# The Development of a Bismuth Feed System for the Very High Isp Thruster with Anode Layer VHITAL Program

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**Abstract: A bismuth feed system was developed for the VHITAL Program to deliver 8-12 mg/s of bismuth vapor at a few Torr to the VHITAL-160. An carbon vaporizer was developed to control vapor flow rates to the thruster. A hot-spot flow sensor was developed to measure the flow rates in the liquid phase of the feed system. An electro-magnetic pump was developed to control the pressure of the liquid bismuth at the inlet to the vaporizer. The system has demonstrated #-# mg/s of bismuth vapor at # mg/s/W with 1 mg/s flow sensing resolution at less than 1 kW.**

## Nomenclature

| | | |
|---|---|---|
| $A_{ch}$ | = | cross-sectional area of capillary channels |
| $m$ | = | total mass flow rate |
| $m_{ch}$ | = | mass flow rate in single capillary channel |
| $\mathbf{n}$ | = | gas number density |
| $P_{in}$ | = | pressure at inlet to capillary channels |
| $P_{out}$ | = | pressure at exit from capillary channels |
| $P_v$ | = | vapor pressure |
| $r_t$ | = | tube radius |
| $\mathrm{r_c}$ | = | capillary channel radius |
| $\mathrm{r_h}$ | = | hydraulic radius |
| T | = | temperature |
| z | = | length along flow channel |
| $\alpha_v$ | = | sticking coefficient of bismuth vapor on liquid front |

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|---|---|---|
| $\eta$ | = | dynamic viscosity |
| $\gamma$ | = | surface tension coefficient |
| $\lambda$ | = | mean free path length |

## I. Introduction

A Bismuth feed system has been under development at JPL, NASA MSFC and Energy Science Laboratories, Inc. as a component of the Very High Isp Thruster with Anode Layer (VHITAL) technology assessment program. The objective of this program is to resurrect the very high Isp and power TAL, developed by TSNIIMASH over 25 years ago and characterize its performance, lifetime and potential for spacecraft contamination. TSNIIMASH is responsible for the VHITAL-160 design, fabrication and acceptance testing at TSNIIMASH. [1] It is a radiatively cooled thruster capable of operating at 25-36 kW at 6000-8000 s. The system will be delivered to JPL with a hollow cathode and feed systems for both the thruster and cathode. The configuration of the TSNIIMASH feed system on the thruster is shown in Figure 1. **The dimensions of this thruster are ##.**

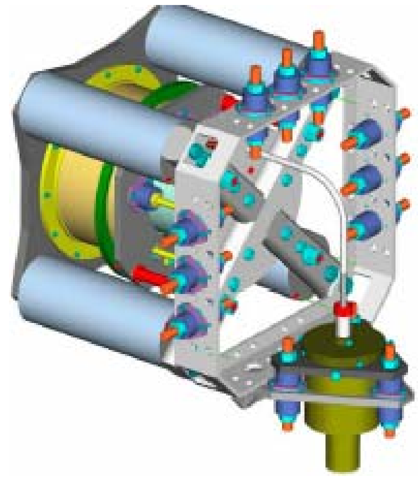

**Figure 1. The VHITAL-160 feed system configuration on the thruster.**

The objective of the feed system development effort is to provide continuous bismuth flow and flow rate monitoring with prototype components that could evolve into a flight compatible feed system. The flow rate range objective is 8-12 mg/s. JPL is responsible for the overall feed system development, the vaporizer design with ESLI and complete system testing and thruster integration. NASA MSFC is responsible for the flow sensor and bismuth pump development. The feed system design, component specifics and performance are discussed in this paper.

## II. The Feed System Design

The feed system assembly and specific components are shown in Figure 2. The system consists of a bismuth tank, liquid bismuth pressurization system, a bismuth pump, a liquid flow rate sensor and a bismuth vaporizer. The component designs are discussed in this section with performance data.

