Development and Study of the Very High Specific Impulse Bismuth TAL

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Abstract: Since early 60-th bismuth has been used as a typical propellant in majority of the USSR research programs on development of thrusters with anode layer (TAL) having high power and great specific impulse. During 60-th…70-th such research programs were oriented to future interplanetary missions, and this goal determined range of parameters of studied laboratory thrusters - high specific impulse up 8000 sec, power range of a thruster from dozens to hundreds kilowatts. TSNIIMASH laboratory anode layer thrusters developed in early programs – namely D-160 (also called Drift-5) and D-200 demonstrated range of required performances. After 80-th such sort of programs in the Russia were stopped. During several last years the resumption of interest to the similar tasks is observed again. Given paper contains the results of the TSNIIMASH efforts aiming on development, fabrication and testing of the laboratory two stage thruster VHITAL-160 with average diameter of discharge chamber 160 mm. The laboratory thruster D-160 earlier developed in TSNIIMASH was used as a prototype. Unlike D-160 the new thruster ensures radiant cooling during the long operation. The VHITAL-160 design was developed based on the known and approbated solutions. Two operating modes of the VHITAL-160 at the discharge power level 25 and 36 kW were demonstrated. The values of specific impulse about 5400 and 7700 s were achieved correspondingly. In this paper the features of measurements of characteristics and feed systems design of the powerful bismuth TAL are discussed also.

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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]

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 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.[4]

As it was mentioned above the main feature of the interplanetary electric propulsion systems (EPS) is the high specific impulse about 5000-10000 sec that is necessary for mass decreasing of both the propellant and propulsion system. In contrast to the single stage Hall thrusters (fig.1) with Isp up to 3000 sec used onboard conventional spacecrafts (SC)[5], the TAL thrusters for interplanetary SC EPS initially employed the double stage scheme (fig.2) that provides a possibility to get high specific impulse[3,6].

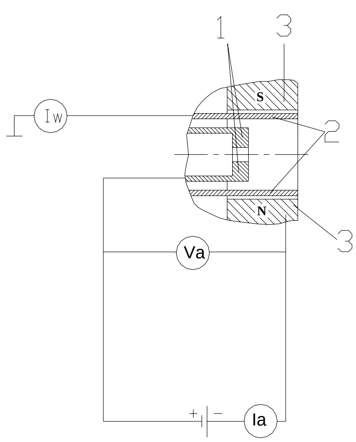

Figure 1. One–stage thruster scheme.

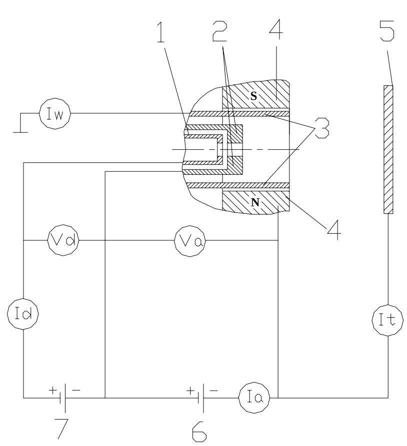

Figure 2. Two–stage thruster scheme.

The first stage (discharge chamber or source of ions) consists of an anode-vaporizer ***1*** and ring-shaped cathodes ***2***. The latter serve also as the second stage anodes. So together with cylindrical screens ***3*** they form the second stage (acceleration chamber). Both stages (let us name them a unit of electrodes) are placed in a ring-shaped gap of a magnetic system ***4*** (with N-S poles) produced a radial magnetic field. Rectifiers ***6*** and ***7*** serve as sources for both accelerating and discharge voltage. Target ***5*** is used only during tests in the vacuum chamber[7,6].

In a double-stage thruster with anode layer (TAL) two sequential $E \times H$ layers (low-voltage and high-voltage) are used. Purpose of the first layer is to ensure an effective ionization of a propellant, of the second one is to ensure acceleration of ions. The separation of ionization and acceleration zones allows reaching a high velocity of accelerated ion flow that can't be reached in single stage thrusters[8,7].

The interaction between stages is of fundamental importance for a two-stage thruster operation. The proportion between discharge and accelerating voltage values is important for effective (normal) acceleration mode, and it has influence on the transition point to the abnormal (so called anomalous) mode accompanied with efficiency decrease and appearance of the intense oscillations in the thruster discharge. First-stage voltage value should be selected under the requirement of effective ionization and coordination of first- and second-stage operation. Existent theoretical models don't let us to carry out analysis of adjustment conditions with satisfactory accuracy therefore this question studied only experimentally. More results of the bismuth two-stage TAL tests are given below. Here only main qualitative correlations are mentioned.

There are some discharge modifications in the first-stage:

- Relatively high-voltage (several hundred volts) self-maintained discharge existing whether there is second-stage discharge or not.
- Non-self-maintained discharge of 100…200 V voltage that can't exist without discharge in accelerating stage.

In respect to obtaining maximal thrust efficiency just the latter is of interest. But these results were got only for some accelerating voltage range and verification is required for every specific mode.

Results of research on a bismuth TAL operation characteristics were discussed in a number of papers which main results are shown below.[1,2,7]

II. Description of pre-existing TSNIIMASH Bi-fueled thrusters

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. The external view and cross section of D-160 are shown in fig.3 and fig.4 correspondingly.

Figure 3. External view of D-160.

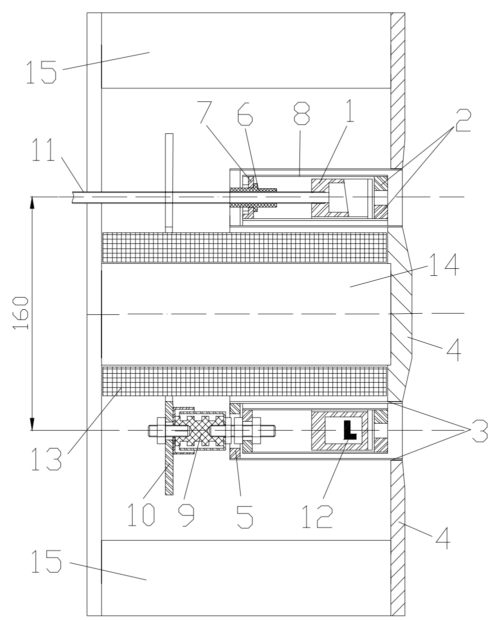

Figure 4. Cross section of D-160 .

The magnetic system pole pieces ***4*** are water cooled to prevent their overheating by the unit of electrodes radiation shown in fig. 4.

The coil winding ***13*** is put on the central core ***14*** of the magnetic system. The external part of the magnetic circuit is made of 4 rods ***15***. A magnetic field strength at the average diameter of the magnetic gap varies from 0 up to 2 kGs. All values of the magnetic field strength are given below for the average diameter.

The discharge chamber walls ***3*** consist of the two molybdenum co-axial cylinders fixed on a flange ***5***. The molybdenum anode vapour–distributer ***1*** is fixed on a flange ***7*** by the high voltage insulators ***6***.

There are also the first stage cathodes ***2*** fixed on the flange ***7*** by means of cylinders ***8***. The discharge chamber and the acceleration chamber are installed on the adapter flange ***10*** which is attached to the magnet. All electrodes are isolated by means of high–voltage insulators fixed on metal pins. The gap between the surfaces of the anode and cathode is about 1 mm to prevent gas discharge breakdown. From the vaporizer of the feed system bismuth vapour goes to annual inner hole of anode–distributer through a vapor pipeline ***11***.

