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

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Abstract: The Very High Isp Thruster with Anode Layer (VHITAL) is a two stage Hall thruster program that is a part of NASA's Prometheus Program in NASA's New 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 ago in Russia (TsNIIMASH). Two stage Hall thrusters offer the high thrust density

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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 test 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. Fabrication of the thruster and associated support systems are underway at both institutions. The TsNIIMASH test facility is complete and demonstration of the pre-existing TAL160 is underway 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 are under development 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 are under development to understand the physics of two-stage hall thruster operation and erosion. This paper will present an overview of the thruster fabrication, pre-existing TAL 160 demonstration, feed system development, lifetime assessment, contamination assessment, and mission study activities performed to date.

Nomenclature

E = electric field
H = magnetic field
d_c = accelerating channel diameter
Isp = specific impulse
TAL = thruster with anode layer

I. Introduction

THE Very High Specific Impulse Thruster with Anode Layer (VHITAL) program, led by a team of NASA, Academia, and Industry experts, 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 it demonstrated specific impulses up to 8000s at efficiencies greater than 70% and operating power levels up to 140 kW[1]. Such levels of operation and performance are consistent with the required performance for NASA high power exploration missions to the outer planets[2]. The bismuth-fueled two stage thruster with anode layer technology is being resurrected because of its unique power, specific impulse, performance capabilities and propellant attributes that are attractive for NASA missions. This propulsion technology is attractive for NEP missions to the outer planets and SEP Mars and lunar cargo missions because it has demonstrated excellent performance (60-80%) at 2000-8000 s specific impulse at 10-100 kW per thruster. These two stage anode layer thrusters were developed at TsNIIMASH more than 25 years ago. The water-cooled TAL-160 demonstrated up to 140 kW and 8000 s. The radiatively-cooled TAL-200 demonstrated 10-34 kW at 2000-5200 s.

The VHITAL Program is a technology assessment program led by Stanford University and the Jet Propulsion Laboratory, to evaluate the potential for spacecraft application of the two-stage TAL technology for future use on NASA science missions. The Russian company TsNIIMASH, is the primary subcontractor, responsible for designing and fabricating a radiatively-cooled 160mm diameter, two-stage thruster, designed for operation at 6000-8000s at 25-36 kW (Table 1). The thruster performance and lifetime will be characterized at two critical operating points, 25 kW at 6000 s and 36 kW at 8000 s at TsNIIMASH.

The thruster lifetime and plume will be characterized experimentally and theoretically) to determine the viability of the technology for high power primary propulsion system application on NASA exploration missions. A test program at the Jet propulsion laboratory in conjunction with lifetime diagnostics from Stanford University and Colorado State University will be used to assess the thruster lifetime with a series of short duration tests. A computational model of the thruster discharge and acceleration region plasma and plume is under development at the University of Michigan to predict the thruster performance, component level wear rates, and model the plume expansion and potential for contamination. The computational physics-based models will be validated with experimental data and used to provide a quantitative insight into how to design longer lasting two-stage TAL's. A feed system development activity is also underway at TsNIIMASH and NASA/JPL, to control and measure the mass flow rate of bismuth to the thruster. TsNIIMASH is developing a laboratory model feed system similar to that previously demonstrated in with the TAL 160 and TAL 200 in the 1980's. NASA/JPL is developing a flight-like system with the requirements for electrical efficiency, reduced mass, compact size, and high measurement accuracy being the primary design drivers.

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 Regimes[3].

The two-stage thruster technology has several systems engineering advantages for high power operation over the conventional single stage Hall thrusters including a primarily robust metal construction, the two stage configuration for higher specific impulse operation, smaller size for higher thrust density, a propellant that has a much lower cost than xenon and is much less expensive to pump in ground test facilities. The maximum specific impulse that advanced single stage Hall thrusters have demonstrated is 3700 s with the SPT-1[4],[5]. 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 and the electron current to the anode increase 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 specific impulse necessary for potential NEPmissions to the outer planets (6000 to 9000 s) requires ion accelerating voltages greater than 4 kV. Two stage TALs have demonstrated increasing efficiency with operating voltage through 8 kV.

