Summary of the VHITAL Thruster Technology Demonstration Program: A Two-Stage Bismuth-Fed Very High Specific Impulse TAL

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Abstract: The Very High Specific Impulse Thruster with Anode Layer (VHITAL) program has successfully resurrected the two-stage bismuth fueled thruster with anode layer (TAL) technology. The two-stage technology was developed over 25 years ago in Russia, at that time demonstrating specific impulses up to 8000s at efficiencies greater than 70%. The technology offers a unique combination of previously demonstrated performance, throttle-ability and low mass propellant system attributes that are attractive for a wide range of NASA missions. The VHITAL program has led the design, fabrication, and test of the VHITAL-160 thruster, a two-stage 160mm accelerating channel TAL with a radiative

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cooling scheme. The VHITAL program has also led the development of an advanced bismuth propellant management system to engineer and demonstrate key technologies required to operate a high temperature condensable metal propellant. VHITAL has also initiated a life assessment program focused on the development of computer tools and plasma diagnostics to quantify thruster erosion and optimize performance. To date, the VHITAL-160 thruster has demonstrated stable operation up to 36kW and 7700 seconds at efficiencies in excess of 63%. The propellant management system has demonstrated control and measurement of bismuth in the liquid and vapor states up to 12 mg/s and 1200°C. The life assessment program has developed a hydrodynamic model of the first and second stage plasma that compares well with existing experimental data. LASER Induced Florescence and Cavity Ring Down Spectroscopy have been demonstrated in representative plasmas. The results of thruster, feed system, and plasma diagnostic testing will be presented. Key findings from the model development will also be presented.

Nomenclature

U_D = Discharge voltage
I_D = Discharge current
U_A = Acceleration voltage
I_A = Acceleration current
F = Thrust
η = Efficiency
dm/dt = Flow rate
I_{sp} = Specific impulse
NRA = NASA research announcement
TRL = Technology readiness level
ExH = Hall current layer

I. Introduction

The Very High Specific Impulse Thruster with Anode Layer (VHITAL) program was a technology demonstration program selected under the 2002 Research Opportunities in Space Sciences NASA Research Announcement (NRA) in support of the In Space Propulsion program. The goal of the VHITAL program was to resurrect the Russian two-stage bismuth fueled TAL technology for potential future use as a propulsion system on NASA exploration missions. The technology assessment program was led by the Jet Propulsion Laboratory, NASA, TsNIIMASH Export, Stanford University, University of Michigan, and Colorado State University representing a unique synergy of mission focused technology research and development.

The two-stage TAL technology was developed over 25 years ago in Russia at TsNIIMASH, at that time demonstrating specific impulses from 3000 to 8000s at efficiencies greater than 70% as well as power consumption from 1 to 140 kW per thruster[1,12]. The two-stage TAL is unique electric propulsion device. Its separation of the ionization and acceleration regions of the plasma provides an electrical efficiency and specific impulse capability similar to an ion thruster but with the simple low-cost construction and high thrust density typical of a hall thruster. The ability of the two-stage TAL to operate over a large power range is advantageous as it enables multiple missions in a range of cost categories with a single propulsion technology development program. The throttle-ability of the two-stage TAL is unique among Hall thrusters, in that it delivers consistent performance and efficiency with increasing power availability, made possible by the separation of the ionization and acceleration regions. The two-stage TAL also has significant development heritage from the conduct of the D-160, D-200, and now VHITAL test programs conducted by TsNIIMASH. Specifically these programs developed engineering modeling tools for materials selection and electrode/magnetic design, thruster erosion data as a function of accelerating channel geometry, as well as fabrication and testing techniques needed to operate with a condensable metal propellant.

The two-stage thruster technology has several systems engineering advantages over conventional single stage Hall thrusters including a (primarily) robust and low-cost metal construction, higher specific impulse operation and efficiency, smaller size, higher thrust density, and reduced pumping speed requirements for ground testing. The use of the condensable propellant bismuth also has several system level performance and cost advantages. As compared to a xenon based propulsion system, the use of bismuth significantly reduces tankage fraction, propellant cost, overall feed system mass, and utilizes a smaller footprint on the spacecraft. Table 1 is a comparison of the properties of bismuth and xenon. To quantify these advantages, comparative mission studies were performed in references 4 and 5. The studies indicate that a VHITAL propulsion system compares favorably to other high power electric propulsion systems.

property	**Bi**	**Xe**
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 1. Properties of bismuth and xenon propellant[3].