The anode-distributer must ensure azimuthal uniform feed of bismuth vapour into the discharge zone.[6,7] The design pressure in the inner anode hole is about 2 torr for the flow rate of 22 mg/s (10 A), that pressure of saturated bismuth vapour corresponds to the temperature of about 1000 °C. To heat the anode up to this temperature a graphite heater ***12*** is used. The heater is placed inside the anode annual inner hole.

Other components of the unit of electrodes including anode and cathodes are heated by the anode radiation. All metal parts of the unit are made of molybdenum, and insulators — of pure alumina.[7,6] The first stage cathodes are the most heat affected elements, because of electron flux from an accelerating layer.

As a rule, the electrode unit is placed in a magnetic system so that the accelerating layer would be in the gap, where the magnetic field strength is maximal, and the curvature of magnetic field lines is insignificant. It allows easily an adjusting of plane front surfaces of the both anode and cathodes (facing to the accelerating layer) with magnetic field lines. At such arrangement of the acceleration chamber the discharge stage is in the area of a decreasing magnetic field. This is favorable for the ion source, because magnetic field value acceptable for effective ionization is smaller than that for acceleration.

In case of misalignment of the electrodes with magnetic field lines, all electrons from the layer are "intercepted" by the local areas of electrodes protruding in the direction perpendicular to H. In these zones local overheating occurs and that may result in the thruster part melting.

If the pressure in the vacuum chamber is of 10^{-5} torr and energy of ions is up to several keV, ionization of the background gas and emission from the walls of the vacuum chamber provide an effective neutralization of an ion beam. So there is no need to use a special source of electrons for ground testing. Nevertheless, the Bi hollow cathode-neutralizer with LaB_6 emitter was developed and later used in tests.[9] It can be underlined that during operation at the accelerating voltages more than 2 kV there was no difference observed in thruster performance whether with cathode–neutralizer or not.

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. Total thruster mass is about 70 kg.

The performance characteristics obtained during D–160 testing are given in ref.[7,6]. The volt-ampere characteristics of D-160 for several mass flow rates (5…25 mg/s) are shown in fig.5.

The maximum current of accelerated Bi ions achieved during D-160 testing was 14 A. It is important that in all experiments the value of Ia coincides with the Bi mass flow rate expressed in current units $e\dot{m}/M$ (M – atomic mass). This fact confirms the assumption that the value of electron current across the magnetic field lines is much less than accelerated ion current.

There are two distinct ranges on these curves where accelerating stage current depends on accelerating stage voltage quite differently. Effective operating mode with focused ion beam named "accelerating" one relates to the region of nearly constant discharge current. When the accelerating voltage decreases to some value, the current begins to rise and the thruster transits to "anomalous" or "abnormal" operating mode characterized by enhanced oscillation level and low thrust efficiency. As one can see (Fig.5) the threshold of transition to "anomalous" operating shifts to higher accelerating voltage area with increasing mass flow rate. Such effect can confine possibilities of both thruster power and thrust increasing at some given value of accelerating voltage.

The threshold of transition from accelerating mode to anomalous one depends on thruster operating mode and test conditions. In ref. it is shown that accelerating voltage value according to transition threshold is described by empiric regularity:

$$U_a^* \approx \frac{I_a}{H^2 P}$$

where H – magnetic field strength; P – background pressure.

Due to substantial design margin and water cooling magnetic system D-160 thruster allows realizing high power operating regimes. Maximum achieved power level was about 140 kW.

Fig.6 shows thrust efficiency (curve 3) and bismuth average outflow velocity versus TAL second stage voltage, theoretically calculated (curve 2) and experimentally measured one (curve 1). In the experiments velocity of accelerated beam was determined as a ratio of measured thrust to mass flow rate values.

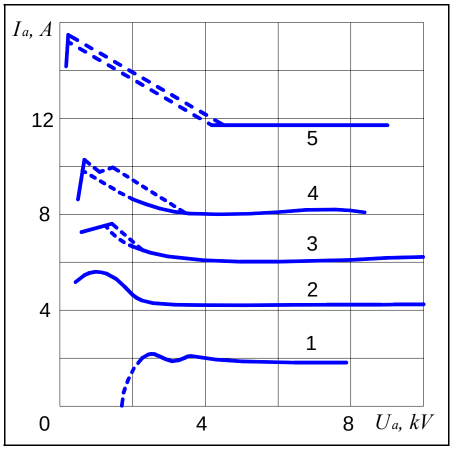

Figure 5. Volt-Ampere Characteristics of Bismuth TAL.

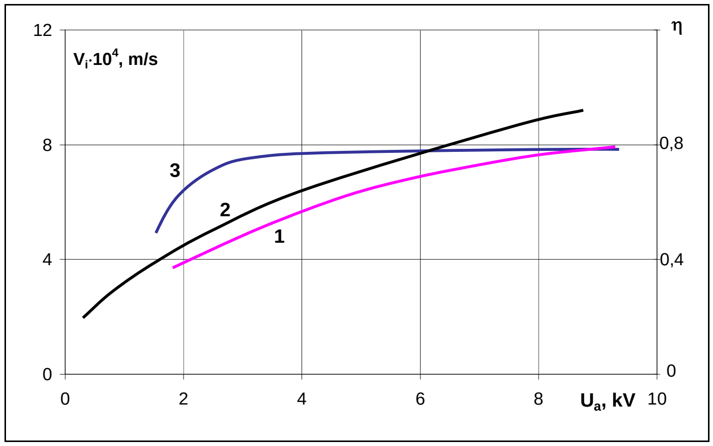

Figure 6. Ion Velocity & Thruster Efficiency vs Accelerating Voltage.

Experimental outflow velocity was about 0.89 of theoretical limit in all studied range.

Study of ion flow energy spectra at exit plan of radial two-stage accelerator with anode layer, which was used for two-stage discharge research[10], showed that in spite of presence of main ion group arising in first stage with energy close to accelerating voltage there are significant (up to 10…20%) portion of low velocity ions. These slow ions appear due to ionization of some propellant portion in accelerating layer.

Ion average velocity and thruster efficiency monotonically increase with accelerating voltage rising (see Fig.6). Thus specific impulse up to 8000 s and thruster efficiency more than 70% can be achieved.

Thrust value in accelerating mode is linearly depends on mass flow rate at constant voltage (Fig.7). As a rule discharge voltage *Ud* required for Bi propellant effective ionization varies in the range 150 – 220 V and it slightly decreases with Bi mass flow rising. Thus, when accelerating voltage *Ua* exceeds 1 kV, losses connected with propellant ionization reach comparatively low level.

Thruster characteristics changing with discharge voltage variation are shown in Fig.8.

Obviously, there is range of optimal discharge voltages where the most effective operating mode of two-stage TAL can be reached. In Fig.8 this range corresponds to horizontal part of I_a - curve.

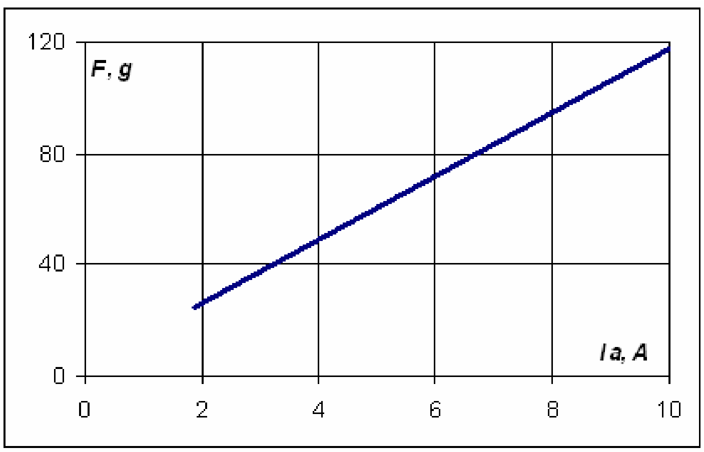

Figure 7. Thrust vs Accelerating Current.

