating range.

Operating Point	ma	Vd	Id	F	N	Isp	Efficiency
	Mg/s	V	amps	MN	watts	s	
Nominal operating points	4.51	351	4.34	86.28	1523	1952	0.54
	4.34	350	4.12	81.06	1442	1902	0.52
	4.72	300	4.71	84	1413	1815	0.53
	2.91	300	2.48	41.4	744	1454	0.4
High thrust	5.50	300	5.31	102.1	1593	1893	0.60
High Isp	4.52	400	4.02	91.4	1608	2062	0.58
Regulating possibility: Power Level 850 W	2.65	400	2.07	45.5	829	1751	0.47
	3.41	297	3.07	53.5	911	1599	0.46
	4.52	200	4.24	61.9	849	1396	0.5
	5.50	150	5.65	64.8	850	1201	0.45

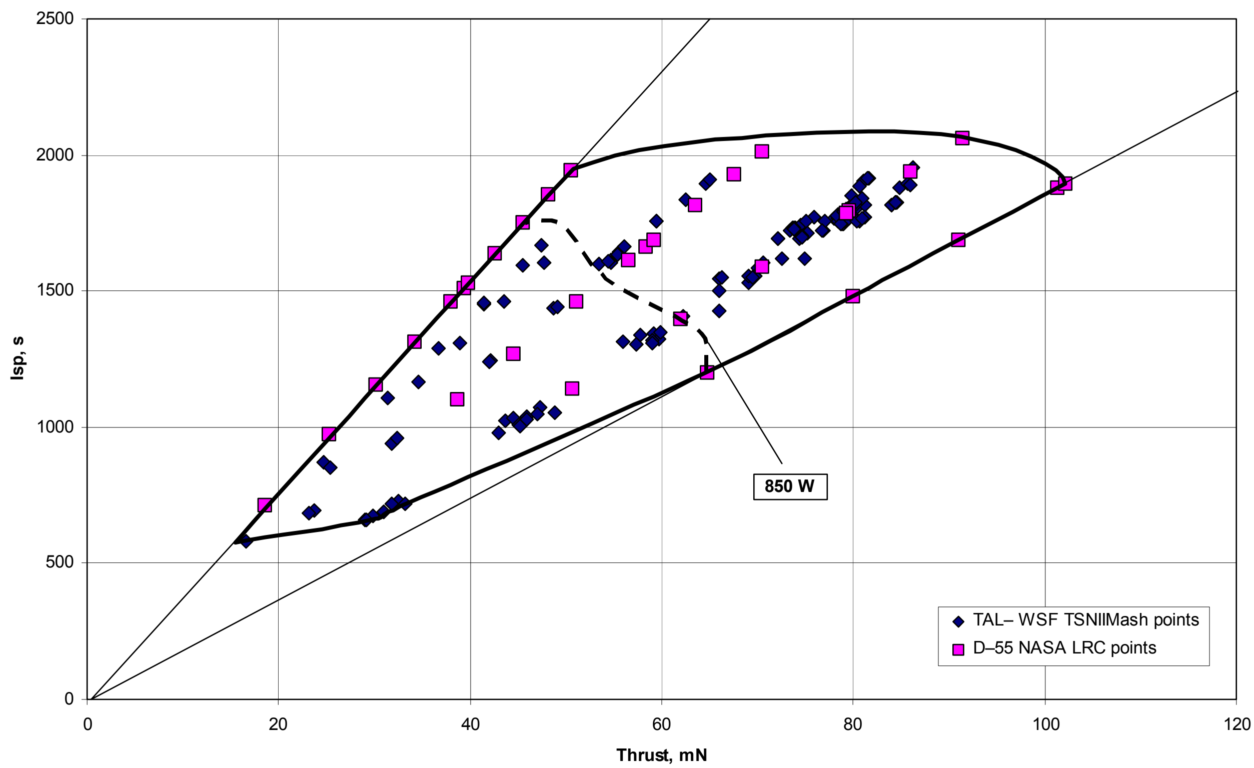

Figure 2. D-55,TAL-WSF operating range.