The use of the condensable propellant bismuth propellant 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 10 more dense than xenon stored at high pressures. This results in significant tankage fraction and overall feed system mass savings over Xe-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 mission this could result in a $20M cost savings for a 10,000 kg throughput mission. 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. 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).

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 Xe Propellant[3].

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 footprint 1/20 the size

**** 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.

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 established 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 current layer of electrons ionizes neutral 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.

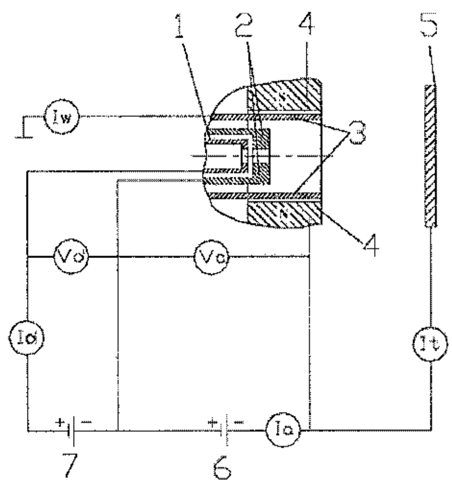

Figure 1. Functional diagram of a two-stage TAL showing the (1) first stage anode, (2) first stage ring cathode (second stage anode), (3) second stage cathode, (4) pole piece magnets, and (5) beam target for current collection measurement (not part of the thruster)[1].

A two-stage TAL works much the same way as 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 200 V, but that is all that is required produce Paschen breakdown and electron emission and subsequent ionization. The accelerating voltage, setup 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 to the first ExH layer, little ionization or double ionization occurs in the second stage, further contributing to thrust efficiency. 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 VHITAL160 is shown in Figure 2. The VHITAL160 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. VHITAL uses higher temperature wiring, refractory and magnetic materials and improved high voltage tolerances, to withstand the thermal environment imposed at 36kW of operating. 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 vaporizer distributor and surrounding ring cathode assembly. The anode vaporizer is design to provide an azimuthally uniform flow of vaporized bismuth into the annulus. A heater is used to preheat the anode to prevent bismuth condensation during startup 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 performance[6]. 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 in this stage is up to 8 kV, the full accelerating voltage, between the anode and cathode. The entire electrode unit is made from refractory materials such as molybdenum and niobium, to withstand up to 1000 C operating conditions. Each part of the electrode unit is also electrically isolated from each other and the thruster with vacuum ceramic insulators.

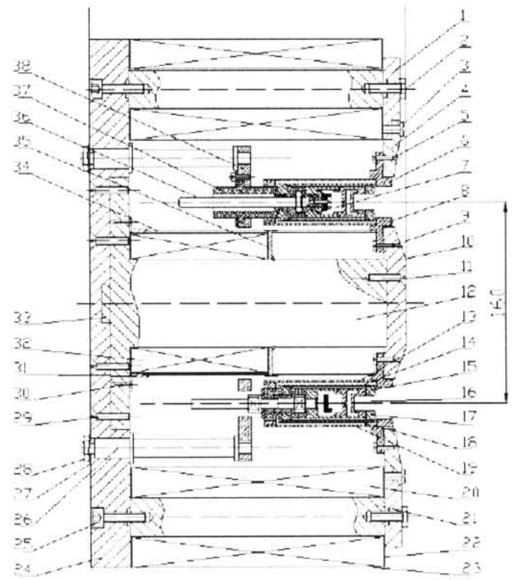

Figure 2. Schematic of the VHITAL D160[7].

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 minimum field in 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 installed near the thruster exit plane. This potential is therefore tens of volts above ground.

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 two 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 pre-existing TsNIIMASH built D160 thruster, on which the VHITAL 160 thruster design is based. The status of the VHITAL160 hardware development and fabrication a D160 test program and performance data obtained to date is summarized in the following sections.

