Energetics of Propellant Options for High-Power Hall Thrusters

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Several propellant options for use in high-power Hall thrusters are investigated for their suitability as a propellant. Krypton, cadmium, iodine, cesium, mercury, and bismuth are compared to xenon in several areas of performance, including thrust, specific impulse, probability of ionization, maximum theoretical efficiency, and sputter yield. For high-I_{sp} missions, krypton may prove advantageous as it provides 25% higher I_{sp} than xenon for a given acceleration voltage. For high-thrust, low-I_{sp} missions, however, the large heavy atoms may provide a benefit. Bismuth provides 26% higher thrust per unit mass than the xenon given equal accelerating voltages and is very easy to ionize. Condensible propellants also offer significant advantages over gases in ground testing, as they do not require costly and complex pumping apparatus.

Nomenclature

E_i .... Ion energy (eV)
E_{ion} .... Ionization energy (J/kg)
E_{th} .... Sputtering Threshold Energy (eV)
F .... Thrust (N)
g .... gravitational acceleration (9.8 m/s^2)
I_{sp} .... Specific Impulse (s)
JPL .... National Aeronautics and Space Administration Jet Propulsion Laboratory
k .... Boltzmann Constant (1.38x10^{-23} m^{2}kgs^{-2}K^{-1})
L .... Discharge chamber length (m)
$\dot{m}$ .... mass flow rate (kg/s)
M_i .... Ion mass (kg)
M_n .... Mass of species n (kg)
M_s .... Surface atomic mass (kg)
M_{Xe} .... Mass of a xenon atom (kg)
n_e .... Electron density (m^{-3})
P_{ion} .... Power required for propellant ionization (W)
P_{kin} .... Exhaust kinetic power (W)
q_i .... Ion charge (C)
Q_s .... Surface sputtering parameter
$S_e(\varepsilon)$ .... Reduced Lindhard electronic stopping cross section (m^2)
$S_n(\varepsilon)$ .... Nuclear stopping cross section (m^2)
STP .... Standard Temperature and Pressure (0 °C, one atmosphere pressure)
T .... Temperature (K)
t_r .... Residence time (s)
u_e .... exhaust velocity (m/s)
$(u_e)_{Xe}$ .... velocity of xenon (m/s)
U_0 .... Surface binding energy (eV)
V_a .... Effective acceleration voltage (V)
VHITAL .... Very High Impulse Thruster with an Anode Layer

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v_e .... Average electron velocity (m/s)

v_n .... Average neutral atom velocity (m/s)

Y_E .... Sputter Yield (atoms/ion)

Z_i .... Ion atomic number

Z_s .... Surface atomic number

α_s .... Surface sputtering parameter

γ .... Elastic energy transfer factor

ε .... Reduced energy parameter (eV)

v .... Ionizing collision frequency (Hz)

$\bar{\sigma}$ .... Average electron-impact ionization cross section (m^2)

1. 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, several disadvantages preclude the use of xenon in very high power thrusters. The first disadvantage to xenon as an Electric Propulsion (EP) propellant is its high cost. Currently xenon can be purchased for approximately $6.65 per standard liter ($1140/kg) in small quantities.[1] Using current commercial prices, a 500 kW Hall thruster operating at 60% efficiency and 2,000 s Specific Impulse (I_{sp}) will consume $6,400 of xenon per hour of operation. These costs can be extrapolated to $153,600 per test day, and $64M 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 reduce 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.[2]

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 s I_{sp} and 60% efficiency, 1.56 g/s of xenon will enter the chamber. In order to maintain a pressure of 1×10^{-5} Torr (6.7×10^{-4} Pa),[3] the facility vacuum pumps must be capable nearly 20M liters-per-second of pumping throughput. This pressure reduces the facility effects on thruster performance, however corrective calculations may be made to measurements to allow testing at higher pressures. At a cost of roughly $1 per-l/s,[4] this translates to roughly $20M in pumping equipment. The pumping requirements scale linearly with thruster power, so a 1 MW thruster will require nearly $40M 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.