Table 4.D-80 operating parameters.

D-80. Dry mass <7.5 kg. Overall dimensions: 151x151x141										
		The first stage		**The second stage**						
Operating Point	**ma**	**Vd**	**Id**	**Va**	**Ia**	**Vsum**	**F**	**N**	**Isp**	**Efficiency**
	mg/s	**V**	**amps**	**V**	**amps**	**V**	**mN**	**watts**	**s**	
Minimum Power Level	3.48	-	-	202	3.03	202	42.5	612	1246	0.42
Maximum Thrust	7.97	100	8.30	500	8.03	600	226.2	4845	2896	0.66
Power Level 2.1 kW										
High Isp	3.26	124	2.60	701	2.57	825	82.6	2124	2585	0.49
High Thrust	9.04	-	-	207	9.67	207	137.8	2006	1554	0.52
Power Level 2.6 kW										
High Isp	3.88	106	3.25	701	3.17	807	106.1	2567	2787	0.56
High Thrust	8.82	-	-	245	10.20	245	153.5	2499	1773	0.53
High Thrust	10.13	-	-	205	12.75	205	162.3	2614	1634	0.50
Power Level 3.4 kW										
High Isp	4.27	105	3.50	900	3.50	1005	127.4	3518	3040	0.54
High Thrust	10.13	-	-	275	12.30	275	197.5	3383	1988	0.57
Power Level 4 kW										
High Isp	4.27	105	3.50	1000	3.53	1105	133.0	3898	3174	0.53
High Thrust	9.23	-	-	416	9.56	416	216.2	3989	2386	0.64

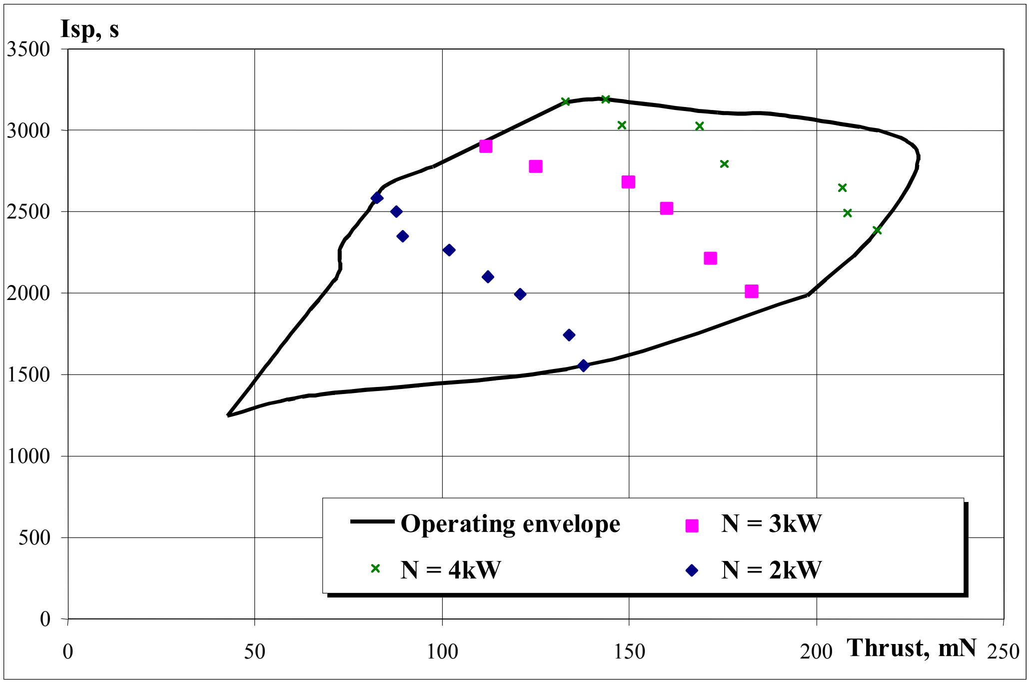

Figure 3. D-80 constant power lines.