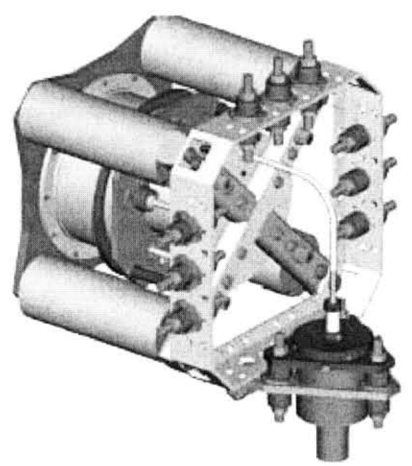

Figure 3. The TsNIIMASH VHITAL-160 thruster design[7].

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 main design tasks associated with the VHITAL160 development are the thermal, structural, and thermo-mechanical validation of the radiative cooling scheme over the required operating regime. The plasma physics design was already completed as part of the original D160 and D200 test program[10,1].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 heating on all 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 reference [8]

The VHITAL160 thruster fabrication is underway at TsNIIMASH. To date all high temperature ceramics, wiring, and 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. The bismuth reservoir, evaporator, propellant lines have all been fabricated. More details on the thruster fabrication can be found in reference [8].

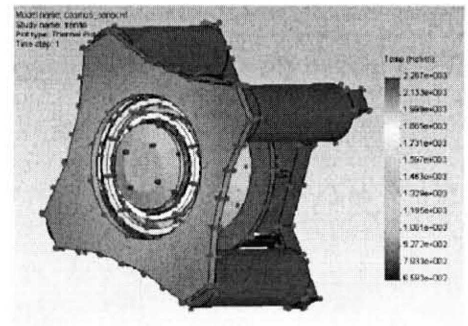

Figure 4. 3-D thermal model of the VHITAL160 Thruster[9].

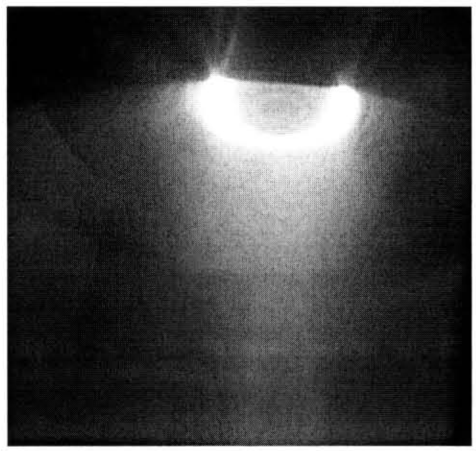

Figure 6. D160 2-stage TAL operating at 3kV in TsNIIMASH test facility.

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)[10]. The thruster refurbishment consisted of disassembling the thruster, performing a failure inspection of all piece parts, recovery and cleaning of re-usable 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 BOL 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 calculations[11]. 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 cathode's to the first stage anode, and second stage cathode to the feed system were all verified. The D160 is

Figure 5. Refurbished D160 lab model 2-stage hall thruster[11].

a 160cm diameter, water cooled, two-stage, anode layer thruster[10]. The 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 X. Details on the thruster refurbishment can be found in reference [11].

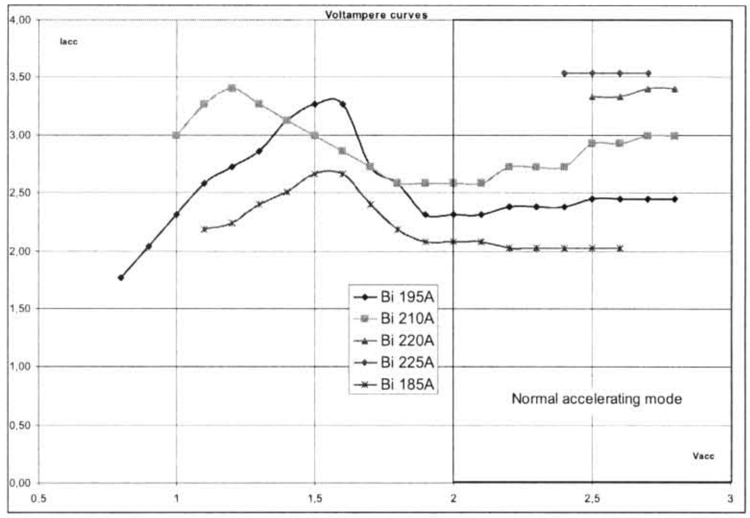

Figure 7. D160 Current-Voltage Data (TsNIIMASH) Error! Bookmark not

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. Variation of the magnetic field was also investigateThrust measurements taken with a thrust stand have also been obtained and compare well to test data taken previously on the D160 thruster in 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 reference [**Error! Bookmark not defined.**]. The thruster will be tested at up to 36kW in the near future when a higher voltage power supply under fabrication is completed and integrated into the test facility in the near future.