Condensible propellants, defined as those species existing in either solid or liquid state at STP (0 °C, one atmosphere pressure), 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. Condensible propellants may also cost less than xenon or krypton, reducing testing costs further. Vacuum facility contamination may be an issue with condensable propellants, however. The coating of interior surfaces with propellant may require special handling procedures, especially for toxic and reactive propellants.

2. Analysis of alternative Propellants

Many factors contribute to the suitability of a Hall thruster propellant. Factors that affect performance include ionization energy, atomic mass, and ease of mass flow system construction. Condensible propellants offer a challenge in mass flow systems, as traditional gas-fed systems utilized on xenon and krypton thrusters cannot be used. Generally, the higher the melting and boiling points of a propellant, the harder it will be to design and fabricate a mass flow system. Propellant ionization is another source of inefficiency. As energy spent on ionization is not available for acceleration, reduction of ionization energy will directly increase the efficiency of a thruster. Several practical issues also contribute to the suitability of a candidate propellant. These include cost, toxicity/reactivity, and potential for spacecraft contamination. Reducing propellant cost is of obvious benefit, as less-expensive propellants allow for reduced testing and mission costs. Several alternative propellant options have been considered.[5,6,7,8,9,10] 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.

Several of the Hall thruster propellants considered are toxic and/or reactive. These include cadmium,[11] cesium,[12] iodine,[13] and mercury. [14] While each of these propellants offer lower propellant costs and ionization energy than xenon, they all present problems handling in a testing environment. Of these, iodine and cesium present significant reactivity hazards, while each presents a significant chronic and/or acute toxicity hazard. Currently there are no active development efforts on these propellants.

Three of the propellants considered are relatively non-toxic and non-reactive. Xenon and krypton present essentially no toxicity threat except through displacement of oxygen.[15,16] Reactivity is also of little concern, as krypton will not spontaneously react with any substance, and xenon will react only with fluorine. Bismuth presents little hazard. It is considered mildly toxic and safety precautions involve exposure limitation only.[17] While conversion of a Hall thruster from xenon to krypton requires trivial redesign of the mass flow system, bismuth presents significant development issues due to its condensable nature. Bismuth thruster development is under consideration at Stanford/JPL under the VHITAL program, Busek, Michigan Technological University, and Aerophysics, Inc.

Table 1: Physical properties of candidate Propellants

Propellant	Melting Point (C)	Boiling Point (C)	Ionization Energy (eV)	Atomic Mass (amu)	Cost Per Kg
Bismuth (Bi)	271	1559	7.3	209.0	$6[18]
Cadmium (Cd)	321	765	9.0	112.4	$25[19]
Cesium (Cs)	29	685	3.9	132.9	$40,000[20]
Iodine (I)	113	182	10.4	126.9	$484[21]
Krypton (Kr)	NA	NA	14.0	83.8	$295[22]
Mercury (Hg)	-39	356.73	10.4	200.6	$4[23]
Xenon (Xe)	NA	NA	12.1	131.3	$1138[1]

3. Energetics of propellant alternatives

A. Acceleration Kinetics

The most obvious disparity between propellant performance characteristics is a change in thrust under identical discharge voltage due to the different atomic mass. The mass ratio of the propellants is defined as:

$$MR = \frac{M_n}{M_{Xe}} \tag{1}$$

where *MR* is the mass ratio of the propellant to xenon. The thrust produced by a thruster is defined as:

$$F = u_e \dot{m} . \tag{2}$$

Assuming that ions of any species are accelerated through the same voltage, the exhaust velocity will be:

$$u_e = \sqrt{\frac{2q_i V_a}{M_{xe}}} \sqrt{\frac{1}{MR}} = \left(u_e\right)_{Xe} \sqrt{\frac{1}{MR}} \tag{3}$$

and the thrust force is:

$$F = (u_e)_{Xe} \, \dot{m} \sqrt{\frac{1}{MR}} \tag{4}$$

which is the thrust force of a xenon thruster divided by the square root of the mass ratio. 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. If the mass ratio is adjusted so molar flow rate and thus thruster current is constant, then the thrust will be the thrust of a xenon thruster multiplied by the square root of the mass ratio. The trends in thrust for different propellant ion masses are plotted in **Error! Reference source not found.**.
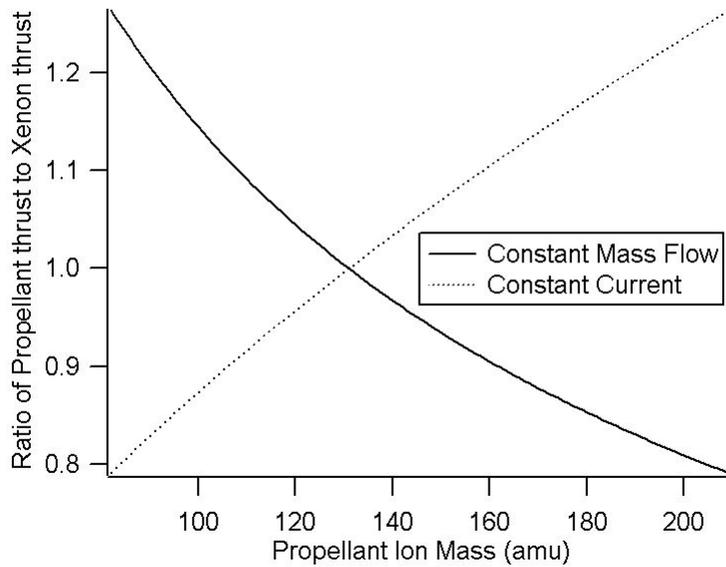
Figure 1: Change in thrust as a function of propellant ion mass, assuming constant acceleration voltage

I_{sp} under constant discharge voltage will be modified similarly to exhaust velocity. As I_{sp} is given by the equation:

$$I_{sp} = \frac{u_e}{g} \tag{5}$$

I_{sp} is equal to the value for a xenon thruster, divided by the square root of the mass ratio. So a thruster that would normally operate on xenon at 2,000 s I_{sp} would operate on krypton at 2,500 s, and on bismuth at 1,583 s for the same discharge voltage, with the other propellant options falling between the krypton and bismuth specific impulses. In order to maintain the same I_{sp} with different propellants, the discharge voltage would need to be modified. Large variations in the discharge voltage (outside the current SOA of 200-600V) cause complications in plasma acceleration physics that may preclude the use of heavy atoms at high I_{sp}, or light atoms at low I_{sp}.

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 conversion to beam kinetic energy. 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, and can be calculated by dividing the ionization energy by the mass of an atom. E_{ion} can then be employed in the equation:

$$P_{ion} = \dot{m}E_{ion}. \tag{6}$$

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

$$P_{kin} = \frac{1}{2}\dot{m}u_e^2 = \frac{\dot{m}g^2I_{sp}^2}{2}. \tag{7}$$

Combining Eqn (6) with Eqn (7) yields:

$$\frac{P_{ion}}{P_{kin}} = \frac{2E_{ion}}{g^2I_{sp}^2}. \tag{8}$$

Eqn 8 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.
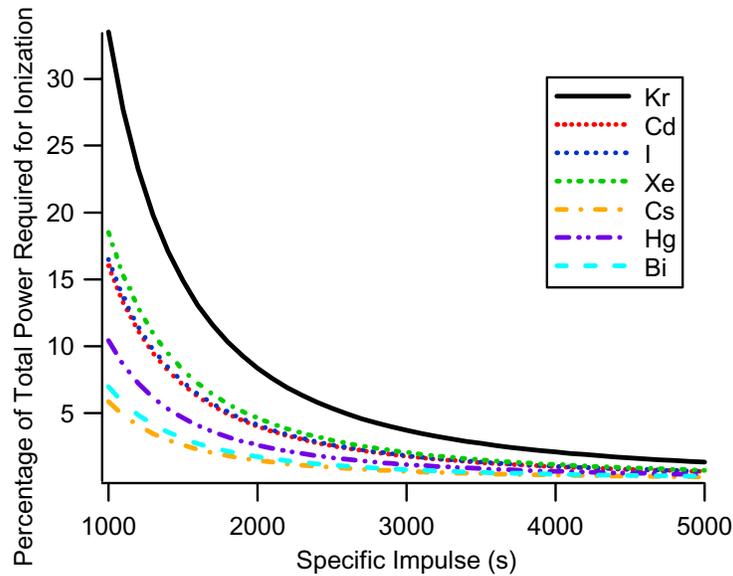
Figure 2: Fraction of thruster power required for ionization vs. I_{sp} for all propellants examined

The 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 I_{sp}. At 1,000 s, the fractions range from approximately 6% for cesium up to 34% for krypton, while at 5,000 s 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, no energy is spent promoting atoms or ions to excited states, and all of the ions are produced only once; there is no wall recombination and re-ionization. Any re-ionization process will present an energy loss as an ion is essentially being created twice, requiring twice the energy expenditure. The ionization power will differ in a real thruster, however the relative scaling between propellants should remain similar.

