Proceedings of the Space Nuclear Conference 2005
San Diego, California, June 5-9, 2005
Paper 1092

Energetics of Propellant Options for High-Power Hall Thrusters

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Several propellant options for use in high-power Hall thrusters are analyzed. Krypton, Cadmium, Iodine, Cesium, Mercury, and Bismuth are analyzed and compared to Xenon in several areas of performance. Performance parameters examined include thrust, specific impulse, probability of ionization, maximum theoretical efficiency, and sputter yield.

I. INTRODUCTION

An emerging hurdle in high-power Hall thruster development has been the use of Xenon as the propellant of choice. While Xenon has several advantages as a propellant, namely low ionization energy, high atomic mass and easy storage and flow metering, there are several disadvantages that preclude the use of Xenon in very high power thrusters. The first disadvantage to Xenon as an EP propellant is its high cost. Currently Xenon can be purchased for approximately $5 per standard liter ($850/kg). Using current commercial prices, a 500-kW Hall thruster operating at 60% efficiency and 2,000-sec Specific Impulse (I_{sp}) will consume $4,773 of Xenon per hour of operation. These costs can be extrapolated to $114,550 per test day, and $47.7M for a 10,000-hour mission. Longer-duration missions utilizing larger thrusters or many smaller thrusters can quickly become relatively expensive to supply with propellant. To defer this cost, more economical propellants need to be utilized. Studies have focused on Krypton as a more-economical alternative to Xenon, while maintaining the general design of a gas-propelled thruster.[1]

The second major disadvantage to Xenon is in ground testing. Thruster exhaust must be evacuated from a test facility in order to maintain a space-like vacuum. Typically this is accomplished with cryogenic vacuum pumps. For a 500-kW thruster operating at 2,000-sec I_{sp} and 60% efficiency, 1.56g/sec of Xenon will enter the chamber. In order to maintain $5x10^{-6}$ Torr, the pumping capacity must be at least 40M liters per second. At a cost of roughly $1 per-liter per-second, this translates to roughly $40M in pumping equipment. The pumping requirements scale linearly with thruster power, so a 1-MW thruster will require over $80M in pumping equipment. Additional costs include the large vacuum chamber, support infrastructure and recurring costs such as Liquid Nitrogen. Unlike propellant costs, facility costs cannot be reduced unless gaseous propellant usage is eliminated, as any gaseous propellant will require evacuation from the facility.

The combination of the need for a more economical propellant, and also a propellant that does not require expensive pumping apparatus is apparent. Condensible propellants, defined as those species existing in either solid or liquid state at STP, offer significant advantages for facility cost. While Xenon, Krypton, and other gaseous propellants must be actively evacuated from the test chamber, condensible propellants will naturally condense on the chamber walls, requiring no pumping. Thus condensible propellants are ‘self-pumping,’ requiring only enough vacuum pump capacity to reach and maintain high vacuum with little to no gas load.

II. ANALYSIS OF ALTERNATIVE PROPELLANTS

Several alternative propellant options have been considered. Some physical properties of these propellants, including Xenon as a point of comparison, are in Table 1. This section will discuss the relative merits and difficulties with the many propellant alternatives.

Bismuth has many attractive properties as a propellant. Bismuth has a low ionization energy, allowing for more efficient ionization. The atomic mass of Bismuth is the heaviest of any stable atom. Bismuth is nearly 100 times cheaper than Xenon. Bismuth in solid form also has low toxicity. Vapor-form toxicity has not been established, but is assumed to be low. The main drawback to Bismuth use is it has a higher melting and boiling point than other condensible propellant options. Limited literature indicates that Bismuth was used in Soviet Hall thruster development.[2] More recently, Bismuth thruster development is under consideration at JPL, under the Very High Isp Thruster with Anode Layer,

Table 1: Physical properties of candidate Propellants

Propellant	Melting Point (C)	Boiling Point (C)	Ionization Energy (eV)	Atomic Mass (amu)	Cost ($/kg)
Bismuth (Bi)	271.3	1559	7.287	208.98	9
Cadmium (Cd)	321.03	765	8.991	112.4	25
Cesium (Cs)	28.64	685	3.893	132.9	30,000
Iodine (I)	113	182	10.44	126.9	500
Krypton(Kr)	-157.2	-152.3	14	83.8	295
Mercury (Hg)	-38.86	356.73	10.434	200.59	50
Xenon (Xe)	-111.9	-108.1	12.127	131.3	850

