An Overview of the TsNIIMASH / TsE efforts under VHITAL Program

IEPC-2005-141

Presented at the 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005

Oleg S. Tverdokhlebov*
TsNIIMASH, Pionerskaya 4, Korolev, Moscow region, Russia 141070

Sergey O. Tverdokhlebov†
TSNIIMASH-EXPORT, Pionerskaya 4, Korolev, Moscow region, Russia 141070

Alexander V. Semenkin‡
TsNIIMASH, Pionerskaya 4, Korolev, Moscow region, Russia 141070

Abstract: Following a NASA initiative aimed on preparation of missions to outer planet of Solar System the present consideration of TALs utilizing bismuth propellant has been initiated among with the study of the other electric propulsion options. TsE/TsNIIMASH team efforts described in the paper were made under the Contract between Jet Propulsion Laboratory and Joint Stock Company TSNIIMASH-EXPORT. The main goal is to manufacture and to deliver to JPL experimental Very High Impulse Thruster with Anode Layer (VHITAL-160) operating on Bismuth with Isp up to 8000 sec and power level 25 – 36 kW. The VHITAL-160 is considered by NASA as a possible engineering solution to put into practice the projects of space vehicle with electric propulsion for outer planet investigations. This paper provides an overview of TsNIIMASH/TsE efforts under VHITAL-160 Program. State-of-art of Bi D-160 and D-200 thrusters designs, characteristics and test experience is presented. The results of the VHITAL-160 main design features, thermo–mechanical and magnetic system analysis are presented. The VHITAL-160 support systems design specific are represented. The preparation of pre-existing D-160 thruster for demo- and risk reduction tests is described. D-160 thruster testing results are discussed.

Nomenclature

Va	=	accelerating voltage
Ia	=	accelerating current
Vd	=	discharge voltage
Id	=	discharge current
A	=	atomic mass
F	=	thrust
$\dot{m}$	=	bismuth mass flow rate

* R&D Engineer, Electric Propulsion Laboratory, olekos@infoline.su.

† Executive Director, JSC "TSNIIMASH-EXPORT", sot@tse.ru.

‡ Head of section, Electric Propulsion Laboratory, avs@tse.ru.

I_{sp} = specific impulse
N = discharge power
B = magnetic induction
49КФ = permendure
ПОЖ 700 = high temperature wire
Δ = gap

I. Introduction

An interest to condensable propellants has turned back in all over the world after decades of very low related activity. This is because of natural difficulties associated with design and testing of high specific impulse and high-power gas-fuelled thrusters currently under consideration for space flights to outer planets of solar system. Condensable propellant allows to overcome basic limitation of gas-fueled thrusters – huge pumping systems and vacuum tanks required for testing a high-power thrusters in ground conditions. One can note, that achieved level of xenon flow rates in the Hall thrusters currently under development at NASA Glenn Research Center is already close to upper level of pumping speed of one of the greatest vacuum facility in the world–NASA GRC Tank 5.

In 60-70ies time frame significant amount of scientific efforts have been performed and published in former USSR, USA and other countries in regard to potential utilization of mercury (Hg), lithium (Li), bismuth (Bi), cadmium (Cd), etc. These research programs have been oriented to future interplanetary missions, and this goal has pre-determined a range of parameters of studied laboratory thrusters - high specific impulse up 8000 sec, power range of a thruster from dozens to hundreds kilowatts[1].

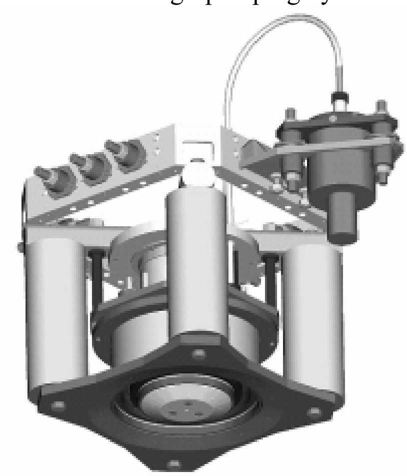


Figure 1. VHITAL-160 in assembly with feed system.

So, since early 60s bismuth (Bi) has been used as a typical propellant in majority of the USSR research programs focused on the development of thrusters with anode layer (TAL) of high power and great specific impulse[1,2,3]. Among other metals which vapors can be applied as propellant for TALs (Cs, Tl, Pb, Cd, Hg), bismuth has the greatest atomic mass (A = 208.98), rather low potential of ionization (7.3 eV) and relatively low melting point of 271.3 Cº. Being compared with toxic mercury, bismuth is much more convenient propellant, because it does not require extra ordinal protection and safety procedures during testing and hardware handling.

Following a NASA initiative aimed on preparation of missions to outer planet of Solar System the present consideration of TALs utilizing bismuth propellant has been initiated among with the study of the other electric propulsion options. TSNIIMASH laboratory anode layer thrusters developed in early programs – namely D-160 and D-200 have demonstrated range of performances, which is very close to one for NASA Very High Specific Impulse TAL (VHITAL) Program goals. Scientific and technical background available at TSNIIMASH provides significant benefit for the NASA VHITAL Program especially for manufacturing of laboratory thruster for experimental study at JPL.

The paper represents the efforts aimed on VHITAL laboratory bismuth thruster manufacturing, delivery and testing at JPL facility, and includes systemized results of the research of Bi thrusters, performed at TSNIIMASH.

