

An Overview of the VHITAL Program: A Two-Stage Bismuth Fed Very High Specific Impulse Thruster With Anode Layer

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Abstract: VHITAL or Very High Isp Thruster with Anode Layer is a two stage Hall thruster technology assessment program that is part of the Prometheus Program in NASA's Exploration Systems Mission Directorate (ESMD). It is a potentially viable low-cost alternative to ion engines for near-term NEP applications with the growth potential to support mid-term and far-term NEP missions. The technology previously demonstrated the high power, efficiency, and specific impulse required for Prometheus missions, over 25 years

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ago in Russia (TsNIIMASH). Two stage Hall thrusters offer the high thrust density characteristic of single stage Hall thrusters, but with much higher specific impulse capability due to separation of the ionization and acceleration regions. The VHITAL program consists of a team of university, government, and industry experts overseeing the fabrication and testing of the VHITAL-160, a design based on existing TsNIIMASH two-stage Bismuth TAL technology. The technology assessment program, which started in the fall of 2004 has completed the thruster and feed system preliminary design and is in the fabrication and component testing phase. The final designs of the thruster, cathode, vaporizer, and liquid metal propellant feed system have been completed by TsNIIMASH, JPL, and NASA MSFC. The thruster and associated support systems are in fabrication.. The TsNIIMASH test facility is complete and successful demonstration of the existing TAL160 has been made to verify the test facility, feed system, and power supplies. The lifetime assessment program is underway at Stanford University, Colorado State University, and the University of Michigan. LASER induced fluorescence (LIF) and Cavity Ring Down Spectroscopy (CRDS) diagnostics have been developed to characterize the thruster plume and quantify sputter erosion of the second stage cathode guard rings. Computer models of the plasma discharge and acceleration region and thruster plume expansion have been developed to understand the physics of two-stage hall thruster operation and erosion. This paper will present an overview of the thruster fabrication, TAL 160 demonstration, feed system development, lifetime assessment, and contamination assessment activities performed to date.

Nomenclature

<i>NEP</i>	= nuclear electric propulsion
<i>E</i>	= electric field
<i>H</i>	= magnetic field
d_c	= accelerating channel diameter
<i>I_{sp}</i>	= specific impulse
<i>TAL</i>	= thruster with anode layer

I. Introduction

THE Very High Specific Impulse Thruster with Anode Layer (VHITAL) program is underway to resurrect the two-stage bismuth fueled TAL technology. The two-stage TAL technology was developed over 25 years ago in Russia at TsNIIMASH, at that time demonstrating specific impulses up to 8000s at efficiencies greater than 70% as well as power consumption up to 140 kW per thruster¹. The technology offers a unique combination of previously demonstrated performance and propellant attributes that are attractive for a range of NASA missions including NEP missions to the outer planets and Mars and lunar cargo missions^{2,3}.

The VHITAL Program is a technology assessment program led by Stanford University and the Jet Propulsion Laboratory, to evaluate the potential for use of the two-stage TAL technology as primary propulsion on NASA science missions. The preliminary design phase (Phase 1) of the program was completed in December of 2004. The final design, fabrication and test phase (Phase 2) was started in February of 2005. Stanford University is responsible for the life assessment of the thruster, with lifetime diagnostic development at both Stanford and Colorado State University and physics based lifetime and plume model development at the University of Michigan. The Russian company TsNIIMASH is the primary subcontractor, responsible for designing and fabricating a radiatively-cooled 160 mm diameter, bismuth-fed two-stage thruster, capable of operation from 6000-8000s at 25-36 kW (Table 1). The Jet propulsion laboratory is responsible for the program management and condensable metal propellant feed system architecture and implementation. NASA Marshall Space Flight Center is responsible for the design and fabrication of the liquid metal feed system components.

The two-stage thruster technology has several systems engineering advantages for high power operation over conventional single stage Hall thrusters including a (primarily) robust and low-cost metal construction, higher specific impulse operation, smaller size for higher thrust density, lower propellant cost compared to xenon and reduced pumping speed requirements for ground testing. The maximum specific impulse that advanced single stage Hall thrusters have demonstrated is 3700 s with the SPT-1^{5,6}. At voltages greater than 1 kV, single stage Hall thrusters exhibit a decrease in efficiency. This limitation results from a fundamental change in the behavior of the electrons in the discharge chamber at such high voltages. Deleterious anode heating occurs as the energy and flux of electrons collected by the anode increases with increasing accelerating voltage. The maximum achievable ion velocity is, therefore, limited by the thermal constraints of the anode for single stage TAL's. In a two stage TAL, separation of the ionization and acceleration regions decouples anode heating from the accelerating voltage allowing higher specific impulse operation. As accelerating voltages in excess of 4 kV are necessary for potential NEP missions to the outer planets (6000 to 9000 s) only two-stage TAL's are competitive with ion thrusters².

Parameter	Mode 1	mode 2
Specific Impulse (s)	6000	8000
Power (kW)	25	36
Flow Rate (mg/s)	9	11
Magnetic Induction (T)	0.2	0.2
Thruster (mN)	650	710
Thrust Efficiency (%)	78	79

Table 1. VHITAL-160 operating regimes⁴.

property	Bismuth	xenon
Density ⁺⁺⁺⁺ (kg/m ³)	9780	2000
Atomic mass (AMU)	208.9	131.3
Melting temperature (C)	271	N/A
Ionization potential (eV)	7.29	12.12
Typical cost (\$/kg)	75	2000

Table 2. Properties of bismuth and xenon propellant⁴.

The use of the condensable propellant bismuth also has several system level performance and cost advantages over xenon fed propulsion systems (Table 2). Bismuth is stored as a solid at room temperature and is a factor of 5 more dense than xenon stored at supercritical pressures. This results in significant tankage fraction and overall feed system mass savings over xenon-fed propulsion systems. Bismuth is also a non-toxic, readily available, and comparatively inexpensive consumable. Bismuth is less than 1% the cost of xenon per kg. For a deep space 10,000 kg throughput mission, this could result in a \$20M cost savings. This estimate does not include the propellant expended as part of the ground test qualification program for a particular mission, which could be up to 1.5 that used in space, leading to even further cost savings. Bismuth also has a higher atomic mass and lower ionization potential than xenon, which for the same propellant utilization, increases electrical and thruster efficiency respectively (Table 2).