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Cadmium was briefly examined as a propellant for Hall thrusters.[3] It has a lower melting and boiling point than Bismuth, allowing for sufficient gas evaporation rates at lower temperatures. The ionization energy is slightly higher than Bismuth, however, and Cadmium is also several times more expensive. Both of these properties are improvements on Xenon. The difficulties with Cadmium arise with the low atomic mass and toxicity. The low atomic mass will reduc1e thrust over a Xenon thruster, but increase the I_{sp}. Cadmium also has low toxicity in solid form, however it is highly toxic in vapor form.[4]

Cesium is a much more efficient alternative to Xenon. The extremely low ionization energy allows for significant energy savings in propellant ionization, while the mass is similar enough to Xenon that thruster performance will be almost identical. The difficulty with Cesium arises from the cost, reactivity, and toxicity. Cesium is extremely expensive, over 35 times as costly as Xenon. It is also highly dangerous to handle, exploding spontaneously on contact with water. Cesium and its compounds are also highly toxic. Between cost, reactivity and toxicity, use of Cesium is not reasonable. Studies have been performed on Cesium as a propellant, but little experimental data is available.[5]

Krypton is used in applications where either a high I_{sp} is desirable or where Xenon is prohibitively expensive. Krypton is a much lighter atom than Xenon, allowing for very high specific impulses. Krypton is also approximately one-third the price of Xenon. The slightly higher ionization cost hinders performance and the low atomic mass is responsible for a decrease in net thrust over Xenon. As Krypton is a gaseous propellant at temperatures of interest, it will not provide any benefit for ground-testing over Xenon.

Iodine is another propellant that will operate similarly to Xenon.[6] Both the ionization energies and atomic masses are very similar, allowing for operation very similarly to Xenon. Iodine is nearly as expensive as Xenon. Iodine is toxic and highly reactive with organic compounds. Iodine also may have the propensity to form negative ions, which would be disastrous to Hall thruster operation. These concerns make Iodine less desirable than other options such as Bismuth and Cadmium. Mercury saw extensive use in gridded-ion thrusters for many years, and a Mercury-propelled thruster was flown on the NASA SERT-II spacecraft[7]. Mercury has many desirable attributes, such as lower ionization energy than Xenon and atomic mass almost as high as Bismuth. Mercury is also extremely easy to handle, as the propellant tankage does not need to be heated significantly to maintain the propellant as a liquid, unlike Bismuth, Cadmium, or Iodine. Mercury is also quite inexpensive. Mercury is extremely toxic, however, and due to its liquid form at room temperature, is very difficult to safely deal with. Usage of Mercury in gridded-ion thrusters has completely ceased in favor of other propellants.

III. ENERGETICS OF PROPELLANT ALTERNATIVES

III.A. Acceleration Kinetics

All propellants will behave differently in a Hall thruster. The most obvious disparity between propellant performance characteristics is a change in thrust due to the different mass of a propellant atom. The mass ratio of the propellants is then defined as:

$$MR = \frac{m_N}{m_{Xe}} \tag{1}$$

Where MR is the mass ratio of the propellant to Xenon, m_N is the atomic mass of the propellant being examined, and m_{Xe} is the mass of a Xenon atom. The thrust produced by a thruster is defined as:

$$T = u_e \dot{m} \tag{2}$$

Where T is the net thrust of the thruster, $\dot{m}$ is the mass flow rate of the propellant, and u_e is the effective exhaust velocity. Mass flows may either be the same between different propellants, or they may be adjusted so the same number of moles of propellant are utilized per second. In the case where mass flow is constant, $\dot{m}$ will be the same for all propellant options. In the case where molar flow is constant, the mass flow will change according to the ratios of masses, while the discharge current will remain approximately constant. Velocity is directly affected by propellant mass, however, since the acceleration mechanism takes place electrostatically. As exhaust velocity is defined by:

$$u_e = \sqrt{\frac{2E_i}{m_i}} \tag{3}$$

where E_i is the kinetic energy of an ion in the beam and m_i is the ion mass. Assuming that ions of any species are accelerated to the same energy (equivalently, accelerated through the same electrostatic potential), the exhaust velocity will be as shown in the equation:

$$u_e = \sqrt{\frac{2E_i}{m_{xe}}}\sqrt{\frac{1}{MR}} = (u_e)_{Xe}\sqrt{\frac{1}{MR}} \tag{4}$$

where $(u_e)_{Xe}$ is the exhaust velocity of Xenon given the same exhaust kinetic energy (discharge voltage).

The thrust will be modified by the choice of propellant. If mass flow is kept constant, the thrust will be modified from the value for Xenon by:

$$T = (u_e)_{Xe}\dot{m}\sqrt{\frac{1}{MR}}\,. \tag{5}$$

If mass flow is adjusted so molar flow rate and thus thruster power is constant, then the relationship will be the square root of the mass ratio. The trends in thrust for different propellant ion masses are plotted in Figure 1.