The keys issues associated with implementing a two-stage condensable propellant TAL on future spacecraft are high temperature operation, plume contamination, thruster lifetime, and propellant feed system development. Each of these issues was addressed with the VHITAL program with a combination of computer simulations and/or component level technology development and demonstration. Thermal modeling, high temperature material selection and thermocouple measurements of the operating thruster were used to validate the radiative cooling scheme. Plasma physics codes were developed to model the ionization and acceleration region of the plasma enabling performance and erosion assessment of the thruster. A plume model was also developed to predict plume expansion and the extent of impingement on neighboring spacecraft surfaces. The development of a flight like feed system was also tackled with the demonstration of low mass and energy consumption electronics, pump, tank, flow sensor and vaporizer technology.

II. Thruster Technology

The two-stage VHITAL differs from a single stage TAL in that there are two hall current layers, each with a circulating ExH layer of electrons. Neutral propellant gas introduced into the first stage is ionized by the azimuthal Hall electron drift current established by the radial magnetic field and axial electric field between the anode and surrounding ring cathode. The axial electric field, established between the first stage cathode (second stage anode) and second stage ring cathode electrostatically accelerates the newly created ions out of the device producing thrust. The potential between the first stage anode and cathode is on the order of 150 to 250 V, which is required produce Paschen breakdown, electron emission and subsequent ionization. The acceleration voltage, between the second stage anode and cathode is several kilovolts (3-9kV), directly acting on the ionized propellant particles to accelerate them out of the thruster. Axial electron transport is limited to collisional diffusion, as first stage electrons are constrained in the in the first ExH layer. As a result the propellant is 80% to 90% ionized in the first stage. The two-stage design effectively confines ionization and electrons to the first stage and accelerates ions in the second stage.

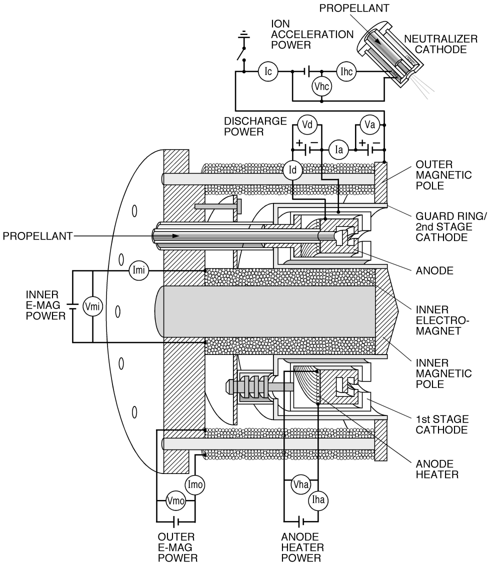

Figure 1. Functional diagram of a two-stage TAL.

In a single-stage TAL the total acceleration voltage is used to both ionize and accelerate the propellant resulting in high energy electron production that does not contribute to thrust and dissipates a significant amount of power in anode heating. This reduces total

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[§§§] 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.

efficiency and applies thermal constraints on the anode. In a two-stage TAL, separation of the regions of the plasma improves ionization efficiency as only ~150 V is required to ionize the propellant (as compared to ~kV). The absence of high energy electron production enables a higher specific impulse operation and a significant reduction in anode power dissipation. Electrical efficiency is further enhanced as the fist stage ExH layer serves to limit the back-streaming electron current through the accelerating layer. 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 sputter erosion; therefore the two-stage design has the potential to improve the lifetime of the TAL.

A functional schematic of the VHITAL-160 is shown in Figure 1. VHITAL has a 160-mm channel diameter with a magnetic circuit and accelerating channel design essentially identical to the existing D160[1, 2]. VHITAL differs only in its radiative cooling scheme and use of high temperature refractory and magnetic materials to accommodate said scheme. Similar to the D160, the VHITAL peak magnetic field is at the thruster exit plane with a value of 0.2 T in the center of the accelerating channel [3]. This value enables stable operation by providing a focused ion beam and sufficient ionization to prevent anomalous mode operation[6].