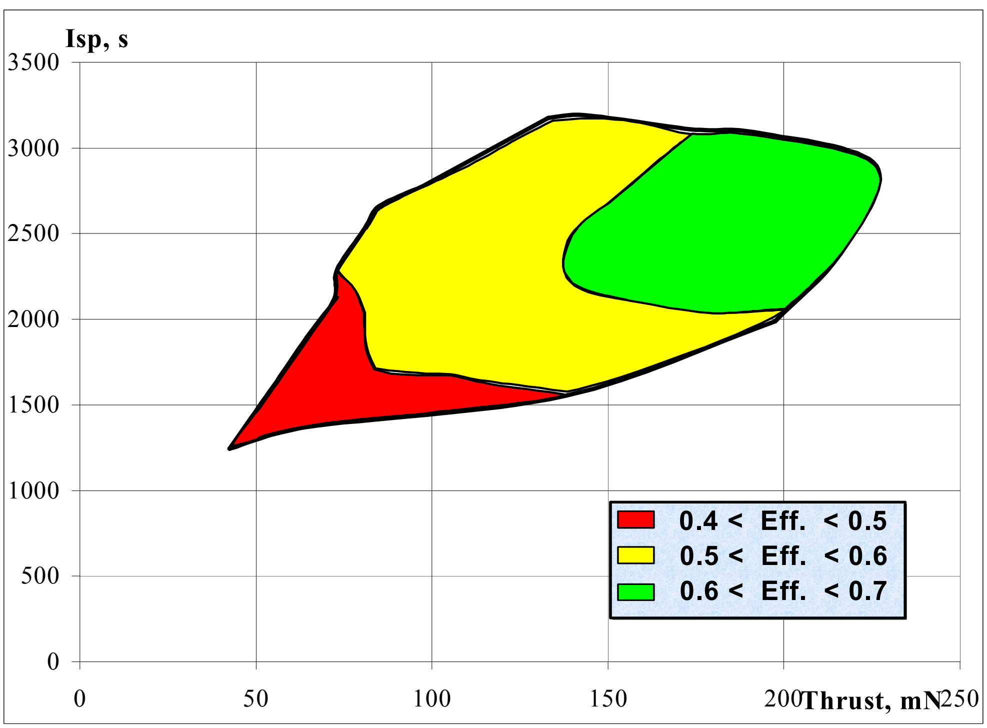

Figure 4. D-80, operating range.

Table 5.TAL110 operating parameters.

TAL-110. Dry Mass = 5.3 kg. Overall Dimensions: 154x154x100							
Operating Point	**ma**	**Vd**	**Id**	**F**	**N**	**Isp**	**Efficiency**
	mg/s	**V**	**amps**	**mN**	**watts**	**s**	
Minimum Power Level	4.87	150	4.31	43.2	647	904	0.30
Power Level 1800 W							
High Isp	4.87	450	4.20	92.9	1890	1907	0.45
High Thrust	11.30	150	11.44	135.2	1716	1220	0.47
Power Level 3400 W							
High Isp	9.01	400	8.47	192.2	3388	2181	0.61
High Thrust	13.31	250	13.92	240.1	3480	1839	0.62

