Very High I$_{sp}$ Thruster with Anode Layer (VHITAL): An Overview

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This article describes the two stage bismuth fueled Hall thruster technology that was developed at TsNIIMASH [1] and the Very High Isp Thruster with Anode Layer (VHITAL) technology assessment program that is funded by NASA Exploration Systems Mission Directorate (ESMD)' Prometheus program. The overall objective of this program is to evaluate the potential for this Russian-developed thruster technology to enable near-term, Nuclear Electric Propulsion (NEP)-enabled ESMD missions to the outer planets. This 2.5 year program will provide the technology basis for the development of even higher power anode layer thrusters for rapid outer planet exploration missions and, ultimately, human exploration of the solar system. The first 6 month phase is currently in progress. If this phase is successful, the second (1 year) and third (1 year) phase of the proposed program will follow. In this program, the thruster performance, lifetime and spacecraft contamination potential will be characterized at 25 kW (6000 s) and 36 kW (8000 s).

I. Introduction

The Very High Isp Thruster with Anode Layer (VHITAL) is a two stage Hall thruster under consideration by NASA's Prometheus program in NASA's Exploration Systems Mission Directorate (ESMD). This technology, developed by TsNIIMASH, is an alternative to ion engines for potential near-term NEP applications with the growth potential to support mid-term and far-term nuclear electric propulsion (NEP) missions. This technology has already demonstrated high power, high Isp, high efficiency, and low specific mass; the primary propulsion system performance required for potential Prometheus missions. These requirements include total system power of 100-250 kW, with Isp ranging from 6000-9000s at efficiencies greater than 65%. The TAL-160 demonstrated 6000-8000s with single thruster operating powers up to 140 kW and efficiencies over 70% using bismuth propellant more than 25 years ago in Russia at TsNIIMASH.

Two stage Hall thrusters are uniquely configured to offer the high thrust density characteristic of Hall thrusters with much higher specific impulse capabilities. Single stage Hall thrusters utilizing xenon propellant are currently operating on several Russian and U.S. satellites. This technology has been developed for flight by many Russian

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and U.S. companies. However, this technology is not capable of operating in the specific impulse range required by potential NEP Prometheus missions. The maximum specific impulse that advanced single stage Hall thrusters have demonstrated is 3700 s. This specific impulse was demonstrated by the SPT-1.[2] At voltages greater than 1 kV, the 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 of the electrons collected by the anode increases with increases in the voltage applied for ionization and ion acceleration. The maximum achievable ion velocity is, therefore, limited by the thermal constraints for the anode. This problem is solved in a two stage TAL that separates the ionization and acceleration regions and decouples anode heating from the accelerating voltage. The high Isp necessary for potential NEP missions to the outer planets (6000 to 9000 s) requires ion accelerating voltages greater than 5 kV. Two stage TALs have demonstrated increasing efficiency with operating voltage through 8 kV.[1] The TAL-160 demonstrated efficiencies greater than 70% at ~8400 V and 8000 s.

II. Two Stage TAL Operation

In a two stage TAL, the ion generation region is separated from the acceleration region to limit back-streaming electron current through the accelerating layer. This configuration maximizes the accelerating efficiency and minimizes the power used for ionization. A VHITAL design optimizes the split of ionization between the acceleration and ion production regions to maximize overall efficiency. 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.

The two-stage configuration enables effective ionization at current densities much lower than that in the single-stage devices. This capability leads to longer lifetime because current density has a first-order impact on thruster wear mechanisms.

The thruster employs a magnetic system similar to traditional Hall device designs with inner and outer pole pieces and an inner electromagnet. A schematic of a two-stage TAL developed by TsNIIAMSH is shown in Figure 1. The VHITAL magnetic field topography minimizes the inclination of the ion beam from the thruster axis to improve thruster efficiency.

Figure 1. Schematic of a two stage TAL.

The first stage (low-voltage stage) is comprised of the annular anode distributor and a ring cathode. To provide anode pre-heating for operation with condensable propellant, the anode is equipped with a special ring heater located inside the anode body. The anode is fabricated from refractory metals because of the necessity to keep the anode-distributor at the temperature (1000 C) corresponding to a Bi saturation pressure of about a few hundred Pascal.

The second stage (high-voltage stage) is formed by the ring cathodes of the first stage and the guard rings positioned at the downstream end of the thruster. These guard rings protect the magnet pole pieces from 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.