Use of a high density, compact 2-stage thruster also takes up less real estate on the spacecraft. The power processing to beam area footprint ratio of a two-stage TAL is ten times that of a high power ion engine. For multi-thruster systems this could result in a footprint 1/20 the size for a 2-stage TAL propulsion system.

An often times overlooked issue in the development of high power plasma propulsion systems is the ability to test them in a simulated environment (vacuum facility) on the ground. The melting temperature of bismuth, at 271°C, enables it to condense at room temperature on vacuum facility walls, significantly reducing the pumping speed requirements placed on facilities used for testing bismuth fueled thrusters. Multiple two-stage TAL's operating on Bi propellant could be tested at a total power consumption exceeding 1 MW in existing facilities. This is not possible within the constraints of existing test facilities for gas-fed thrusters.

II. The Thruster Technology

In a traditional anode layer thruster, neutral propellant gas is ionized by an azimuthal Hall electron drift current. The Hall current is established by the crossed radial magnetic field and axial electric field between the anode and surrounding ring cathode. The resultant Lorentz force acts on the electrons in the azimuthal direction, setting up the traditional circulating Hall current, also referred to as the ExH layer. This layer of electron current ionizes neutral

⁺⁺⁺⁺ The density of bismuth is stated for atmospheric pressure at 20°C. The density of xenon is stated for supercritical storage conditions of 2800 psi at 40°C.

propellant flowed into the region through the anode propellant distributor. The axial electric field, established between the anode and ring cathode electrostatically accelerates the ions out of the device producing thrust.

A two-stage TAL is functionally similar to a single stage TAL (Figure 1). The primary difference is that there are two hall current layers, each with a circulating ExH layer of electrons. The electron current density, however, in the first stage is much higher than that in the second stage. In fact 90% of the ionization occurs within the first stage. The potential between the first stage anode and cathode is quite low, on the order of 150 to 250 V, but that is all that is required produce Paschen breakdown, electron emission and subsequent ionization. The accelerating voltage, between the second stage anode and cathode is several kilovolts, directly acting on the ionized propellant particles to accelerate them out of the thruster. As the first stage electrons are highly constrained in the azimuthal direction in the first ExH layer, axial electron transport is limited to collisional diffusion, and the propellant is 80% to 90% ionized in the first stage¹. Therefore the two-stage design confines ionization and electrons to the first stage and accelerates ions in the second stage.

Separation of the regions of the plasma has several advantages. The first is an obvious improvement in ionization efficiency. Only 150 to 250 V is required to fully ionize the propellant in a hall thruster. In a single-stage device the total accelerating voltage is used to both ionize and accelerate the propellant. This results in energy lost to creating high energy electrons which do not contribute to thrust. In addition, those high energy electrons are collected by the anode which results in severe heating of the anode, eventually posing a materials constraint on the device at high accelerating voltage (specific impulse). For comparison, anode power dissipation in the VHITAL is expected to be approximately 25% of the anode power dissipation in a single-stage thruster at the same operating conditions. Restricting or constraining the electrons to the hall current layer also serves to limit the back-streaming electron current through the accelerating layer. This also enhances the electrical efficiency of the device.

A two-stage design also has the potential to improve the lifetime of the VHITAL. The two-stage configuration results in effective ionization at lower current densities than in a single-stage configuration. Current density has a first-order impact on thruster wear due to sputter erosion.

A schematic of the VHITAL-160 is shown in Figure 2. The VHITAL-160 design is very similar to the D160 in terms of magnetic circuit and accelerating channel geometry. The differences primarily come from the use of a radiative cooling scheme that requires VHITAL to operate at higher temperatures than the water-cooled D160. The VHITAL-160 uses higher temperature wiring, refractory and magnetic materials and improved high voltage tolerances to withstand the thermal environment imposed at 36kW. The thruster is composed of the electrode unit, magnetic system, and structural housing and interface. The first stage of the electrode unit consists of the first stage anode gas distributor and surrounding ring cathode assembly. The anode gas distributor is designed to provide an azimuthally uniform flow of bismuth vapor into the annulus. A heater

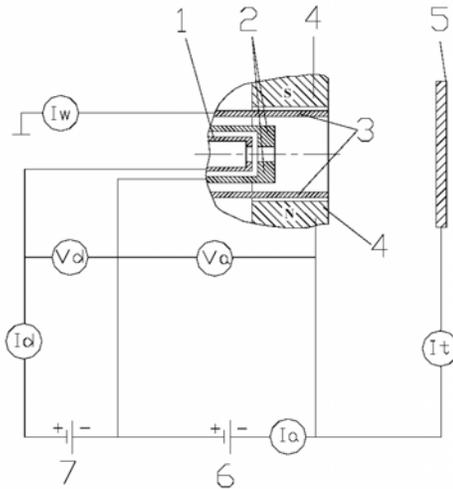


Figure 1. Functional diagram of a two-stage TAL showing the (1) first stage anode, (2) first stage ring cathode (second stage anode), (3) second stage cathode, (4) pole piece magnets, and (5) beam target for current collection measurement (not part of the thruster)¹.