The primary components of the thruster are the electrode unit, anode heater, magnetic system, guard rings, and structural housing / interface (Figure 1 and 2). The first stage of the electrode unit consists of the first stage anode gas distributor and surrounding ring cathode assembly. The second stage consists of the first stage cathode and second stage ring anode. The second stage cathode is coved by sputter resistant guard rings to protect the pole piece magnets from direct ion impingement sputter erosion. 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, four surrounding electromagnets, and pole piece magnets located at the downstream ends of the central and side coil cores. This configuration ensures uniformity of the magnetic field along the azimuth. An external hollow cathode is used to provide charge neutralization of the ion beam and is at the same potential as the second stage cathode. More details on the thruster design can be found in references 3,7 and 8.

III. Thruster Fabrication and Testing

A. Fabrication

The fully assembled VHITAL-160 thruster is shown in Figure 2. The thruster was fabricated by TsNIIMASH export from 2005 to 2006. The electrode system was machined from heat resistant refractory materials including molybdenum and niobium to allow for high temperature operation. A graphite heater was machined for the purposes of pre-heating the first stage anode prior to thruster ignition. The anode distributor was machined with over one hundred precision orifices to ensure a uniform neutral injection into the first stage. Two sets of removable guards rings were machined, one from stainless steel to allow for accelerated erosion tests and the other graphite to allow for extended duration testing. The magnetic circuit manufacture consisted of the central magnetic core, pole piece magnets, and four outer coil electromagnets. All permanent magnetic materials were selected to be of high magnetic permeability with a Curie point in excess of 600ºC, to prevent demagnetization at 36 kW[8]. The central and side electromagnets were fabricated from coil windings with thermal screens. All electrode spacings are maintained by ceramic insulators. The feed system is described in section IV. More details of the fabrication can be found in reference 9.

Figure 2. Fully assembly VHITAL-160 thruster attached to mounting flange in TsNIIMASH test facility[9].

B. Acceptance Testing

VHITAL was tested in the TsNIIMASH 2-Stage TAL test facility. The facility is a diffusion pumped, 2m x 1.8m vertical vacuum chamber that provides a base pressure of 3×10^{-3} Pa (2×10^{-5} Torr). The thruster was mounted to a flange affixed to the top of the chamber firing in the direction of the gravity. The test facility was equipped with a vertical thrust stand and floating beam target. The thrust stand operates by mechanical registration of spring displacement due to applied force. The beam target consisted of a metallic plate downstream of the plume that is floated relative to ground enabling measurement of ion current from the thruster plume. The thruster was also instrumented with thermocouples on the outer electromagnet coil and pole surface. An indirect thermal measurement of the magnetic system was obtained from measuring coil resistance as it changes with temperature.

Parameter	**Set point**	**Achieved**	**Set point**	**Achieved**
Mode	**1**		**2**	
Power (kW)	**25**	**25.4**	**36**	**36.8**
I_{sp} (s)	**6000**	**5375**	**8000**	**7667**
U_D	**150**	**130**	**150**	**130**
I_D (A)	**6**	**5.85**	**5**	**4.85**
U_A (A)	**4750**	**4800**	**8400**	**8500**
I_A (A)	**5**	**5.1**	**4.2**	**4.25**
dm/dt (mg/s)	**11**	**9.8**	**9**	**8**
F (mN)	**650**	**527**	**710**	**618**
η	**0.78**	**0.56**	**.79**	**.63**

Table 3. Comparison of Mode 1 design and actual operation electrical and performance parameters[9, 3].

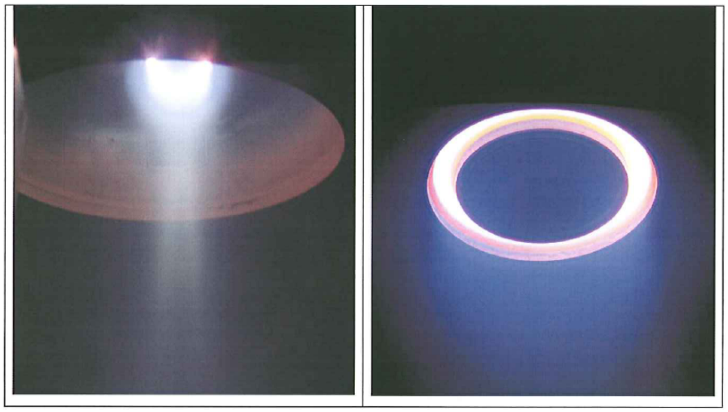

Figure 3. VHITAL-160 firing at 36 kW at TsNIIMASH test facility[9].

