AN INVESTIGATION OF FULLERENE PROPELLANT FOR RF ION THRUSTERS

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Abstract

A radio-frequency ion thruster that operates on C₆₀ propellant was constructed and its operation and performance were investigated. The thruster would not operate on C₆₀ propellant alone without an electron source in the discharge chamber to sustain the plasma. A Langmuir probe was used to characterize the C₆₀ plasma and it was found that the positive and negative ion densities were approximately equal. The large ratio of negative ions to electrons strongly reduces the Bohm velocity of positive ions required to sustain a stable sheath at the grid apertures and this limits the beam current which may be extracted from the thruster. Substantial fragmentation of the C₆₀ molecule in the discharge chamber was observed under a variety of operating conditions. ExB measurements of a beam extracted from a direct-current thruster, however, show that fragmentation can be significantly reduced by operating at low C₆₀ flow rates.

Introduction

Buckminsterfullerene (C₆₀) has been proposed as a propellant for electrostatic thrusters because of its relatively low ionization potential, large electron-impact ionization cross section, and large molecular mass. The large mass could facilitate a greater thruster electrical efficiency than xenon thrusters on missions requiring relatively low specific impulses. Properties which are potentially unattractive include a substantial electron affinity for the molecule (i.e. its tendency to make negative ions) and a tendency to fragment into smaller carbon clusters. In addition, C₆₀ will decompose into amorphous carbon on surfaces at temperatures greater than ~1000 K. These issues have been addressed by research performed by several groups in the past few years for both direct-current (DC) and radio-frequency (RF) thrusters and for non-propulsive ion source applications. The fragmentation problem has received considerable attention, but there are few discussions of the problems with negative ions.

Anderson and Fitzgerald used an ExB probe to determine the composition of the beam extracted from their DC thruster and it was estimated that 70-80% of the singly-ionized particles in the beam were fragmented fullerenes. Additionally, chemical analysis of the considerable residue collected from the discharge chamber revealed no fullerenes. Anderson et al. reported unsuccessful attempts to sustain an RF discharge in an ion thruster on C₆₀ alone. They observed that when sufficient C₆₀ was added to a xenon discharge the plasma extinguished.

Maiken and Taborek reported near-complete fragmentation in their beam at a discharge current of 600 mA. Gruen et al. operated an argon microwave discharge seeded with C₆₀ to grow carbon films and optical spectroscopy showed very extensive fragmentation of C₆₀ in the discharge.

Over the last several years much research has been focused on understanding the C₆₀ molecular fragmentation process. It has become clear through these investigations that the main mechanism for fragmentation is the ejection of a C₂ molecule through the process of unimolecular decay, whereby a molecule which has acquired sufficient internal energy may spontaneously break into two components. For the positive C₆₀ ion, this process is C₆₀⁺ → C₅₈⁺ + C₂. The fragment molecules undergo the same process, as do neutral molecules and multiply-charged fullerenes. C₆₀ is kinetically stable, but thermodynamically unstable relative to graphite under ambient conditions. Thus, once its kinetic stability is breached, it will eventually decompose into small carbon groups and amorphous...
The C₆₀ molecule is capable of storing large amounts of energy because of its special shape and stiff bonds, and energy imparted to the molecule by a collision, for example, is rapidly converted to vibrational energy which is spread throughout the whole molecule. Several values have been suggested for the internal energy required before the onset of fragmentation on a microsecond timescale, but most of the reported values are close to 40 eV.

Of the mechanisms studied to impart internal energy to the cluster, the dominant one in a thruster discharge chamber will be electron impact. Experiments with single electron impacts on C₆₀ molecules have shown that fragment molecules do not appear until electron energies reach 44 eV. Since extensive fragmentation is observed in DC sources with discharge voltages of 40 V and less, it is not likely that single-impact events are the main cause of fragmentation in these C₆₀ plasmas. Fragmentation studies in the literature, however, do not appear to address the problem of vibrational energy addition by repeated electron bombardment.

Another possible mechanism for energy addition to C₆₀ involves the formation of negative ions. When an electron is captured by C₆₀, the molecule gains an internal energy equal to the C₆₀ electron affinity (2.65 eV plus the kinetic energy of the electron). When an electron is ejected, the energy of the captured electron remains as vibrational internal energy. Repeated attachment and detachment can thus successively add energy to the molecule until ~40 eV is acquired and fragmentation may occur.