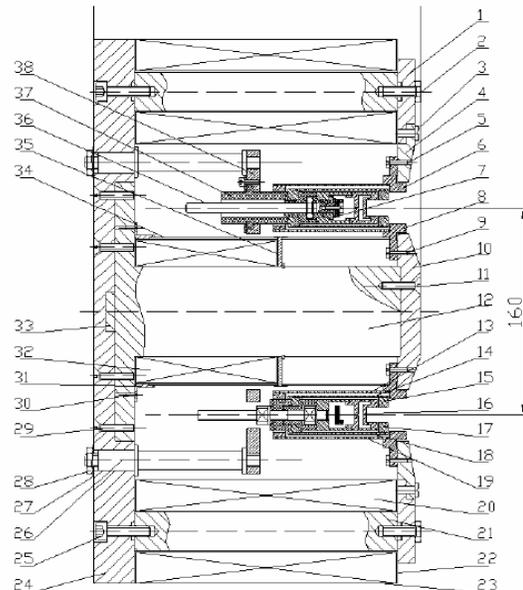


Figure 2. Schematic of the VHITAL D160⁷.

is used to preheat the anode to prevent bismuth condensation during startup, outgas the thruster, and may also be used during nominal operation. The remainder of the electrode system is heated passively, via radiative heat transfer. The potential in the first stage is on the order of 150 to 250V to maintain stable engine performance⁸. Electron emission is enabled by a Paschen breakdown in the several millimeter gap between the first stage anode and cathode. The second stage of the electrode unit consists of the first stage cathodes which serve as the second stage anode and the surrounding second stage ring cathode. Sputter resistant guard rings are placed over the second stage cathode pole piece magnets to protect them from direct ion impingement sputter erosion, as that is the primary thruster life limiter. The potential difference between the second stage anode and cathode can be up to 8 kV. The entire electrode unit is made from refractory materials such as molybdenum and niobium to withstand 1000°C operating temperatures. All electrode units are electrically isolated from each other and the thruster with vacuum compatible ceramic insulators.

The magnetic circuit consists of a central electromagnet and four surrounding electromagnets. Pole piece magnets are located at the downstream ends of the central and side coil cores. The VHITAL magnetic field is such that the peak field is located at the thruster exit plane where the field in the center of the accelerating channel is 0.2 T. As mentioned previously, the outer pole piece magnets which comprise the second stage cathodes, are covered by sputter resistant guard rings to protect them from ion impingement. These guard rings protect the magnet pole pieces from the sputtering, but are themselves subject to sputter erosion. The cathode material for the first and second stages (i.e., the guard rings) must also have a high melting temperature (exceeding 1500 °C) and good radiating characteristics at high temperature.

Space charge and current neutralization of the ion beam is provided by an external cathode, installed near the thruster exit plane (Figure 3). The neutralizer cathode flange, the magnetic system, and guard rings are maintained at the same electric potential as the cathode-neutralizer.

III. Thruster Development and Testing

The Phase 2 thruster development and test program is being conducted by TsNIIMASH Export. The primary focus of the TsNIIMASH Phase 2 program is the fabrication and acceptance testing of the VHITAL-160 thruster and the setup and demonstration of the 2-stage TAL vacuum test facility. As the VHITAL-160 thruster fabrication will not be completed until the early spring of 2006, the test facility and operational experience in testing 2-stage bismuth TAL's is obtained by testing the existing TsNIIMASH built D160 thruster, on which the VHITAL-160 thruster design is based. The status of the VHITAL-160 hardware development and fabrication and D160 test program and performance data obtained to date is summarized in the following sections.

A. VHITAL-160 Design and Fabrication

The VHITAL-160 thruster utilizes the magnetic channel and physical geometry of the D160 and the radiative cooling scheme of the TsNIIMASH D200 as the design basis to meet the performance requirements in table 1. The plasma physics design was already verified as by the D160 and D200 test programs^{11,1}. The main design tasks associated with the VHITAL-160 development are the thermal, structural, and thermo-mechanical validation of the radiative cooling scheme over the required operating regime. To accomplish these tasks TsNIIMASH completed an extensive set of engineering analyses as part of the Phase 2 program A 3-D thermal model was developed to determine the maximum temperature of all the thruster components at 25 and 36kW of operation with and without self-heating of the anode. The model validated the radiative cooling scheme and provided thermal constraints for appropriate high temperature materials selection. A thermo-mechanical (structural model) was created to determine the appropriate mechanical tolerancing for electrode spacing at high temperature operation. More details on the thruster design can be found in Ref. 9.

The VHITAL-160 thruster fabrication is underway at TsNIIMASH. To date all high temperature ceramics, wiring, and magnetic materials have been procured. The ceramic high voltage insulators, second stage cathode guard rings, and, magnetic circuit have been fabricated. The feed system subassembly is also nearing completion. More details on the thruster fabrication can be found in Ref. 9.

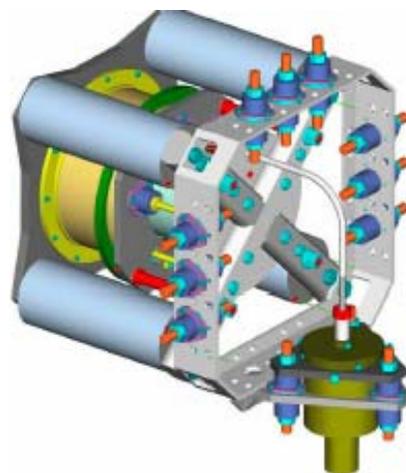


Figure 3. The TsNIIMASH VHITAL-160 thruster design⁷.

B. D160 Refurbishment and Testing

As part of the VHITAL Phase 1 activity, TsNIIMASH refurbished their existing D160 lab model 2-stage Hall thruster, last used in Russia during the 1980's (Figure 5)¹¹. The thruster refurbishment consisted of disassembling the thruster, performing a failure inspection of all piece parts, recovery and cleaning of reusable hardware, fabrication of non-recoverable hardware, reassembly of the D160, measurement of the magnetic field of the refurbished thruster, preparation of the feed system, and an electrical insulation check of the re-assembled thruster.