IV. Feed System Development and Testing

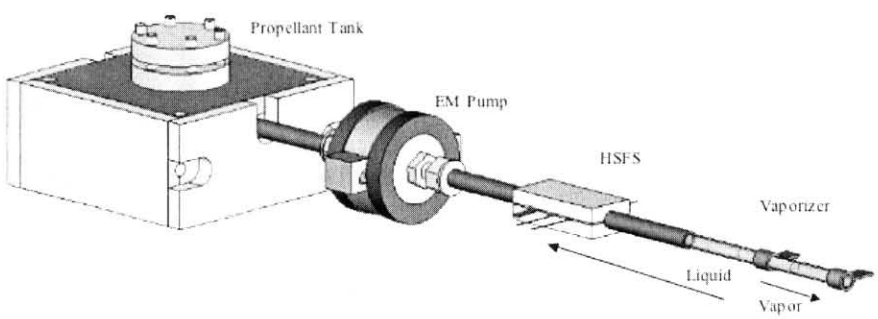

Figure 8. The feed system component assembly.

Two bismuth propellant feed systems are under development in parallel in the VHITAL Program. A prototype flight-like bismuth feed system is under development at JPL and NASA MSFC. NAsa MSFC is developing 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 developing 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 and the chamber does not have to be prevented between operating points.

A more conventional laboratory feed system is also being 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 US testing. This system does not allow real time measurement and active control of flow rate. 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%.

C. Liquid Metal Feed System

The liquid metal feed system is used to convert solid bismuth propellant into liquid form for vaporization. NASA MSFC developed two approaches as part of the Phase 2 program. The first approach uses a simple gas pressurized heated tank and associated pressurant and drain valves to force liquid bismuth out through a propellant tube. This system was developed to serve as a laboratory workhorse with which to supply and test the first generation bismuth vaporizer. The second approach is more representative of a flight-like configuration in terms of overall mass, operating power requirements, and active and good resolution flow rate control. It utilizes at prototype electro-magnetic pump and heat pulse flow sensor to provide up to 20 mg/s of bismuth with a measurement accuracy of 0.1 mg/s bismuth. Both systems are fully computer controlled and have demonstrated melting, flowing, and controlling liquid metal propellant flow.

The gas pressurized approach uses a computer controllable argon gas pressurized system with an actively heated tank to force liquid out of the tank through the exit propellant tube. The propellant tank consists of a stainless steel pressure vessel surrounded by copper heaters. The tank has a fill port into which the solid bismuth propellant slugs are inserted, a gas inlet port, through which argon gas is flowed, and a drain valve / exit tube through which liquid bismuth flows. Copper heaters are used to bring the bismuth propellant up to its melting temperature. The heaters and tank are monitored with type K thermocouples. After sufficient time is allowed for the propellant to melt, the tank is pressurized with a "bang-bang" pressure regulator. The pressure rise is actively computer controlled through an electrical solenoid valve on the bang-bang regulator. An in line pressure transducer is used to measure the pressure inside the tank. After a predetermined pressure has been reached the computer commands the drain valve open and liquid bismuth flow is established through the tube. As the pressure regulator can maintain a fixed pressure within the tank, the pressure can be used to regulate the flow rate. The system has been tested and with the bismuth vaporizer and constant vapor flow rate control has been established. Reference [12] and 13] contains a detailed review of the design of the gas pressurized feed system. The limitations of this system are the

