Stationary Plasma Thruster Plume Emissions

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Prepared for the
23rd International Electric Propulsion Conference
sponsored by the American Institute of Aeronautics and Astronautics
Seattle, Washington, September 13–16, 1993
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The emission spectrum from a xenon plasma produced by a Stationary Plasma Thruster provided by the Ballistic Missile Defense Organization (BMDO) was measured. Approximately 270 individual Xe I, Xe II, and Xe III transitions were identified. A total of 250 mW of radiated optical emission was estimated from measurements taken at the thruster exit plane. There was no evidence of erosion products in the emission signature. Ingestion and ionization of background gas at elevated background pressure was detected. The distribution of excited states could be described by temperatures ranging from fractions of 1 eV to 4 eV with a high degree of uncertainty due to the non-equilibrium nature of this plasma. The plasma was over 95% ionized at the thruster exit plane. Between 10 and 20% of the ions were doubly charged. Two modes of operation were identified. The intensity of plasma emission increased by a factor of two during operation in an oscillatory mode. The transfer between the two modes of operation was likely related to unidentified phenomena occurring on a time scale of minutes.

Introduction

The stationary plasma thruster (SPT) developed in the former Soviet Union over the past several decades offers performance levels attractive to western spacecraft manufacturers for north-south station-keeping. In order to more fully assess the suitability of this technology for fulfilling such mission requirements, the NASA Lewis Research Center (LeRC) has begun evaluating performance and integration issues using an SPT provided by the Ballistic Missile Defense Organization (BMDO). Integration issues include the impact of the thruster induced plasma environment on spacecraft subsystems. These impacts may be estimated based on measurements of SPT plasma properties in an appropriate altitude simulation chamber.

The energetic xenon plasma produced by the SPT is sustained within an annular discharge chamber by an axial electric field established between an external hollow cathode and an anode located at the rear. The acceleration of the ions formed in the discharge chamber by the electric field provides thrust. A unique aspect of the SPT is the interaction between the axial electric field and a radial magnetic field established by electromagnets which imparts a circumferential force on the magnetized electrons and decreases their axial electron conductivity. Collisional processes involving the electrons dominate many of the phenomena which determine the thermo-chemical state of the exiting plasma. However, complete specification of the characteristics of the plasma jet as it exits the discharge chamber requires knowledge of the alignment and strength of the electric and magnetic fields, the type and frequency of interactions of the plasma constituents with one another and the dielectric thruster walls, and the interaction of the thruster efflux with the ambient environment.

The complexity of the various processes mentioned above currently precludes the use of analytic or numerical methods for predicting this behavior and, in spite of an extensive flight history for the SPT-70 (the 70 designates the exit diameter in mm), integration of these engines onto western satellites still requires assessment of the potential impacts of the exhaust on various subsystems. Experimental measurements of the SPT plasma using electrostatic probes have provided data on the charged particles in the plume. However, in some cases optical diagnostics can provide detailed, specie-specific, non-intrusive measurements on neutral particles and ions. Optical measurements have been made by several SPT investigators. The BMDO sponsored assessment of the SPT at LeRC includes optical diagnostics for the measurement of the plasma characteristics in the SPT-100's plume. This report describes the current status of an investigation of the plume using emission spectroscopy.

Nomenclature

\[ \begin{align*}
A_{ik} & \text{ transition probability from state } i \text{ to } k, \text{s}^{-1} \\
E_i & \text{ energy of state } i, \text{J} \\
g_i & \text{ degeneracy of state } i \\
l(v) & \text{ spectral intensity, } \text{W/m}^2\cdot\text{sr}\cdot\text{s}^{-1} \\
l_m(v) & \text{ measured spectral intensity, } \text{W/m}^2\cdot\text{sr}\cdot\text{s}^{-1} \\
k & \text{ Boltzmann's constant, } \text{J/K} \\
k(v) & \text{ spectral absorption coefficient, } \text{m}^{-1} \\
L & \text{ spatial extent of plasma, } \text{m} \\
n & \text{ number density, } \text{m}^{-3} \\
n_i & \text{ number density of state } i, \text{m}^{-3} \\
Q_e & \text{ electronic partition function} \\
T & \text{ temperature, K} \\
T(v) & \text{ radiation transmission function, } \text{s} \\
z & \text{ spatial coordinate, } \text{m} \\
\varepsilon(v) & \text{ spectral emission coefficient, } \text{W/m}^3\cdot\text{sr}\cdot\text{s}^{-1} \\
\phi(v) & \text{ spectral line shape function, } \text{s} \\
v & \text{ frequency, } \text{s}^{-1} \\
v_0 & \text{ transition frequency, } \text{s}^{-1}
\end{align*} \]