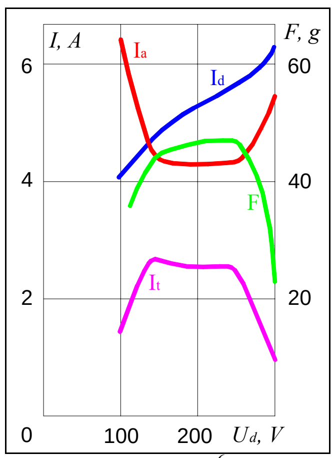

Figure 8. [6]

As it was mentioned above, discharge and accelerating voltage values betweenness relation affects the transition threshold from accelerating to anomalous mode. Experimental diagram[2,6] of U_d to U_a proportion characterizing the transition for D-160 is represented in Fig.9. Area on the right of the curves corresponds to accelerating mode and on the left – to anomalous one.

It is clear; that the range of allowable discharge voltage variation is expanded with accelerating voltage increasing. At the same time minimally allowable value of U_d decreases. For example, in the case of U_a =2 kV discharge voltage value must be in the range of 200…300 V, and for U_a =4 kV corresponding discharge voltage value range is 100…400 V. Decreasing of minimally possible value of U_d makes easier first stage erosion problem solution.

Figure 10 shows the magnetic induction (B) effect upon accelerating current value I_a.

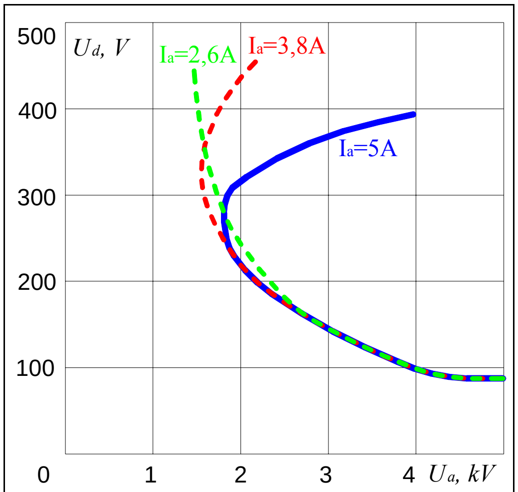

Figure 9. [2,6]

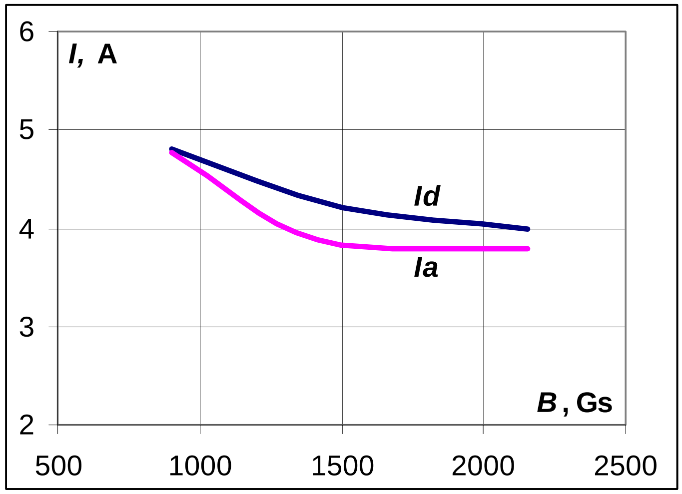

Figure 10. Discharge and accelerating current versus magnetic induction .

It is obvious that accelerating stage current I_a is reduced with increasing of the value B and reaches the minimum value at B = 1.5 kGs. This minimum current value is retained approximately constant for all approved values of B > 1.5 kGs and corresponds to bismuth mass flow rate expressed in current units accurate within a few percents.

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. Such a TAL (*Fig. 11*) with average diameter of 200 mm named D-200 was tested at TSNIIMASH. D-200 has demonstrated outstanding characteristics for radiation cooling thruster: specific impulse – 2000…5200s at 10 – 34 kW power level.

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 Figure 12 and Figure13.

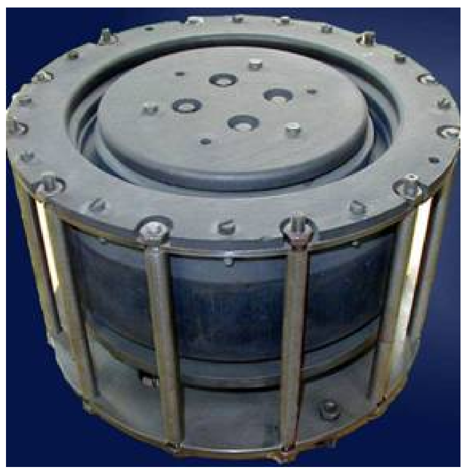

Figure 11. TAL D-200.

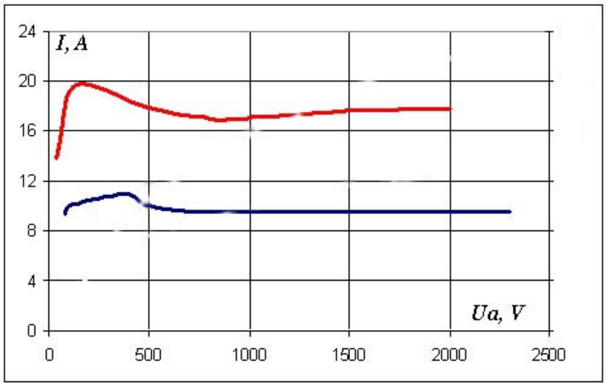

Figure 12 . Accelerating current vs Accelerating Voltage .

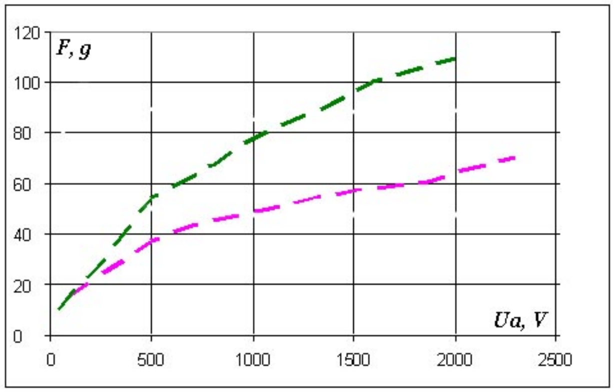

Figure13. Thrust vs Accelerating Voltage .

Unlike to D-160 thruster, D-200 was tested with cathode-neutralizer using. Cathode-neutralizer application allowed significantly reducing the threshold of transition from accelerating regime to anomalous one. As it can be seen from Figure 13 this threshold went down to 500…1000 V. 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.

With cathode-neutralizer the value U_a* corresponding to transition threshold is no longer described by regularity $U_a^* \approx \frac{I_a}{H^2 P}$. Moreover, opposite tendencies are observed – the value *Ua** is reduced with the anode mass flow rate rising and decreasing of magnetic field strength in the discharge zone. This allows to suppose that physical mechanisms causing transition from accelerating to anomalous mode are quite different and depend on cathode-neutralizer presence.