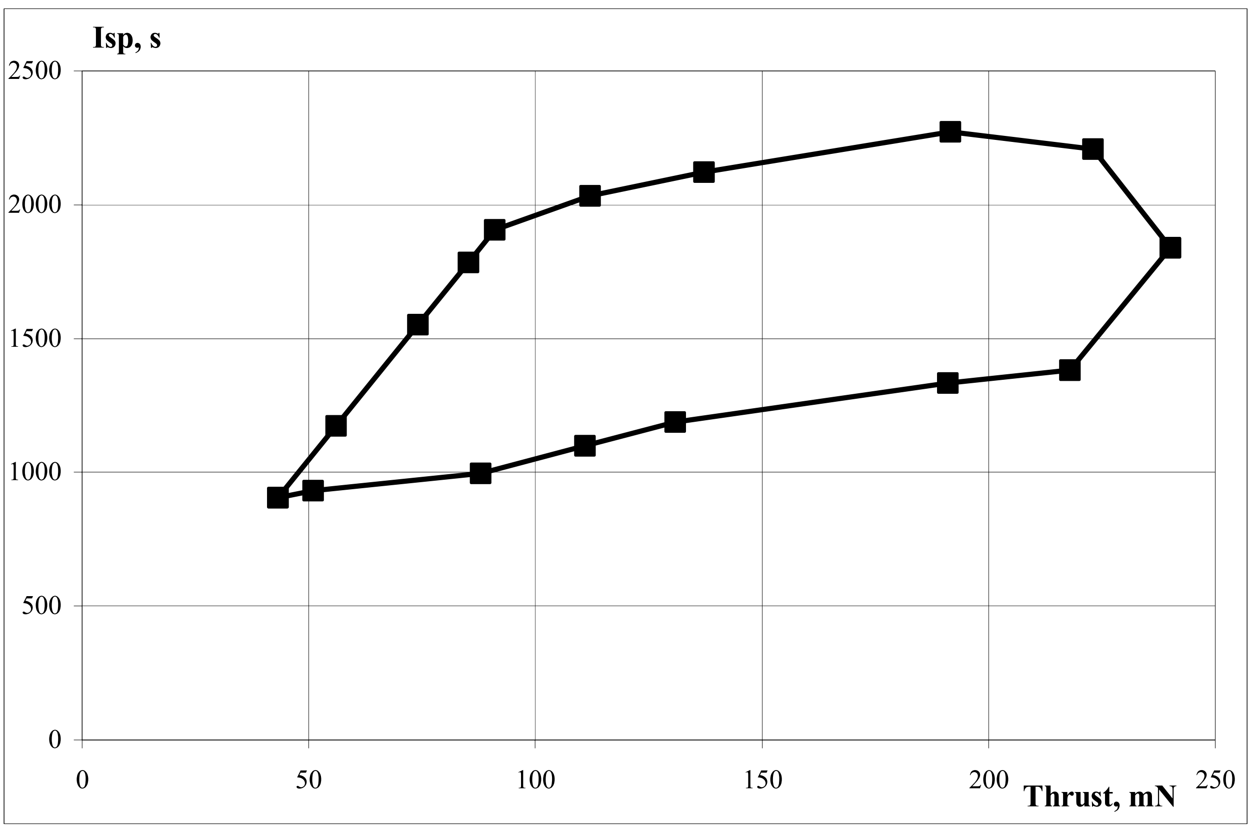

Figure 5. TAL-110 operating range.

Table 6. D-150 operating parameters.

D-150. Dry Mass = 18 kg. Overall Dimensions: 340x340x130							
Operating Point	**ma**	**Vd**	**Id**	**F**	**N**	**Isp**	**Efficiency**
	mg/s	**V**	**A**	**MN**	**W**	**s**	
Minimum Power Level	7.90	100	9.30	68.6	930	886	0.32
Demonstrated Max Isp	16.00	550	19.80	490.3	10890	3125	0.69
Demonstrated Max Thrust	33.00	300	50.00	794.3	15000	2455	0.64
Power Level 4650 W							
High Isp	7.90	550	8.40	205.9	4620	2658	0.58
High Thrust	23.40	150	31.50	323.6	4725	1410	0.47
Power Level 6500 W							
High Isp	12.00	500	13.70	333.4	6850	2833	0.68
High Thrust	23.40	200	32.00	402.0	6400	1752	0.54
Power Level 8600 W							
High Isp	12.00	550	16.00	343.2	8800	2917	0.56
High Thrust	21.30	300	28.00	480.5	8400	2300	0.65
Power Level 10750 W							
High Isp	16.00	550	19.80	490.3	10890	3125	0.69
High Thrust	25.30	300	35.50	588.4	10650	2372	0.64
Power Level 15000 W							
High Isp	21.30	550	27.10	647.2	14905	3099	0.66
High Thrust	33.00	300	50.00	794.3	15000	2455	0.64