**Analyses**

One can infer information on the state of a plasma by interpreting the spectra of the light radiated by that plasma. One mechanism which produces this radiation is spectral line emission which occurs when excited plasma constituents spontaneously decay to lower energy states. The intensity of the light emitted from one of these transitions can be related to the population of the excited state whose decay gives rise to the spectral line. This is accomplished through a solution to the one dimensional equation of radiative transfer.

\[
\frac{dI}{dz} = (\epsilon(v,z) - k(v,z)) I(v,z)
\]  

(1)

This equation can be integrated from \( z = 0 \) to \( z = L \) for a homogeneous plasma of known extent.

\[
I(v,L) = \frac{\epsilon(v)}{k(v)} \left[ 1 - \exp(-k(v)L) \right] + L I(v,0) \exp(-k(v)L)
\]  

(2)

For an optically thin plasma, \( i.e. k(v)L \ll 1 \), with negligible incident radiation, the intensity of the light emitted by the plasma is directly proportional to the spectral emission coefficient.

\[
I(v,L) = \epsilon(v) L
\]  

(3)

Considering only line emission, the spectral emission coefficient can be related directly to the number density of the excited state whose spontaneous decay results in the spectral line. For this case equation (3) becomes:

\[
I(v,L) = \frac{\hbar v}{4\pi} A_{ik} n_i \phi(v) L
\]  

(4)

This relation can be used to determine the excited state number density if the frequency dependent spectral intensity can be measured. However, it was not possible to directly measure the frequency dependent spectral intensity in this investigation because measurements were made with an instrument which had a non-negligible radiation transmission function. Therefore, the observed intensities can be represented as a convolution of equation (4) and an appropriate radiation transmission function, \( T(v) \).\textsuperscript{18}

For this case equation (4) becomes:

\[
\int_{0}^{
fty} I(v',L) T(v-v') dv' = \frac{\hbar v}{4\pi} A_{ik} n_i L \int_{0}^{
fty} \phi(v') T(v-v') dv'
\]  

(5)

When the transmission function is wide and approximately constant in the frequency range corresponding to the spectral line shape function, the integral on the right hand side of this equation can be evaluated. The left hand side of the equation is the measured intensity, which is the convolution of the emitted intensity and the transmission function. Therefore, the number density of state \( i \) can be determined from the measured intensity providing the transition probability is known.

\[
n_i = \frac{4\pi}{\hbar v} \frac{I_{m}(v,L)}{A_{ik} L T(v-v_0)}
\]  

(6)

To determine the plasma conditions based on the number density of excited states, one needs to consider the mechanisms responsible for populating these states. The populations of all the excited states are determined by various collisional and radiative processes occurring in the plasma. When the forward rates of all collisional processes are balanced by their reverse rates, a plasma is said to be in local thermodynamic equilibrium. For this case the distribution of excited states can be described by the plasma temperature based on Boltzmann statistics.\textsuperscript{19}

\[
n_i = \frac{g_i \exp(-E_i/kT)}{\Omega_{i}}
\]  

(7)

Furthermore, based on the temperature and total atom number density a Saha relation can be used to determine the ion and electron density.\textsuperscript{19}

Past investigations into the SPT plasma have suggested that not all states exhibit this type of equilibrium behavior and that ground state collisional excitation and radiative decay of excited states are the mechanisms responsible for determining the distribution of excited states.\textsuperscript{10-12} This type of equilibrium is often referred to as corona equilibrium. The existence of several long lived metastable states of Xe I such as the 6s[3/2]\textsubscript{1} and 6s'[1/2]\textsubscript{0} levels which have radiative lifetimes of 150 sec and 78 msec respectively\textsuperscript{20} suggest collisional processes involving these states may also be important.