Since the value of D-200 thruster magnetic induction is twice as little as one for D-160, the value of *Ia* significantly exceeds anode mass flow rate expressed in current units.

The D-200 thrust varies approximately proportional to $\sqrt{U_a}$. For the low voltages this dependence is not correct. The fact can be explained by significant ionization losses in this range in comparison with high voltage case when *Ua>>Ud*.

III. Hardware description

The performance specification has determined the following general characteristics of the VHITAL-160:

Operating mode	Power, kW	Specific impulse, s
1	25	6000
2	36	8000

VHITAL-160 design is for the most part similar to the thruster D-160 earlier developed in TSNIIMASH. However, there are some differences in VHITAL-160 design because of radiant cooling scheme requirement.

VHITAL-160 is a two-stage thruster with anode layer and its design does not almost differ from a typical TAL design. The average diameter (160 mm) of the thruster and the discharge channel basic geometry were kept the same as in the thruster D-160, since the required modes with the specific impulses of 6000 and 8000 s can be realized in this case.[1,2,3,6,7,9] However, high temperatures, currents and voltages, along with using of the condensed propellant, impose some limitations on the thruster design.

The main parts of the thruster are the electrode unit, magnetic system and the constructive parts designed for the thruster assembling and mounting (Fig. 14).

The electrode unit of the thruster consists of the first (discharge) stage anode – distributor (1), second stage anode (2, 3) and second (accelerating) stage cathode (4, 5). All electrode unit parts are made from heat resistant refractory metals (molybdenum, niobium) due to high temperature mode conditions. The gap between the anode-distributor and the cathodes and the gap between cylindrical surfaces of the anode and the first- and second stage walls are chosen due to the requirement of electric breakdown prevention. Similar to the D-160 all electrodes are insulated by high-voltage insulators (6) made of vacuum ceramics, and are fixed to the mounting flange (7) by means of the niobium studs (8) serving at the same time as current leads. The mounting flange is fixed to the magnetic system parts (10, 11) by means of four studs made of stainless steel (9). Bismuth vapors from the feed system come in the anode-distributor through the pipeline made of molybdenum. The anode-distributor must ensure uniform feeding of the bismuth vapors into the discharge gap between the cathodes. Hundred output anode orifices ensure such uniform distribution. The graphite heater (12) is used for the anode heating to prevent the bismuth vapor condensation during thruster operation. The heater is disposed inside the anode. The other elements of the electrode unit are heated by the anode thermal radiation.

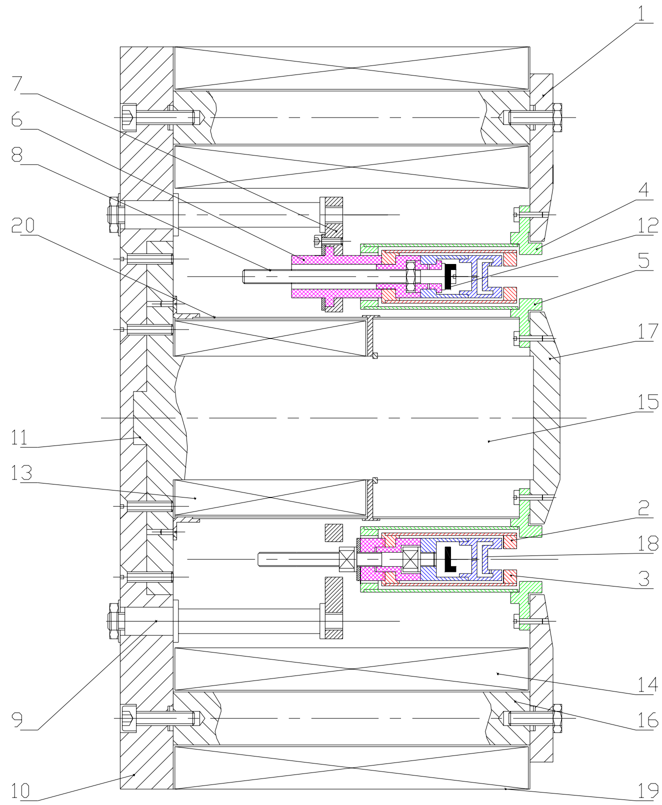

Figure 14. VHITAL-160 Thruster structural layout.

The VHITAL-160 magnetic system consists of the magnetic circuit, the central coil (13) and four side coils (14). The magnetic circuit of the thruster is formed by the cores of the central (15) and side (16) coils which are mounted to the cruciform element in the thruster's rear side (see fig. 17). The central magnetic pole (17) is mounted to the central coil core and the side magnetic pole (18) is mounted to the cores of the side coils in the thruster's frontal side. During the thruster operation all magnetic system parts are in the hard temperature conditions, therefore, all magnetic circuit elements are made from iron-cobalt alloy – permendur. This alloy has a high Curie point (960º).[11]

The magnetic system poles are protected from erosion in the usual way by means of guard rings made of graphite (4,5), which are at the same time served as the second (accelerating) stage cathodes.

The central and side magnetic coils are wound with the heat-resistant wire of the thread diameter of 1.5 mm. To lessen the magnetic system temperature mode several design approaches were used. Thus, the central coil is wound directly round the part of central core, and this part of the core does not face the anode unit. There are several thermal screens to reduce heat flow from the electrode unit, the one attached to each of the side coils (19) and two attached to the central coil and core (20).

The magnetic system is designed so that the magnetic induction in the gap is about of 0.2 tesla. The number of side coils is chosen equal to 4 to ensure acceptable uniformity of the magnetic field along azimuth. The four series-connected side coils and central coil are supplied by the independent power supplies, what essentially simplifies the tests and increases the possibility to adjust the thruster output parameters.

The main element of the thruster assembling and mounting is the load-carrying mounting frame made in the form of box (see fig. 17) situated in the thruster's rear part. The thruster thermal mode along with mechanical loads does not allow to fabricate the frame from light structural materials such as aluminum alloys. Therefore, to ensure mechanical strength and high-temperature stability the frame is made from stainless steel. Set of high-voltage and high-current terminals with insulators are mounted on the frame (see fig. 17). The electric energy inputs are performed through these terminals disposed all around the frame in the rear side of the thruster. The value of the current leads cross section is chosen so that the current passing through each one can be up to 250 A (such high value of current required for powering heater and bismuth feed system). There are also mounting elements on the mounting frame to install the feed system both in vertical and horizontal thruster disposing.

In order to provide supply of bismuth vapors into the thruster anode the feed system with resistive heat of thin-walled molybdenum pipeline is used.[12] This scheme also allows to prevent the bismuth vapors condensation in the tube between bismuth tank and anode-distributor.

The laboratory bismuth feed system used during the testing at TSNIIMASH consists of: bismuth tank, vaporizer, pipeline through which the bismuth vapors from the feed system come into the anode-distributor, mounting elements. Feed system scheme is shown in the fig. 15.

It is important that vaporizer is disposed directly inside the tank and already vaporized bismuth comes through the pipeline into the anode. This scheme is most acceptable during the testing and its dependability is confirmed by numerous tests.