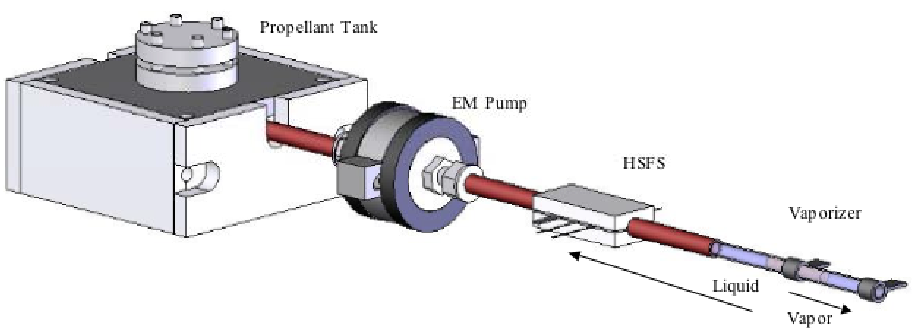


**Figure 2. The feed system component assembly.**

### A. The Pressure Control System

The pressure control system was designed to allow continuously adjustable gas pressurization to the bismuth reservoir in the range of 0-200 Torr. It consists of a pressure vessel, hand operated valves, a hand operated regulator, a electro-pneumatic regulator, and solenoid operated valves. The pressure vessel is a 0.7 liter fiber wound cylinder with a 4500 PSI capacity. The pressure vessel is filled through a hand-operated ball valve to 100 PSI periodically. A hand operated regulator is used to reduce the high pressure in the reservoir to the lower pressure required by the electro-pneumatic regulator. (~20 PSI). The electro-pneumatic regulator provides a means to remotely control the reservoir gas pressure. It uses a bang-bang arrangement of solenoids operated valves. It sets the reservoir pressure by alternately opening and closing the high pressure and vacuum valves to pressure set point sent to it. It also outputs the actual value for verification. One solenoid-operated valve enables the user to vent the reservoir to vacuum. The other solenoid operated valve sends the argon gas to the reservoir for pressurization. The pressurization system can provide up to 200 Torr of argon to the bismuth tank with +/-2 Torr accuracy. The regulator was calibrated with an MKS capacitance manometer. The pressure control system provides low precision pressure control of the liquid bismuth. The bismuth pump is responsible for the fine control of the pressure.

### B. The Bismuth Reservoir

The propellant tank is shown in Figure 4. It consists of a stainless steel tank surrounded by copper plates on each of the four sides with two embedded cartridge heaters. The heaters can run in series at up to 70 W to bring the tank to the operating temperature of 300 °C within 1.5 hours. A type E thermocouple is used to monitor the tank temperature on the bottom tank surface.

### C. The Bismuth Pump

Electromagnetic pumps are very robust, containing no moving parts and allow for the isolation of the bismuth metal inside the feed line so that the pumping action can be attained without having to bring additional materials into contact with the fluid. Figure 3 shows a schematic illustration of our prototype bismuth EM pump design. The pressure developed is a function of the pump geometry, magnetic field strength, and current. With the required flow rates, the Re number will be low enough for the pump flow to be laminar; negligible viscous pressure drop is anticipated. The magnetic Reynolds number is very small for our operating conditions, which means that the flow will not be retarded by the dragging of magnetic field lines downstream (that is, the magnetic flux will not be "frozen" in the fluid). The main power loss in the pump will be Ohmic dissipation (Joule heating) in the electrodes. This power is expected to be ~1 W. Prototypes of these pumps have been fabricated at MSFC and demonstrated already on gallium. [2]

### D. The Liquid Flow Rate Sensor

A hotspot flow sensor (HSFS) was developed for flow rate measurements. [3] 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 (they are "tagging" the flow with a 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