A collisional-radiative equilibrium (CRE) model based on the rates of the individual exciting and depopulating mechanism could be used to interpret the number density of excited states if collisional and radiative processes are both dominant relative to convective transport in the SPT plasma. Collisional and radiative rates can be calculated based on transition probabilities, collision cross sections, and a suitable electron energy distribution function. A CRE model was constructed in this fashion to interpret the spectra of a hydrogen arcjet.\textsuperscript{21}

While a CRE model may be the appropriate model to describe the distribution of excited states in an SPT produced xenon plasma, no such model was developed during the course of this investigation for several reasons. First, the atomic structure of xenon makes a CRE model of the SPT far more complex than hydrogen. Figure 1 is a partial Grotrian energy
level diagram for xenon constructed from published energy levels. This shows the splitting of states with the same principal quantum number due to spin-orbit coupling of the valence electrons. Since a CRE model requires a rate equation for each level, the number of states for xenon necessitates a very large matrix of equations or appropriate lumping of multiple states to reduce the number of coupled, nonlinear differential equations. The collision cross sections needed to determine the rates for the various processes considered in a CRE model can often be calculated based on an oscillator strength and an electron energy distribution function. However, many xenon oscillator strengths remain unknown. Additionally, while investigations of the electron energy distribution function in SPTs have been conducted, there remains a large degree of uncertainty as to the appropriate distribution function. Future work is required to resolve these issues in hopes of developing a xenon CRE model if warranted.

Figure 1: Partial Xenon Energy Level Diagram

Experimental

An experimental apparatus was implemented to take spectroscopic measurements of the plasma produced by the Russian SPT-100 thruster. Preliminary data were taken concurrently with performance measurements in Vacuum Facility 5 of the Electric Propulsion Laboratory at the NASA Lewis Research Center. The 19 m long and 5 m diameter cylindrical chamber was cryogenically pumped with two 41 m² helium cryopanels installed at one end of the chamber partially separated from the remainder of the tank by an auxiliary baffle and movable louvers. These louvers were in the open position during operation. The pumping system's twenty, 0.8 m diameter oil diffusion pumps were not employed. The thruster was mounted on a thrust balance in a 1 m diameter test port that could be isolated from the main chamber with a gate valve. The configuration for these tests is shown in Figure 2.

The effect of chamber pressure on operation was considered during performance evaluations. The tank pressure was varied by introduction of either nitrogen or xenon into the main chamber for these tests. The pressure was monitored using two hot-cathode ionization gauges. One gage was located in the test port. The other was located in the main chamber. During thruster operation the tank pressure ranged from $1 \times 10^{-4}$ Torr to $3 \times 10^{-6}$ Torr.

Figure 2: Tank 5 including SPT and cryopanels

The remainder of the spectroscopic measurements were taken with the SPT operating in Vacuum Facility 8 of the Electric Propulsion Laboratory. The 5 m long by 1.5 m diameter cylindrical chamber depicted in Figure 3 was pumped by four 0.82 m oil diffusion pumps, a lobe type mechanical blower, and two piston type roughing pumps. The thruster was mounted in a 0.6 m diameter test port. The ambient pressure as measured by an ionization gauge during testing was $3 \times 10^{-5}$ torr in the main chamber and $6 \times 10^{-5}$ torr in the test port.
In both cases optical measurements were taken through a window located on the test port to permit transverse viewing of the exhausting plasma. The transmissivity of this window declined significantly at wavelength below 3500 Å. A 80 mm x 0.08 mm cross sectional slice of the plasma at the thruster exit was collimated using a 25 mm diameter achromatic lens. The collimated beam was directed to a 0.5 m Czerny-Turner scanning monochromator using front surface mirrors where it was focused onto the entrance slit using a 25 mm diameter achromatic lens. For the preliminary measurements in Tank 5 the collimating lens had a 600 mm focal length and the focusing lens had a 200 mm focal length. Tank 8 measurements were conducted with a 400 mm focal length collimating lens and a 100 mm focusing lens. A simplified schematic of this detection scheme is shown in Figure 4.

![Figure 3: Tank 8 with SPT](image)

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![Figure 4: Simplified Schematic of the Optical Path for Emission Measurements](image)

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The 0.5 m monochromator's grating was 64 x 64 mm, had 1200 grooves/mm, and was blazed for maximum throughput at 5000 Å. The reciprocal linear dispersion was 17 Å/mm. The transmission function of this system was determined to be Gaussian in shape with a full-width-at-half-maximum of 4.5 Å. The photodetector was a 28 mm diameter, red and blue sensitive, side-on, photomultiplier tube (PMT) biased to 1000 Volts. Phase sensitive detection was employed to discriminate against light from sources other than the SPT. An optical chopper operating at 400 Hz was located in front of the collimating lens. The PMT anode current was converted to a voltage across a 10 kΩ load resistor and measured using a lock-in amplifier phase locked to the optical chopper. The lock-in amplifier was operated with a 100 millisecond time constant. For the majority of scans a long pass interference filter with a 5500 Å cut-off was used at wavelengths above 7000Å to avoid second order spectra.