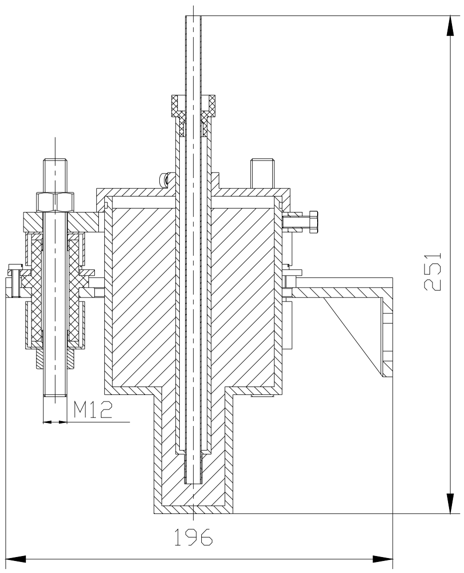

Figure 15. Feed system basic scheme.

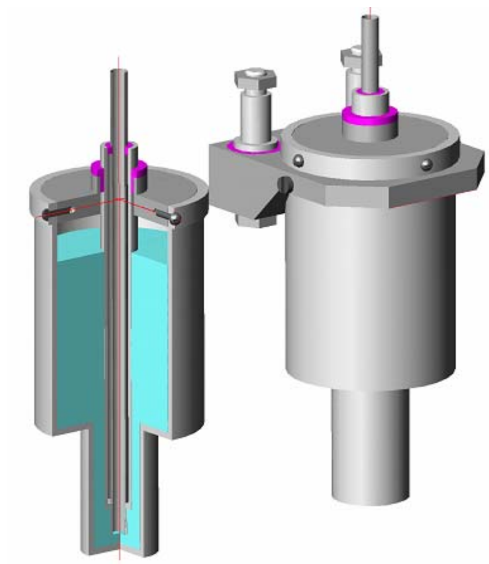

Figure 16. General view of the feed system.

Feed system fueled with solid bismuth is assembled together the thruster into the vacuum tank.

Depends on orientation of the thruster in the vacuum chamber the bismuth tank must be mounted differently in order to provide vertical orientation of the vaporizer drowned into the bismuth volume as it is shown in the Fig.17 and 18.

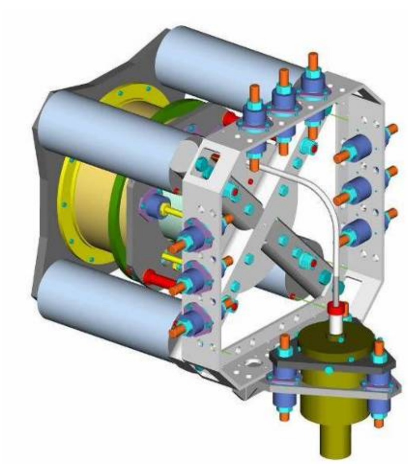

Figure 17. Feed system mounting in case of horizontal thruster orientation.

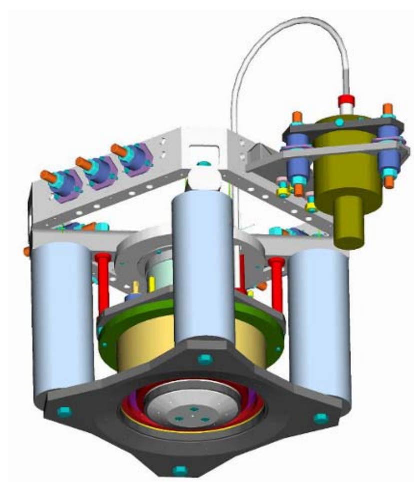

Figure 18. Feed system fastening in case of vertical thruster orientation.

To feed the propellant into the thruster the bismuth in tank is heated up to melting temperature (271 °C) by means of ohmic heat from molybdenum propellant pipeline. Liquid bismuth streams into the vaporizer pipeline and vaporizes in a contact with heated pipeline's walls. Vaporizer consists of two tubes hermetically welded at one end. The connected end of vaporizer is drowned into the bismuth volume almost about the tank bottom. The inner tube actually is the vaporizer which is fueled with bismuth streaming under gravity. Exterior tube is a heat shield of inner one and it serves as a part of electric circuit providing the heating of vaporizer.

Vaporizer representative temperatures providing required bismuth vapor pressure in feed system are about 1000° C.[1,2]

The vaporizer heating is performed by electric current direct passing through the inner tube. The pipeline though which the vapors come to the anode of thruster is vaporizer's continuation and also is heated by current direct passing. Power supply generating the current through the vaporizer tube and pipeline is connected to bismuth storage tank body and thruster anode by means of studs. Correspondingly, anode, tube-pipeline, vaporizer and bismuth storage tank are galvanic connected.

IV. Test facility and procedures description.

Thruster testing was performed on vertical TSNIIMASH's vacuum facility. The general view of vacuum tank is shown in Fig.19.

Vacuum tank is volume of 5m^3 composed of two parts: measuring part 1 meter in diameter and 0,8 meters in height, and vacuum tank 1,8 meters in diameter and 1,3 meters in height. Tank has a water-cooling jacket.

Vacuum system allows to rich vacuum value up to 1x10^{-5} mmHg at operating on condensable matters.

The power supply system required for thruster operation includes the following power supplies:

1. Thruster magnetic system power supplies that provides DC currents up to 5 A into inner and side coils;
2. Power supply of alternating current in order to pre-heat a bismuth feed system (tank fueled with bismuth and feed system pipeline). This power supply provides the current value up to 300 A;
3. Power supply of direct current to pre-heat the heater (located in the anode-distributor) up to 300 A.
4. Power supply of thruster first stage that provides the value of DC discharge voltage up to 500 V;
5. Power supply of thruster second (accelerating) stage that provides the value of DC voltage up to 10000 V.

Figure 19. Test stand general view.

The electrical schematic of the bismuth thruster and electrical parameter measurement are shown in Fig.20 and 21.[1,6,13]

The thruster can be tested both with the cathode-neutralizer (Fig.20) and without one (Fig.21). In the second case, the thruster body should have a galvanic coupling with an ion beam target and a vacuum chamber.

During all tests of VHITAL-160 at TSNIIMASH the electric scheme excluding cathode-neutralizer was 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.

The amperemeter indications of all high current circuits were checked with the digital clamp meter. Variation in indications was not more than 1% that is a permissible value.

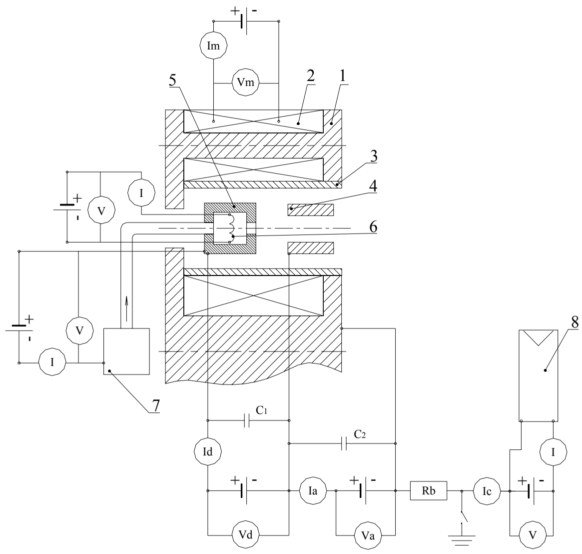

Figure 20. The electrical schematic for the bismuth thruster with the cathode-neutralizer.