Prior to acceptance testing at the design set points (Table 3), functional testing of the thruster was performed at <25kW to a ensure thruster health, gain operational experience, and address any needed modifications. The primary findings from the functional test program were the need to reduce the accelerating channel gap and decrease the contact area between the guard rings and magnet pole. The gap reduction improved thruster stability most likely by increasing the magnetic field profile and strength in the accelerating channel. The reduction was accomplished with the manufacture of new inner and outer pole rings. The reduction in contact area was needed to prevent bismuth condensation on the guard rings to facilitate thruster startup. This was accomplished by reducing the guard ring attachment area to the pole[9].

Another finding from thruster functional testing was the sensitivity of thruster discharge ignition and stability to application of the second stage voltage. It was found that the thruster discharge was ignited and more stable with the application of the second stage (acceleration) potential in addition to the first stage potential. The thruster was also able to recover more easily from anomalous mode operation in this configuration. Anomalous mode operation is characterized by an unstable discharge due acceleration current exceeding ion current and an unfocused ion beam[6]. Another important point is that as Paschen breakdown is the source of ionizing electrons for VHITAL, thruster startup is also sensitive to vacuum chamber pressure and thruster out-gassing.

The purpose of the acceptance test program was to collect thruster electrical, performance, and thermal data at the 25 and 36 kW operating points. Data collected during the test program included discharge voltage and current, acceleration voltage and current, measured thrust, magnetic system temperatures, and magnetic and feed system current and voltage. Performance data reduced from these measurements include power, bismuth flow rate, specific impulse, and thrust efficiency. Figure 3 is an image of the VHITAL-160 thruster firing at 36 kW. A comparison of the electrical and performance parameter measurements made at mode 1 and 2 are shown are shown in Table 3. The discharge current and flow rate were ~3% and 11% lower than the design set-point for both mode 1 and 2. The measured thrust and efficiency was 19% and 28% below nominal for mode 1 as compared to 13% and 20% below nominal for mode 2. The thrust stand, electrical parameter measurements, and flow rate had a measurement error up to 10%. In addition there was a known bismuth vapor leakage between the propellant feed line upstream of the thruster and its connection to the anode feed line. Post test inspection of the thruster revealed the presence of Bi condensate at the coupling between the two portions of the feed line. A reduction in total flow into the thruster would have reduced ionization for a given flow rate set point. The degree of leakage was not possible to quantify but is the most likely cause of the lower than nominal measured efficiency and thrust at 25 and 36 kW. This is also consistent with the reduced performance relative to nominal of mode 1 (higher flow rate) as compared to mode 2 operation.

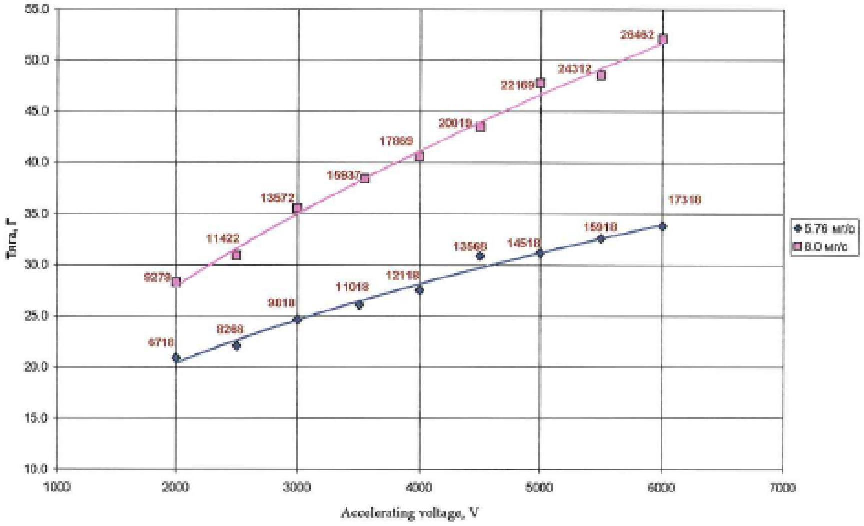

Figure 4. VHITAL-160 thrust as a function of acceleration voltage and flow rate[9].