I_{sp} will be modified similarly to exhaust velocity. As Isp is given by the equation:

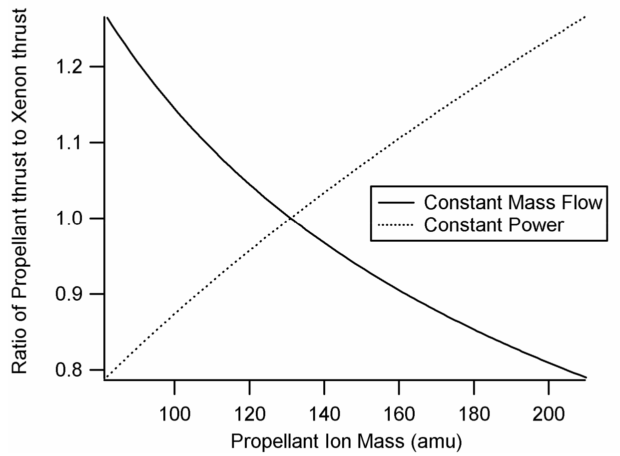

Figure 1: Change in thrust as a function of propellant ion mass, assuming constant acceleration voltage

$$I_{sp} = \frac{u_e}{g} \tag{6}$$

where g is the gravitational acceleration at the Earth's surface ($9.81 m/s^2$) Thus I_{sp} will be different from the Xenon value by exactly the square root of the mass ratio. So a thruster that would normally operate on Xenon at 2,000-sec I_{sp} would operate on Krypton at 2,500-sec, and on Bismuth at 1,583-sec for the same discharge voltage, with the other propellant options falling between the Krypton and Bismuth specific impulses.

Aside from the exhaust kinetics, the choice of propellant has a direct influence on thruster efficiency. Ionization energy represents a fundamental source of inefficiency, since any energy spent in creating an ion from a neutral is not available for kinetic thrust. As the ionization energy is exhibited as a direct power loss from the thruster, keeping the ionization energy at a minimum will increase thruster efficiency. While ionization energy is typically expressed as the energy required to singly ionize one neutral atom (eV/atom), a more convenient form for thruster analysis is the amount of energy required per-kilogram of mass flow. This factor, E_{ion}, then accounts for the difference in ionization potentials as well as the difference in atomic masses of the candidate species. E_{ion} can then be employed in the equation:

$$P_{ion} = \dot{m}E_{ion} \tag{7}$$

Where P_{ion} is the power required to completely ionize the neutral mass flow of propellant entering the thruster. We can use P_{ion} to calculate the maximum theoretical efficiency of an acceleration process assuming that the only energy loss is propellant ionization. Expressing the kinetic power in the exhaust beam as

$$P_{kin} = \frac{TgI_{sp}}{2} = \frac{\dot{m}g^2 I_{sp}^2}{2} \tag{8}$$

Where P_{kin} is the kinetic power in the exhaust beam. Combining Eqn (7) with Eqn (8) yields:

$$\frac{P_{ion}}{P_{kin}} = \frac{2E_{ion}}{g^2 I_{sp}^2} \tag{9}$$

Eqn 9 is then the theoretical minimum efficiency penalty required to singly ionize the propellant as a function of I_{sp}. These ratios are plotted in Figure 2.

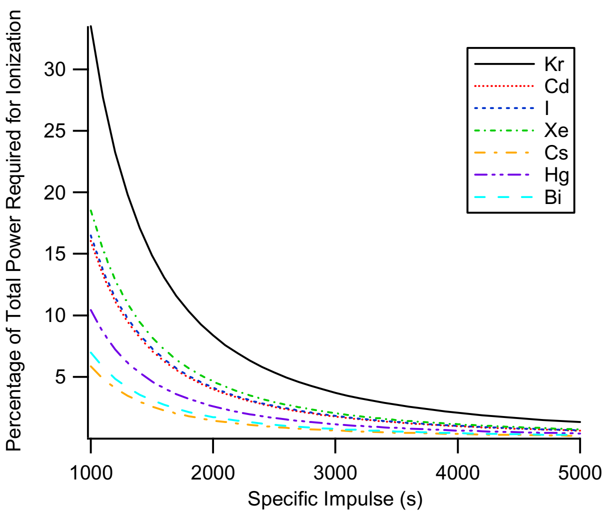

Figure 2: Fraction of thruster power required for ionization vs. I_{sp} for all propellants examined

The ratios behave as expected, where propellants with lower ionization energies require a smaller fraction of the total thruster power to ionize the propellant. It is also interesting to note that the difference between propellants becomes nearly insignificant at high Isp. At 1,000 sec, the fractions range from approximately 6% for Cesium up to 34% for Krypton, while at 5,000 sec no propellant option requires significantly more than one percent of total thruster power (Krypton is highest at 1.3%). It should be noted that these calculations are a theoretical minimum where all of the propellant is ionized, there are no doubly-charged ions, and all of the ions are produced only once; there is no neutralization and re-ionization. The ionization power will differ in a real thruster, however the relationships between propellants should remain similar.