The SPT-100 thruster provided by BMDO was fabricated in Russia. A description of the internal construction of the thruster can be found elsewhere. The inner and outer diameters of the annular discharge chamber were 56 and 100 mm. The external hollow cathode, mounted in the 12 o'clock position during the majority of the tests, was heated by an internal heater prior to start up. A laboratory model power supply, designed and built at Lewis, was used to run the thruster and operate the cathode heater. For tests conducted in Tank 8 the thruster operated at the conditions shown in Table I. These values are compared to values obtained during similar tests conducted by Fakel Enterprises in Kaliningrad, Russia. All tests were conducted using commercially available research grade xenon (99.9995% pure) as the propellant. A complete performance characterization of this thruster can be found in Reference 2.

Table I: SPT-100 Operating Conditions

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<tr>
<th>Quantity, units</th>
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<th>Fakel</th>
</tr>
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<td>Total Xenon Flow Rate, sccm</td>
<td>47.4</td>
<td>49.6</td>
</tr>
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<td>Thruster Voltage, volts</td>
<td>296.8</td>
<td>300</td>
</tr>
<tr>
<td>Discharge Current, amps</td>
<td>4.38</td>
<td>4.35</td>
</tr>
<tr>
<td>Thruster Power, watts</td>
<td>1300</td>
<td>1305</td>
</tr>
<tr>
<td>Cathode to Ground Voltage, volts</td>
<td>21.4</td>
<td>21.1</td>
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For each test the thruster was allowed to run for a minimum of ten minutes to establish steady state prior to taking spectroscopic measurements. Emission measurements were obtained by scanning the monochromator from 3000 to 9000 Å at a rate of 1 A/s. During the emission measurements taken in Tank 5 the thruster operating conditions were varied as the performance characteristics were measured. These changes in operating conditions were reflected in changes in the measured intensities. Subsequent dedicated tests were conducted at a one operating condition.

In several instances during steady state thruster operation the thruster transitioned from a quiescent mode characterized by nearly constant discharge current to a oscillatory mode characterized by significant current oscillations. The transition between modes was abrupt and unanticipated. The temporal behavior of the thruster power is displayed for each of the modes in Figure 5. The 12 kilohertz oscillation in the thruster power was primarily the result of a 4 Amp peak to peak variation in the discharge current. The regular high frequency spikes were indicative of the power processing unit's 40 kHz switching transients. All spectroscopic data reported in the following section were taken while the thruster operated in a quiescent mode unless otherwise indicated.

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Figure 5: Time Dependent Behavior of Thruster Power in the Quiescent and Oscillatory Modes.

After measuring the emission spectra from the SPT an in situ intensity calibration of the spectroscopic system was conducted. The SPT was removed from the test port and a tungsten ribbon lamp at 2300 K was placed in the same location. Gray body continuum radiation was measured using the spectroscopic system with no modifications. The emissive power of the filament image on the detector was calculated using a Planck function and published values for the emissivity of tungsten. The estimated uncertainty in this calibration was less than ten percent.

Results and Discussion

The measured emission spectrum from the exit plane of the SPT-100 is shown in Figure 6. Approximately 270 individual atomic and ionic transitions were identified based on tabulated data. The majority of the emission occurred in the blue part of the spectrum between 4200 and 5000 Å. This was primarily due to Xe II, the singly ionized xenon ion. Over the entire spectral region measured, neutral xenon atom emission lines were of lesser but comparable intensity to the Xe II emission lines. The most prominent emission lines from doubly ionized xenon, Xe III, which were in the UV, were also detected. These Xe III lines were weaker in intensity. No continuum radiation was measured. The measured line shapes were primarily instrument broadened prohibiting spectral line analysis. No emission was measured below 3500 Å due to the decreased transmissivity of the window at these wavelengths.