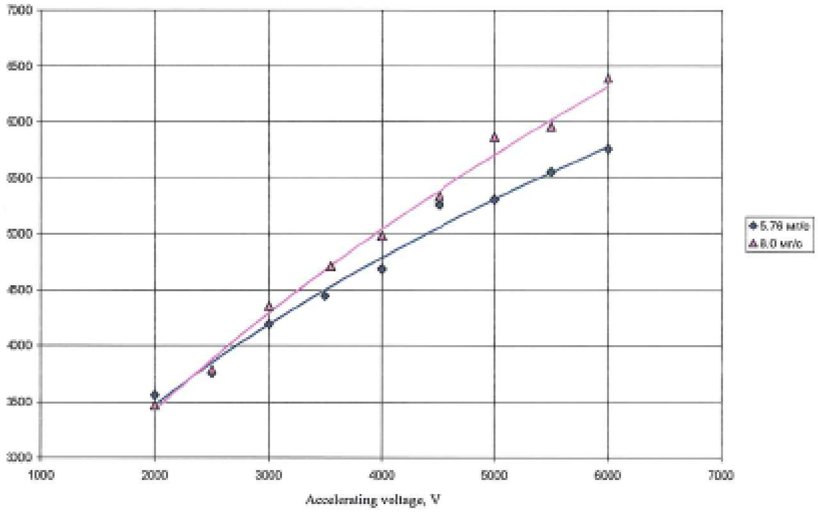

Figure 5. VHITAL-160 specific impulse as a function of acceleration voltage and flow rate[9].

Thruster performance mapping was performed to determine thruster stability and sensitivity to acceleration voltage and flow rate. Figures 4 through 6 illustrate measured thrust, specific impulse, and thrust efficiency as a function of acceleration voltage and bismuth flow rate. All three parameters increased with increasing acceleration voltage, but thrust efficiency was least sensitive to this change. Similarly, increasing flow rate increased thrust and I_{sp}, but to a lesser degree efficiency. This suggests that at the nominal set point ionization is neutral limited, and increasing flow can improve ionization and total efficiency. The thruster did operate stably over the entire regime suggesting stable plasma production and thermo-mechanical operation of the electrodes. It should be noted that all acceptance tests were performed without a cathode neutralizer. Beam neutralization was achieved from electron production from the tank walls by electrically connecting neutralizer common to facility ground. The cathode-neutralizer was tested separately and is discussed in reference 9.

A limited thermal mapping of the thruster was performed with the thermocouples and coil resistance measurement discussed previously. At 25 kW operation the inner and outer magnetic circuit temperature was 470ºC and 300ºC respectively[9]. These values are less than the maximum allowable for thruster materials and compare well to temperature predictions from reference 8. Thermal mapping was not performed at 36 kW as thermal equilibrium was not reached during testing.

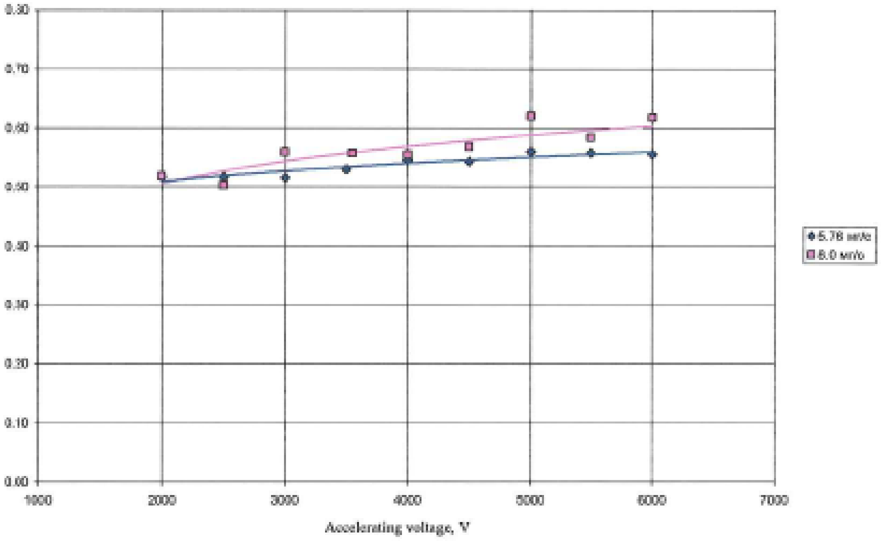

Figure 6. VHITAL-160 efficiency as a function of acceleration voltage and flow rate[9].