III.B. Collision Considerations

Any neutral propellant that is not ionized within the discharge chamber prior to escaping the thruster internal volume represents inefficiency in propellant utilization (it is not available for thrust). The probability of ionization for a given atom subject to an electron collision is given by the ionization cross section. These cross sections are dependent on the energy of the impacting (ionizing) electron and the atomic structure of the propellant atom. As experimental data for many of the propellant species examined could not be found in the literature, the Binary-Encounter-Bethe (BEB) model was applied[8]:

$$\sigma_i = \frac{S}{t+u+1}\left\{\left(1-\frac{1}{t^2}\right)\frac{\ln(t)}{2} + \left[\left(1-\frac{1}{t}\right) - \frac{\ln(t)}{t+1}\right]\right\} \tag{10}$$

where $\sigma_i(t)$ is the electron-impact ionization cross section of a given electron shell of an atom as a function of incident electron energy, and S, t, and u are reduced energy variables defined by:

$$S = 4\pi a_0^2 N\left(R/B\right) \tag{11}$$

$$t = E_e/B \tag{12}$$

$$u = U/B \tag{13}$$

where a_o is the Bohr radius (5.29×10^{-11}m), N is the number of electrons in the shell being examined, R is the Rydberg energy (13.6eV), B is the binding energy of an electron in the shell being examined, E_e is the incident electron energy, and U is the kinetic energy of an electron in the shell being examined. As the equation only calculates the ionization cross section for a single electron shell, one calculation must be made for each shell the atom possesses. The sum of these is the total ionization cross section of the atom, as a function of incident electron energy. Calculations were performed for each propellant species examined, and were compared to experimental data for Xenon,[9] as shown in Figure 3. The calculated and experimentally measured Xenon cross sections agree to within 10% near the peak of the distribution, indicating the model estimates the cross-sections very well. A comparison of Xenon with the other propellants is plotted in Figure 4.

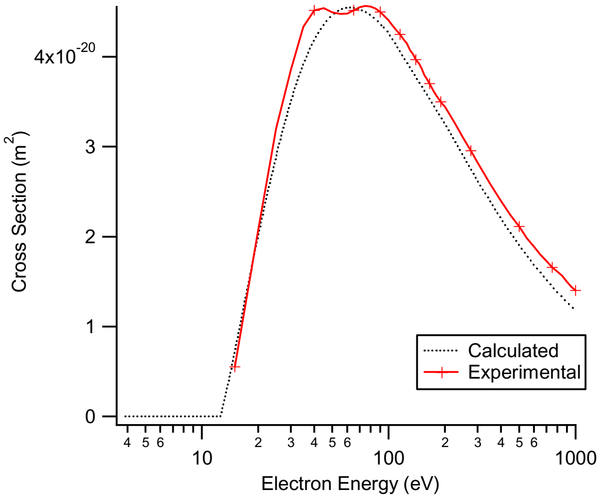

Figure 3: Comparison of Ionization Cross Section for Xenon as calculated with experimental results from Ref (9)

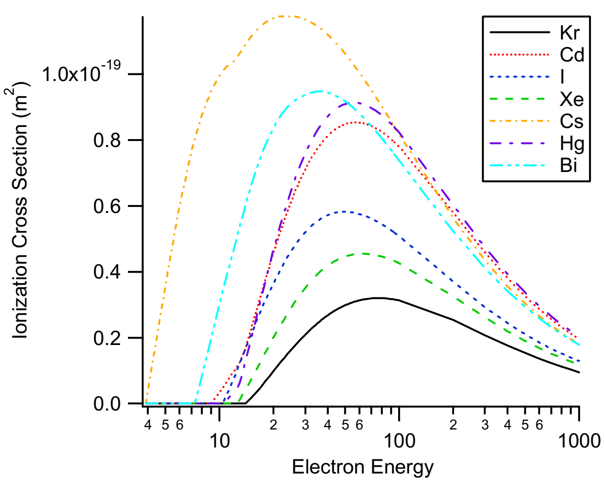

Figure 4: Electron-Impact Ionization Cross Sections for Bismuth and Xenon between threshold and 1,000eV

The cross sections varied significantly between atom species. In general, the lower the atom's ionization energy the larger the ionization cross section. Thus Cesium shows itself to be the most amenable to ionization, due to the extremely low ionization energy. However, Bismuth, Mercury, and Cadmium do not have significantly lower cross sections. The smallest cross sections calculated were for the two propellants currently in use; Xenon and Krypton. Thus any change from Xenon or Krypton to another propellant discussed here will result in an increased probability of ionization within the discharge chamber.