The second liquid metal feed system approach utilizes a prototype electromagnetic pump to push liquid bismuth from the storage tank to the propellant feedline. The EM pump utilizes the electrical conductivity of bismuth and an applied magnetic field to exert a Lorentz force on the charge particles (Figure 9). The pump consists of two electrodes and two permanent magnets oriented at 90 degrees with respect to each other. These crossed fields are oriented such that the resultant force acts on the propellant particles in the direction desired fluid flow. By varying the current between the electrodes, the force, or pressure on the fluid can be changed. A calibration curve is generated relating current to flow rate, and therefore flow control is obtained with a high level of accuracy and digital control. A hot spot flow sensor (HSFS) placed downstream of the pump and is used to measure the flow rate. A pulse of thermal energy (derived from a current pulse and associated joule heating) is applied near the inlet of the sensor. This thermal feature is convected downstream by the flowing bismuth. A downstream thermocouple records a "ripple" in the local temperature associated with the passing "hot-spot" in the propellant. By measuring the time between the upstream generation and downstream receiving of the thermal feature, the flow speed can be calculated using a "time of flight" analysis. The primary advantage of this technique is that it doesn't depend on an absolute measurement of temperature

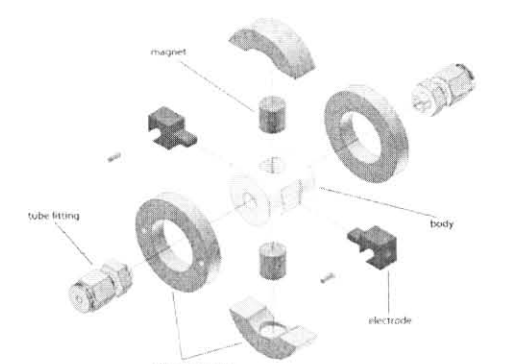

Figure 9. An assembly drawing for the EM pump under development at NASA MSFC.

but, instead, flow thermal features are observed, which makes the technique insensitive to other system thermal fluctuations. Prototypes of the flow sensor have been demonstrated at NASA MFC on gallium. A detailed review on the HSPS design and performance is found is reference [13].

D. Vaporizer Development and Testing

A flight-like bismuth vaporized was developed by the Jet Propulsion Laboratory and Energy Science Laboratories Incorporated. The vaporized design is based on the porous plug approach initially developed for the mercury ion thruster programs of the 1960's[14]. In the Mercury 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 a porous geometry that forces liquid propellant to wet to a solid surface while at the same time reaching sufficient temperatures to overcome the heat of vaporization. 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 for a given 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.

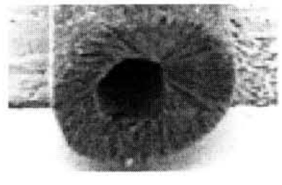

Figure 10. A carbon fiber vaporizer plug (ESLI)[12].

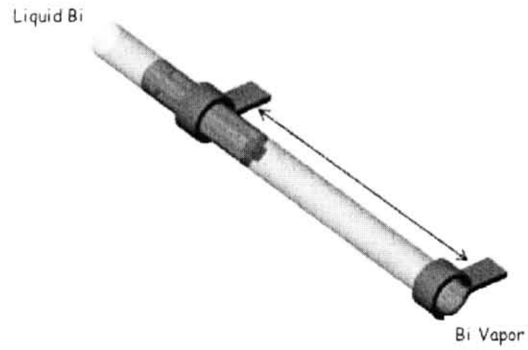

Figure 11. The all-carbon bismuth vaporizer configuration (ESLI)[12].

An all carbon porous plug and carbon tube assembly was selected for VHITAL to eliminate any CTE mismatches and the need for dissimilar material brazes and weld joints. The carbon plug consists of carbon fibers grown inside a graphite tube 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. The prototype (first generation) vaporizers was designed to provide and has already demonstrated 1 mg/s of bismuth flow at the maximum allowable plug temperature of 1130°C. The second generation vaporizer, currently under fabrication at ESLI, is designed to provide up to 12 mg/s at the maximum allowable plug temperature. A detailed review of the design, fabrication, and performance of the carbon bismuth vaporizer is contained in reference [12].