II. State-of-art of Bi D-160 and D-200 thruster designs, characteristics and test experience

The beginning of the efforts was the review of the state-of-the-art of Bi thruster designs, characteristics and test experience. In TSNIIMASH different laboratory models of TALs with Bi as a propellant were developed and studied in 1960-1985. Main data were obtained with the two laboratory thrusters D-160 (second name "Drift-5") and D-200. Both thrusters underwent several modifications. Thruster D-160 was developed for physical research. Its design wasn't optimized for both mass and energy consumption of auxiliary systems. So the thruster had appreciable design margin. The D-200 was especially designed model for researches of radiant cooling scheme.

The performance characteristics obtained during D–160 testing are given in Ref.[4,5]. The volt-ampere characteristics of D-160 for several mass flow rates (5 to 25 mg/s) are shown in Fig.2.

Given experimental data were obtained at D-160 with water cooled magnetic system. The D-160 design was optimized neither for mass nor for both coil and start warming-up system power consumption. D-160 investigation allowed receiving data in regard to physical features, operating range boundaries and reachable efficiency of bismuth TAL. Subsequent works in the area of bismuth thruster were aimed at adjustment of engineering solutions required for support systems simplification and thruster mass reducing.

Efforts aimed at development and test of radiation cooling thruster were made[4]. Such a TAL (Picture 1) with average diameter of 200mm named D-200 was tested at TSNIIMASH. D-200 has demonstrated outstanding characteristics for radiation cooling thruster: specific impulse – 2000 to 5200s at 10 to 34 kW power level[4].

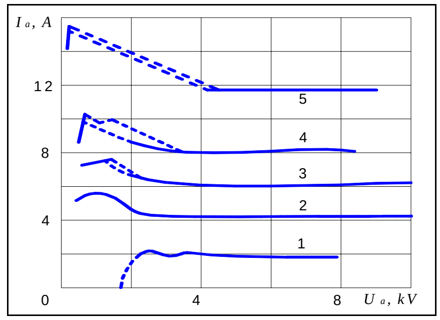
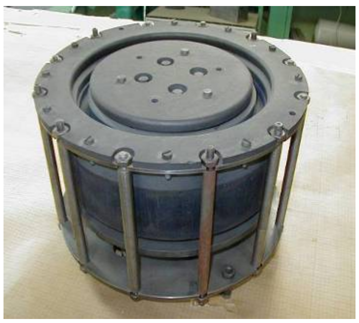


Figure 2. Volt-Ampere Characteristics of Bismuth TAL



Picture 1. TAL D-200

The thrust of 1130 mN, specific impulse about 3000 s and efficiency of 67% were demonstrated at 25 kW power level. Graphite was widely used as electrode material in the D-200. Therefore in spite of large average diameter the thruster mass was about 20 kg. Volt-ampere and thrust characteristics of D-200 for mass flow rates 10 and 15 mg/s are represented in Fig.3 and Fig.4[4].

Unlike to D-160 thruster, D-200 was tested with cathode-neutralizer using[4]. Cathode-neutralizer application allowed significantly reducing the threshold of transition from accelerating regime to anomalous one. As it can be seen from Fig.3 this threshold went down to 500V. Without cathode-neutralizer the transition to anomalous mode happened at accelerating voltage of 2 kV, it was in close agreement with D-160 test results. Any difference between thruster characteristics obtained with and without cathode-neutralizer was not observed at the accelerating voltage more than 2 kV.

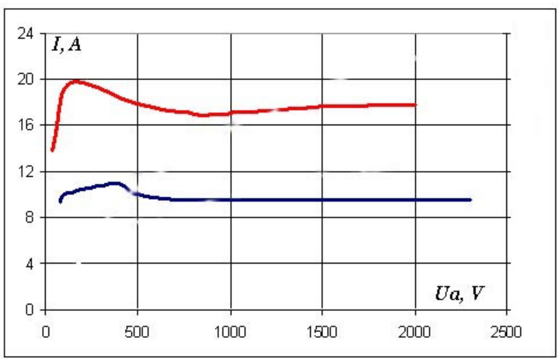


Figure 3. Accelerating current vs Accelerating Voltage

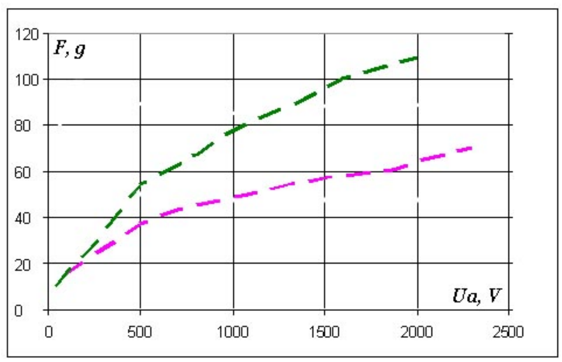


Figure 4. Thrust vs Accelerating Voltage

III. VHITAL-160 main design features

After State-of-the-art reviewing the next step was the thruster VHITAL-160 and Support Systems Requirements, Conceptual Design and Analysis Package producing.

Based on the comparison of the required VHITAL-160 characteristics and the characteristics of the existing laboratory bismuth TALs[3,4], the D-160 and D-200 thrusters earlier developed and tested in TSNIIMASH were chosen as a prototype.

The D-160 thruster demonstrated the power and specific impulse (up to 8000 s) meeting the performance specification requirements. Moreover, the capability to operate with power up to 100 to 140 kW was demonstrated. This power level is much greater than the required one. The numerous D-160 tests were carried out, including the study of thruster lifetime, plasma discharge electromagnetic noises and so on. Thus, the reliable database of performance and operating features of the Bi thrusters with anode layer was obtained. However, the D-160 design employed a water-cooling scheme that ensured high-power thruster operation, so this thruster can't be used for work on VHITAL program necessitating a fully radiant cooling scheme.

The D-200 was developed with a radiant cooling scheme but it was designed for specific impulse lower than 5000 s and, therefore, couldn't be used directly for VHITAL program purposes.