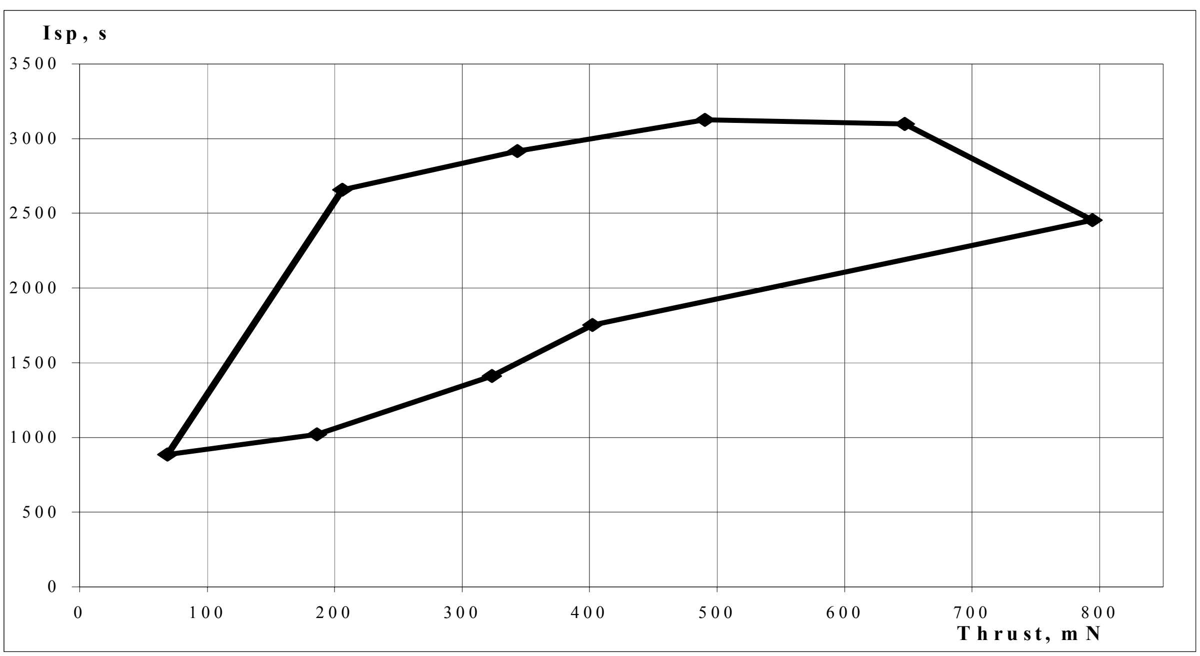

Figure 6. D-150 operating range.