IV. Propellant Management System

A critical challenge of working with condensable metal propellants is the development of a propellant management system. This challenge is further exacerbated by the expansion of Bismuth in the solid state and a melting (271ºC) and vaporization (~1000ºC) temperature which impose thermal constraints on traditional feed system component materials. There are three functional elements to a bismuth feed system, the storage of the propellant, melting the solid to liquid form, and vaporizing the liquid to provide a stable flow rate of gas to the thruster propellant distributor. Two propellant management systems were fabricated and tested as part of the VHITAL Program. A gravity-fed bismuth feed system was developed and tested by TsNIIMASH to provide a robust means to test the thruster. A more sophisticated, light-weight and compact feed system was developed and tested by NASA MSFC and JPL to develop the next generation of technologies needed to address the challenges of working with bismuth[10].

A. Gravity Fed System

A robust gravity-fed laboratory model feed system was fabricated and used for thruster acceptance testing by TsNIIMASH. The system consists of an evaporator tube inside a bismuth reservoir and a molybdenum propellant tube to connect the evaporator to the anode propellant distributor (Figure 2). The Bismuth tank is resistively heated to bring the bismuth to the liquid state where it is gravity-fed into the evaporator tube. The evaporator consists of two molybdenum tubes hermetically welded at one end, enabling resistive heating and vaporization of the liquid Bi. After the propellant is melted, the evaporator is brought to a temperature of 1000ºC allowing the liquid in the evaporator tube to evaporate and travel through the propellant tube to the thruster. The propellant tube and anode distributor are also maintained at a temperature of 1000ºC to prevent bismuth condensation. The flow rate and vapor pressure of bismuth is controlled by adjusting the evaporator power. The system does not allow real time measurement of flow. Instead a calibration curve is generated to relate heater current set point to propellant mass flow rate by measuring the mass of the reservoir before and after operation at a given thruster set-point. This yields an accuracy of 10%.

Testing of the feed system proved to be far from straightforward and led to the development of precise heat-up and cool down procedures to prevent evaporator cracking due to bismuth expansion within the molybdenum tubing. After the start-up procedures were refined and the system was allowed to reach steady state prior to discharge ignition, stable feed system operation was achieved. Details on this system can be found in references 6, 7, and 9.

B. Compact-Light Weight System

The NASA architected feed system was developed to address the thermal, mass, and power consumption challenges of working with a propellant at high temperature and voltage relative to its mounting structure. The development of candidate technologies to pump, vaporize, and measure flow to a high accuracy is critical to infusion of the VHITAL technology and represents an advancement of the state of the art. Real time flow rate measurement capability is also required to perform a comprehensive thruster performance assessment. The NASA developed system (Figure 5) consists of a reservoir, electromagnetic (EM) pump, hot-spot flow sensor, and vaporizer[10,11,12]. The EM pump operates on the principle of the Lorentz force. It uses a pair of permanent magnets oriented perpendicular to a pair of electrodes to push the conductive bismuth fluid through the device[13]. The hot-spot flow sensor (HSFS) is used to monitor the liquid propellant flow rate downstream of the pump. The flow is 'tagged' by pulsing current through the propellant. This local increase in temperature is measured by a thermocouple at a known distance downstream. The time of flight of this pulse yields the flow rate for a known density. The vaporizer is a porous all-carbon plug that uses a balance between surface tension and capillary forces, on a non-wettable porous substrate, to control and limit the vaporization of propellant atoms. The rate of vaporization and propellant flow rate is a function of the applied temperature and pore diameter and was sized for 20 mg/s to cover all possible ranges of VHITAL operation[11].

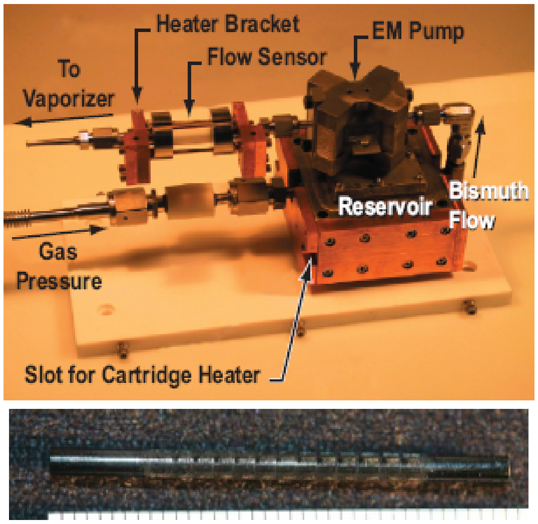

Figure 5. (Top) Flight-like bismuth propellant management system.[10] (Bottom) Carbon plug vaporizer.