The obtained database of the D-160 and D-200 performance and design features enables to design the thruster meeting the requirements of the NASA Very High Specific Impulse Thruster with Anode Layer Program with respect to the laboratory thruster to conduct the research at the Jet Propulsion Laboratory test facilities.

The main design features of the VHITAL-160 are followed from the analysis of prototypes[6]:

- two-stage scheme of propellant ionization and acceleration
- requirement of thruster pre-heating to the high temperatures (950 to 1000 C^0) for keeping bismuth in vaporous state by means of the special heater
- necessity to use in design the materials with a high melting temperature (Mo, Nb, graphite) for all thruster electrodes
- high-voltage insulators
- integrated laboratory feed system of bismuth
- insulators protection against Bi vapor condensation

The design features of the VHITAL-160 in comparison with the existing thrusters are

- radiant cooling scheme including the maintenance of the required magnetic system thermal mode
- minimum level of erosion
- capability of heat discharge utilization for keeping the working temperatures in the thruster

Though separately these features were realized in the earlier studied thrusters with anode layer, their integration in the one bismuth TAL involves a certain technical problem.

The existing D-160 and D-200 performance data allow to define the VHITAL-160 target performance:

Value	Mode 1	Mode 2
Power N, W	25000	36000
Specific impulse I_{sp}, s	6000	8000
Discharge voltage U_d, V	150	150
Discharge current I_d, A	6	5
Accelerating voltage U_a, V	4750	8400
Accelerating current I_a, A	5,0	4,2
Bi flow rate $\dot{m}$, mg/s	11	9
Magnetic induction, B, Tesla	0.2	0.2
Thrust, F, mN	650	710
Thrust efficiency	0,78	0,79

IV. VHITAL-160 analysis

After the VHITAL-160 main design features determination the wide analysis of the thruster and support systems requirements were provided. The carried out by the authors analyses includes the analysis of the thruster baseline geometry, thermal and magnetic system analysis, thermo-mechanical analysis of the thruster structure and preliminary analysis of the thruster baseline configuration lifetime along with consideration the options for the life-time extension. Besides, the analysis of materials and technologies were carried out. After that the thruster top assembly preliminary drawings and electric schematic were produced. At last, the feed system and laboratory Bi cathode requirements, general design and integration with thruster questions were examined. As a result the "Thruster VHITAL-160 and Support Systems Requirements, Conceptual Design and Analysis Package"[7] was made.

A. Thruster baseline channel geometry

The geometry of the thruster discharge gap is chosen as a result of the D-160 thruster data analysis[1-3], and its comparison with required VHITAL-160 operating regimes. One of the main examined questions here was the erosion rate of the thruster parts. The erosion rate of the thruster parts, thrust efficiency and minimal value of the accelerating voltage may change in dependence of thruster channel geometry features.

The analysis of the channel geometry influence on thruster characteristics based on experimental test results of D-160 is given in Ref.[1-3]. The final analysis of the geometric parameters is carried out with requirements of maximal thruster efficiency and location of the discharge stage in the area with increasing magnetic field so that the ion beam is well focused. The magnetic poles thickness and magnetic gap width is determined by analysis of the magnetic system. However, the magnetic gap variation possibility is limited due to influence of the erosion rate on guard rings sputtering[8]. The results of the channel geometry analyzing are present in the table below.

VHITAL-160 channel geometry parameters:

Magnetic gap	40 mm
Accelerating channel length	10 mm
Magnetic poles thickness	6 to 10 mm
Guard rings thickness	5 to 10 mm

B. Magnetic system analysis

Magnetic system analysis goals were the determination of the parameters of the magnetic coils, magnetic circuit cross-cut and magnetic field distribution in the discharge channel.

Basic data for magnetic system analysis were as follows:

- Required magnetic field induction in the discharge gap is not less than 0.2 Tesla
- Basic geometry of the VHITAL-160 magnetic system
- Temperature of the VHITAL-160 parts

As a result of the analysis the following parameters are defined:

- Required number of the magnetic coil ampere turns
- Geometrical and electrical parameters of the magnetic coils
- Magnetic field distribution and its value in the discharge zone

The important part of the analysis was the selection of the materials for the magnetic system parts which was made based on the results of the thermal analysis and is meeting a requirement of the guaranteeing the necessary magnetic and strengthening properties. It is evident; Curie point of a chosen material must exceed the maximum temperature of the magnetic system. For the magnetic circuit working temperature of 400 ^{0}C the alloy 49КФ was selected as a magnetic system material (taking into account the safety factor 1.5). Curie point of alloy 49КФ is 800 ^{0}C. For alloy 49КФ as a magnetic system major material, ampere turn numbers of the central and side coils are respectively 2700 and 8000, computer modeling was made using the finite-element method. The modeling results are presented on the figures below.

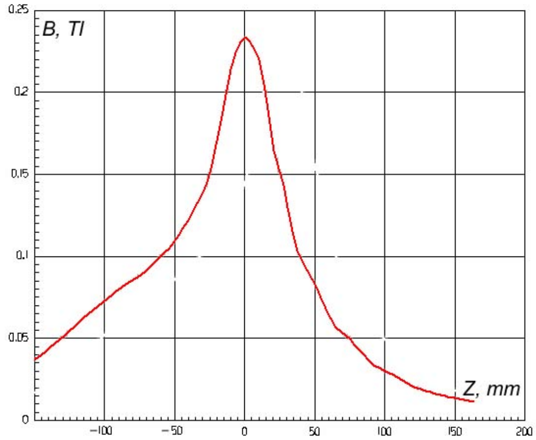


Figure 5. Magnetic field distribution along accelerating channel axis

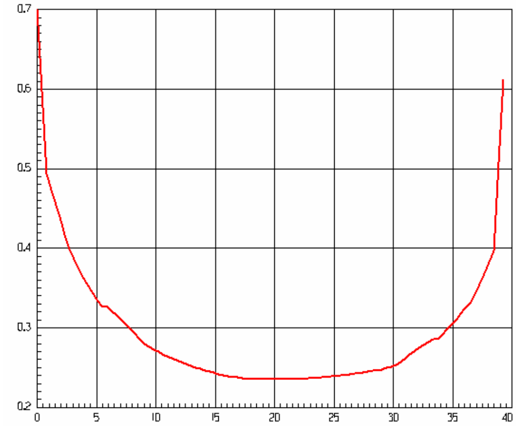


Figure 6. Magnetic field distribution along radius in the gap between the pole centers