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 electrostatically accelerated and contributes negligibly to 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. Experimentally determined ionization cross-sections for bismuth[24], cesium[25] [26], iodine[27], krypton[28], mercury[29], and xenon[28] were available in literature. Cross-section measurements for cadmium could not be found. A comparison of xenon with the other propellants is plotted in Figure 3.
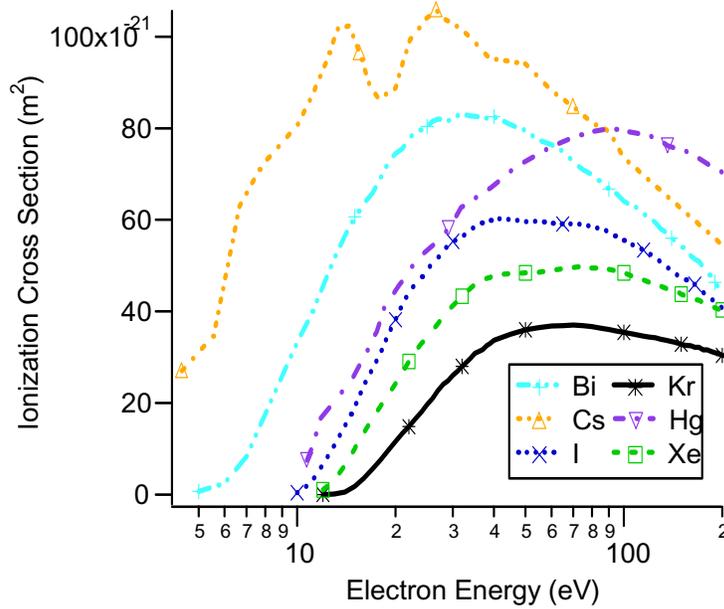

Figure 3: Electron-Impact Ionization Cross Sections for bismuth[24], cesium[25], iodine[26], krypton[28], mercury[29], and xenon[28] between threshold and 200 eV

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 and mercury do not have significantly lower cross sections than cesium. 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:[30]

$$ \nu = \bar{\sigma} n_e \sqrt{\bar{v}_n^2 + \bar{v}_e^2} \ . \tag{9}$$

In order to calculate estimates of ν the electron velocity distribution function was calculated based on an assumed 20 eV temperature and the Maxwellian distribution.[31] The average electron-impact ionization cross section was calculated by integrating the product of the electron energy distribution function and the ionization cross section. The average neutral propellant atom velocity is estimated assuming the propellant atoms are emitted with a thermal velocity distribution in equilibrium with the anode/diffuser temperature. Average electron velocity is estimated similarly, assuming the temperature of the electrons is 20 eV. Given typical anode temperatures of 700 °C, the neutral velocity will be in the range of 300-500 m/s for all species. Since the average 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 2×10^{18} m^{-3} was measured by Haas and Gallimore in Ref. 31 and is used here as a representative value to calculate collision frequencies that may be typical within a Hall thruster discharge. 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. Calculated values of the collision frequency are in Table 2.

While the trends in collision frequency among the propellant candidates simply mirror the cross section scaling of Figure 3, the magnitude of ν becomes particularly important in calculating the propellant utilization efficiency. In order to

measurably 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 $t_r=L/v_n$ and v_n is defined as:

$$v_n = \sqrt{\frac{8kT}{\pi m n}}$$

(10)

The factor $v t_r$ 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 a discharge chamber of length L. 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 mm to leave the channel, the average number of ionizing collisions normalized to xenon for each propellant species is shown in Table 2.