All major thruster components were recovered except for high voltage insulators and the central magnetic core. Cleaning of the recovered hardware primarily involved removal of condensed bismuth propellant. The magnetic system was also refurbished to return the D160 to its nominal accelerating channel magnetic field arrangement. The refurbishment of the magnetic system involved fabrication of a new central core assembly, re-coiling the outer pole piece magnets, and replacement of the stainless steel outer casings of the side coils. A gauss meter was used to map the magnetic field of the newly refurbished thruster in both the axial and radial direction. A peak magnetic field strength 0.2 T axially and 0.45 T radially, corresponded well to the predicted magnetic field calculations¹². Feed system preparation included fabrication of high temperature pipeline parts, anode-distributor conjunctive parts, filling the bismuth feed system, and integrating feed system to the thruster. An electrical insulation check was performed following assembly of the thruster and feed system components. Adequate impedance between the first and second stage cathodes, both cathodes to the first stage anode, and second stage cathode to the feed system were all verified. The D160 is a 160 mm diameter, water cooled, two-stage, anode layer thruster¹¹. Although the thruster had not been used for many years, it was refurbished in the fall of 2004 as part of the VHITAL program Phase 1 activity, in support of the follow on Phase 2 program. The refurbished thruster is shown in figure 5. Details on the thruster refurbishment can be found in Ref. 12.

The TsNIIMASH 2-Stage TAL test facility was refurbished as part of the Phase 2 activity to allow testing of the refurbished D160. The diffusion pumped, 2m x 1.8m vertical vacuum chamber provides a base pressure of $3e10^{-3}$ Pa ($2e10^{-5}$ Torr) and is equipped with the refurbished D160 feed system. The thruster is mounted to a flange that is affixed to the top of the chamber. The thruster was allowed to outgas for a 24 hour period prior to firing. Also prior to firing, the feed system and thruster were pre-heated with the feed system heater lines and anode heater respectively, to prevent bismuth condensation on startup. To date, the D160 has successfully operated over a large range of voltages and currents, up to 3kV and 4A of accelerating current, the limits of the power supply currently available (Figure 6). The thruster has been operated in anode-heating mode with neutralization by secondary electron emission from the chamber walls. A schematic of the current-voltage data collected to date is shown in Figure 7. Thrust measurements taken with a thrust stand have also been obtained and compare well to test data taken previously on the D160 thruster in

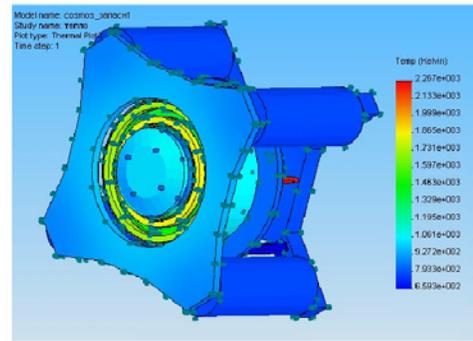


Figure 4. 3-D thermal model of the VHITAL-160 Thruster¹⁰.



Figure 5. Refurbished D160 lab model 2-stage hall thruster¹².



Figure 6. D160 2-stage TAL operating at 3kV in TsNIIMASH test facility.

the 1980's, suggesting the thruster is operating nominally and the refurbishment was successful. Details on the testing and thruster performance can be found in Ref. 9.

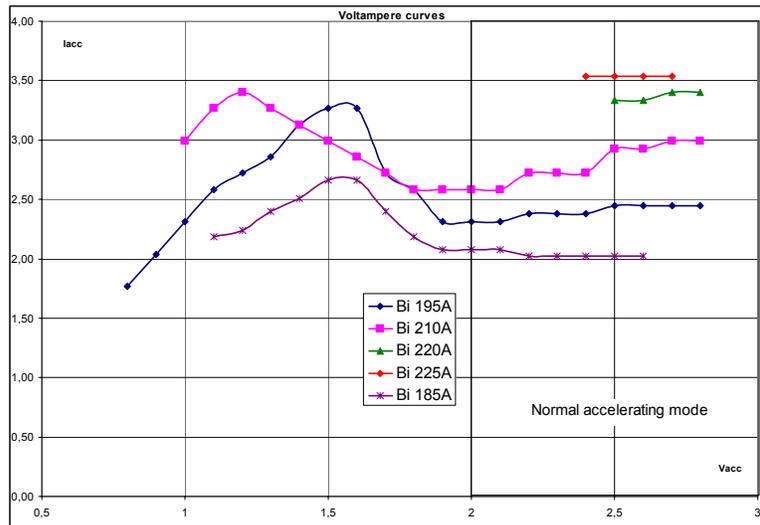


Figure 7. D160 Current-Voltage Data (TsNIIMASH)⁹.

IV. Feed System Development and Testing

Two bismuth propellant feed systems have been developed in parallel for the VHITAL Program. A prototype flight-like bismuth feed system has been developed by JPL and NASA MSFC. NASA MSFC is responsible for the liquid metal portion of the feed system, which converts the solid propellant to liquid form and supplies the liquid at a known pressure and flow rate to the vaporizer. JPL is responsible for the vaporizer and associated propellant line interfaces to the thruster. The vaporizer converts and actively controls the conversion of liquid bismuth to a vapor. The goal of the flight-like system activity is to develop and integrate the prototype technologies that minimize mass, footprint, and electrical power consumption of a condensable metal propellant feed system. This system provides real time flow rate measurement capability to an accuracy of 1%. Higher integrity propellant flow rate measurements enable a more comprehensive thruster performance assessment and an improved testing duty cycle.

A more conventional laboratory feed system has been developed by TsNIIMASH. This laboratory feed system is robust in design, and therefore is not optimized for mass or power requirements. The TsNIIMASH feed system will be used to acceptance test the thruster in Russia and will serve as the back-up system for a future test program. This system does not allow real time flow rate measurement. Flow rate measurements are made by measuring the propellant mass before and after testing at one operating point for several hours. The accuracy of this measurement is expected to be within 10%.

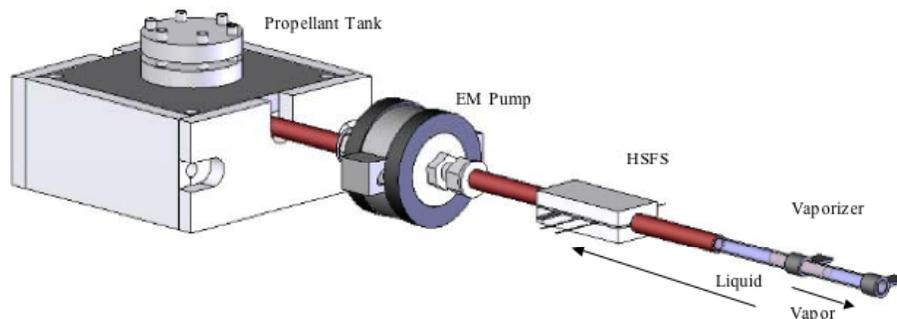


Figure 8. The NASA/JPL flight-like feed system component assembly.