Zero corresponds to the outer pole, 40 corresponds to the inner pole surface

Thus, the analysis results verify feasibility of the required magnetic field parameters of the VHITAL-160 in the discharge gap and thruster availability. Obtained parameters of the excitation current and power consumption of the coils were used for establishing the power supply requirements.

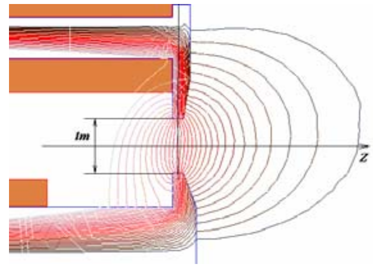


Figure 7. Magnetic field lines for the VHITAL-160

C. VHITAL-160 thermal analysis

The thermal analysis goals were the determination of the working temperatures of the thruster parts and to compare them with the permissible temperatures of the thruster materials.

The upgraded 3-dimensional computer modeling was used to define more accurately the VHITAL-160 thermal modes. The thermal model was considerably enlarged by both the thruster parts and physical processes that ensured the maximum likeness to the real conditions. The thermal model sections are presented on the Fig. 8 and Fig. 9. The thruster elements are pointed.

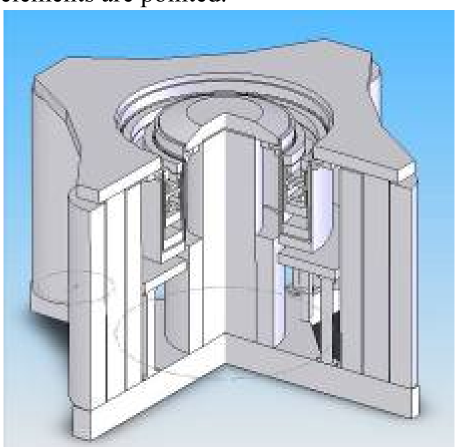


Figure 8. The thermal analysis model

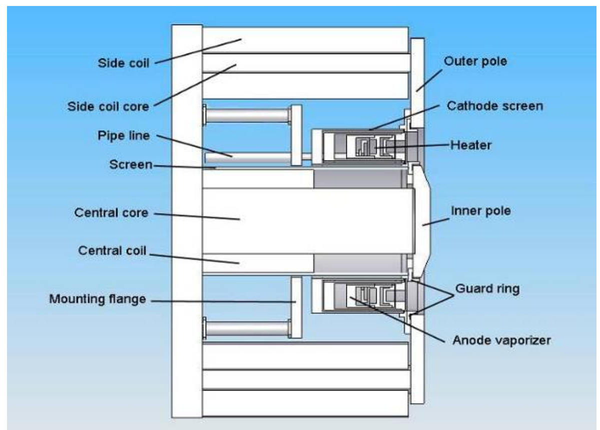


Figure 9. Elements of the thruster thermal model

As shown in Fig. 8 and Fig. 9, the anode-distributor being the important element of the thermal analysis is assembled and reproduces the real geometry.

The heat sources of the thermal analysis are the following:

Thruster element	Heat power, W
Heater	2000
First stage cathodes	1800 (for each) / 1250 (for each)[§]
Central magnetic coil	77
Pipeline	1600 ºC
Side magnetic coils	150 (for each)

Thermal analysis was carried out for six thruster thermal modes in accordance with operating regimes. The modeling was carrying out based on the heat transfer basic laws[9].

Meshing of the thruster parts is the first stage of the thermal modeling. The illustration of the meshing is shown in Fig.10. After meshing the view factors are defined. After that the thruster temperature distribution is defined taking into account geometry of the thruster parts, emissivity of the materials, thermal-conductivity coefficient, mutual surface radiation and radiation to background. The thermal analysis results are presented below in the form of temperature distribution image in Fig.11.[**].

[§] 10% from the total discharge power

[**] The temperature distribution image is given for maximum heat power mode.