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 evaporating tube (Figure 12). The tank assembly is heated to the bismuth melting temperature by means of a resistive heater enclosing the tank. Liquid bismuth is forced into the evaporator tube due to gravity. After the propellant is converted entirely to liquid form, the evaporator is brought to a temperature of 1000°C. The liquid in the evaporator tube then evaporates and travels through the propellant tune to the thruster. The propellant tube is also 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 temperature. As stated

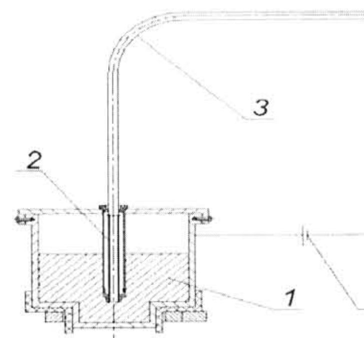

Figure 12. Schematic of TsNIIMASH feed system[1]. The above refers to (1) bismuth reservoir, (2) evaporator, (3) propellant tube, and (4) heater electrical connection.

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 propellant 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, the VHITAL life assessment program, under the direction of Stanford University, is a critical part of the technology effort to ensure future use of the technology on NASA exploration missions. The life assessment 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 be 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 the predictive performance and lifetime models require physical component level erosion measurements and experimentally obtained performance data for validation and future design optimization.

A. Spectroscopic Lifetime Diagnostics Development

1. Bismuth Spectroscopy for Lifetime Diagnostic Implementation

Laser-induced fluorescence (LIF) was selected to measure the three-dimensional velocity (energy) distribution of neutral and ionized bismuth atoms in the VHITAL160 plume. To initiate the LIF activity, an analysis of the bismuth spectrum was performed by Stanford University to determine appropriate transition line selection for spectroscopic absorption measurement techniques. The study determined that several electronic transitions of neutral and ionized bismuth are accessible with laboratory-laser systems. The transition selected for ground state BiI number density determination by atomic resonance absorption spectroscopy was the line at vacuum wavelength 306.86nm (6p3 4S3/2 – 7s 4P1/2). Unfortunately, there are no BiI lines within the ranges that can be probed using the Velocity laser systems above. In addition, as 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 when compared with that of the ion lines, the BiI line at 784nm and 854nm may still be accessible to the less expensive Vortex class lasers from New Focus.

For bismuth ions, the 680.86nm line was chosen due to its measured existence and the capacity of a TLB-6309 LASER to detect its presence. In addition a transition with the ground state as the lower state is located at 143.68nm (6p2 3P0 – 7s 3P1), which poses some difficulty as it is in the far vacuum-ultra-violet range, but may also beused for bismuth ion LIF measurement. It was also found that line selection for bismuth ions must be modeled in terms of hyperfine splitting and broadening mechanisms. Therefore basic Doppler broadened (Gaussian) profiles will need to be modified to account for the more irregular velocity.

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 thruster. 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 generated a high velocity bismuth plasma, for future analysis of bismuth ion line selection[15]. This SPT will also be used to acceptance test the flight-like bismuth feed system and will be discussed in section VI.

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 thruster[16]. As the lifetime of the VHITAL thruster is largely governed by low sputter erosion rates of the guard-rings, on the order of microns per thousand hours of operation, the high sensitivity CRDS technique is well suited to measure sputtered products in the plume in dhort duration testing. The other advantage of CRDS is that is it s real time measurement therefore it can be used to measure erosion rates as a function of thruster operating conditions.

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[17,18]. The CRDS diagnostic allows real time measurement of thruster erosion as it uses the sputtered atoms (from second stage guard ring for example) as the absorbing sample (Figure 13). The sputtered atoms in the thruster plume enter a high-finesse optical cavity formed from high-reflectivity mirrors situated downstream and bounding the thruster exit plane. An 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 with and without the absorber or LASER. The difference in the temporal decay rates is related to the sputtered particle concentration and therefore sputtered particle flux. 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 [6-8].