While the gross simplification used in determining the number of collisions precludes any confidence in the absolute magnitude of the numbers, the relative trends between propellants is a reliable indicator of utilization. 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 large cross section and extremely low neutral diffusion velocity of bismuth.

While it is important to have an electron population with enough energy to ionize the propellant, it is equally important not to have an electron population so energetic as to produce significant amounts of multiply-charged ions. Previous studies on xenon thrusters have given maximum electron temperatures above 15eV.[32,33] 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.[31] 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 create 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 $\sqrt{2}$ times more than its single counterpart.

Formation of multiply charged ions may be an issue for some propellants as shown in Table 3. Xenon has the drawback of a 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, with approximately 90% of the xenon ions singly charged.[34] 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.

4. 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 ionize to be useful in a low-Isp thruster.

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

Propellant	Collision Frequency (x10⁵ Hz)	Neutral Diffusion Velocity (m/s)	Number of Collisions
Bismuth	4.1	322	12
Cesium	5.5	404	16
Iodine	2.7	413	9
Krypton	1.4	508	3
Mercury	3.3	329	10
Xenon	2.1	406	5

Table 3: First and Second Ionization Energies

Propellant	First Ionization Energy (eV)	Second Ionization Energy (eV)
Bismuth	7.3	16.7
Cadmium	9.0	16.9
Cesium	3.9	23.2
Iodine	10.4	19.1
Krypton	14.0	24.4
Mercury	10.4	18.8
Xenon	12.1	21.2

The sputter rate of a propellant is highly important to thruster lifetime, especially at high Isp when propellant ions have significant energy. Typically, the maximum lifetime of the thruster is determined by the time required for sputter erosion to wear through the discharge channel walls and start eroding the electromagnet poles. The sputter yield of ions normally incident on a solid surface can be calculated by:[35]

$$Y(E) = 0.42 \frac{\alpha_s Q_s S_n(E)}{U_0 \left[1 + 0.35 U_0 S_e(\varepsilon)\right]} \left[1 - \sqrt{\frac{E_{th}}{E}}\right]^{2.8} \tag{11}$$

α_s, E_{th}, $S_n(E)$, and $S_e(\varepsilon)$ are calculated by the equations:

$$\gamma = \frac{4 M_i M_s}{\left(M_i + M_s\right)^2} \tag{12}$$

$$E_{th} = \left(\frac{4}{3}\right)^6 \frac{U_0}{\gamma} \tag{13}$$

$$S_n(E) = k_n S_n(\varepsilon) \tag{14}$$

$$k_n = \frac{8.478 Z_i Z_s}{\sqrt{Z_i^{2/3} + Z_s^{2/3}}} \frac{M_i}{\left(M_i + M_s\right)} \tag{15}$$

$$\varepsilon = \frac{0.3255}{Z_i Z_s \sqrt{Z_i^{2/3} + Z_s^{2/3}}} \frac{M_i}{\left(M_i + M_s\right)} E \tag{16}$$

$$S_n(\varepsilon) = \frac{3.441 \sqrt{\varepsilon} \ln(\varepsilon + 2.718)}{1 + 6.355 \sqrt{\varepsilon} + \varepsilon \left(6.882 \sqrt{\varepsilon} - 1.708\right)} \tag{17}$$

$$\alpha_s = 0.1 + 0.155 \left(\frac{M_s}{M_i}\right)^{0.73} + 0.001 \left(\frac{M_s}{M_i}\right)^{1.5} \tag{18}$$

$$q = \frac{Z_i^{2/3} \sqrt{Z_s} \left(1 + \dfrac{M_s}{M_i}\right)^{3/2}}{12.6\left(Z_i^{2/3} + Z_s^{2/3}\right)^{3/4} \sqrt{M_s}}$$

(19)

$$S_e(\varepsilon) = q\sqrt{\varepsilon}$$

(20)

Of particular interest is E_{th}, as sputtering does not occur when incident ions have energies below E_{th}. Calculations were made for bismuth, krypton, and xenon ions incident on a carbon surface as a representative thruster material (it is unclear whether or how this model 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 94.5eV 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 **Error! Reference source not found.**.