In addition to emission from various configurations of xenon, emission from other species was considered. Specifically, because the SPT insulator erodes during operation, optical detection of atomic erosion products was investigated. Based on the composition of the insulator, the strongest transitions from neutral and singly ionized B, N, Si, and O were considered. The wavelengths of these transitions are listed in Table II. There was no evidence of emission from these species. Subsequent calculations based on a published end of life volume erosion measurements were consistent with the experimental data. Based on the known volume erosion rate a constant mass erosion rate of 27 mg/hr was estimated, permitting calculation of the flux of erosion products at the thruster exit. Assuming a 20 km/s velocity for these constituents a number density of the erosion products on the order of $10^{-14}$ m$^{-3}$ was determined. If the distribution of excited states can be described using Boltzmann statistics and a distribution temperature of 1 eV, even the most intense Si II line is an order of magnitude below the detectability limit. Improvements in the spectroscopic system to increase the sensitivity are possible and may be considered for future tests.

Table II: Spectral Lines of Potential Erosion Products: Boron, Nitrogen, Silicon, and Oxygen (Reference 27).

<table>
<thead>
<tr>
<th>Species</th>
<th>Wavelength, Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>B II</td>
<td>3451.3</td>
</tr>
<tr>
<td>N II</td>
<td>3995.0</td>
</tr>
<tr>
<td>O II</td>
<td>4075.9</td>
</tr>
<tr>
<td>B II</td>
<td>4121.9</td>
</tr>
<tr>
<td>O II</td>
<td>4189.8</td>
</tr>
<tr>
<td>O II</td>
<td>4649.1</td>
</tr>
<tr>
<td>N II</td>
<td>4630.5</td>
</tr>
<tr>
<td>N II</td>
<td>5005.2</td>
</tr>
<tr>
<td>Si II</td>
<td>5041.0</td>
</tr>
<tr>
<td>Si II</td>
<td>5056.0</td>
</tr>
<tr>
<td>N II</td>
<td>5679.6</td>
</tr>
<tr>
<td>O I</td>
<td>6158.2</td>
</tr>
<tr>
<td>Si II</td>
<td>6347.1</td>
</tr>
<tr>
<td>Si II</td>
<td>6371.4</td>
</tr>
<tr>
<td>N I</td>
<td>7468.3</td>
</tr>
<tr>
<td>O I</td>
<td>7771.9</td>
</tr>
<tr>
<td>O I</td>
<td>7774.2</td>
</tr>
<tr>
<td>O I</td>
<td>7775.4</td>
</tr>
</tbody>
</table>

During performance testing in Tank 5 the facility background pressure was increased to $10^{-4}$ Torr by a controlled flow of nitrogen into the vacuum tank. During these series of tests, spectroscopic measurements were taken in the 8000 - 9000 Å range without a long pass interference filter. Many transitions previously measured were recorded in second order. In addition to the second order xenon transitions, molecular emission from singly ionized molecular nitrogen was measured. The $B^2\Sigma_u^+ \leftrightarrow X^2\Sigma_g^+$ (0,1) transition of N$_2^+$ at 4278.8 Å was the most intense of these transitions. This was clear evidence that there was ionization of the background gas within the SPT produced plasma. An estimation of the mass flux of 300 K nitrogen at $10^{-4}$ Torr based on kinetic theory suggests that an amount of background nitrogen equivalent to approximately 2% of the supplied mass flow was ingested through the exit plane of the thruster. If this ingested mass were ionized within the discharge chamber and accelerated by the applied electric field there would be a measurable effect on thrust. There would be no way to distinguish ingested mass when the background.
was the propellant gas. The effect of facility pressure on performance is discussed in Reference 2.

To determine the brightness of the SPT plume the measured emission spectra was integrated with respect to wavelength. Approximately 0.2 mW of light was emitted by the 80 micron thick slice of plasma at the thruster exit plane. In order to estimate the total power emitted by the plume, this result was extrapolated assuming a homogeneous plasma one exit plane diameter in axial extent. The amount of power emitted from within this volume was 230 mW. This excludes the power emitted by the plasma in the discharge chamber and the power lost through resonance transitions in the vacuum ultraviolet (VUV). These transitions were not measured at this time due to the increased experimental complexity of making VUV emission measurements.

Based on the measured intensities, the number density path length product was determined using equation (6) for those transitions with an unambiguously determined intensity and a known transition probability. The intensity of several transitions could not be determined due to the close proximity of other transitions and limited spectral resolution. The designation of the transitions considered for this analysis, the wavelength (in air), the energy of the upper and lower states, the degeneracy of each state, the published transition probabilities, and the experimentally determined number densities are included in the Appendix.