C. Liquid Metal Feed System

The liquid metal feed system must first convert solid bismuth into liquid form in a reservoir and then deliver the liquid propellant to the vaporizer. As part of the Phase 2 program, NASA-MSFC has developed two alternative approaches to complete this task. The first approach consists of a heated propellant reservoir and a gas pressurization system. This system was developed to serve as a laboratory workhorse which could be used in testing of the first generation bismuth vaporizer. The second approach is more representative of a flight-like configuration in terms of overall system mass, operating power requirements, and high-resolution flow rate monitoring and control. It utilizes a miniature electromagnetic pump and a 'hot-spot' flow sensor to provide flow rates up to 20 mg/s of bismuth with a measurement accuracy of 0.1 mg/s. Both systems are fully computer controlled and have demonstrated melting, pressurization, and controllability of the flow rate.

The gas pressurized approach uses argon gas to force liquid out of an actively heated propellant reservoir through an exit tube. The propellant tank consists of a stainless steel reservoir surrounded by copper plates. It has a fill port to allow for loading of the solid bismuth propellant slugs, a gas inlet port, a propellant exit tube/drain valve and thermocouples for temperature monitoring. Two cartridge heaters embedded into the copper plates are used to melt the bismuth in the reservoir. Once the propellant is melted, the reservoir is pressurized using the system shown in Figure 9. This system uses a "bang-bang" regulator which consists of two solenoid valves opening and closing in rapid succession, alternatively exposing the process line (pressure controlled output) to high-pressure gas and vacuum. An on-board pressure transducer provides feedback control of the regulator. Once the target pressure is reached, the computer commands the drain valve to open, allowing liquid bismuth to exit the reservoir and flow towards the vaporizer. The flow rate can be regulated by adjusting the gas pressure in the system. The system has been tested in conjunction with the vaporizer and vapor flow rate control has been demonstrated¹³. The response time of this system is limited by the time it takes the pressure regulator to adjust its output. In addition, the resolution of the onboard pressure transducer only allows for pressure adjustments in discrete increments. Moreover, this system lacks a flow sensor capable of accurately quantifying the bismuth flow rate.

The second liquid metal feed system approach seeks to address the limitations of the first system. It utilizes an electromagnetic (EM) pump to push liquid bismuth from the propellant reservoir to the vaporizer and a newly-developed 'hot-spot' flow sensor to monitor the flow rate. In the EM pump (shown in Figure 10), two electrodes and two permanent magnets are oriented at 90 degrees both with respect to each other and the flow direction. Current introduced into the bismuth through the electrodes interacts with the applied magnetic field to exert a Lorentz body force which pressurizes the fluid. The force, and consequently the fluid pressure, can be varied by adjusting the current level. Adjustability of the pump pressure has been demonstrated to a high level of fidelity. A more complete review of EM pump design and performance is found in Ref. 14. The 'hot-spot' flow sensor (HSFS) measures the propellant flow rate downstream of the pump. The flow is 'tagged' by pulsing current through the propellant, locally increasing the temperature through joule heating. The bismuth flow convects this thermal feature downstream where it is measured using a thermocouple located in the flow. The time it takes for the peak of the pulse to pass the thermocouple is recorded and a 'time-of-flight' analysis can be used to determine the flow rate. The primary advantage of this technique is that, instead of performing an absolute measure of temperature, thermal



Figure 9. Gas Pressurized feed system electronics and argon supply tank.

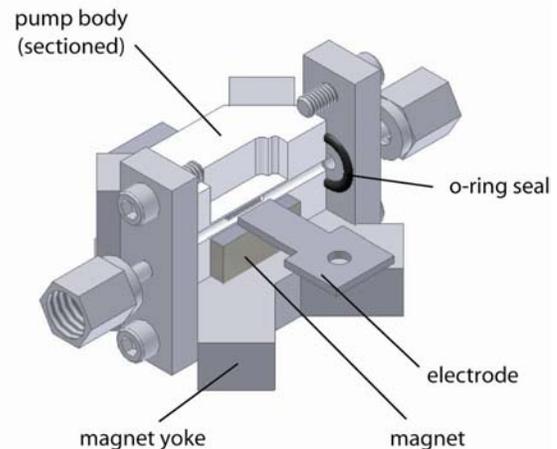


Figure 10. Assembly drawing of a bismuth EM pump under development by NASA-MSFC (sectioned to show inner detail).

features in the flow are observed, making the measurement insensitive to other thermal fluctuations in the system. Prototype flow sensors have been demonstrated at NASA-MSFC on gallium. The design and performance of the HSFS are discussed in greater detail in Ref. 15.

D. Vaporizer Development and Testing

A flight-like bismuth vaporizer was developed by the Jet Propulsion Laboratory and Energy Science Laboratories Incorporated (Figure 11 and 12). The vaporizer design is based on the porous plug approach initially developed for the mercury ion thruster programs of the 1960's and 1970's¹⁶. In the mercury ion thruster program, one and two stage vaporizers were developed to convert room temperature mercury propellant into gaseous form prior to injection into the thruster. These vaporizers used the principle of surface tension forces to control and limit the vaporization of propellant atoms as a function of the plug geometry and applied temperature. The plug refers to the porous geometry in which the bismuth propellant is vaporized. There are several requirements on the porous plug to ensure that only bismuth vapor exits the vaporizer. It must be made of a material that is not wetted by bismuth and the liquid pressure must not exceed the capillary pressure of the plug. Proper selection of the pore diameter and length can be used to determine the evaporation rate and therefore achievable flow rate for a given plug geometry as a function of temperature, liquid, and upstream pressure. Therefore, if the temperature and pressure upstream of the plug can be actively controlled, a flow metering capability is obtained by the plug.