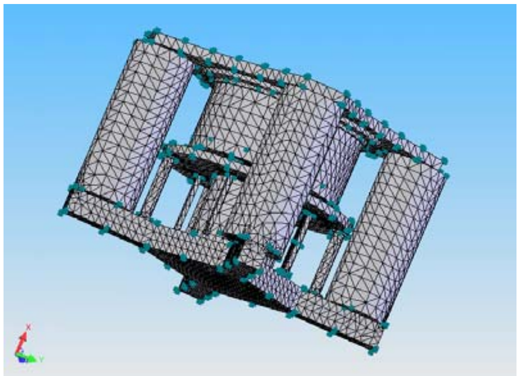


Figure 10. Thermal model meshing

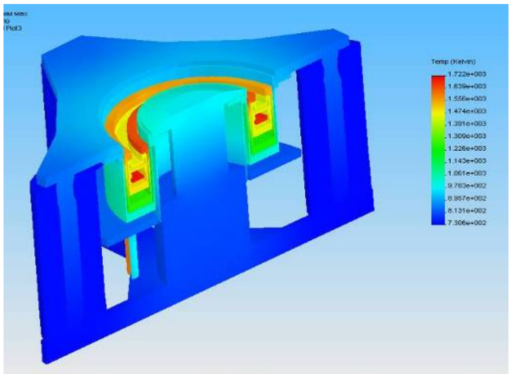


Figure 11. Temperature distribution

Thruster thermal analysis showed that temperatures of the magnetic circuit parts are within the temperature range from 600 up to 1000 K. Such temperatures exclude the possibility of using common steel grades that confirms the necessity of using iron-cobalt alloy 49КФ without exceeding Curie point. Temperature of magnetic coil wire allows us to use the ПОЖ 700 (in Russian) wire for the central and side magnetic coils and avoid water cooling, which was used in D-160. Temperatures of the anode unit parts during the pre-heating and thruster operation are higher than bismuth vapor condensation temperature. The thruster design meets the requirement of the complete radiant cooling scheme of the thruster. Temperatures of the elements in all modes do not adversely affect the structural strength of the thruster and its joints. Temperature values of the accelerating channel parts in modes without heater operating confirm the possibility of the self-heating mode.

Then the thermal analysis results were used in the form of data array as the input data for structural analysis.

D. Thruster structural analysis

The thruster structural analysis was carried out to prove that there are no changes of fundamentally important thruster dimensions. The most important thing is a change of the gap values between the cathode screens as a result of thermal expansion of the thruster parts.

The VHITAL-160 thruster design ensures the possibility of free thermal expansion of the different temperature thruster elements that exclude occurrence of significant mechanical stresses in the thruster construction due to non-uniform heating and difference between the thermal-conductivity coefficients. Moreover, all materials being used in the thruster design have similar thermal-conductivity coefficient values.

The analysis of the thermal expansion and stresses arousing in result of deformation is carried out after definition of boundary conditions according to scheme and thermal distribution application to the thruster parts[††].

The disposition and value of absolute displacements of the thermal screen free faces are shown in Fig.12. The disposition and value of absolute displacements of the central and side coil free faces are shown in Fig.13.

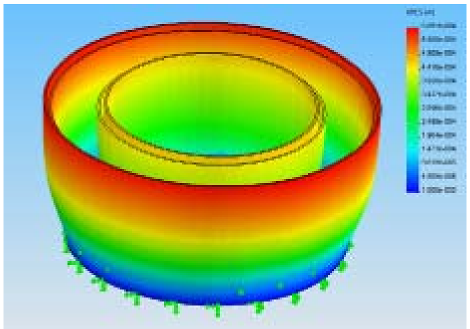


Figure 12. The disposition and value of absolute displacements of the thermal screen free faces

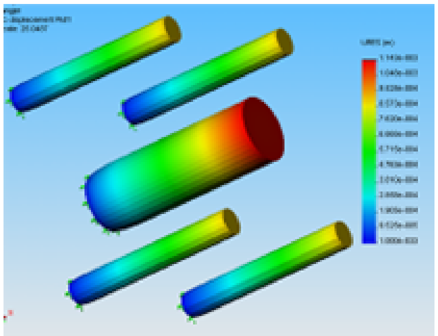


Figure 13. The disposition and value of absolute displacements of the central and side coil free faces

The design of the thruster ensures the possibility of electrode unit free displacement along the thruster axis at thermal extension of the fastening elements. The displacement is realized without mechanical stresses and, hence, without distortion and alignment failure. Absolute displacement of the magnetic poles is practically compensated by absolute displacement of free faces of the cathode screens due to their extension and extension of the mounting flange studs. Maximum expansion of the thruster thermostressed elements does not lead to the electric locking and thruster breakdown. During thruster pre-heating no locking between the electrodes is occurred.

E. Procedures and Arrangements

The full set of drawings, documentation, arrangements and procedures were made after all physical analyses completion. The most interesting thing was the "Analysis of a special test/diagnostics thruster design arrangements".

Thruster testing

Before installation into a vacuum tank, the thruster is mounted to the .thrust stand placed on the vacuum tank flange. The thruster movement to the tank is performed by means of a telpher due to the thruster's big mass as shown in Fig.14. During the tests the thruster is disposed vertically in the vacuum tank as shown in Fig.15. The thruster's mount to the thrust stand is performed by means of special bars.

The cathode-neutralizer is mounted on the individual flange that makes easier its mounting and connection with power supplies. The distance between the thruster's face and cathode-neutralizer is set within 10 to 20 sm.

The non-intrusive methods of investigation are advisable to use for the thruster's plume and discharge characteristics investigation. The best ones are the optical diagnostics methods. For application of thruster's plume and discharge investigation optical methods there are two illuminators in the tank's wall, which axes are on the angle for better viewing.

Along with the optical methods the use of plume diagnostics probe methods is possible. The best tool for the probe investigation is a shooting probe.