The feed system was tested at the component and subsystem level but not with the thruster, as the effort was independent of the TsNIIMASH acceptance test program. The EM pump demonstrated up to 10 kPa of hydrodynamic pressure with operation on Gallium at 30A. Pump pressure as a function of applied current correlated well with design predictions. The HSFS was operated in conjunction with the vaporizer and demonstrated 6 mg/s with a 1200ºC vaporizer temperature[10].

In summary, the NASA feed system provided stable Bi flow with an accuracy of 3% in control and measurement. The primary technical challenges of utilizing the conductivity of the propellant for flow movement and demonstrating high temperature operation with the selected materials were met. However, a full mapping up to 20 mg/s of Bi flow must be conducted prior to integration with the thruster.

V. Lifetime Assessment

Existing lifetime data from TsNIIMASH of the D160 and D200 2-stage TAL test programs indicate the primary life limitation of the two-stage technology is erosion of the second cathode guard rings[1, 2]. Advanced materials such as graphite have been investigated to reduce erosion. Prior testing indicates erosion rates of ~1 micron per hour for MPG-7 graphite, yielding a lifetime of 8khrs. The resultant VHITAL propellant throughput associated with a one micron per hour erosion rate is not sufficient to compete with ion thrusters and must be increased[2,14]. As such, a life assessment program, led by Stanford University, Colorado State

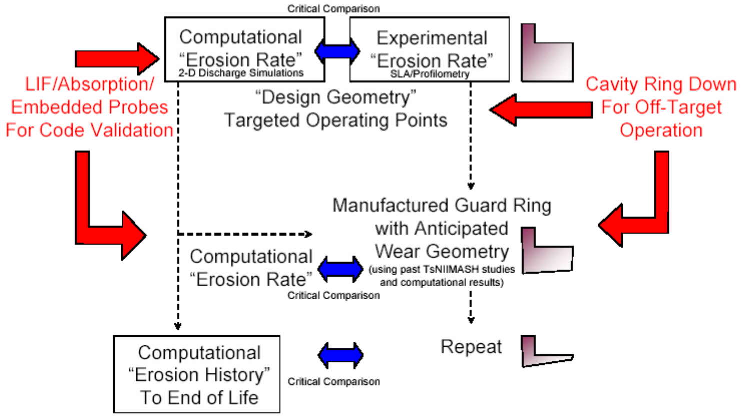

Figure 8. VHITAL Life assessment approach.

University, and the University of Michigan was performed to provide the framework for a quantitative and predictive understanding of the plasma physics that govern the performance and erosion of the 2-stage TAL. This activity included development of spectroscopic diagnostics techniques to resolve particle fluxes and energy distributions, cavity ring down spectroscopy to measure eroded product flux, and physics based computational models of the thruster interior plasma and plume. The experimental techniques in conjunction with the time and spatially resolved physics-based models serve to quantify the internal plasma and plume allowing an assessment and optimization of the existing design to improve lifetime (Figure 8). Details of these efforts can be found in references 15,16,17,18,19, and 20.

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 a two-stage TAL. Development of these optical measurement techniques on a laboratory bismuth plasma has been performed by Stanford University. The 306.86nm ground state transition was selected for atomic resonance absorption spectroscopy. This transition has been successfully measured in a bismuth heat pipe apparatus[15]. The 680.9 nm transition was selected for LIF velocity determinations of singly ionized bismuth. This transition is well populated and shares an upper state with the 660 nm transition, which can be useful for non-resonant LIF.

2. *Cavity Ring Down Spectroscopy*

Cavity ring down spectroscopy (CRDS) is a laser-based adsorption diagnostic developed by Colorado State University (CSU) to provide high precision measurement of thruster component sputter erosion[18]. CRDS provides element specific sputter yield measurements with a short test interval, providing a significant cost and schedule savings over traditional weight loss measurement techniques (that require on the order of 1000 hours to obtain measurable erosion). During the course of the VHITAL program CSU identified appropriate spectroscopic transitions for candidate guard ring materials and made angular sputter yield measurement of candidate guard ring materials in a representative laboratory environment (Figure 9). CSU also designed and fabricated a test apparatus with alignment scheme for large-scale thruster system testing. Details of the development and results of the CRDS program are found in references 18 and 19.