Cross sections for C₆₀ negative-ion and positive-ion formation are shown in Fig. 1 as a function of electron energy. The negative ion cross section, which is very large at electron energies less than about 10 eV, does not become less than that for positive ions until electron energies exceed 14 eV. For this reason, high negative ion densities are expected at typical ion thruster discharge chamber electron temperatures.

**Experimental Apparatus**

Experiments were conducted in a 44-cm dia. bell-jar vacuum facility, a portion of which is shown in Fig. 2 along with the RF ion thruster. The quartz discharge chamber is closed on the upstream end and has a 20-mm dia. hole in the side wall to accommodate the quartz vaporizer assembly. The inner tube of the vaporizer serves as an argon feed and the outer tube forms a crucible in which the C₆₀ is placed. Resistive heaters and radiation shielding surround the vaporizer and the discharge chamber.

Fig. 1 Cross Sections for C₆₀ Positive and Negative Ion Formation.

The chamber rests on a stainless-steel plate to which the thruster grids are attached. The beam diameter was limited to 35 mm so the chamber pressure could be kept high and so that electrical feedthroughs could pass through holes in the masked area. The 189-hole grid set has a screen grid hole diameter and transparency of 2.1 mm and 0.63, respectively, and an accelerator grid hole diameter and transparency of 1.9 mm and 0.50, respectively. For some...
experiments, a 0.38-mm dia. tantalum filament placed in the discharge chamber served as an electron source. The filament was electrically connected to the stainless-steel plate and heated to thermionic emission temperatures using an AC power supply. A meter was used to monitor the electron current that flowed between the filament and plate.

Radio-frequency power is supplied to the thruster at a frequency of 13.56 MHz by means of a flat, pancake-like spiral antenna. The antenna, formed from 6-mm dia. silver-coated copper tubing, is housed in an inverted pyrex "hat" that forms the vacuum boundary and is connected at each end to an electrical matching network. A high-voltage variable capacitor is used to tune the network and minimize the reflected power. The antenna and portions of the matching network are water cooled.

Argon and C₆₀ are supplied to the discharge chamber in any mixture ratio with the argon flow being monitored using a conventional thermal flow meter. The C₆₀ flow rate is monitored using an Inficon XTM/2 quartz crystal microbalance (QCM). When the vaporizer is heated to ~700 K the C₆₀ will sublime. A fraction of the C₆₀ flows through a small hole in the rear of the vaporizer assembly and condenses on the QCM which is located outside of the ground screen 2 cm from the vaporizer hole. A time history of the flow rate measured by the QCM is logged on a strip-chart recorder. The C₆₀ mass sublimated from the vaporizer is determined by weighing the vaporizer before and after each experiment and the total mass deposited on the QCM is given directly by the QCM controller. A flow calibration constant is then defined by the mass sublimated from the vaporizer divided by the mass accumulated on the QCM. The flow rate to the discharge chamber is assumed to be proportional to the QCM flow rate and is determined by multiplying the QCM flow by the flow calibration constant.

A Langmuir probe was employed to measure plasma properties inside the discharge chamber. Langmuir probes for use in RF plasma sources must be specially designed in order to make accurate measurements. Plasma potential fluctuations over the RF period will cause the DC bias between the probe tip and the plasma to fluctuate about the mean probe bias, and analysis of the probe traces with conventional theories will yield erroneous results. The solution is to make the probe tip "follow" the plasma potential fluctuations so the DC bias between the probe and plasma is constant. This was accomplished by placing three self-resonant inductors in series with the probe tip and a capacitor in between the body of the probe and the plasma. The inductors and the large body capacitance allow the probe tip to follow the plasma potential closely. The probe tip (75 μm dia. tungsten wire for argon plasmas, and 25 μm dia. for C₆₀) and quartz tip holder dimensions (1.6 mm dia.) are much less than the electron and ion mean free paths in the plasmas that were investigated. Complete discussions about probe construction and theory can be found in Refs. 14-15.