Using the ionization cross section, the rate of ionizing collisions can be calculated. The rate of ionizing collisions is given by:[10]

$$\nu = \sigma n_e \sqrt{\bar{v}_i^2 + \bar{v}_e^2} \tag{14}$$

Where ν is the collision frequency, n_e is the electron number density in the channel, v_i is the average neutral atom velocity, and v_e is the average electron velocity. The collision cross section is as calculated from the BEB model. Assuming an electron temperature of 20eV the average thermal velocity of electrons is 2.65x10^6 meters per second. The neutral propellant atom velocity will be given by the temperature of the anode/gas distributor, since the emitted gas will be in equilibrium with this structure. Given typical anode temperatures of 700 C, the neutral velocity will be in the range of 200-300 meters per second for all species. Since the electron velocity is four orders of magnitude higher, the neutral velocity can be neglected. Thus, collision frequencies will scale simply with ionization cross section and electron density. An electron number density of 2x10^{18} m^{-3} was measured by Haas and Gallimore in Ref. 13 and is used here as a representative value to calculate collision frequencies from Eqn. 14. Calculated values of the collision frequency are in Table 2 assuming electrons at 20eV

While the trends in collision frequency among the propellant candidates simply mirror the cross section scaling of Figure 4, the magnitude of ν becomes particularly important in calculating the propellant utilization efficiency. In order to contribute to the thrust, a propellant atom must be ionized before it is permitted to escape the discharge chamber. Thus if the residence time is defined as $t_r=L/v_d$, where L is the length of the thruster discharge chamber and v_d is the neutral diffusion velocity:

$$v_d = \sqrt{\frac{8kT}{\pi m}} \tag{15}$$

The factor νt_r gives the ratio of residence time to collision time. Physically, this factor represents the average number of ionizing collisions experienced by a propellant atom before diffusing out of the discharge chamber. If this factor is low, it is probable that propellant atoms will escape the discharge without being ionized.

Using the calculated collision frequencies, assuming neutral atoms leave the gas diffuser with a temperature of 700C, and assuming the neutral atoms must travel 100 millimeters to leave the channel, the average number of ionizing collisions for each propellant species is shown in Table 2.

Table 2: Total number of ionizing collisions experienced by propellant atoms in a 100-mm channel

Propellant	Collision Frequency (Hz)	Neutral Diffusion Velocity (m/s)	Number of Collisions
Bismuth	4.44×10^5	321.94	13.8
Cadmium	2.43×10^5	438.98	5.5
Cesium	6.21×10^5	403.7	15.4
Iodine	1.94×10^5	413.4	4.6
Krypton	5.23×10^4	508.4	1
Mercury	2.47×10^5	328.6	7.5
Xenon	1.06×10^5	406.16	2.6

The calculated ionizing collision rates show significant differences between species. When compounded with the neutral diffusion velocity, some propellants show a much higher utilization than others. Krypton suffers here, as it has the lowest ionization cross section and the highest neutral diffusion velocity. Cesium, as expected, will experience the most ionizing collisions due to its very high ionization cross section. Of particular interest here, however, is Bismuth, with an estimated number of collisions only slightly less than Cesium. This is due in large part to the high cross section and extremely low neutral diffusion velocity of Bismuth.

Of critical importance to determination of the propellant utilization of a thruster is the electron temperature in the discharge channel. As it is impossible to determine the exact effect switching to another propellant will have on the electron temperature, values of electron temperature measured in xenon thrusters are used here for calculations.

Previous studies on Xenon thrusters have given maximum electron temperatures above 15eV.[11,12] Probe-based studies of a 5-kW thruster at several operating points show the temperature is dependent on flow rate, and can be nearly 30eV in low mass flow conditions.[13] Higher mass flows appear to cool the electrons, as the drifting electrons cannot acquire as much energy through 'falling' towards the thruster anode after a collision. Any population of electrons with temperature greater than the second ionization potential of the propellant may be able to form multiply ionized propellant ions through either collision with propellant atoms or singly charged ions. Multiply charged ions represent an inefficient use of propulsive power. For instance, a doubly charged ion will contribute twice the discharge current (and hence, draw twice the power) as a singly charged ion, however will only be accelerated to a velocity of $\sqrt{2}$ times its single counterpart.