An all carbon porous plug and carbon tube assembly was selected for VHITAL to ensure a uniform thermal expansion and eliminate the need for dissimilar material brazes and weld joints. The carbon plug consists of carbon fibers grown inside a graphite tube (Figure 11). The plug geometry is cylindrical with radial oriented fibers so that the fluid flows along the inner diameter of the plug to a solid plug in the end and out radial as a vapor along the carbon fiber shafts. The entire assembly is resistively heated to provide the temperature necessary for vaporization. Two vaporizer types were designed and fabricated as part of the Phase 2 activity by JPL and Energy Science Laboratories Inc (ESLI). The prototype (first generation) vaporizer was designed to provide and has already demonstrated 1 mg/s of bismuth flow at a plug temperature of 1130°C. The second generation vaporizer is designed to provide up to 12 mg/s at less than 1200°C. A detailed review of the design, fabrication and performance of the vaporizer is contained in Ref. 13.

E. TsNIIMASH Feed System Development

A laboratory model feed system is also being developed and fabricated by TsNIIMASH. The system consists of an evaporator tube inside of a bismuth reservoir and a propellant tube connected to the evaporator tube (Figure 13). The tank assembly is heated to the bismuth melting temperature by means of a resistive heater enclosing the tank. Liquid bismuth is gravity-fed into the evaporator tube. After the propellant is melted, the evaporator is brought to a temperature of 1000°C. The liquid in the evaporator tube then evaporates and travels through the propellant tube to the thruster. The propellant tube is also

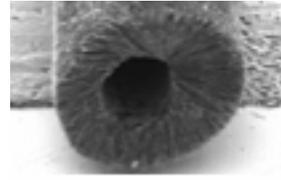


Figure 11. A carbon fiber vaporizer plug (ESLI)¹³.

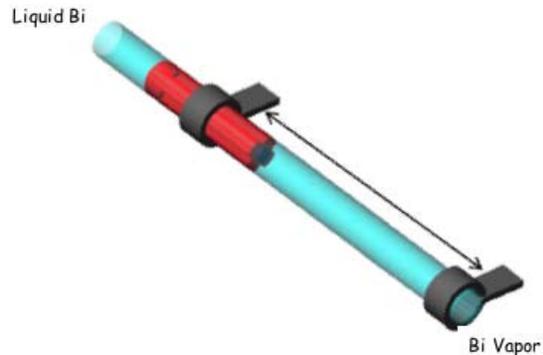


Figure 12. The all-carbon bismuth vaporizer configuration (ESLI)¹³.

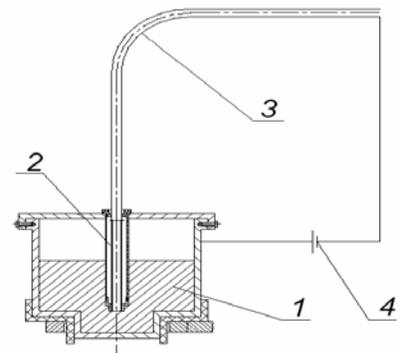


Figure 13. Schematic of TsNIIMASH feed system¹. The above refers to (1) bismuth reservoir, (2) evaporator, (3) propellant tube, and (4) heater electrical connection.

maintained at a temperature of 1000°C to prevent bismuth condensation. The flow rate and vapor pressure of bismuth is controlled by adjusting the evaporator power. As stated previously, this system does not allow real time measurement of flow. Instead, the mass of the reservoir is measured before and after operation to determine the amount of propellant used for a given period of time. This provides a measurement of the average flow rate.

V. Lifetime Assessment

In order to develop and advance the technology readiness level of a two-stage Bi-fed Hall thruster for eventual flight application, there is a need for a quantitative understanding of the plasma physics that govern the performance, erosion, and ultimately lifetime of the propulsion technology. Such an understanding can lead to precise optimization of thruster geometry and operating conditions for life and performance considerations as well as accurate predictions of component wear and potential for spacecraft contamination. As such, a life assessment program, led by Stanford University, was developed as part of the Phase 1 effort. The approach uses a combination of spectroscopic diagnostics techniques to resolve particle fluxes and energy distributions, sophisticated and traditional physical measurements of thruster erosion rates and sites, and physics based computer plasma models to predict erosion and performance. The experimental and computational efforts are intrinsically linked as the model development and validation are contingent upon a characterization of the internal and near-field neutral bismuth (BiI) and bismuth ion (BiII) energy distribution, velocity field, and particle flux. Similarly, predictive performance and lifetime models require physical component level erosion measurements and experimentally obtained performance data for validation and future design optimization efforts.

A. Spectroscopic Lifetime Diagnostics Development

1. Bismuth Spectroscopy for Lifetime Diagnostic Implementation

A combination of atomic resonance absorption spectroscopy and laser-induced fluorescence (LIF) was selected to measure the three-dimensional number density and velocity (energy) distributions of neutral and ionized bismuth atoms in the VHITAL-160 plume. To initiate this activity, an analysis of the bismuth spectrum was performed by Stanford University to determine appropriate transition selection for these spectroscopic measurement techniques¹⁷. All candidate transitions have been modeled in terms of hyperfine splitting and various broadening mechanisms.

The transition selected for ground state BiI number density determination by atomic resonance absorption spectroscopy was the line at vacuum wavelength 306.86nm ($6p^3\ ^4S_{3/2} - 7s\ ^4P_{1/2}$). For BiII, the resonance transition (with the BiII ground state as the lower level of the transition) is located at 143.68nm ($6p^2\ ^3P_0 - 7s\ ^3P_1$), which poses some difficulty as it is in the far vacuum-ultra-violet range; further refinement of the method for determining BiII number density may yet be required.