In order to determine plasma conditions based on the number density of excited states a description of the equilibrium model was needed. The utility of Boltzmann statistics, which implies collisional equilibration among excited states and a Maxwellian electron energy distribution, was considered. Boltzmann plots for Xe II and Xe I are shown in Figures 7 and 8. These figures show the quantity n_i L divided by the degeneracy of state i plotted on a log scale versus E_i. The uncertainties are primarily due to uncertainties in the transition probabilities. Those points without error bars were determined using calculated transition probabilities.

If the plasma were in Boltzmann equilibrium each of these points would fall on a line with a slope of -1/kT according to equation (7). Even if electron collision frequencies were not adequate to maintain such an equilibrium for all excited states, states close in energy to the ionization continuum may still be in equilibrium with an excited state distribution reflecting the electron temperature. While the measured distribution shown for Xe II is bounded by values of kT between 0.45 and 3.9 eV, the scatter indicates that collisional phenomena do not dominate the processes giving rise to the distribution of the excited states measured. Similarly, the fact that there are levels populated which are not coupled to the ground state by an optically allowed transition indicates that a corona type equilibrium is also inappropriate. Therefore, a plasma model taking into account both collisional and radiative processes would be needed for an accurate description of the excited state distribution.
The levels whose excited state populations were suppressed were generally from a manifold of states coupled to the ground state via strong resonant radiative transitions or close in energy to a manifold of states collisionally coupled to the ground state via strong resonant radiative transitions. Because states close in energy are more likely to be collisionally coupled than states spaced further in energy, this can provide an efficient two step process for depopulating a normally long lived excited state when collisionally coupled to a state which strongly radiates to the ground state. A specific example of this is the 6p manifold of Xe I. The four lowest energy points depicted in Figure 8 are from this manifold. The population of all of these states is suppressed relative to the collisional dominated equilibrium suggested by the other states. The 6p[1/2]1 state is strongly coupled to the ground through an optically allowed transition. Similarly, as can be seen in Figure 1 the lowest energy state in the 6p manifold is close in energy to a state in the 6s manifold which is also strongly coupled to ground, providing a rapid depopulating mechanism. The two other states from this manifold are suppressed to a lesser extent, but are still coupled to ground through collisional transfer in the manifold.

![Figure 8: Boltzmann Plot for Xe I](image)

The ionization fractions for singly and doubly ionized xenon were determined based on a total xenon number density of $2.5 \times 10^{17}$ m$^{-3}$ at the thruster exit plane, estimated from the propellant flow rate and specific impulse, an average geometric optical path length of 54 mm, and the experimentally determined excited state number densities. A representative excited state number density was related to the total number density of that ionization state and the distribution temperature using equation (7). With the assumption of a common distribution temperature, a total of three of these Boltzmann relations, one for each ionization state detected, and an atom balance equation provided a closed set of equations for the total number density of each constituent and the distribution temperature. The calculated common distribution temperature was 0.7 eV and the composition of the plasma was <1% Xe I, 89% Xe II, and 11.9% Xe III. This ionization fraction was consistent with a previous report which indicated an ionization fraction in the discharge chamber above 0.95.

While the result of this calculation was insensitive to the optical path length, deviations from Boltzmann equilibrium for a low pressure, recombining plasma with ground state resonance radiation trapped, would have resulted in an under predicted temperature. Doubling the distribution temperature to 1.4 eV, a more reasonable value based on the Xe II Boltzmann plot and probe measurements taken downstream of the exit plane, resulted in a plasma composition of 5% Xe I, 76% Xe II, and 19% Xe III. While it was not possible to calculate the uncertainties, it seems likely that no more than 5% of the plasma at the exit of the discharge chamber remains neutral, and that less than 20% of the ions are doubly charged.