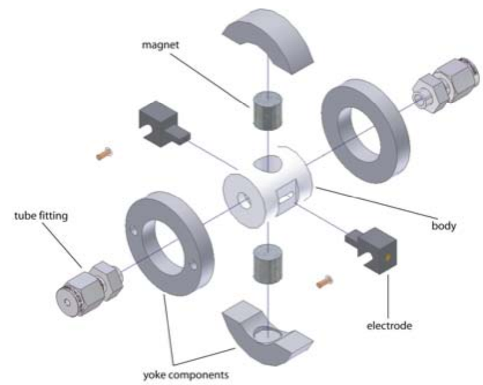


**Figure 3. An assembly drawing for the EM pump under development at NASA MSFC.**

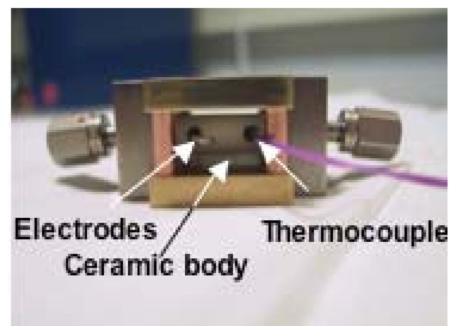


**Figure 4. The hot spot flow sensor under development at NASA MSFC.**

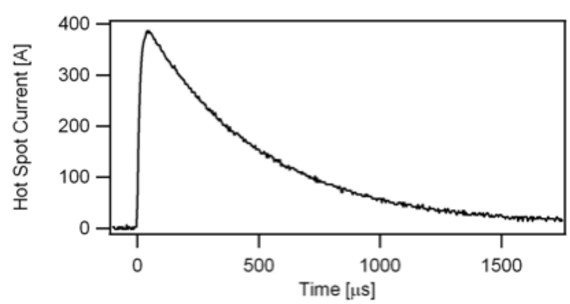


**Figure 5. The heat pulse signal delivered by the HSPS.**

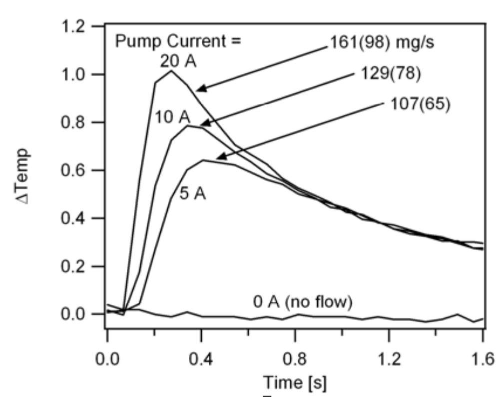


**Figure 6. The transported heat pulses detected for time of flight flow rate analysis by the HSFS.**

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 but, instead, flow thermal *features* are observed, which makes the technique insensitive to other system thermal fluctuations. The hotspot in the upstream flow is generated by pulsing current directly across the bismuth channel flow; by doing so we exploit the high resistivity of bismuth, and obviate the need for a separate resistive heating element. In order for the HSFS to provide useful results, the spatial integrity of the hotspot must be maintained until it reaches the thermocouple location. The hotspot will tend to "flatten out" as it propagates, due to thermal diffusion. Therefore we must design the device such that the thermal diffusion time scale is much smaller than the convective time scale. In our present design the convective time scale is ~1 sec, whereas the (calculated) diffusion timescale is ~15 sec, so we expect to convect a resolvable feature past the thermocouple position. The current pulse (<400 A, 1 msec) is expected to induce a local temperature rise of ~10 $^oC$. Prototypes of the flow sensor have been demonstrated at NASA MFC on gallium. The heat pulse signal is shown in Figure5 and the detected hot-spot signature is shown in Figure 6.

### E. The Vaporizer

The vapor phase of the feed system employs a resistively-heated carbon vaporizer tube, a carbon fiber porous plug and will possibly include a propellant isolator. The porous plug vaporizer was demonstrated with electric propulsion in a zero gravity mercury-fueled ion thruster feed system [4]. The design of the vaporizer is a highly constrained problem because of the low vapor pressure of bismuth, shown in Figure 23, and the desire for minimal operating temperatures and pressures. Also, the plug and tube wall material at the plug must not be wettable by bismuth to prevent liquid flow through it. The desired bismuth vapor pressure entering the thruster is a few Torr. The EM pump for the liquid entering the thruster will require 1 A/Torr. To minimze the current requirement on the pump for a more desirable system, the pressure drop through the porous plug and the vapor pressure must be minimized. The pressure of the liquid entering the vaporizer must be greater than the vapor pressure at the vaporizer temperature and less than the sum of the capillary pressure and the vapor pressure at the vapor front:

$$P_{vapor}(T_{inlet}) < P_{inlet} < P_{vapor}(T_{inlet}) + P_{surf.tension}$$

The vapor pressure of bismuth can be represented by the following equation [5]
with pressure in Pascal and temperature in Kelvin.

$$P_v = \log^{-1}(13.317 - \frac{10114}{T} - 0.86 \log T)$$

The capillary pressure can be represented by the following relationship with capillary diameter, D (cm), and temperature sensitive surface tension coefficient [6], γ, for a non-wetting interface in the porous plug

$$P_{surf.tesion} = 4\gamma/D, \quad \gamma = 378 \text{ dyne/cm } (271°C),$$

$$d\gamma/dT = -0.07 \text{ dyne/°Ccm}.$$

The flow rate of bismuth to the thruster is controlled by the vaporization rate of the bismuth in the vaporizer with vaporizer power. Each capillary channel in the porous plug will contribute to the total mass evaporation rate as defined by the Hertz-Knudsen equation