For LIF measurement of species velocity distribution, New Focus has been selected as the source for readily available, portable diode laser systems suitable for this analysis. Of primary interest in velocity measurements will be the speed of ions in the thruster plume; for this purpose, the New Focus Velocity line of lasers have been selected for their wide tuning range capabilities, suitable to capture the Doppler shift of high velocity ions as well as the very broad (~0.2nm) hyperfine splitting of many BiII transitions. While several BiII transitions are accessible to Velocity class laser systems, the 680.9nm line ($6p7s\ (1/2,1/2)_1 - 6p7p(1/2,1/2)_1$) has been selected for excitation by the TLB-6309 laser for LIF measurements of ion velocity. Non-resonant fluorescence will then be collected at 660.0nm ($6p7s\ (1/2,1/2)_0 - 6p7p(1/2,1/2)_1$). Emission from the 680.9nm transition has been measured experimentally. Further, both of these transitions are relatively intense and are connected to “bottleneck” states between the ground and excited electronic levels of BiII, which should increase signal strength in LIF measurements. Unfortunately, there are no BiI lines within the ranges that can be probed using the Velocity laser systems useful for ion analysis. However, neutral Bi particles are not expected to be accelerated to the same high velocities as the ions and the hyperfine splitting of BiI is relatively narrow, so the BiI lines at 784nm and 854nm may be accessible to the less expensive Vortex class lasers from New Focus for LIF analysis.

2. Bismuth Plasma Source Development

Recent work at Stanford has focused on the development of a means to measure the selected transitions in the bismuth spectrum prior to testing with a bismuth-fed thruster¹⁷. A bismuth heat pipe apparatus has been developed allowing measurements of the Bi spectrum. The heat pipe has been used to successfully record both absorption and emission from the 307nm resonance transition of neutral bismuth. It is noteworthy that the corresponding bismuth partial pressure estimated from this scan is close to the equilibrium pressure for bismuth at a temperature of 800°C (discussed below), within experimental uncertainty of the cell operating temperature of 850°C. As the chamber is cooled, the absorption disappears because the vapor pressure of the bismuth is decreasing; this verifies that the line observed is indeed bismuth.

In addition a laboratory stationary plasma thruster (SPT) is being modified to run on bismuth propellant to generate a high velocity bismuth plasma, for future analysis of bismuth ion line selection (Figure 14)¹⁷. This SPT will also be used to acceptance test the flight-like bismuth feed system.

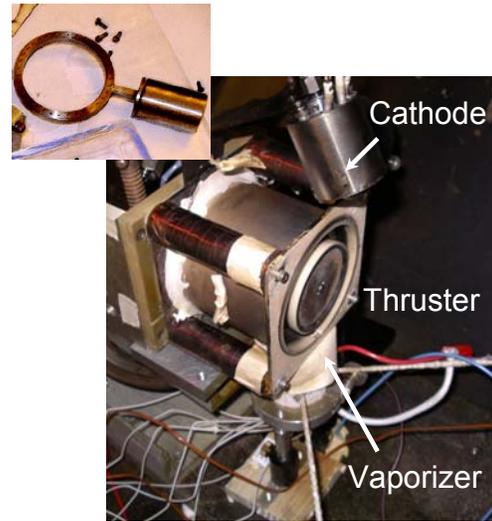


Figure 14. Photograph of the modified SPT thruster for Bi operation. Inset shows the details of the vaporizer/distributor¹⁷.

3. Cavity Ring Down Spectroscopy Diagnostic Development

A cavity ring down spectroscopy diagnostic (CRDS) is being developed by Colorado State University (CSU) as a diagnostic tool to study sputter erosion of the VHITAL thruster¹⁸. The lifetime of the VHITAL thruster is largely governed by low sputter erosion rates of the guard-rings (on the order of 0.1-10 microns per hour), so that the high sensitivity of CRDS makes it well suited to the measurement of sputtered products within the thruster plume. The CRDS measurements can be performed in (near) real time, and will be particularly useful for quantifying how the sputter erosion varies as the thruster operating conditions (set-points) are changed.

CRDS is a highly sensitive laser-based absorption technique that is directly quantifiable and thus well suited for measurements of low concentrations of sputtered particles^{19,20}. The CRDS diagnostic will allow measurement of sputtered atoms (expected to originate primarily from the second stage guard ring) in the plume of the thruster. As shown in Figure 15, the optical axis of the CRDS cavity will surround the thruster plume. The high-finesse optical cavity is formed from a pair high-reflectivity mirrors. The interrogating laser beam is coupled into the optical cavity where it “bounces” many times back-and-forth between the mirrors. A detector placed behind the cavity measures the temporal decay rate of optical intensity within the cavity. Absorption of resonant laser light by the sputtered particles increases the decay rate of light within the cavity. The difference in the temporal decay rate caused by the absorbing atoms is measured and yields the (path-integrated) sputtered particle concentration. The technique has been used widely for the measurements of trace species in flames, plasmas, and the atmosphere, and CSU has recently pioneered it for use in sputter measurements for electric propulsion applications^{21,22,23}.

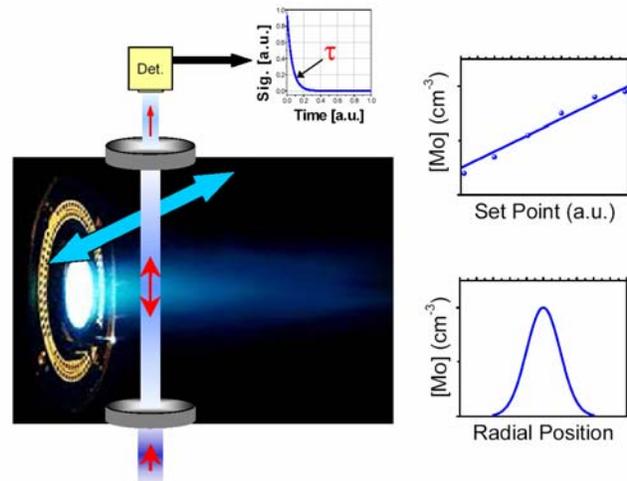


Figure 15. Approach to CRDS measurements in plume of VHITAL thruster. A CRDS cavity will surround the plume (actually with horizontal orientation), and measure sputtered Mo within the plume¹⁸.