This is a much larger issue for some propellants than others, as shown in Table 3. Xenon has the drawback of a fairly high first ionization energy, but its second ionization energy is quite high (21.2eV); thus it does not readily produce Xe^{2+} in typical Hall thruster plasmas. Cesium and Krypton also will not form large fractions of multiple ions. Other elements, such as Bismuth and Cadmium, may be sensitive to multiply charged ion efficiency losses in an electron population with temperatures similar to those seen in xenon devices.

Table 3: First and Second Ionization Energies

Propellant	First Ionization Energy (eV)	Second Ionization Energy (eV)
Bismuth	7.287	16.7
Cadmium	8.991	16.91
Cesium	3.893	23.16
Iodine	10.44	19.13
Krypton	14	24.36
Mercury	10.434	18.76
Xenon	12.127	20.98

IV. ANALYSIS OF SPACECRAFT INTERACTIONS FOR BISMUTH, XENON, AND KRYPTON

At this point, Bismuth, Xenon and Krypton will be chosen for further analysis. As Bismuth is nearly as efficient as Cesium, without the toxicity or reactivity drawbacks, it appears to be the best choice for a high-thrust, low-Isp thruster. Krypton is chosen as an alternative only for high-Isp operation, as it is too energetically costly to be useful in a low-Isp thruster.

The sputter rate of a propellant is highly important to thruster lifetime, especially at high Isp when propellant ions have significant energy. The sputter yield of ions normally incident on a solid surface can be calculated by:[14]

$$Y(E) = 0.42 \frac{\alpha_s Q_s S_n(E)}{U_0 \left[1 + 0.35 U_0 S_e(\varepsilon)\right]} \left[1 - \sqrt{\frac{E_{th}}{E}}\right]^{2.8} \quad (16)$$

Where the $Y_E(E)$ is the sputtering yield (ejected atoms per incident ion) for ions with energy E at normal incidence, α_s and Q_s are empirical parameters defined from experimental sputtering data, E_{th} is the sputtering threshold energy, ε is a reduced energy parameter, $S_e(\varepsilon)$ is the reduced Lindhard electronic stopping cross-section, $S_n(E)$ is the nuclear stopping cross-section, and U_0 is the surface binding energy. α_s, E_{th}, $S_n(E)$, and $S_e(\varepsilon)$ are calculated by the equations:

$$\gamma = \frac{4 M_1 M_2}{\left(M_1 + M_2\right)^2} \quad (17)$$

$$E_{th} = \left(\frac{4}{3}\right)^6 \frac{U_0}{\gamma} \tag{18}$$

$$S_n(E) = k_n S_n(\varepsilon) \tag{19}$$

$$k_n = \frac{8.478 Z_1 Z_2}{\sqrt{Z_1^{2/3} + Z_2^{2/3}}} \frac{M_1}{(M_1 + M_2)} \tag{20}$$

$$\varepsilon = \frac{0.3255}{Z_1 Z_2 \sqrt{Z_1^{2/3} + Z_2^{2/3}}} \frac{M_1}{(M_1 + M_2)} E \tag{21}$$

$$S_n(\varepsilon) = \frac{3.441\sqrt{\varepsilon}\ln(\varepsilon + 2.718)}{1 + 6.355\sqrt{\varepsilon} + \varepsilon(6.882\sqrt{\varepsilon} - 1.708)} \tag{22}$$

$$\alpha_s = 0.1 + 0.155\left(\frac{M_2}{M_1}\right)^{0.73} + 0.001\left(\frac{M_2}{M_1}\right)^{1.5} \tag{23}$$

$$k = \frac{Z_1^{2/3}\sqrt{Z_2}\left(1 + \frac{M_2}{M_1}\right)^{3/2}}{12.6\left(Z_1^{2/3} + Z_2^{2/3}\right)^{3/4}\sqrt{M_2}} \tag{24}$$

$$S_e(\varepsilon) = k\sqrt{\varepsilon} \tag{25}$$

Where γ is the energy-transfer factor for elastic collisions, Z_1 is the ion atomic number, Z_2 is the surface atomic number, M_1 is the ion mass, and M_2 is the mass of the atoms in the surface. Of particular interest is E_{th}, as sputtering does not occur when incident ions have energies below E_{th}. Calculations were made for Bismuth and Xenon ions incident on a Carbon surface as a representative thruster material (it is unclear whether or how this relation can be applied to BN as a target material).

The sputtering threshold for ions on the surface was found to be different for each species; 201.6eV for Bismuth, 134.6eV for Xenon, and 94.48eV for Krypton. These results mean that for a given distribution of ion energies, fewer Bismuth ions will be above the sputtering threshold than Xenon or Krypton. For ions above threshold, the model can be used to predict sputter rates. The calculated sputter rates over a range of ion energies are plotted in Figure 5.