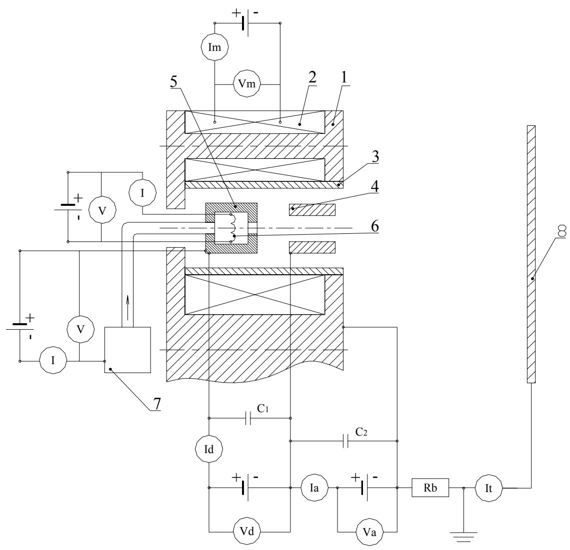

Figure 21. The electrical schematic for the bismuth thruster with the beam target without cathode-neutralizer.

The designed vertical thrust stand was used for the thrust measuring during VHITAL-160 testing at TSNIIMASH facility (fig. 23). The thrust load generated by the thruster was measured by the registration of 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 P_1 and P_2 which are connected differentially.

The P_1 and P_2 rolling diaphragm volumes are connected to each other that allows to compensate atmosphere pressure change during thrust measuring. At the same time the P_2 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.

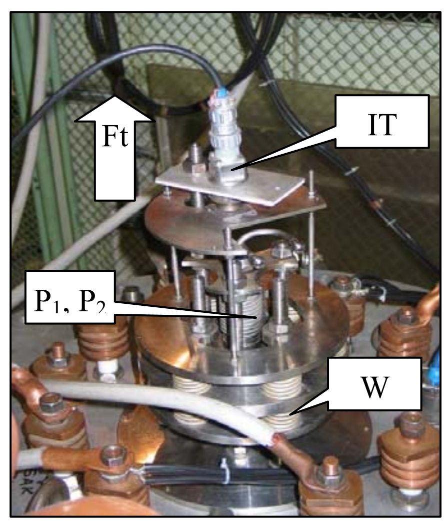

Figure 23. Thrust stand

V. Tests of the VHITAL-160

After thruster assembling with the feed system it was mounted on detachable flange of vacuum tank. The external view of the VHITAL-160 is shown in fig.24. Then the thruster was placed in the vacuum tank (Fig.25).

Figure 24. The external view of the VHITAL-160.

Figure 25. The thruster placed in vacuum tank.

When the thruster is placed in vacuum tank, degassing procedure was performed. During initial degassing procedure the thruster was kept in vacuum conditions during 10 days. During this procedure the thruster magnetic system was periodically powered by DC of 5A, as a result of that heating of the thruster occurs and correspondingly degassing effectiveness increase.

For the hardware safety reasons the initial testing of the thruster was made in the accelerating voltage range up to 4500 V and total power not more than 16 kW.

To provide the hardware protection the following elements were included in the electric circuit:

- ballast resistor of 100 Ohm was connected in the discharge electric circuit in-series and two capacitor values of 40 and 0,1 μF connected in-parallel.
- ballast resistor of 300 Ohm was connected in the accelerating electric circuit in-series and two capacitor values of 40 and 0,1 μF connected in-parallel.

All further tests were made with these protection elements.

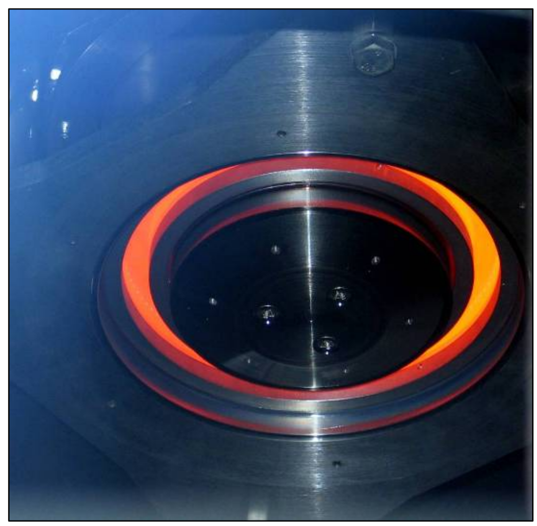

Figure 26. Thruster preheating.

Photo of the thruster on preheating stage is shown in the Fig.26, the thruster operating in accelerating mode is shown in the Fig.27.

As an example, fig.28 and fig.29 show the main thruster performances at bismuth flow rate of 5.21 mg/sec. Total thruster power in each point (magnet coils and heating subsystem power are not included) is figured on the curve of thrust dependence on accelerating voltage. First stage discharge voltage is 150…185 V. Accelerating current is 2.7…2.8 A. The transfer to the accelerating mode (magnet pole pieces gap is 30 mm) occurs at accelerating voltage value of 1800…2000 V.

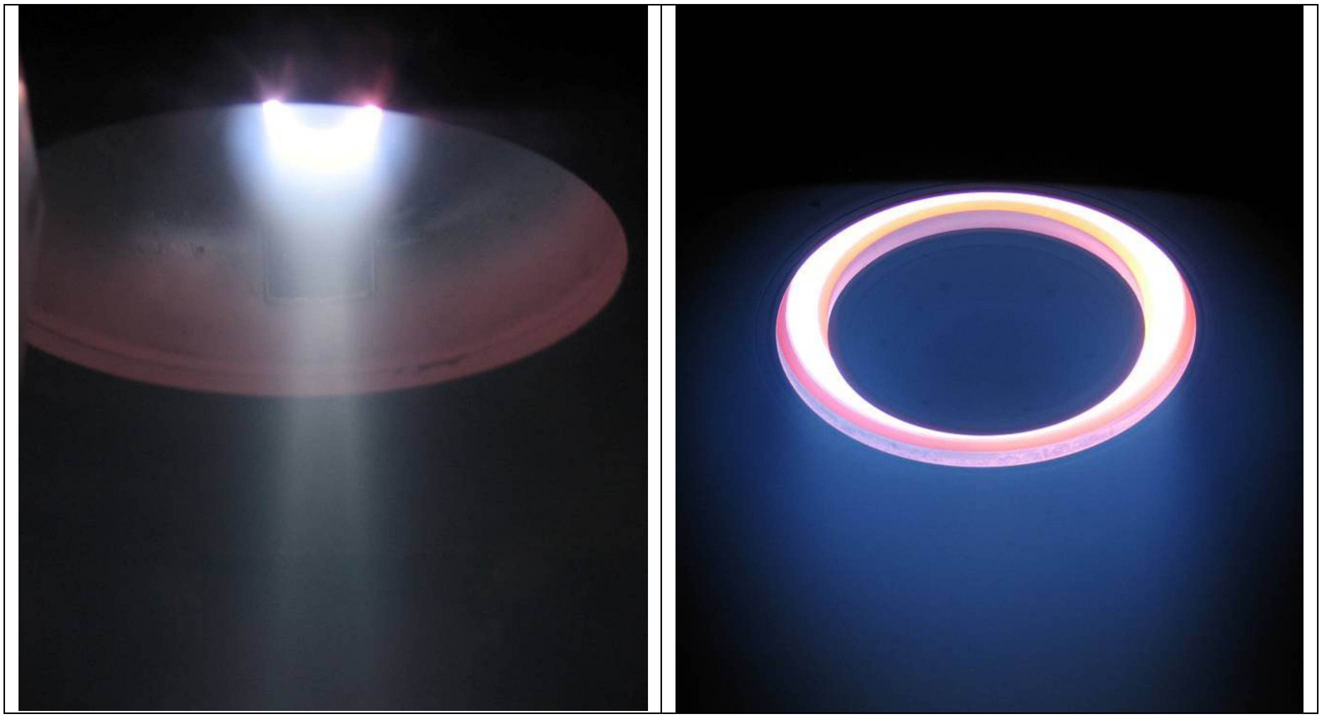

Figure 27. Operating thruster, acceleration mode.