**Experimental Results and Discussion**

**Initial Experiments with C₆₀**

The first attempts to operate the thruster on C₆₀ propellant were performed by introducing a C₆₀ flow to the thruster when it was operating on argon, then slowly decreasing the argon flow until the thruster was operating only on C₆₀. In all the tests that were conducted in this fashion, however, there was no observable plasma discharge and no measurable beam current when the argon flow was shut off. Because the inductive RF electric fields alternate with time, they decelerate as well as accelerate free electrons during the RF period, and each electron may be expected to spend a portion of its time at energies less than 14 eV. Since the electron attachment cross section is so large at the lower electron energies, C₆₀ molecules scavenge many of these free electrons. It is argued that this loss of electrons decreases positive-ion production to the point where the discharge extinguishes. It was reasoned, therefore, that a plasma might be sustained if an electron source was placed in the discharge chamber to re-supply electrons lost to negative ion production.

The main attractive feature of RF thrusters compared to DC thrusters for C₆₀ propellant is the lack of a need for a hot electron source upon which C₆₀ would degrade. Nevertheless, a hot-filament electron emitter was used to supply electrons to the discharge chamber so that C₆₀ RF ion thrusters could be studied and their operation characterized. C₆₀ plasmas do not produce significant visible luminosity, so the presence of a C₆₀ plasma was inferred by a DC current flowing between the filament and downstream plate. With the addition of the hot-filament electron source to the discharge chamber, it became possible to operate the thruster on C₆₀ propellant alone. Initial experiments, however, yielded beam currents that were less than 200 μA at propellant flow rates of 20-30 mA eq. It was found that by placing the filament closer to the upstream end of the chamber substantial increases in beam current were achieved. This is because the electric fields radiated from the antenna are stronger near the antenna, and the electrons emitted from the
filament are accelerated to the higher energies at which positive-ion formation is more probable.

The performance of the thruster was next examined at higher C₆₀ mass flow rates. Beam current as a function of RF power is compared in Fig. 3 for argon and C₆₀ propellants under similar operating conditions. The maximum C₆₀ beam current measured was about 1.5 mA, far lower than that measured with argon propellant (32 mA). The normalized permeance per hole associated with the 1.5 mA C₆₀ beam extraction is 9.1 × 10⁻¹¹ A/V₁.₅, whereas the theoretical maximum is 1.6 × 10⁹ A/V₁.₅, so it is clear that the beam extraction is not permeance limited. In addition, the beam ion energy cost is very high, about 170,000 eV/ion at an RF power of 260 W (neglecting the filament power). The energy cost for the argon beam at 260 W is 8200 eV/ion, which is large compared to conventional DC noble gas thrusters. The thruster had no magnetic confinement, however, and the ratio of grid open area to total interior surface area is only 0.02. A baseline plasma ion energy cost of 145 eV/ion is estimated using the thruster geometry and performance curve and this is moderately higher than efficient DC thrusters operating on argon.

**Langmuir Probe Measurements**

The Langmuir probe was used to measure plasma properties inside the discharge chamber. Semilog plots of the voltage-current traces indicated that the electron energy distribution functions in the bulk of the plasmas were Maxwellian or very nearly Maxwellian in nature. Probe measurements acquired in the bulk of argon and C₆₀ plasmas are shown in Fig. 4. It is noteworthy that they are typical of those acquired at other operating conditions and that the magnitude of the argon probe trace has been scaled to facilitate comparison with the C₆₀ trace. The argon probe trace analyzed using standard techniques yields an electron temperature of 10 eV and an electron density of 5.4 × 10¹⁰ cm⁻³. A beam current of 26 mA was calculated using these values and the open area of the screen grid, whereas the corresponding measured beam current was 50 mA.

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![Fig. 3 Thruster Performance with Ar and C₆₀](image-url)

During the experiments with C₆₀, a direct correlation was observed between the beam current and the filament heater current. If a discharge was obtained and then the heater current was turned off (i.e., no electrons were being emitted), the discharge would extinguish and no beam current would be measured. Increasing the heater current would cause the discharge to re-ignite and a beam current would be measured. Thus it is apparent that, at the RF powers and C₆₀ mass flow rates investigated here (0-300 W and 0-100 mA eq., respectively), a continuous electron source is required to sustain a C₆₀ plasma using an inductive RF power supply.