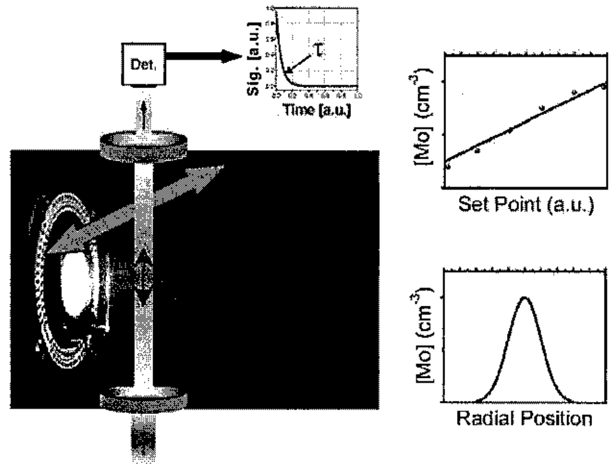

Figure 13. Approach to CRDS measurements in plume of VHITAL thruster. A CRDS cavity will surround the plume (actually with horizontal orientation), and measure Mo within the plume.

As part of the VHITAL program phase 2, CSU has demonstrated the use of CRDS for the detection of sputtered molybdenum from 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 operation of the VHITAL160 thruster in the JPL Condensable Liquid Metal Vacuum Test facility have also been completed as part of the phase 2 program. There are several challenges associated implementing the diagnostic technique due to the relatively long axis of the JPL test chamber as the potential for cavity misalignment and reduction of effective cavity finesse (and CRDS sensitivity) due to mirror contamination from condensed bismuth or sputter products require a careful optical design solution.

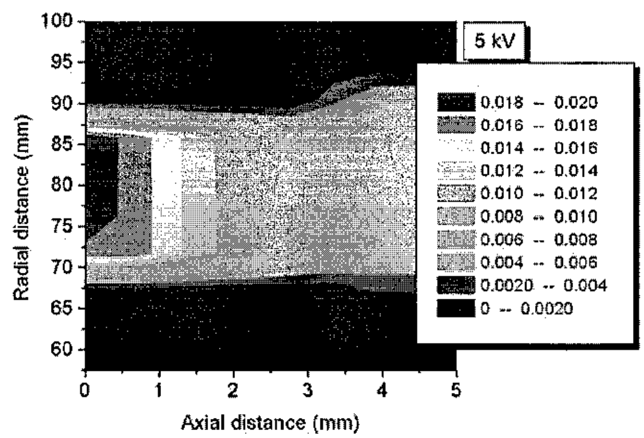

Figure 14. Electron density distribution in the acceleration channel. The wall has the cathode potential. Electrons are depleted from the sheath due to large potential drop.

B. Computational Life and Contamination Assessment

A computational model of a two-stage thruster with anode layer is being developed by the University o Michigan[19]. The model is based on a 2D hydrodynamic approach where the first (ionization) and second (acceleration) stages are modeled separately. The solution of the first stage provides the boundary conditions for second stage.

Quasi-neutrality is assumed and therefore the plasma presheath-sheath interface is considered as the lateral boundary for the plasma flow region. Current-voltage characteristic of the discharge in the 1st stage is calculated and is found to be in agreement with experiment, suggesting the physics of the discharge are accurately capture by the model. In the acceleration channel the plasma-wall interactions are studied in detail to enable calculation of guard ring erosion by the energetic ions. An expansion of the high voltage sheath near the acceleration channel wall is studied. It is predicted that under the typical conditions the sheath expands significantly and the quasi-neutral plasma region is confined in the middle of the channel (Figure 14). Comparison of D160 erosion profile measurements to preliminary model predictions yield reasonable predictions. Details on the model development and comparison to experimental data are contained in references [19] and [20].

A 2D-3D PIC-DSMC hybrid 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. Charge exchange and momentum exchange collisions are included in the simulation. The computational domain begins at the exit plane of the thruster using output from the second stage model as boundary conditions to the simulation. The simulation extends for several meters downstream of the thruster. A comparison of predicted current densities to radial profiles measured by TsNIIMASH in te 1950's is being used to validate the code. Details on the model development and validation are discussed is greater detail in reference [19].