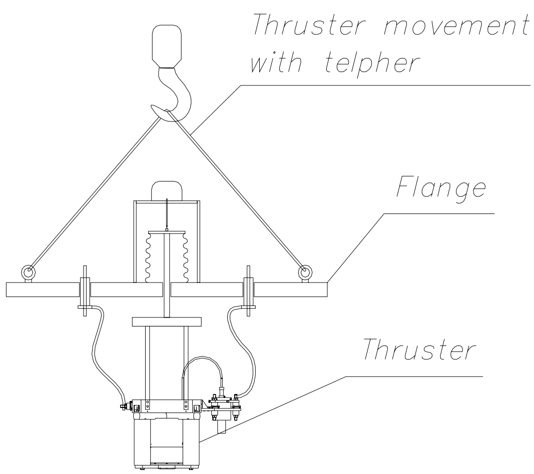


Figure 14. Scheme of moving the thruster mounted on the flange

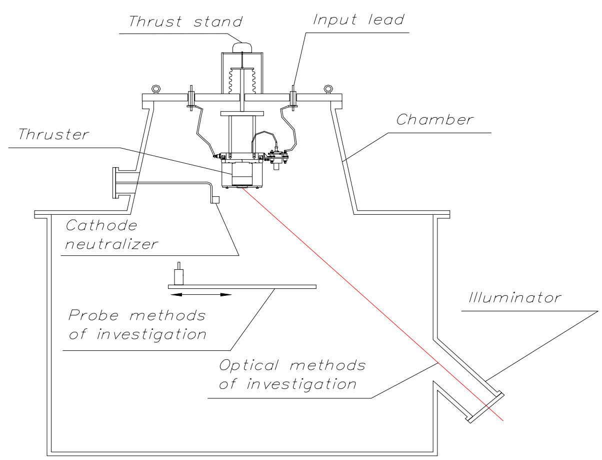


Figure 15. VHITAL-160 testing arrangement scheme

During the thruster tests it is necessary to control the temperature of some thruster parts. The temperature control is necessary to prevent thruster overheating and, therefore, one or another thruster part breakdown. There are several places in the thruster design which can be used for thermocouples, such as the central coil, central core, side coil surfaces and side magnetic pole faces. The thermocouples are placed according to scheme given in Fig.16.

†† The thermal distribution is taken from the most thermostressed mode

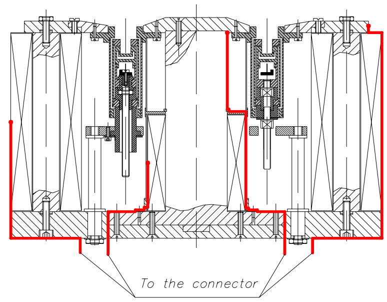


Figure 16. The thermocouples installment points and its layout

List of procedures

The full list of procedures was elaborated for thruster VHITAL-160 and support systems handling and testing, such as:

- Geometry control
- Electrical circuit and insulation check up
- Magnetic field value control
- Weighing
- Degassing in the vacuum tank
- Electrodes training
- Propellant filling
- Feed system calibration
- Assembling of the thruster with the feed system.

The thruster/feed system assembly manuals and acceptance test procedure were also developed. At last we have finished the bismuth feed system design documentation.

F. Laboratory bismuth feed system design

During thruster testing to provide propellant mass flow in a range 1 to 30 mg/sec the laboratory bismuth feed system can be used. The feed system is based on thin walls molybdenum tube putted into the bismuth and heated by direct electric current passed through it[10]. This system also allows to prevent condensation of the vapor inside along the whole length of pipeline from the tank to the anode-distributor.

Design description

The laboratory system for bismuth supply consists of the bismuth tank, vaporizer, pipeline for vaporized bismuth feeding from the vaporizer into the inner space of the anode-distributor, fastening. The scheme of the feed system is shown on Fig.17. It is important that the evaporator is placed directly inside the reservoir for propellant storage, and bismuth is supplied through the pipeline already in its vapor phase. This scheme is the most acceptable for laboratory tests; its reliability is verified in numerous tests, including the life time ones.

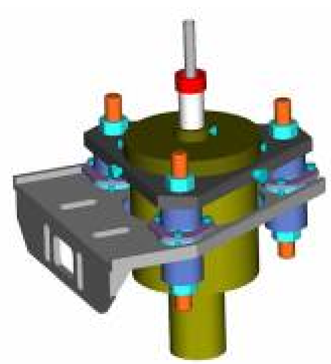


Figure 17. General view of the feed system

V. D-160 thruster and facility verification tests

After all paper work having been done the most exciting part of the VHITAL program was started. This stage of the work includes the following tasks:

G. Vacuum facility preparation and check test

The modification of the vacuum system was the first step in reconstruction of the vacuum facility “MNION”. During this modification the vacuum pumps were replaced, the vacuum monitoring system was updated by the vacuum gage replacement. The next step for the vacuum chamber check-out was the evacuation of the chamber with the mounted thruster and all systems connected. After pumping to the mentioned pressure the chamber was blanked off and the pumps were stopped. The leakage check was conducted. For 24 hours the pressure in the chamber changed in two orders that is acceptable value, which followed the past results.

H. Power supply system modification, preparation and acceptance test

The power supplies of different power and operating parameters are used in the bismuth Hall thruster testing. Moreover, both AC and DC current type power supplies must be used.

During the TsNIIMASH test facility conservation period most part of the power supplies has lost their working capacity. Therefore, to demonstrate the D-160 and test facility operation the transformers were chosen and the power supply rectifiers were fabricated. Based on the D-160 past testing data it can be noted that the parameters of the power supplies provided the thruster operation stable mode at the accelerating voltage of 2 kV. It should be noted that used power supplies do not completely answer the posed goals. The regulating range and output voltage stability of the transformers and regulators are not enough to test the thruster at the high accelerating voltages.

I. Parameter control and measuring system preparation and calibration

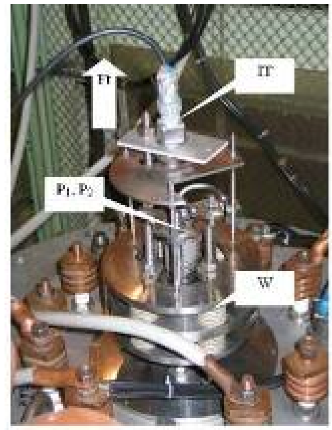
During high power bismuth thruster testing the “regular” digital multimeters can’t be used. Since the bismuth thrusters operate at the high voltages and currents there are no possibility to measure the operating parameters directly without special equipment. So the necessary set of meters was defined for preparation and calibration of the measuring system. The operable meters were defined and their verification testing was conducted. The analog meters were used as current and voltage measuring equipment. The calibration of all analog meters was carried out using the digital multimeters to define the accuracy of indications.