The excited state populations for each of the various species normalized by the estimated line of sight averaged total number density and the appropriate degeneracy and partition function are shown in Figure 9. The distribution of excited state number densities for Xe II and Xe III appear self consistent while the Xe I distribution reflects a relatively lower temperature. As previously mentioned the scatter among the data from an individual species was attributed to a low xenon-electron collision frequency relative to radiative processes. However, the differences between the Xe I distribution relative to Xe II and Xe III are likely due to inhomogeneities along the integrated optical path length. Temperature variations within the optical detection volume were likely. A different distribution of the atoms among the various ionization states within these different temperature regions would result. For example, a less energetic region of plasma adjacent to the walls of the discharge chamber would consist of a disproportionately high amount of atomic xenon relative to a more energetic region near the center of the annular discharge chamber. In this work emission from such a region was indistinguishable from these other regions. In order to investigate this, the spatial variation of the excited state number densities is required. This can be determined from Abel inverting spatial maps of each of the transitions used in such an analysis.
These data were all recorded while the thruster was operating in a quiescent mode. Additional data were taken to examine the changes in the plasma emissions while the SPT operated in the oscillatory mode previously described. This was accomplished by monitoring the intensity of one particular atomic or ionic transition as a function of time. While simultaneous tests monitoring both an atomic and ionic line were not performed, the similarity of results for both indicated that the intensity from one line was indicative of the intensity of the entire emission spectrum. No data on the change in the distribution of excited states during operation in the oscillatory mode were taken.

The intensity of the 5419.2 Å Xe II line as a function of time is shown in Figure 10 for two different flow rates. The maximum intensities were measured while the thruster was operating in the oscillatory mode. The minimum intensities, approximately half the maximum value, were measured while the thruster operated in the quiescent mode. The transition from quiescent to oscillatory mode was not immediate. The thruster would intermittently run in each mode and would stay oscillatory for increasing durations until remaining stable in this mode. The cathode to ground floating voltage also decreased from approximately 20 to 19 volts during this transition. The steady state discharge current, and therefore, the average thruster power increased by approximately 5% in the oscillatory mode. However as shown in Figure 5, the instantaneous power may have been as high as 40% above the quiescent value. Because the phenomena giving rise to electronic excitation are nonlinear with power, the factor of two change in intensity may be the result of this fluctuation in thruster power. The change in plume emission maybe indicative of a change in plasma properties. This is supported by the performance measurements of Sankovic.2

This behavior suggests the duration and periodic nature of the transition between modes was affected by phenomena occurring on a time scale of minutes. While thermal effects and surface phenomena generally take place on these longer time scales no evidence as to the actual mechanism was indicated by these data. Increasing the mass flow rate by 5% increased the frequency of the periodic oscillation and the relative duration of the oscillatory mode. The increase in flow rate was accompanied by a small increase in discharge current. This periodic behavior was indicative of one series of tests and is not necessarily indicative of operation at any other time.
collisional-radiative model will be required for a complete description of the measured emission spectra. Ionization fractions of above 95% were estimated at the thruster exit plane. Between 10 and 20% of the ions may have been doubly charged. Two modes of operation were identified. The intensity of plasma emission increased by a factor two in the oscillatory mode. The transfer between the two modes of operation seems to be affected by thermal or surface phenomena.

Acknowledgements
The author would like to thank M.A. Cappelli for his contribution to the interpretation of these data. This work was supported by the Ballistic Missile Defense Organization's Office of Innovative Science and Technology.

References
24. Personal communication: Tom Randolph, Space Systems/Loral.


**Appendix A**

Table A1: Xenon II Transitions and Physical Constants including measured values of $n_k^L g_k$

[Table with specific data and calculated values]

Energy levels from Ref. 22, Uncertainties: A<25%, B<30%, C<40%, D<50%, E<50%
Table A2: Xenon I Transitions and Physical Constants including measured values of $n_k L/ g_k$

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Energy levels from Ref. 22, Uncertainties: A<10%, B<25%, C<40%, D<50%, E>50%.
Stationary Plasma Thruster Plume Emissions

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The emission spectrum from a xenon plasma produced by a Stationary Plasma Thruster provided by the Ballistic Missile Defense Organization (BMDO) was measured. Approximately 270 individual Xe I, Xe II, and Xe III transitions were identified. A total of 250 mW of radiated optical emission was estimated from measurements taken at the thruster exit plane. There was no evidence of erosion products in the emission signature. Ingestion and ionization of background gas at elevated background pressure was detected. The distribution of excited states could be described by temperatures ranging from fractions of 1 eV to 4 eV with a high degree of uncertainty due to the nonequilibrium nature of this plasma. The plasma was over 95% ionized at the thruster exit plane. Between 10 and 20% of the ions were doubly charged. Two modes of operation were identified. The intensity of plasma emission increased by a factor of two during operation in an oscillatory mode. The transfer between the two modes of operation was likely related to unidentified phenomena occurring on a time scale of minutes.