The results of sputtering calculations, displayed in Figure 5, show that while Bismuth will induce less sputtering on Carbon substrates at low energies, it will cause higher sputtering than Xenon and Krypton at incident energies above approximately 1,200eV and 1,400eV respectively on a purely atoms-per-ion basis. Thus if the molar flow rate is preserved between propellants, Bismuth will sputter more when accelerated above 1,200 or 1,400eV. However, the reduced number of Bismuth ions for a given mass flow must be taken into account if an equal mass flow between propellants is desired. As Bismuth has an atomic mass of 209 amu,

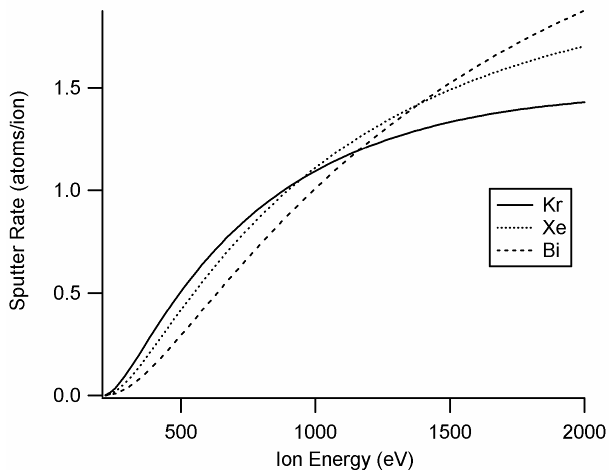

Figure 5: Sputter Yield of Carbon under Bismuth, Xenon and Krypton ion collisions

nearly 60% greater than the atomic mass of Xenon (131 amu) and 2.5 times as high as Krypton (83.8amu), a given mass flow of Bismuth will contain fewer ions. To determine the effect of the increased mass of Bismuth, the calculations were scaled to indicate the mass of surface sputtered away per unit mass of ions. These results are displayed in Figure 6 and show that for equal mass flows of Bismuth, Xenon, and Krypton, the surface erosion is significantly lower for Bismuth. These results are encouraging for the lifetime of a Bismuth thruster, as the thruster structures should exhibit lower erosion for the same total mass throughput. The erosion rate for Bismuth remains less than Xenon or Krypton until the ion energies approach 10,000eV, at which point the erosion rates converge. For ion energies higher than 10,000eV, which are not included in Figure 6, the lighter propellants become favorable.

It should be noted that the erosion rate is primarily driven by the ion mass and atomic number, and the ratios of these to the atoms in the surface. As the other propellants analyzed fall between Krypton and Bismuth in size, they will exhibit sputter rates somewhere between those of Krypton and Bismuth.

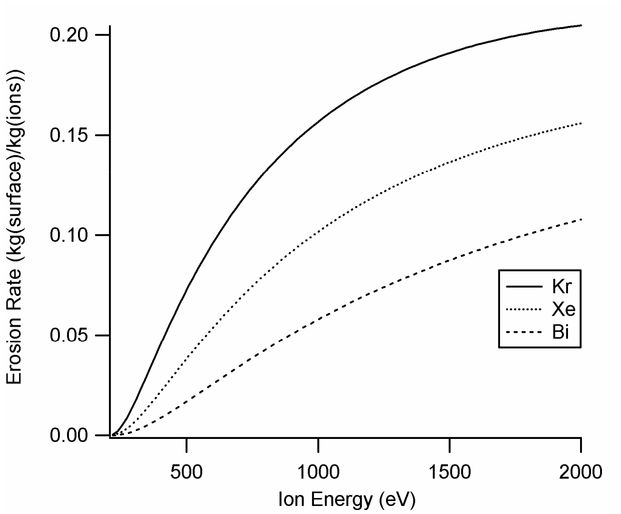

Figure 6: Erosion Rate of Carbon per kilogram of Bismuth, Xenon, and Krypton ions

One complicating factor for use of Bismuth or any other condensable propellant is deposition on spacecraft surfaces. As with the possible exception of Cesium the surfaces of a spacecraft will be well below the melting point of a condensable propellant, ions impacting on spacecraft surfaces will stick similarly to the interior of a vacuum tank. This may present a problem for solar panels and other optical systems, as it is not desirable to have coatings of opaque metals on the transparent lenses and plates of such systems. Spacecraft design and interaction studies warrants future research.