J. Thrust stand modification and calibration

The specially designed vertical thrust stand[6] was used for the thrust measuring during last D-160[4-6] testing at «MNION» facility. The thrust load generated by the thruster was measured mechanically by the registration of the spring hanger displacement.

During thrust stand modification it was decided to keep the thrust stand mechanical part and replace only the recording device (Picture 2). After modification the thrust measuring system registers the gap Δ between the moving part W and inductive sensor IS. The Ft force which produces by the thruster acts on the spring hanger and causes the gap Δ variation. Then IS signal changes proportionally to the thrust. The thruster weight is balanced by the spring tension W.

Vacuum chamber tightening is performed with two rolling diaphragms P1 and P2 which are connected differentially. The P1 and P2 rolling diaphragm volumes are connected to each other that allows to compensate atmosphere pressure change during thrust measuring. At the same time the P2 rolling diaphragm is a dampener of the vertical variable component. This component appears during the periodical or momentary external action which is defined by registration device as a positive signal.



Picture 2. Thrust stand appearance

K. Test of the facility with pre-existing D-160

After all preparation work having been done we have proceed to the D-160 thruster testing. The TAL-160 was mounted on the flange (Picture 3) and then installed into the vacuum chamber (Picture 4). Than the discharge and accelerating stages of the thruster were checked with megger (the resistance was more 500 MOhm). All thruster electric circuits were connected to the power supplies through the mounting flange pins (Picture 5). After that the vacuum chamber was pumped (the pressure was about 1.1×10^{-5} torr). And after 24 hour degassing the thruster was ready for the testing.

Picture 3. Thruster mounting

Picture 4. Thruster orientation in the vacuum chamber

Picture 5. Thruster connections

L. D-160 testing

As it was mentioned above to avoid the bismuth vapor condensation on the cool parts of the thruster the special graphite heater inside the anode distributor is used. So before the thruster running during the first 1.5 hour the thruster is warming up. The preheating is performed by the step by step heater current increasing up to the value of 190 amperes. In the same time the feed system must be also preheated.

Thus, the D-160 was well preheated before testing as shown in the picture 6. After thruster and feed system preheating the high-voltage was applied to the discharge and accelerating stage. Upon completion of the thruster thermal soaking and electrode training the bismuth feed system current was increased and the discharge was ignited (Picture 7)!

Picture 6. View of the preheated anode unit

Picture 7. D-160 discharge and plume

The thruster, vacuum chamber, power supplies and electrical circuits were pre-tested at the following parameters:

Discharge stage	220 to 240 V
Accelerating stage	Up to 2.8 kV
Heater	2000 W
Bismuth feed system	185 to 200 A
Magnetic field	0.2 Tesla
Pressure	(1 to 2.3)×10^{-5} torr

During the D-160 thruster testing the several volt-ampere characteristics were obtained for the different mass flow rate (Fig.18). In this series the thruster was tested without cathode-neutralizer. Due to that in the range of the accelerating voltages less than 1.8 kV the normal accelerating mode already have transformed to the abnormal one. All of operating regimes were investigated at the constant magnetic field about 0.2 Tesla.

The Bi mass flow rate is given in amperes of feed system current.

Unfortunately, the bismuth feed system is not calibrated yet. But the bismuth mass flow rate can be estimated in [mg/s] with help of the past experimental data. Moreover, the D-160 feed system design wasn't changed. So, the estimated Bi mass flow rates are given in the table below.

Feed system current, A	Bi mass flow rate, mg/s
185	4.4
195	5.3
210	6.35
220	7.38
225	7.7

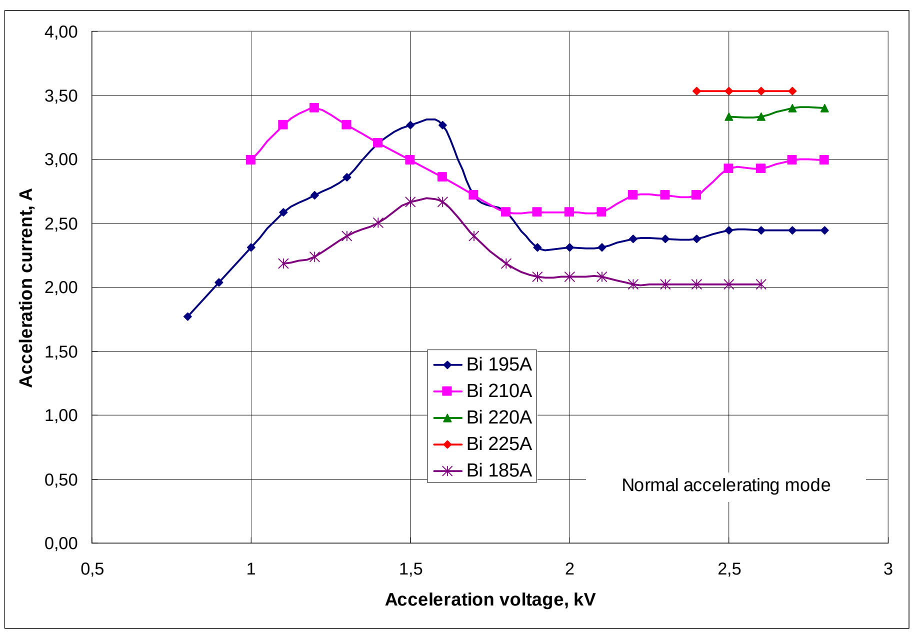


Figure 18. D-160 Volt-ampere characteristics

During D-160 testing the thrust measurements were conducted at the maximum accelerating voltage for all regimes at the different mass flow rates (Fig.19).