The results of sputtering calculations show that bismuth will induce less sputtering on Carbon substrates at energies anticipated in Hall thruster operation. At high energies (greater than 1,200 eV) bismuth will cause higher sputtering than xenon and krypton, however this range is beyond the operational envelope of SOA Hall thrusters. Bismuth's erosion advantage is further extended if sputtering is analyzed under constant mass flow. As bismuth has an atomic mass of 209 amu, nearly 60% greater than the atomic mass of xenon (131 amu) and 2.5 times as high as krypton (84 amu), 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 5 and show that bismuth will cause less erosion than xenon or krypton given equal mass flows. 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 5, 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.
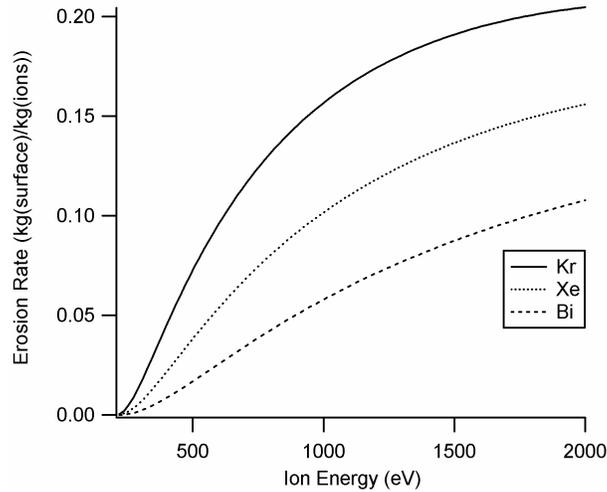

**Figure 4: Sputter Yield of carbon under bismuth, xenon and krypton ion collisions**
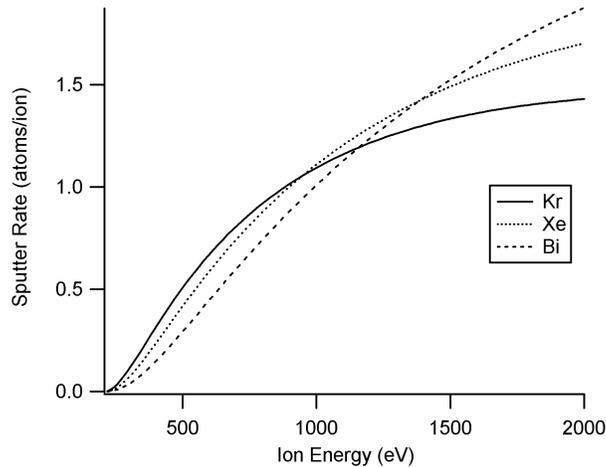
Figure 5: Erosion Rate of Carbon per kilogram of bismuth, xenon, and krypton ions

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 thus ions impacting on spacecraft surfaces will stick similarly to the interior of a vacuum tank. This would 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. Other spacecraft integration issues include coating of radiator and dielectric surfaces. Coatings of propellant atoms on radiators will reduce emissivity and radiative efficiency. Dielectrics are very vulnerable to propellant deposition, as conductive coatings on the surface of a dielectric will render it ineffective. Spacecraft design and interaction studies warrant future research.

5. Feed System for Condensible Propellant Operation

Development of a 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 with little heat input and the only significant need for external heating was for the evaporator.[36] 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 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.[37] This method may present a problem, however, in that a number of heaters consuming significant amounts of power are likely 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. The use of condensible metal propellants in future Hall thrusters will require development of an energy-efficient feed system.

6. Conclusions

For high-I_{sp} missions, krypton may prove advantageous as it provides the highest I_{sp} of the options presented here for a given acceleration voltage, and at such high exhaust energies the large ionization cost is minimized. The erosion rate due to sputtering will also be lower for krypton than other propellants at very high energies. For high-thrust, low-I_{sp} missions, however, the large heavy atoms may provide a benefit. Bismuth provides higher thrust per unit mass than the lighter propellant options given equal accelerating voltages 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. Condensible propellants may cause spacecraft contamination issues, as unlike the gaseous propellants condensibles will deposit on spacecraft surfaces.

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 higher thrust at the same discharge current as a xenon thruster, 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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