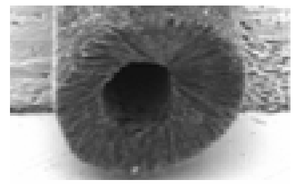

**Figure 7. A carbon fiber vaporizer plug (ESLI)**

**Figure 8. A resistively heated carbon vaporizer tube with porous radial fiber carbon plugs (ESLI).**

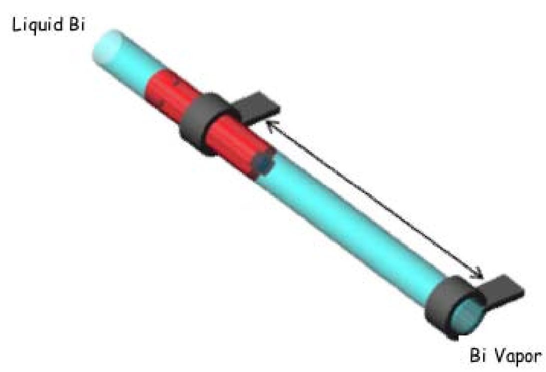


**Figure 9 The all-carbon bismuth vaporizer configuration (ESLI.)**

where $\alpha_v$ is the sticking coefficient of the bismuth vapors impinging on the liquid surface, m is the atomic mass of bismuth, k is the Boltzman constant, $A_{ech}$ is the surface area of the vaporizing liquid. The pressure at the

$$\dot{m}_{ch} = \alpha_v m A_{ech} \frac{P_v - P_{in}}{\sqrt{2\pi mkT}}$$

evaporating surface, $P_{in}$, which is the fluid surface in the each of the pores depends on the pressure at the exit of the capillary channels, $P_{out}$, vaporizer temperature, capillary radius, $r_c$, atomic mass, m, length of the pores, $\Delta z$, and mean free path in the pores, $\lambda$, number density, n, and dynamic viscosity, $\eta$, with the following relationship for the slip flow conditions that exist.

$$\Delta P = P_{in} - P_{out} = -\frac{\frac{\dot{m}_{ch}}{nm}\frac{8\eta}{\pi a^4}}{\left(1+\frac{8}{3}\frac{\lambda}{r_c}\right)}\Delta z$$

The model assumes parallel circular flow channels, which is an approximation to the true channel geometry that exists in the carbon fiber plug where the vapor will flow along the length of the fibers. The capillary diameter in this plug is characterized by a hydraulic diameter, which is an average diameter of the channels. With a feed system pressure requirement to the anode and flow rate requirement, we can estimate the total mass flow rate as a function of the number of channels and the mass flow rate per channel, $m_{ch}$,

$$\dot{m}_{tot} = N_{channels}\dot{m}_{ch} = \frac{P_v - P_{out}}{\left(\frac{\sqrt{2\pi mkT}}{\alpha_v m A_{ech}} + \frac{8\eta\Delta z}{nm\pi r_c^4}\left(\frac{1}{1+\frac{8}{3}\frac{\lambda}{r_c}}\right)\right)}.$$

Axial and radial flow plug geometries were considered. The radial flow channels were preferred because of the more straightforward fabrication process. 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 model predicts the minimum flow rate expected as a function of vaporizer temperature. The temperature of the liquid is estimated by the vaporizer temperature. Based on this model of vaporizer performance, a carbon fiber porous plug vaporizer was designed with a resistively heated circular carbon exterior tube. A prototype vaporizer has been used to successfully demonstrate 2 mg/s bismuth evaporative flow rates at 1170 °C (1443 K) at ESLI. The vaporizer construction has no joints, welds, brazes or CTE mismatch issues because the construction is entirely carbon with a carbon CVD process used to join the two components. Initial testing of the vaporizer will help to identify liquid pressure limitations and validate the model with pressure drop characteristics through the plug. Then minor plug geometry changes will be made to ensure 12 mg/s at <1200 °C (1473 K). Figures 7-9 show the bismuth vaporizer configuration.