VI. Conclusion

The 2-Stage Russian bismuth TAL technology has been successfully resurrected with the pre-existing D160 thruster demonstrating nominal operation at up to 3 kV and 4A accelerating current on bismuth at TsNIIMASH. The VHITAL160 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 require 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 design parameters that impact 2-Stage TAL life and performance limitations to advance the technology for eventual flight application. This will be addressed by the experimental and computational life assessment portion of the VHITAL program.

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References

[1] Tverdokhlebov, et. al., "Overview: State of the Art High Power Bismuth Fueled Hall Thruster," JPL Contractor Report, August 2004.

[2] Bob Frisbee Mission Studies Paper Reference

[3] Marrese-Reading, C., "The VHITAL Program to Demonstrate the Performance and Lifetime of a Bismuth-Fueled Very High Isp Hall Thruster," Presented at the 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA-2005-4564, Tucson, AR, July 2005.

[4] Manzella, D., et. al., "High Voltage SPT Performance," 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA-2001-3774, Salt Lake City, UT, July, 2001.

[5] Kim, V., "An Overview of Russian EP Activities," Presented at the 40th AIAA/ASME/ASE/SAEE Joint Propulsion Conference, AIAA-2004-4440, Huntsville AL, July 2004.

[6] Ageev, V.P., "Operating Mode Characteristics and Performance of Two-Stage Anode Layer Accelerator with Low Voltage and Magnetic Field," Sov. Journal of Appl. Mech. and Tech. Phys., No. 6, 1987.

[7] Tverdokhlebov, S., et. al., "Thruster VHITAL-160 and Support Systems, Requirements, Conceptual Design, and Analysis Report," JPL Contractor Report, October 2004.

[8] Tverdokhlebov, O., et. al., "TsNIIMASH Progress under the VHITAL Program," IEPC-2005-XXX, Presented at the 27th IEPC, Princeton NJ, November 2005.

[9] Tverdokhlebov, S., et. al., "Thruster VHITAL 160 and Support System Design Documentation," JPL Contractor Report, May 2005.

[10] Grishan, S.D. et. al., "Performance of a Two-Stage Ion Accelerator with Anode Layer," Sov. Journal of Appl. Mech. and Tech. Phys., No. 2, 1978.

[11] Tverdokhlebov, S., et. al., "Refurbishment of the Pre-existing TAL160 Thruster," JPL Contractor Report, November 2004.

[12] Marrese-Reading, C., et. al., "The Development of a Bismuth Feed System for the Very High Isp Thruster with Anode Layer VHITAL Program," IEPC 2005-218, Presented at the 27th IEPC, Princeton NJ, 2005

[13] Markusic, T.M., et. al., ""Liquid Metal Flow Sensors for Electric Propulsion," IEPC-2005-030, Presented at the 20th IEPC, Princeton NJ, November 2005.

[14] Kerrisk, D. J., Masek, T. D., "A Zero Gravity Mercury Propellant Feed System," AIAA Paper 66-250.

[15] Scharfe, D., and Capelli, M., "Stationary Reference Bi Discharge Cell for Optical Diagnostics of a Bismuth Hall Thruster" IEPC-2005-XXX, Presented at the 29th IEPC, Princeton NJ, November 2005.

[16] Yalin, A., Surla, V., and Williams, J., "Erosion Measurements by Cavity Ring-Down Spectroscopy for the VHITAL Program," , IEPC 2005-XXX, Presented at the 20th IEPC, Princeton NJ, October 2005.

[17] Busch, K.W. and M.A. Busch, Cavity-Ringdown Spectroscopy - ACS Symposium Series 720, ed. B.K.W.a.B. A.M. Vol. 720. 1999.

[18] Berden, G., R. Peeters, and G. Meijer, *Cavity Ring-Down Spectroscopy: Experimental Schemes and Applications.* Int. Reviews in Physical Chemistry, 2000. **19**(4): p. 565-607.

[19] Keidar, M., et. al., "Modeling a Two-Stage High-Power Bismuth Anode Layer Thruster and its Plume," IEPC-2005-045, Presented at the 29th IEPC, Princeton NJ, November 2005.

[20] M. Keidar, I.D. Boyd and I.I. Beilis, Modeling of a high-power thruster with anode layer, Physics of Plasmas, 11, No. 4, 2004, pp. 1715-1722.