Both the first-stage and second-stage electrodes are electrically isolated from the thruster body and from each other with ceramic insulators. The electrode assembly is installed inside the magnetic system on a mounting flange, providing additional thermal insulation of the electromagnets from the discharge chamber elements. This flange, the magnet system, and guard rings are maintained at the same electric potential as the cathode-neutralizer installed near the thruster exit plane.
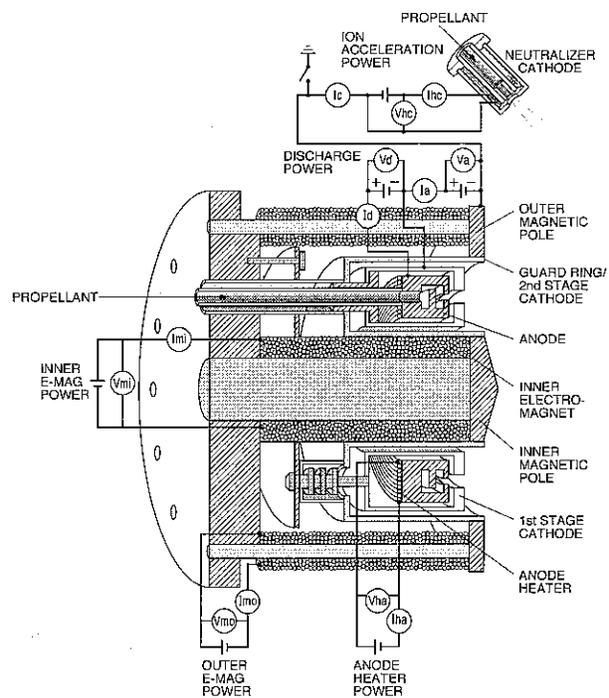
Evaporated Bi propellant is supplied to the anode for azimuthal distribution in the discharge chamber. Ionization occurs in the first stage, where a low discharge voltage (typically 150 to 250 V) is sustained. The ions are accelerated in the second stage by the accelerating voltage applied between the guard rings and the first-stage cathode (several kilovolts). While the optimal discharge voltage in the first stage is only slightly sensitive to operating conditions, the accelerating voltage is regulated over the range required to produce the desired Isp. Space charge and current neutralization of the ion beam is provided by the external cathode.

II.   Bismuth Propellant

The bismuth propellant introduces potential advantages to the two stage TAL over the xenon-fueled ion thrusters. The most significant advantages to using a bismuth-fueled thruster over a thruster that uses xenon or even lithium are identified in Table 1. This table shows how inexpensive bismuth is relative to xenon and lithium. Bismuth exists in the Earth's crust at the same abundance level as silver and is a byproduct of the process used to extract silver from the Earth's crust. Assuming an NEP mission requires 20,000 kg of propellant, the propellant could cost $40.0 M for xenon and only $1.5 M for bismuth.

The high density of bismuth relative to xenon and lithium enables a much more attractive tankage fraction for propulsion system propellant management on spacecraft. For example, 20,000 kg of propellant could be stored as solid bismuth in a single tank volume of 2.0 m³. In comparison, the tank required for solid lithium storage would consume 37 m³, and xenon, in the supercritical slush state, would consume 10 m³ (2000 kg/m³ at 2800 psi and 40°C). The spacecraft mass savings associated with this difference would likely be an important factor in consideration regarding future investments in maturing this technology within Prometheus.

The melting temperature of bismuth, at 271°C, enables it to condense at room temperature on vacuum facility walls. This attribute of the propellant significantly relaxes the pumping speed requirements placed on facilities used for testing bismuth fueled thrusters, which is a significant factor when testing at increasingly high power levels for high power electric thruster performance and lifetime assessments. Two stage TALs operating on Bi propellant could be tested at power levels exceeding 100 kW in existing facilities.

Table 1. Characteristics of bismuth propellant which make it an attractive alternative to conventional electric propulsion system propellants.

	Bismuth	Xenon	Lithium
Density (kg/m³) at 20°C	9780 (solid)	2000 (supercritical at 2800 PSI, 40°C)	535 (solid)
Cost ($/kg)	75	2000	137

Additional potential benefits to using bismuth propellant include its low ionization potential and that it is environmentally friendly (because of its non-toxic and non-carcinogenic nature). The low ionization potential of bismuth enables high efficiency propellant ionization in the thruster.