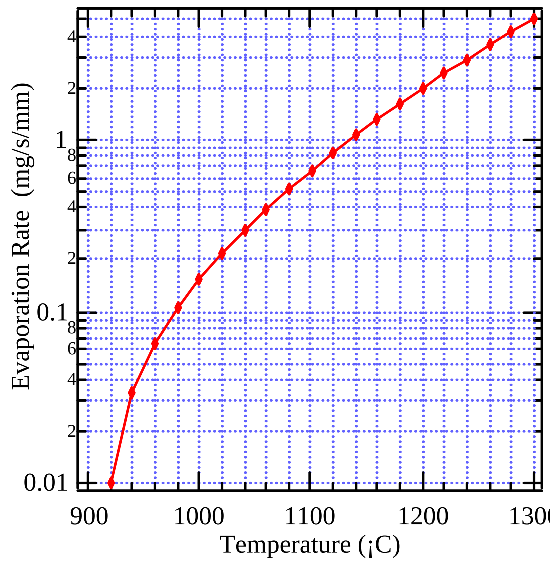


**Figure 10. Vaporization rate of bismuth per mm of vaporizer plug length.**

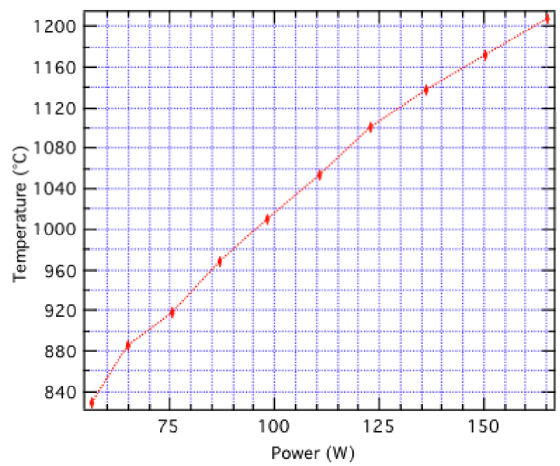


**Figure 11. The carbon vaporizer tube external surface temperature as a function of input power.**

Two prototype vaporizers, #5 and #6 were delivered to JPL for characterizations and to demonstrate the general design and concept and to deliver 1 mg/s of bismuth vaporization. The expected bismuth evaporation rates per millimeter of plug length as a function of liquid temperature are given in Figure 10 for Vaporizer #5. The hydraulic diameter of the capillary channels in this plug is 56.5 um. The open area fraction of the plug was estimated to be 0.9 and the number of channels/mm was estimated to be 6527. The length of the vaporizer tube is approximately 5 cm and the length of the porous plug is approximately 2 cm. The expected evaporation rate of bismuth from the vaporizer is given in Figure 10.

## III. Feed System Performance Demonstrations

Initial feed system performance demonstrations consisted of vaporizer testing with the bismuth tank with pressure control of the liquid. The thermal characteristics of the vaporizer tube with the porous plug were measured and are shown in Figure 11. The testing configuration is shown in Figure 12. A glass jar was used to collect bismuth in this arrangement to roughly estimate the vaporization rates generated, as shown in Figure 12. Thermocouples and an optical pyrometer were used for temperature monitoring. The prototype vaporizer built to demonstrate the general vaporizer design and concept provided >0.8 mg/s with the external tube temperature at 1100 °C in testing at JPL. The vaporizer operated at < 130 W. The total system power with the reservoir and line heaters was <200 W.

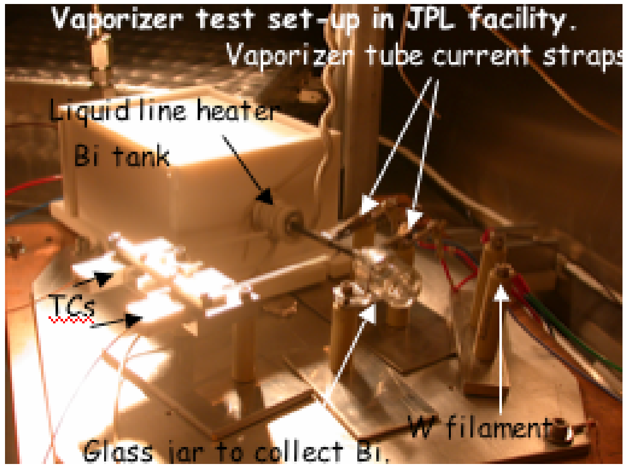


**Figure 12. Vaporizer testing experimental configuration.**

## IV. Conclusions

A bismuth feed system was developed to provide 8-12 mg/s with more flight-like components, lower power and higher mass flow rate resolution than the previously demonstrated TSNIIMASH feed system with continuous monitoring capability.

## Appendix

An appendix, if needed, should appear before the acknowledgements.

## Acknowledgments

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, MSFC, and Energy Science Laboratories. The authors would like to thank Al Owens and Ray Swindlehurst for all of their assistance with the vacuum chamber, feed system test set-up and CAD drawings of the feed system. The research was conducted under a contract with the National Aeronautics and Space Administration. The authors would like to thank John Warren in Prometheus Advanced Systems and Technology Office and Ron Reeve in the Spacecraft Propulsion Technology, Space Exploration Technology Program for support of this work.

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