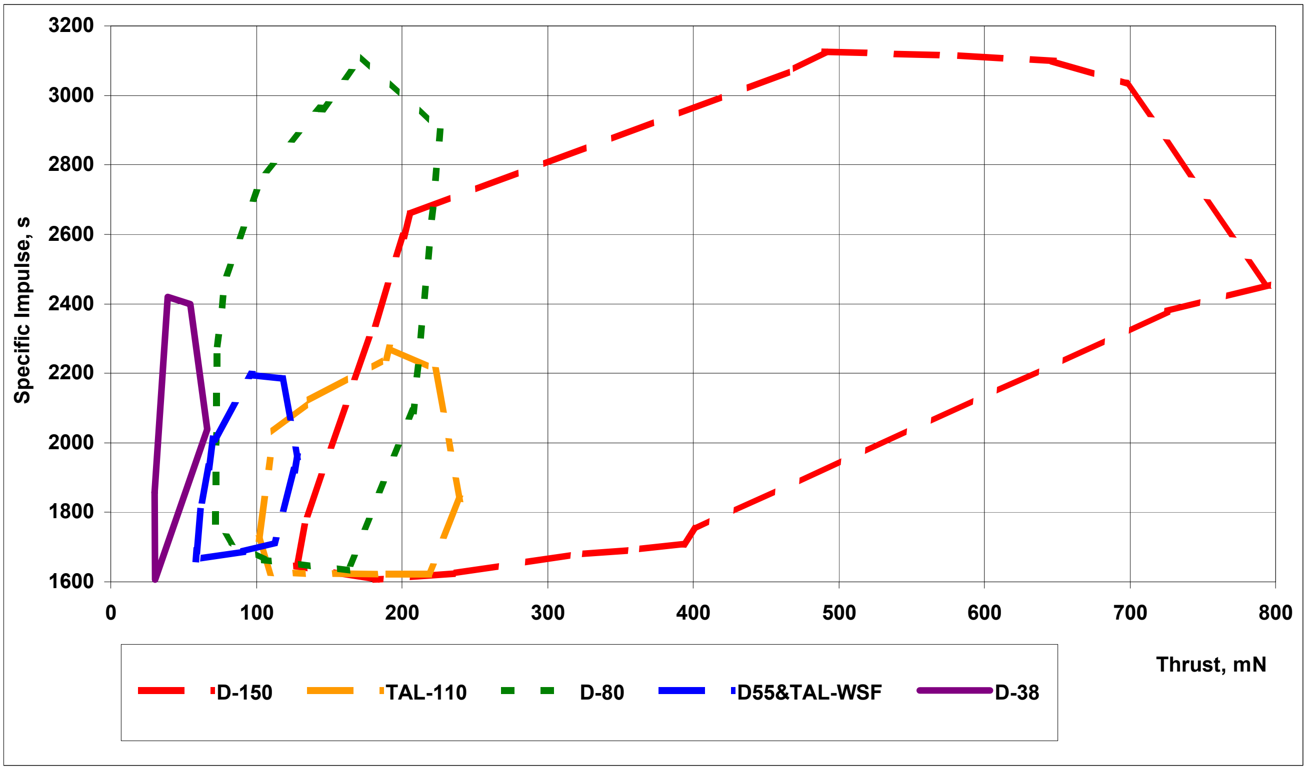

Figure 7 .TAL family envelopes.

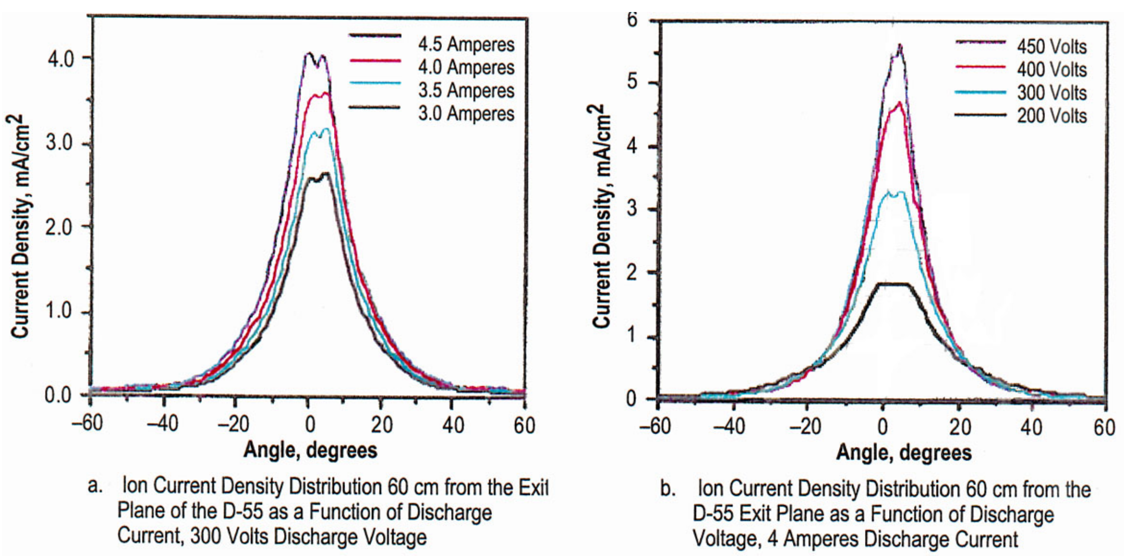

Figure 8. TAL D-55 Current Density Distribution for Different Xe Flows (a) and Discharge Voltage (b). (data obtained by NASA GRC)