III.   The VHITAL Program

The VHITAL Program P-I is Dr. Mark Cappelli of Stanford University. He is also leading the thruster lifetime assessment element. He is responsible for implementing the near-field plume diagnostics and leading the near-field plume characterization and the assessment of the thruster lifetime. Anita Sengupta, a Co-I, is the VHITAL Program Manager at JPL. Dr. Colleen Marrese-Reading is a Co-I as the technical lead of the thruster support system technology development and the thruster performance assessment at JPL. Dr. Iain Boyd, at the University of Michigan, is also a Co-I who will lead the spacecraft contamination- assessment element. He will be responsible for modeling the internal near-field and far-field flow and determine the characteristics of the plasma that will interact' with the spacecraft systems. Tom Kessler (Co-I) and Jim Yuen, at Boeing, will be responsible for the propellant isolator development for this program. Dr. Kevin Rudolph (Co-I), at Lockheed Martin Astronautics Operations, will be lead the spacecraft system analysis element. He will be responsible for system analysis, focusing on the optimal operating conditions and thruster system configurations to provide the best architectures for NEP missions. Dr. John Williams and Dr. Azare Yalin at Colorado State University are participating in the thruster lifetime assessment through erosion product flux and sputter yield measurements. Dr. Lee Johnson and Dr. David Conroy will assist in the implementation of the lifetime and plume diagnostics at JPL.

The program is divided into three phases: a 6-month Phase 1 activity followed by two 1-year phases (Phase 2 and Phase 3). Phase 1 has been awarded, however, phase 2 and 3 are contingent upon the performance of the VHITAL team during the phase 1. The first phase started in June 2004.

Phase 1 objectives are to:

1-1. Review the current two stage Hall thruster state-of-art (SOA), including the potential and limitations of different two-stage Hall thruster technologies to meet the performance goals of the NRA.

1-2. Define the VHITAL 160 design, with supporting analyses, that meets or exceeds the required performance and throughput requirements.

1-3. Develop a detailed plan to experimentally and analytically evaluate the VHITAL 160 performance, life, and contamination potential.

Phase 2 objectives are to:

2-1. Fabricate and acceptance a VHITAL 160 for operation at 25 kW with an Isp of 6000s to 36 kW at 8000 s and an efficiency of > 65%.

2-2. Fabricate and demonstrate a Bi-fed hollow cathode, a feed system and a high voltage propellant isolator.

2-3. Develop life assessment and plume characterization diagnostics.

2-4. Develop VHITAL-160 life assessment models.

2-5. Develop VHITAL-160 plume models.

Phase 3 objectives are to:

3-1. Experimentally assess the performance of the VHITAL 160.

3-2. Assess the lifetime of the VHITAL 160.

3-3. Assess spacecraft contamination potential of the thruster.

3-4. Perform spacecraft systems studies on propulsion and power system configurations and contamination impact.

3-5. Use tools developed and measurements to propose system configurations to meet mission requirements.

A. The Thruster

TsNIIMASH is responsible for fabrication and acceptance testing of the radiatively cooled VHITAL-160. This technology was developed at TsNIIMASH. They are the only company in the world that has demonstrated it. TsNIIMASH will also be responsible for refurbishing an existing TAL-160 for preliminary testing of the technology and the support systems including the facility, power supplies, and the feed system. The thruster has been designed to operate efficiently on bismuth. The expected thruster performance is presented in Table 3. The total efficiency does not include anode heater, neutralizer, and electromagnet power.

Table 2. The primary thruster operating points for performance and life assessment.

Operating Parameters	Operating Points	
	I	II
Power (kW)	25	36
Propellant flow rate (mg/s)	11	9
Isp (s)	6000	8000
Thrust (mN)	650	710
Total Efficiency	0.78	0.79

B. Support System Development

JPL is responsible for support system development. TsNIIMASH is responsible for providing a feed system and neutralizer cathode with the thruster. However, their system will not include a propellant isolator or flow meter. In the phase 1 of the program, a propellant isolator, pump, vaporizer, flow meter, and neutralizer cathode are being designed and cost studies are being carried out. JPL is working with NASA MSFC on the propellant pump and flow meter development. JPL is working with Boeing on the propellant isolator development.

C. The Performance Evaluation

The experimental thruster technology assessment program will be carried out at JPL in a unique facility specially designed for testing electric thrusters operating on condensable metal propellants. It is 3 m in diameter and 8 m in length and has a coaxial cylindrically shaped water-cooled liner. The performance of the thruster will be characterized with thrust and beam current density profile measurements at 25 kW (6000 s) and 36 kW (8000 s). An inverted pendulum thrust stand will be used for the thrust measurements and Faraday probes will be used for current density profile measurements and for estimating the total ion beam current.