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![Fig. 4 Langmuir Probe Traces in Ar and C₆₀ Plasmas](image-url)

Probe measurements were made in C₆₀ plasmas using the same probe. In order to minimize carbon accumulation on probe surfaces, though, the probe was kept outside of the discharge chamber until a strong C₆₀ plasma developed and it could be moved quickly into it to acquire data like that shown in Fig. 4. The obvious differences between the argon and C₆₀ traces are 1) the relative magnitudes of the negative and positive saturation currents and 2) the plasma potentials, which were about 35 V for argon and about 1 V for C₆₀. Additionally, at potentials less than the plasma potentials, the regions of negative particle retardation from the probe surface show different structures. The methods for interpreting probe characteristics in these so-called electronegative plasmas are not as well-established and documented in the literature as those for electropositive plasmas, so the method used to interpret the C₆₀ traces will be described here in some detail.
In the limit where the plasma Debye length is much greater than the radius of a cylindrical probe (i.e., the thick-sheath case), the current to the probe is described by Langmuir’s orbital-motion-limited (OML) theory. Lakamboise has numerically verified the accuracy of the simple form of the OML for probe radii less than the Debye length, which is the case for the C₆₀ plasmas. For positive ions, the OML current to the probe at large potentials compared to the ion temperature is given by

\[ I = e A_p n_+ \frac{-2e(V_{probe} - V_{plasma})}{\pi^2 m_+} \]  

where \( e \) is the electron charge, \( A_p \) is the probe area, \( n_+ \) is the ion density, \( V \) is an electric potential, and \( m_+ \) is the ion mass. If probe data are plotted as \( I^2 \) vs. \( V \), the OML regime appears as a linear portion of the curve and the positive ion density can be calculated from the slope of a linear curve fit at negative probe potentials. This regime, however, must be at potentials that are large compared to the electron temperature to assure that the current to the probe is only ions, but not so large that the probe sheath becomes more spherical than cylindrical and the OML relationship changes. When this process was performed on the C₆₀ data of Fig. 4, the \( I^2 \) vs. \( V \) curve fit in the range \(-42 < V < -27 \) \( V \) yielded a positive ion density of \( 9.3 \times 10^{10} \) cm\(^{-3} \).

The ion current must be subtracted from the total probe current in order to determine the electron temperature in the region of electron retardation. Wainman et al. perform this for the OML ion current by extrapolating the \( I^2 \) linear curve fit until it reaches zero current. The square root of this curve fit is then subtracted from the total probe current. At greater voltages than the zero-current intercept the ion current is assumed to be zero and the total probe current is unchanged. For each of the C₆₀ Langmuir probe traces, the extrapolated OML ion current reached zero at a potential less than the floating potential, so the total probe current at voltages greater than the floating potential was not affected by the ion current subtraction. When the data of Fig. 4 were plotted in a semilog format an electron temperature of 4.2 eV was obtained.

The electron and negative ion densities were determined from the current to the probe at the plasma potential, where no sheath exists around the probe and all charged particles arrive at the probe surface with their thermal velocities. If quasi-neutrality is invoked \((n_+ = n_+ + n_e)\) and it is assumed that all heavy particles are in thermal equilibrium with each other and the chamber walls, the electron density can be calculated using

\[ \frac{I_p}{eA_p} = n_e \left( \frac{eT_e}{m_e} \left( \frac{kT_{wall}}{m_s} \right) \right) \]

where \( I_p \) is the probe current collected at the plasma potential, \( n_e \), \( T_e \), and \( m_e \) are the electron density, temperature, and mass, respectively, \( k \) is Boltzmann’s constant, and \( T_{wall} \) is the chamber wall temperature (800 K). Solution of Eq. 2 yields an electron density of \( 2.7 \times 10^8 \) cm\(^{-3} \) and the quasi-neutrality approximation then gives a negative ion density of \( 9.3 \times 10^{10} \) cm\(^{-3} \). Although the negative ion density is two orders of magnitude greater than the electron density, the electron current to the probe still dominates at plasma potential. These results were repeatable in measurements made under similar operating conditions. An error of \( -10% \) is estimated in determining \( n_+ \) and \( n_e \) from the Langmuir probe data.