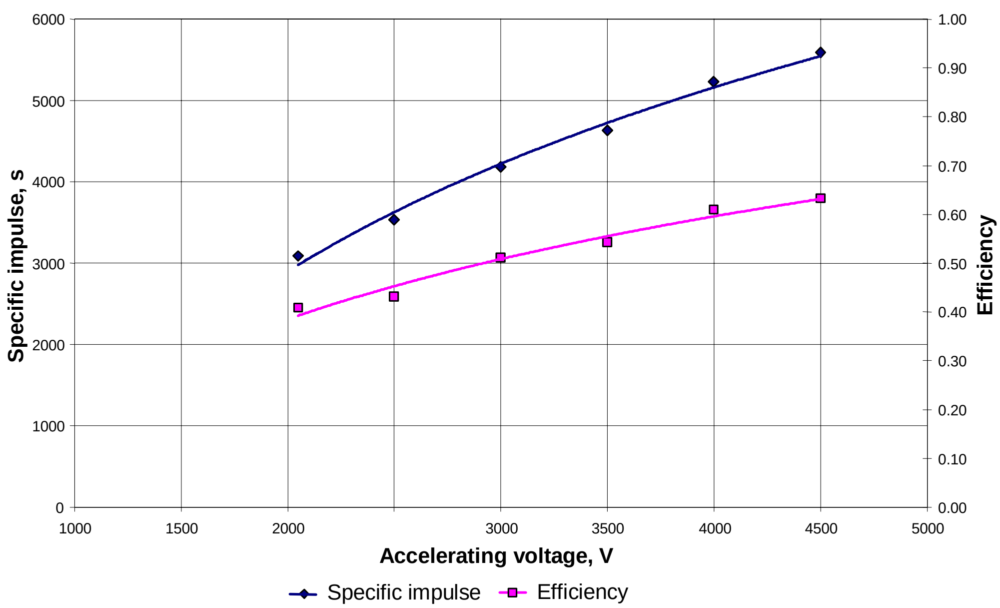

Figure 28. Dependence of specific impulse and efficiency on accelerating voltage.

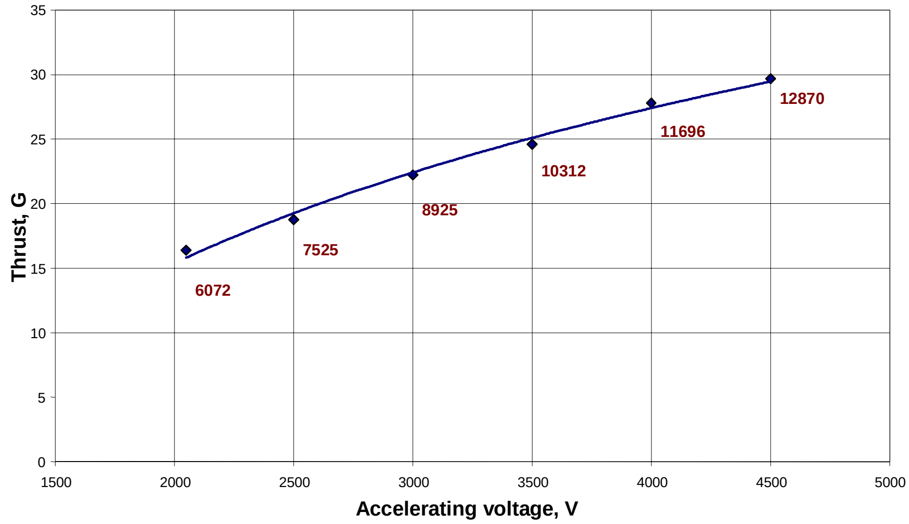

Figure 29. Dependence of the thrust on accelerating voltage.

Data are shown in the Figures 30 and 31 indicate that achieved specific impulse is 5600 sec when the thrust is 30 g, anode efficiency is 0.60 and power is 13 kW.

After preliminary thruster tests up to 4500 V accelerating voltage was varied in the range up to 6000 V. Any electric break downs and disruptions inside the thruster were not observed, operation mode of the thruster was stable.

Figures 30, 31 and 32 show obtained thruster performances at two flow values - 5.76 и 8.0 mg/sec at accelerating voltage up to 6000 V. Total thruster power in each point (magnet coils power is not included) is figured on the curve of thrust dependence on accelerating voltage.

As one can see from data on the figures, the increasing of accelerating voltage implies the increasing of specific impulse, thrust and efficiency.

When stable thruster operation in the range up to 6000 V of accelerating voltage was demonstrated, the following experiment were aimed to demonstrate thruster operating modes stated by performance specification.

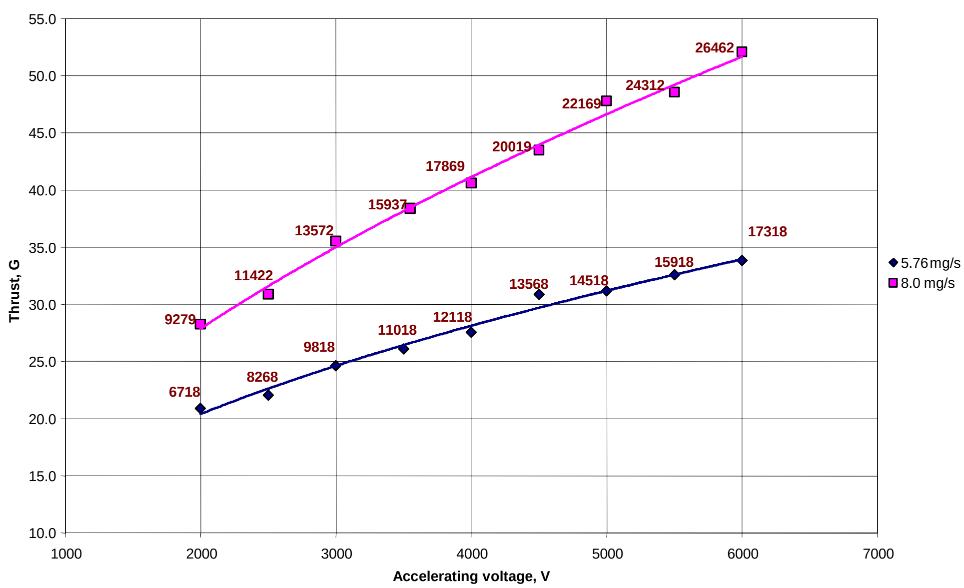

Figure 30. Dependence of the thrust on accelerating voltage at 5.76 and 8.0 mg/sec of bismuth flow rate.