All of thrust measurements performed with described earlier thrust stand. The sensor data registrations have been made by means of the digital multimeters and its own software. The data was obtained in relative units. The calibrating of the thrust has been performed each time with help of the 50g weight (Fig.20).

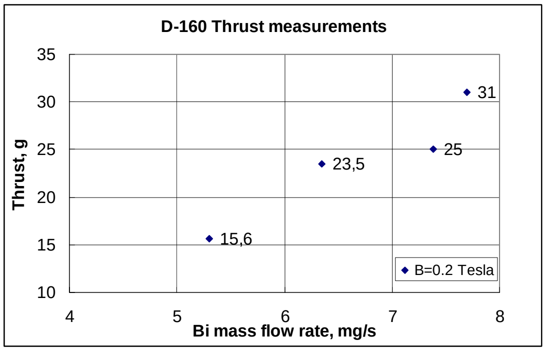


Figure 19. D-160 thrust measurements
all measurements were obtained at the same magnetic field

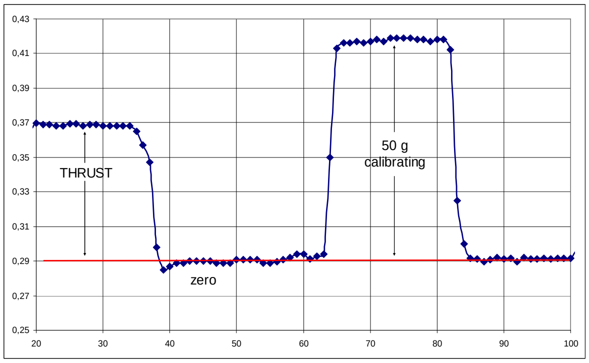


Figure 20. Thrust calibrating

Here the thrust is about 31g, Bi mass flow rate is around of 7.5 mg/s and total discharge power of 10.2 kW.

As one can see the thrust sensor signal is rather stable and constant. The transient processes are quite of short duration. That approves the efforts which were aimed on the thrust stand modification.

At last the maximum reached value of the thrust efficiency in this regime was about 60%.

M. D-160 testing results

It can be said for sure that after refurbishment the thruster is fully operable. During the thruster testing the registration of all electrical parameters was carried out. The thruster was tested in several regimes according to the power supply capabilities. All these regimes are close to the D-160 thruster regimes obtained in the past. That proves the working capability and readiness of all modified facility systems and laboratory thruster D-160 for further tests. Despite cathode-neutralizer absence the thruster operates at a stable accelerating mode at more than 1.8kV.

VI. Conclusion

All planned activities have been successfully performed. The VHITAL-160 laboratory thruster and laboratory feed system design documentation was completed. The analyses of the special test/diagnostics thruster design arrangements were made. The thermal and structural design verification was carried out. The TsNIIMASH "MNION" test facility was modified and prepared. The vacuum system control test was passed. Power supply check-out and high-voltage test were passed. All parts of the electric measurement system were examined, prepared and calibrated. Pre-test of the facility with pre-existing D-160 was conducted.

Moreover, all necessary procedures and documentation of supporting tools and nonstandard equipment for the VHITAL-160 thruster fabrication were made. The set of documentation and materials was brought and passed to the workshop. By now all necessary materials have been procured, the fabrication of the thruster and feed system parts is being processed.

All VHITAL Program efforts have been aimed to meet the program goals. So the authors had perfect confidence in VHITAL Program ability to succeed

References

[1] Grishin S.D., V.S., Leskov L.V. *Spacecrafts electric thrusters* " Mashinostroenie, Moscow 1989.
[2] Grishin S.D. et al, *Electric Propulsion*, Mashinostroenie, Moscow, 1975.
[3] Yerofeev V.S., Leskov L.V., "Hall Plasma Accelerator with Anode Layer", *Plasma Accelerator's Physics and Application, Science and Tech*., Minsk, 1974

[4] Ageev V.P., Safronov I.N., Tverdokhlebov S.O., "Operating Mode Characteristics and Performance of Two-Stage Anode Layer Accelerator with Low Voltage and Magnetic Field", *Sov. Journal of Appl. Mech. & Tech. Phys*., № 6, 1987

[5] Grishin S.D., Yerofeev V.S., Zharinov A.V. et al, "Performance of Two-Stage Ion Accelerator with Anode Layer", *Sov. Journal of Appl. Mech. & Tech. Phys*., № 2, 1978

[6] Overview "State-of-the-art of high power bismuth-fueled Hall thrusters with anode layer. Ground support system requirements and procedures" Tverdokhlebov O.S., Semenkin A.V., Tverdokhlebova S.A., TsNIIMAS 2004

[7] Report "Thruster VHITAL-160 and Support Systems Requirements, Conceptual Design and Analysis Package" Tverdokhlebov O.S., Semenkin A.V., Tverdokhlebova S.A., TsNIIMAS 2005

[8] Lyapin E.A.,Semenkin A.V. "Current status of the thruster with anode layer investigation" in the book "*Ion injectors and plasma thrusters*" Energoatomizdat 1990

[9] Kutateladze S.S., *Reference book of the heat transfer*, Gosenergoizdat, Leningrad, 1959

[10] Willinski M.I., Orr E.C., *Project Snooper. A program for reconnaissance of the solar system with ion propelled vehicles. In ion, plasma and arcjet roket engines*, Gosatomizdat, 1961