Recall that the ion density in the argon discharge was \( 5.4 \times 10^{16} \) cm\(^{-3} \). This is comparable to the positive ion density in the C₆₀ plasma, and yet the C₆₀ beam currents were more than an order of magnitude smaller than those for argon. This apparent discrepancy must be due to differences in the Bohm velocities for positive ions at sheath edges in electropositive and electronegative plasmas. The sheath velocity in a plasma with negative ions is given by

\[ u_s = \sqrt{\frac{e T_e 1 + \alpha}{m_s 1 + \gamma \alpha}} \]

where \( \alpha = n_+ / n_e \) and \( \gamma = T_e / T_s \). Note that if \( \gamma > 1 \) and \( \alpha > 1 \) (\( \gamma = 60 \) and \( \alpha = 350 \) for the data in Fig. 4), this velocity reduces to an expression that depends only on the negative ion temperature. The beam current extracted from the thruster operating on C₆₀ with the measured plasma properties then becomes

\[ I_b = e n_+ A_p \sqrt{\frac{k T_e}{m_s}} \]

and the predicted beam current is 0.9 mA. This value is close to the beam currents given in Fig. 3.

It is clear that a high negative ion density can decrease the beam current that can be extracted from a thruster dramatically. Because C₆₀ has such a high electron affinity and a large cross section for negative ion formation at low electron energies, it
seems likely that negative ion densities will be large and will impose a limit on the maximum extractable beam current at the conditions of RF power and mass flow rate where an RF thruster can operate.

Fragmentation of the C$_{60}$ Molecule

After each experiment in which a C$_{60}$ plasma was produced, whether it was with the hot filament electron source or in conjunction with an argon discharge, black/brown carbonaceous deposits were found on the interior surfaces of the discharge chamber. It is expected that these deposits are from fragmented C$_{60}$, based on the results of residue analysis from other research. In order to determine if this was the case, simple toluene-solubility tests were conducted with residue samples. It was found that samples dissolved to varying degrees in toluene, but amounts of insoluble material were always observed, indicating the presence of non-C$_{60}$ material.

Residue samples were also analyzed by 70-eV electron impact mass spectrometry. A control test was performed by sublimating C$_{60}$ from the vaporizer into the discharge chamber with the RF power and filament off and collecting residue that accumulated on a cool portion of the grid surface (there was no visible accumulation on the quartz walls because they were heated to temperatures at which C$_{60}$ will not condense). The results of the residue analysis, which are presented as the relative abundance of each of the particle mass-to-charge ratios, is shown in Fig. 5. Visible are singly (m/z = 720) and doubly (m/z = 360) charged C$_{60}$ ions as well as some fragments of those ions (e.g. C$_{58}^+$, m/z = 696) which are created by the 70-eV electron impact. Trace amounts of impurities are observed at m/z less than 150 as well as polysiloxane peaks (m/z = 207, 281) which come from silicone greases. The mass spectrum of the as-received C$_{60}$ was the same as Fig. 5 but with lesser impurity levels.

Analysis of the brown/black residue coating the chamber walls after the thruster was operated with a C$_{60}$ plasma discharge is shown in Fig. 6. No signals for ionized C$_{60}$ or fragments are visible. There are large signals at m/z < 150 and an additional peak at m/z = 652 which comes from an unknown but non-C$_{60}$ source. Since fragmented C$_{60}$ is expected to decompose to amorphous carbon on the quartz walls, it is likely that the signals at m/z < 150 are hydrocarbon and other species absorbed by the carbon on the chamber walls from the atmosphere when vacuum is broken. Mass spectrometric analyses of other residue samples were similar to that of Fig. 6, but in some cases small C$_{60}$ signals were observed.

An indication of the extent of fragmentation in the discharge chamber is given by the mass of carbonaceous material that condensed on the chamber walls during an experiment, determined by weighing the chamber before and after each test. The results are displayed in Table 1 for different test conditions. The deposited mass is tabulated as a percentage of the mass that entered the chamber. In each test, the flow rate of C$_{60}$ into the chamber was about the same and the chamber walls were heated to their operating temperature (~ 800 K). The first test shows that, with no RF or filament power applied, there is very little condensation on the walls, as expected. Successively greater fragmentation is seen when the filament is on, the RF is applied, and when an argon discharge is used as the electron source. These results indicate that a hot filament alone will fragment C$_{60}$, and that plasma processes (e.g. bombardment of C$_{60}$ by energetic electrons when the RF is applied and the filament is emitting) will induce slightly greater fragmentation. The greatest fragmentation is seen with the argon discharge where the filament was
Table 1. Mass Deposited on Chamber Walls.