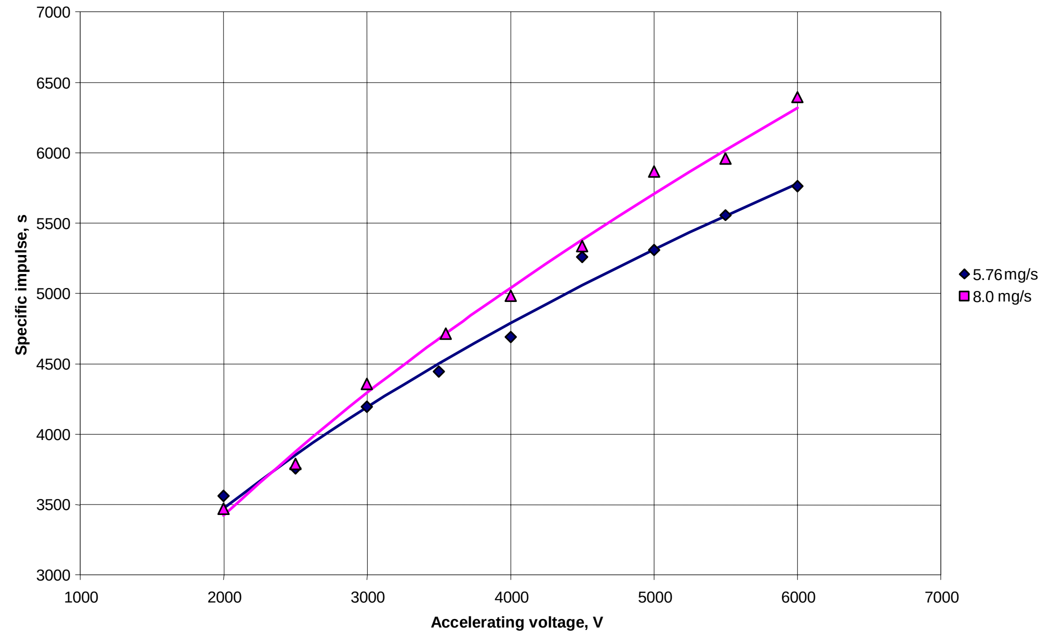

Figure 31. Dependence of specific impulse on accelerating voltage at 5.76 and 8.0 mg/sec of bismuth flow rate.

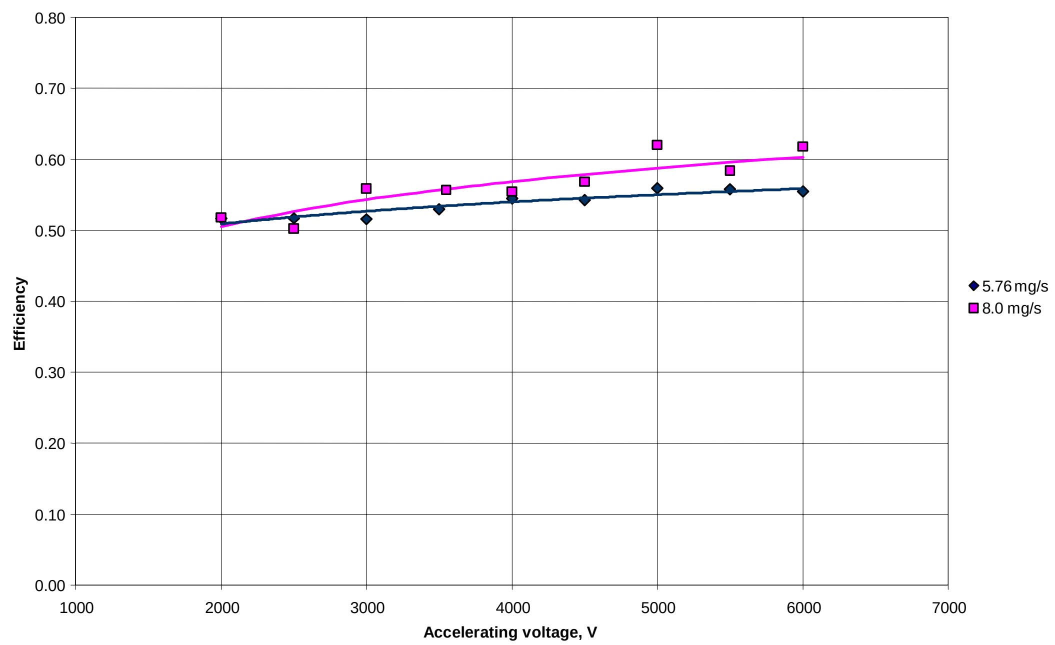

Figure 32. Dependence of the efficiency on accelerating voltage at 5.76 and 8.0 mg/sec of bismuth flow rate.

The main criteria of required mode providing was the following:

- total power value not less than 25 kW at accelerating current 5A
- total power value not less than 36 kW at accelerating current 4,2A.

The obtained thruster performances at 25 kW are the following:

	Designed	Achieved
Power N, W	25000	25240
Specific impulse I_{sp}, sec	6000	5375
Discharge voltage U_d, B	150	130
Discharge current I_d, A	6	5.85
Accelerating voltage U_a, B	4750	4800
Accelerating current I_a, A	5.0	5,1
Bismuth flow rate $\dot{m}$, мг/с	11	9.8
Thrust, F, мН	650	527
Thrust efficiency, η	0.78	0,56

The obtained thruster performances at 36 kW are the following:

	Designed	Achieved
Power N, W	36000	36755
Specific impulse I_{sp}, sec	8000	7667
Discharge voltage U_d, B	150	130
Discharge current I_d, A	5	4.85
Accelerating voltage U_a, B	8400	8500
Accelerating current I_a, A	4,2	4,25
Bismuth flow rate $\dot{m}$, мг/с	9	8
Thrust, F, мН	710	618
Thrust efficiency, η	0.79	0,63

The thruster operation in the modes with U_a =8000 V and above was limited in time in order to minimize risk of hardware damage. Because to reach such a voltages on the thruster the protective ballast resistors were excluded from the power supply system, and in case of random electric break downs there was risk of thruster and supply system damage.

The thruster operation in the mode with self heating anode was not carried out because there was a risk of thruster damage, and experimental demonstration of it is beyond of performed VHITAL-160 acceptance testing.

VI. Discussion

As data in the above tables indicate, achieved thruster performances are below than designed performances. The main reasons of this could be the following factors. Measured thrust values had significant scattering (more than 5 %). This is the result of large thruster weight, and available thrust measuring device operated close to boundary of sensitivity. The second reason of undervaluing could be accuracy of mass flow measurement and bismuth vapor leak at the rate of several percents of total flow value. The possible reasons of propellant vapor leak could be pipeline connection which was made by grinding method. In this case the value of measured flow rate is overstated in comparison with true flow passing through thruster anode. Also, true performances undervaluing may be connected with increased outgassing of the vacuum tank and the thruster itself the input power values 24 kW and above. All these reasons are associated with particular test conditions, and it should be re-considered during further detailed tests of the thruster at JPL.

Nevertheless obtained data allows to conclude that VHITAL-160 thruster operation performances satisfy the SOW requirements since the difference between the achieved and designed parameters are in the range of measurements inaccuracy.

The tested VHITAL-160 thruster has demonstrated the ability to achieve specific impulse up to 8000 sec and power level up to 36 kW and the thruster is ready to be tested at JPL facility.

VII. Conclusion

Based on the known[1,2,3,6,7] and approbated solutions, the radiant cooling bismuth thruster VHITAL-160 and the laboratory Bi feed system were developed. The VHITAL-160 design passed out all required engineering stage including the thermal and structural analyses[4,14]. The VHITAL-160 was manufactured and successfully tested. The specific impulse up to 8000s was achieved at discharge power level of 36 kW. The VHITAL-160 was delivered to JPL for subsequent tests.

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