V. FEED SYSTEM FOR CONDENSIBLE PROPELLANT OPERATION

Development of a propellant feed system for a condensible propellant is a major technical obstacle. A large advantage to Mercury, as used in NASA thrusters, was that it was a liquid at room temperature; it could be transported through propellant lines and the only need for external heating was for the evaporator.[15] This system cannot be implemented for Bismuth or the other condensible propellants analyzed here, as the entire propellant feed system would need to be maintained above the melting point of the propellant. This would not present much of a problem for Cesium due to the very low melting point, but for Bismuth operation the propellant must be maintained in excess of 271C. Bismuth flow will be analyzed here, as it presents the greatest technical challenge. Bismuth thrusters in Soviet research utilized a propellant feed system that was maintained in excess of 1,000C, in order to flow gaseous Bismuth directly into the thruster.[16] This method presented a problem, however, in that a large number of heaters, consuming significant amounts of power, were required. While using large amounts of power for a propellant evaporation system is possible in ground testing, any development of a flight system cannot allow for such expenditures. As the power used by the heater system is non-propulsive, it will cause a significant efficiency loss. Another method for Bismuth evaporation must be developed, that will allow for delivery of a metered gas-phase flow into the discharge channel, while minimizing the external heater requirement.

Bismuth evaporation is dependent on maintenance of a reservoir of liquid bismuth at a temperature which allows significant evaporation. Control of evaporation rate by modification of the reservoir temperature is made possible by the temperature dependence of the vapor pressure of Bismuth. The vapor pressure is dependent on temperature, and can be given by the equation:

$$P_v = \log^{-1}\left[13.317 - \frac{10{,}114}{T} - 0.86\log(T)\right] \quad (26)$$

Where P_v is the vapor pressure and T is the temperature in Kelvin. The mass flow from an open reservoir of liquid at temperature T can be found by:

$$\dot{m} = \frac{P_v}{\sqrt{\frac{2\pi kT}{m}}} A \quad (27)$$

Where $\dot{m}$ is the mass flow, k is the Boltzmann constant, m is the mass of a propellant atom, and A is the open area of the liquid reservoir. It is trivial to then develop an equation for the mass flow per unit area as a function of temperature. Figure 7 illustrates the mass flow rate per unit area as a function of reservoir temperature for an evaporative bismuth source.

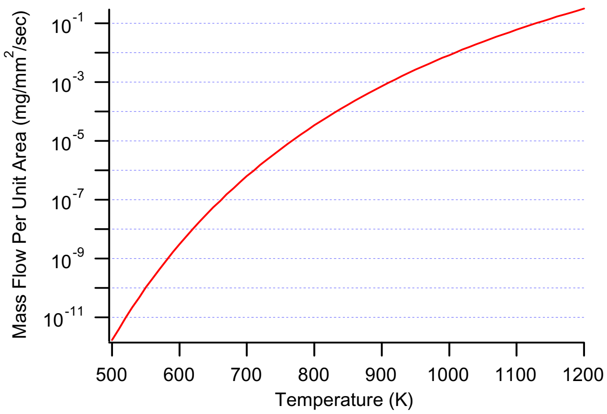

Figure 7: Mass Flow per unit area of Bismuth as a function of temperature

VI. CONCLUSIONS

Modification of the propellant in an EP system presents many issues with thruster performance. It has been shown that from a thrust and I_{sp} standpoint, propellant choice is dependent more on the choice of mission than anything else. For high-I_{sp} missions, Krypton appears to be the best choice as it offers the highest I_{sp} of the options presented here, and at such high exhaust energies the large ionization cost is minimized. The erosion rate will also be lower for Krypton at very high energies. For high-thrust, low-I_{sp} missions, however, the large heavy atoms are best. Bismuth provides higher thrust per unit mass than the lighter propellant options and is very easy to ionize. While Cesium is the easiest to ionize, once the average number of collisions in a Hall thruster channel is analyzed, it proves to be only incrementally better than Bismuth. Cesium is also only marginally better in the fraction of thruster power required for ionization than Bismuth. Heavy atoms also provide an advantage in erosion rate for most ion energies, up to extremely high specific impulses.

Condensible propellants also offer significant advantages over gases. Primary of these is the elimination of the costly and complex pumping apparatus required to maintain acceptable vacuum levels. This benefit is complementary to the increased efficiency of condensable species for low-Isp, and correspondingly high flow rate, missions that are most expensive to ground test.

Bismuth has shown to be a good propellant for Hall thruster use and is likely superior to other candidates for high-thrust, low-Isp missions. It combines the advantages of high thrust, low cost, ease of ionization, and lower sputter erosion rate than the other propellants examined. The main disadvantage to Bismuth, however, is that any thruster design must incorporate a method of heating the Bismuth evaporator to temperatures where evaporation is significant. A second, and possibly significant, disadvantage of Bismuth may be its propensity to form doubly charged ions at lower electron temperatures than xenon.

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