<table>
<thead>
<tr>
<th>RF POWER</th>
<th>ELECTRON SOURCE</th>
<th>( \Delta M_{\text{Chamber}} )</th>
<th>( \Delta M_{\text{Vaporizer}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off</td>
<td>None</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Off</td>
<td>Tantalum Filament</td>
<td>19%</td>
<td></td>
</tr>
<tr>
<td>On</td>
<td>Tantalum Filament</td>
<td>20-30%</td>
<td></td>
</tr>
<tr>
<td>On</td>
<td>Argon Discharge</td>
<td>70%</td>
<td></td>
</tr>
</tbody>
</table>

not operating. Recall that the electron temperatures and densities in argon discharges are much greater than those in a C\(_{60}\) discharge. Thus, more frequent and more energetic electron bombardment of C\(_{60}\) will occur, and it is argued that each collision will add vibrational energy to the cluster until sufficient energy is acquired for fragmentation.

There is some evidence to suggest that ion thrusters may be operated on C\(_{60}\) propellant with little fragmentation. Anderson and Fitzgerald investigated the mass of the beam ions extracted from a DC source operating on C\(_{60}\) with an E\(\times\)B probe and found substantial fragmentation. Recent experiments with the same system, however, indicate that fragmentation in the beam is reduced significantly when the thruster is run at low C\(_{60}\) flow rates. An E\(\times\)B trace acquired at a flow rate of 2.6 mA eq. is shown in Fig. 7 and it shows that the beam consists of primarily singly and doubly ionized C\(_{60}\), although small amounts of fragments are visible. Using the fragmentation fraction bracketing process in Ref. 2, the upper and lower bounds on fragment current fraction are found to be 0.23 and 0.12, respectively, for singly-ionized fragments C\(_{38}\)\(^+\) through C\(_{48}\)\(^+\). When the flow rate was increased to 13 mA eq., the fragment current fraction was bounded by 0.70 and 0.59 for the same group of fragments.

![Fig. 7 E\(\times\)B Probe Measurement from DC Thruster.](image)

![Fig. 8 Fragmentation Fraction in Beam of DC Thruster For Various Operating Conditions.](image)

The fragmentation fraction computed from measured results for several different thruster operating conditions is plotted in Fig. 8 as a function of the product of the C\(_{60}\) neutral density and discharge current in the chamber (\(n_dI_d\)). This product has been selected because it is proportional to the ratio of the characteristic times required 1) for a C\(_{60}\) molecule to diffuse across the chamber and 2) for electron pumping of its vibrational energy. A high ratio, corresponding to a large energy input per chamber transit time, would be expected to correspond to a greater fragmentation fraction. Neutral density appears because molecular diffusion time is limited by collisions between particles of like masses, thereby making the time directly proportional to the neutral C\(_{60}\) density. Discharge current appears because the rate at which electrons pump energy into the molecules is proportional to the electron density, which in turn is proportional to the discharge current. Thus, an increase in \(n_d\) increases the time a C\(_{60}\) molecule spends in the plasma between collisions with a wall and an increase in \(I_d\) increases the rate at which electrons pump energy into it. This is consistent with results obtained by Maien and Taborek indicating that the beam fragmentation decreased with the discharge current as the chamber neutral density was held constant.

Conclusions

Conventional RF thrusters will not operate on C\(_{60}\) propellant unless an electron source is placed in the discharge chamber to maintain electron densities.
in the face of negative ion production losses. Langmuir probing of the RF C₆₀ plasmas formed with an electron source in place reveals positive and negative ion densities that are approximately equal and an electron density that is more than two orders of magnitude smaller. In plasmas such as those where the negative-ion-to-electron density ratio is large, the Bohm velocity and consequently the extractable beam current are greatly reduced. It has also been shown that large fractions of the C₆₀ molecules injected into an RF discharge chamber undergo fragmentation even if hot (> 1000 K) surfaces are not present. It is postulated that fragmentation is induced by repeated energy transfer from electrons. ExB measurements of a beam extracted from a DC source show that, at low C₆₀ flow rates and discharge currents, fragmentation in the beam is substantially reduced. Because of the need for an electron source, the formation of negative ions, and fragmentation in the discharge chamber, it is unlikely that RF ion thrusters can be operated on C₆₀ propellant with the efficiencies and lifetimes needed to make them competitive with thrusters operating on traditional propellants.

Acknowledgement

This research was supported by Jet Propulsion Laboratory Contract 000960197 and this support is gratefully acknowledged.

References