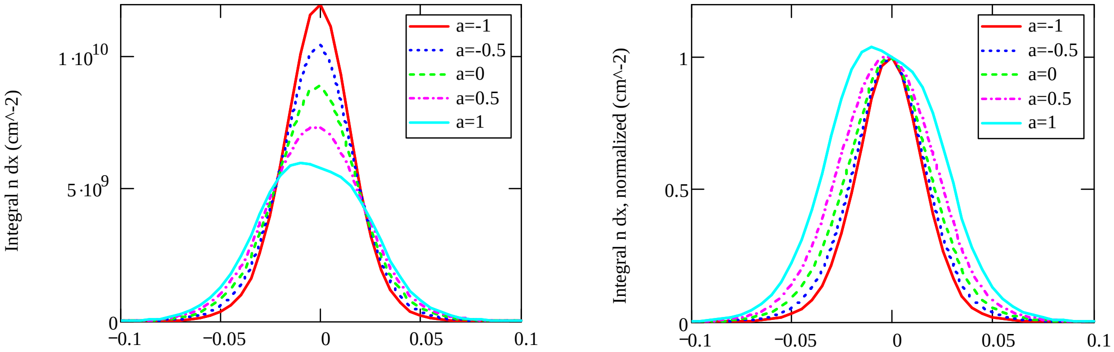

Figure 9. CRDS spatial profiles. a) CRDS signal versus lateral (scan) position *Y*. The curves are for different angular sputter yield profiles (*a* parameters). b) As left, but normalized to give unity at *Y* = 0[18].

B. Computational Life and Contamination Assessment

A 2D hydrodynamic model of the VHITAL thruster was developed by the University of Michigan. It utilizes a two-dimensional hydrodynamic approach where the discharge and acceleration stage are modeled separately and solution of the first stage is used to provide the boundary and initial conditions to the second stage. Detailed descriptions of the model physics can be found in references 17 and 20. The first stage model has been run at the nominal VHITAL discharge operating condition and predicted current-voltage characteristics are found to be in good agreement with TsNIIMASH measurements (Figure 10). Simulations of the second stage have provided detailed insight into the acceleration channel plasma-wall interactions. Specifically, simulations indicate the expansion of the high-voltage sheath near the acceleration channel wall is related to the mechanism for guard ring erosion. The model indicates that the sheath expands significantly and the quasi-neutral plasma region is confined in the middle of the channel. The resulting sheath thickness occupies a significant portion of the channel width, increasing with accelerator voltage. The model also indicates that near-wall sheath expansion leads to a shorter acceleration region. This sheath expansion affects both performance and erosion. With the use of TRIM sputtering coefficients predictions of the ion flux to the guard ring surface and the resultant erosion of the second stage cathode was computed. The predicted erosion profiles and the total erosion rate generally agree well with available experimental data[17].

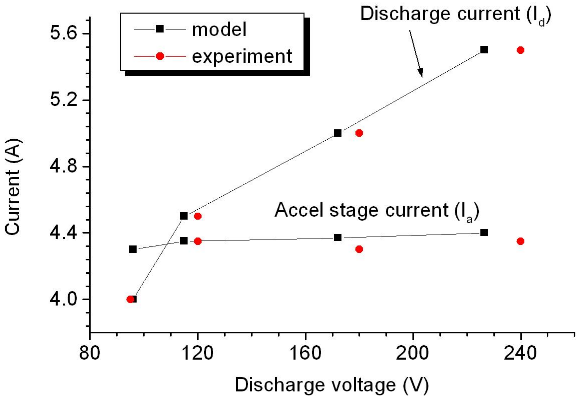

Figure 10. Comparison of simulated and measured first stage current-voltage performance[17].0000000000000

VI. Conclusion

The 2-Stage Thruster with Anode Layer technology was successfully resurrected as part of the VHITAL program. The radiatively cooled VHITAL-160 thruster was designed, fabricated, and demonstrated from 10 to 36 kW demonstrating stable operation at specific impulses up to 7700 seconds and efficiencies in excess of 63%. The successful development and test of an advanced propellant management system has demonstrated the ability to use the conductivity of Bi to move and measure the fluid and developed the material selection and fabrication approaches needed to overcome the high temperatures associated with Bi in its liquid and vapor state. The life assessment program developed key diagnostics and sophisticated plasma physics models needed to improve thruster propellant throughout and measure erosion.

In summary, the technology assessment performed to date on VHITAL has mitigated several of the key development risks associated with this technology namely a radiative cooling scheme and a flight-like propellant management system. These engineering advances in conjunction with a physics based modeling and experimental validation effort provide the framework to advance the technology beyond TRL 3, enabling future efforts to focus on the spacecraft design/infusion phase.

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