D. The Lifetime Assessment

Stanford University is responsible for the thruster lifetime assessment. This program includes a plan for characterizing the internal and near-field Bismuth ion (BiII) and neutral (BiI) flux and energy distribution using a

combination of spatially resolved laser induced fluorescence (LIF), atomic absorption spectroscopy, and distributed embedded/immersed ion probes. LIF is used primarily as a means of characterizing the near-field ion and neutral velocity (energies), in particular, the local velocities in the vicinity of the exit plane and guard ring. Planar ion probes provide a measure of the near-field ion flux. Both measurements generate the needed data to indirectly determine the expected ion-induced erosion/sputtering of the second-stage cathode/guard ring. Total Surface Layer Activation (SLA) will be used to directly measure the erosion rate of the second stage cathode/guard ring at the 25 and 36 kW operating points. Cavity Ring-Down Spectroscopy (CRDS) will be used to estimate the erosion rate of the guard rings in-situ with measurements of the flux of erosion products from the thruster. The SLA technique will be used to calibrate the CRDS technique at a limited number of operating points. CRDS will then be used to quantify the changes in flux of erosion products from the thruster with changes in operating conditions over a broader range of thruster operation. With this multi-pronged approach to these measurements, a large trade space can be explored to determine the effect of operating voltage and current on thruster lifetime with low risk high fidelity measurements at the two critical operating points. This approach ensures that we can identify the lifetime at the critical operating points and the impact of critical operating parameters on thruster lifetime.

These measurements will also be used in a device model that will be developed at the University of Michigan to determine the erosion characteristics of the thruster and to assess the potential of the thruster to contaminate the spacecraft with erosion products and bismuth condensate. Sputter yield measurements of the guard ring material under bismuth ion bombardment will be conducted at Colorado State University. These sputter yield measurements will provide the necessary atomic physics data needed for the prediction of erosion behavior by the device model.

E. The Spacecraft Contamination Potential Assessment

The contamination potential assessment effort will be lead by the University of Michigan. The program includes a plan to develop a model of the plasma flow from the thruster and a model to track the expansion of the exhaust and backflow of condensable species onto spacecraft surfaces. For Hall thrusters, a number of approaches for modeling the interior plasma flow in the acceleration channel have been developed. A model of the plasma generation region and the acceleration zone using a particle approach will be developed. In this approach, the plasma dynamics is simulated using the Particle In Cell (PIC) method [3] and collision dynamics is simulated using the direct simulation Monte Carlo (DSMC) method [4]. This code will be used to predict the flux, energy, and incident angle of energetic particles impinging on the guard rings. Experimental measurements made in the near field of the thruster will be used to validate the model.

Output from the modeling of the plasma generation region will provide boundary conditions for the separate computation of the plasma plume. This separation is desirable because there are many physical phenomena important in the device flow that are negligible in the plume (e.g., magnetic field effects). The plume computations can be numerically expensive as they must be conducted over a large spatial domain and, thus, it is important to simplify the plume modeling as much as possible. Information for the atoms and ions will be communicated from the device model to the plume model via velocity distribution functions. This approach has been successfully applied in the end-to-end modeling of the SPT-100 xenon Hall thruster from thruster anode to plume far field [5].

The plasma plumes of both stationary plasma (SPT) and anode layer (TAL) Hall thrusters using xenon propellant has been modeled numerically in a number of studies [6,7,8,9]. Most of these models employ a particle approach similar to that proposed for the device model. The electrons will be modeled as a fluid, whereas the ions (both Xe^+ and Xe^{2+}) and neutral atoms are modeled as particles. The ions are subsequently accelerated in the electric fields in a self-consistent manner. Detailed models of the relevant collision processes to be used in this model have been developed and successfully applied to predict Hall thruster plume characteristics measured in the lab [10] and in space [11].

Prediction of contamination depends on the number flux of Bi to the guard rings together with a model for surface-absorption processes. Since Bi is highly condensable, it is reasonable to assume a sticking coefficient of one. The guard ring surface erosion rate will be predicted from the flux, energy, and incident angle of ions and models and measurements for the sputter yields of the materials of interest. These models will be developed based on semi-analytical approaches as reviewed by Boyd and Falk [12].

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