As part of the VHITAL program Phase 2, CSU has demonstrated the use of CRDS for the detection of sputtered molybdenum using a bench-top laboratory setup. Sputtered molybdenum number density and velocity measurements, including the dependence on beam current, have been obtained and compared to a numerical sputter model. Design of a test apparatus for future implementation of the CRDS system on the VHITAL-160 thruster in the JPL Condensable Liquid Metal Vacuum Test facility has also been completed as part of the Phase 2 program. There are several challenges associated with implementing the diagnostic technique on the VHITAL-160 thruster including the effect of the relatively long axis of the JPL test chamber on cavity alignment and signal stability, and reduction of effective cavity finesse (and CRDS sensitivity) due to mirror contamination from condensed bismuth or sputter products. Details on the CSU CRDS approach and program can be found in Ref. 18.

B. Computational Life and Contamination Assessment

A computational model of a two-stage thruster with anode layer is being developed by the University of Michigan²⁴. The model is based on a 2D hydrodynamic approach where the first (ionization) and second (acceleration) stages are modeled separately. As the discharge in a two-stage TAL is sustained by the acceleration stage, the model of the first stage is coupled with the acceleration stage providing the downstream boundary condition for the first stage. Similarly the solution of the plasma flow in the first stage provides the boundary conditions for the acceleration stage. Recent efforts at the University of Michigan have concentrated on the development of the first (ionization) stage model. The modeling approach assumes quasineutrality with plasma flow starting at the anode of the first stage and the presheath-sheath interface serving as the lateral boundary. The hydrodynamic model uses the steady state ion and electron mass and momentum conservation equations with only the radial component of the magnetic field considered. Neutral flow is treated as one-dimensional flow in the axial direction. Electron transport in the azimuthal direction is due to ExB drift and transport in the axial direction is assumed to be purely collisional.

In the acceleration stage, a coupled problem of the quasi-neutral plasma region and the near-wall sheath is considered. The acceleration region model analytical approach is discussed in greater detail in Ref. 25. The second stage model indicates that a high voltage sheath forms at the second stage cathode walls (Figure 16). The high voltage sheath confines the quasi-neutral plasma region to the middle of the acceleration channel. Therefore increasing the accelerating voltage decreases the acceleration region length. The axial variation in erosion of the second stage cathode guard ring was calculated using the hydrodynamic model. It was found that the expanding sheath model provided good qualitative predictions of the guard ring erosion profile when compared to existing test data²⁴.

A hybrid particle-fluid model of the thruster plume is also being developed by the University of Michigan. The model tracks plasma flow and plume expansion from the thruster exit plane as well as backflow of condensable species onto spacecraft surfaces. The numerical approach treats bismuth ions and neutrals as particles. The direct simulation Monte Carlo (DSMC) method is used to simulate collisions and the Particle-In-Cell (PIC) method is used to accelerate the ions self consistently in the electrostatic field. Electrons are simulated using a simple hydrodynamic fluid approach that uses the Boltzmann relation to calculate the plasma potential as a function of plasma number density. Number density is obtained from the spatial distribution of the ions under the assumption of charge neutrality. The model takes into account charge exchange and momentum transfer collisions between neutrals. Charge exchange cross sections are based on the semi-empirical model of Sakabe and Isawa²⁶ where no collisional scattering occurs following a charge exchange event. The model also assumes that the momentum exchange cross section between ions and neutrals is identical to that for charge exchange²⁷. The cross section for neutral-neutral momentum transfer is assumed to follow the Variable Hard Sphere (VHS) collision model of Bird²⁸ and momentum exchange is assumed to follow isotropic scattering. The computational domain begins at the exit plane of the thruster using output from the second stage model as boundary conditions to the simulation and the simulation extends for a meter downstream of the thruster. Other model assumptions include an empirically derived ion temperature, finite

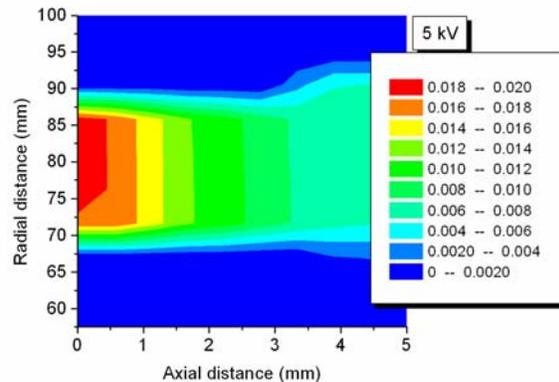


Figure 16. Electron density distribution in the acceleration channel. The wall has the cathode potential. Electrons are depleted from the sheath due to large potential drop.

back pressure of 10-5 torr, and an electron temperature of 15eV and plasma potential of 0V at the thruster exit. Preliminary results clearly indicate the VHITAL thruster plume is very focused. Indications of charge exchange ions escaping from the main beam are also present. The simulation results offer good agreement with the measured data, but are sensitive to the values assumed at the thruster exit plane for the ion temperature. Future plume simulation work will consider additional experimental data sets as well as working towards the inclusion of magnetic field effects on the plume plasma. Details on the plume model development and validation are discussed in greater detail in Ref. 24.

VI. Conclusion

The 2-Stage Russian bismuth TAL technology has been successfully resurrected with the existing D160 thruster demonstrating nominal operation at up to 3 kV and 4A accelerating current on bismuth at TsNIIMASH. The VHITAL-160 thruster fabrication is well underway as is scheduled for acceptance testing in early 2006 at TsNIIMASH. A flight-like liquid metal feed system and bismuth vaporizer have been fabricated and demonstrated at the required operating levels to support 25-36 kW thruster operation. The challenges associated with high temperature and high voltage operation with a condensable propellant have been successfully met. The future of the technology is now dependent on understanding the physics of two-stage TAL operation and the design parameters that impact life and performance limitations to advance the technology for eventual flight application.

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