VARIATION OF A THRUSTER'S LIFE TIME, PLUME FOCUSING AND OSCILLATIONS IN DISCHARGE CIRCUIT

As already it has been noticed above, except for thrust characteristics the operational envelope of a thruster is characterized with:

- the change of life time at a mode variation;
- the change of generated electromagnetic background;
- the change of a plume focusing.

Nowadays, the relevant data base is not sufficient to make it possible the "mapping" of operational modes from all the listed points of view. However, it is possible to distinguish some tendencies.

LIFETIME

The lifetime of Hall-effect thrusters, in particular TALs, is determined by the wear rate of discharge chamber walls. The physics of the process is stipulated by the bombardment of walls by accelerated ions and is described by the expression [10]:

$m = j_i.S.t$

m - eroded mass from given point of discharge chamber wall,

j_i - ion current density on the eroded surface,

s - sputtering coefficient depending on ion energy, angle of incidence and material of the surface,

t - time.

It is possible to expect that for some thruster configuration the change of the walls erosion rate will be approximately proportional to the ion flow density (i.e., the propellant flow rate) and also the coefficient of cathode sputtering, which for most materials in the range of ion energies Ei 200... 1000eV is approximately proportional to Ei. It is possible to suppose that Ei ≈Vd for Hall-effect thrusters. In the case it is also possible to suppose that the erosion rate is directly proportional to the power in a thruster's discharge, and the lifetime of some specified configuration is inversely as the power. It is obvious that such estimation is lawful only for a rather narrow range of parameters and should be validated in tests. However, in conditions of test data insufficiency the estimation is the only available. At the said stipulations the power isolines can be considered as lifetime isolines for a specified configuration. Here, the lifetime is understood as the operating time "T" of a thruster. At the same time the total impulse of a thruster is not constant for the line $T = const$, but varies pursuant to the variation of thrust. E.g., for D80 at 3 kW the thrust can vary from 120 up to 175 mN (the specific impulse is 2900 s and 1900 s, accordingly). It means that in the latter case the total impulse of thrust in the second mode will be on almost 50 % higher than in the first mode.

PLUME DIVERGENCE

With reference to the divergence of a plume the current experimental data allow to notice two important regularities:

1. For a Hall-effect thruster, the angular divergence of a plume decreases with the increase of discharge voltage and specific impulse. The order of magnitude of the change can be illustrated by the Figure 8, where the data are shown for several values of voltage, obtained for D55 in NASA Lewis Research Center.

2. The change of a thruster flow rate - at least, in the area where the efficiency of a thruster remains approximately constant, - does not result in change of the angular divergence. It is also confirmed by experimental data obtained on several thrusters, in particular, for D55 which data are represented as an illustration.

It should be noticed that in some cases - when there is a danger of heavy effect of a thruster's plume on S/C's constructive elements, the angular divergence can become the priority criterion for selection of a thruster working point.

ELECTROMAGNETIC OSCILLATIONS

The oscillations arising in the discharge circuit of a Hall thruster depend on a number of factors: the working mode, characteristics of the cathode-neutralizer, residual pressure and testing conditions. Therefore, the extrapolation of the available experimental data on other conditions requires its validation before it will be possible to speak with certainty about existence of any common tendencies.

Nevertheless, the data obtained in TSNIIMASH for D55 [11] show that the change of spectrum and increase of frequency of the main harmonics of oscillations in the discharge current takes place at an increase of discharge voltage. At the same time, at some specified operational mode (described by discharge voltage and flow rate) the oscillation amplitude essentially depends on the magnitude of magnetic field in the zone of discharge and can be optimized.

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