Experimental and Computer Model Results on an Ion Thruster Charge-Exchange Plasma

S.B. Gabriel*
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California
and
H. R. Kaufman†
Colorado State University, Fort Collins, Colorado

Ion thrusters can be used in a variety of primary and auxiliary space propulsion applications. A thruster produces a charge-exchange plasma that can interact with various systems on the spacecraft. The propagation of the charge-exchange plasma is crucial in determining the interaction of that plasma with the spacecraft. This paper compares experimental measurements with computer model predictions of the propagation of the charge-exchange plasma from a 30 cm mercury ion thruster. Plasma parameters compared include flow directions, ion densities, and directed energies. Good agreement is found in a region upstream of, and close to, the ion thruster optics. Outside of this region, the agreement is reasonable in view of the modeling difficulties.

Nomenclature

e	= electronic charge
j	= ion current density vector
J	= ion current
L	= length
m	= mass of species
n	= ion density
r	= radius
R	= radial distance from axis of ion beam
T	= temperature
v	= ion velocity vector
V	= electric potential
Z	= axial distance from thruster optics plane
η	= propellant utilization factor
κ	= Boltzmann's constant
σ	= cross section for collisions
∇	= divergence operator

Subscripts

b	= beam
e	= electron
f	= floating
i	= ion
in	= in ion beam (computer model)
out	= in region outside ion beam (computer model)
p	= plasma
th neut.	= thermal neutralizer
C.E	= charge-exchange
Hg	= mercury
T	= thruster
0	= at $n_{0,\mathrm{ref}}$
0,ref	= at some reference point

Presented as Paper 82-1946 at the AIAA/JSASS/DGLR 16th International Electronic Propulsion Conference, New Orleans, La., Nov. 17-19, 1982; received Nov. 29, 1982; revision received Sept. 15, 1983.

*Senior Engineer. Member AIAA.
†Chairman, Physics Department. Associate Fellow AIAA.

Introduction

ELECTRIC propulsion can offer significant advantages over chemical propulsion due to its high specific impulse. However, the plasma environment produced by electric propulsion devices can significantly affect sensitive spacecraft surfaces, such as sensors, solar cells, and thermal control devices. If electric propulsion devices are to be successfully integrated into modern spacecraft with a high degree of confidence, then the magnitude of these interactions must be known so that appropriate steps can be taken at the design stage to minimize them.

In the case of ion propulsion it has long been realized that, in a properly designed spacecraft, the most significant interaction problem is due to the charge-exchange plasma. This plasma is formed by a charge-exchange between fast beam ions and thermal atoms and results in the production of slow-moving ions. Together with neutralizing electrons these slow ions constitute the charge-exchange plasma that can flow back toward the spacecraft and interact with sensitive surfaces or cause power drainage on a high-voltage solar array.

The charge-exchange plasma from ion thrusters has been studied both experimentally and theoretically for some time and a comprehensive review of this work has been given by Carruth.[1] Experimental measurements have been plagued by the effects of facility-produced charge-exchange ions and the difficulty of modeling. In the modeling, both analytically and with computer, widely differing values for the density of the charge-exchange plasma have been predicted. Recently, the end effect in a cylindrical Langmuir probe has been used to separate the thruster-produced charge-exchange ions for those produced by the facility.[2,3] In the field of modeling, recent advances have been made in the development of computer models of the charge-exchange plasma.[4,5] Both of these models are based on the barometric equation,[6,7] which essentially assumes that the electrons have a Boltzmann distribution. The model due to Robinson et al.[4] uses the potential from the barometric equation for the ion dynamics, whereas Katz et al.[5] assume the ions to be a cold, hydrodynamic fluid.[2] Katz et al.[5] have compared their model results with the earlier experimental results obtained using the end-effect Langmuir probe[2] while Robinson et al.[4] have compared the results of their model with experimental results on 5 and 15 cm diam thrusters. Additionally, trajectory angles predicted by the Robinson model were in good agreement with the measurements made by Carruth and Brady.[2] However, there has been no detailed comparison of the most recent and probably most reliable experimental results obtained by Carrth et al.[3] with any modeling efforts. This paper presents a comprehensive comparison of the experimental results from a 30 cm mercury ion thruster obtained in Ref. 3 and the computer model predictions of Robinson et al.[4] The parameters compared include ion density, directed ion energy, and flow angles. The motivation for this comparison is in the following areas: 1) validation of the computer model; 2) evaluating limitations of the computer model and ways of improving on it; and 3) strengthening the understanding of the experimental measurements in a ground-based test, with particular reference to the effects of facility-produced charge-exchange ions.

Experimental Arrangement

A schematic diagram of the experimental arrangement is shown in Fig. 1. The vacuum chamber was 2.1 m in diameter and 4.6 m long and was cryopumped by a liner cooled with liquid nitrogen (LN_2). A mercury ion thruster was placed at one end of the chamber so that the ion beam impinged on a frozen mercury target at the other end of the chamber. This target could be rotated through 90 deg, allowing the beam to strike either the frozen mercury target or the end of the chamber. The use of a frozen mercury target reduces sputtering of the steel walls of the vacuum chamber, but has the shortcoming of adding additional mercury to the chamber background. In addition to the cryopumping, the chamber was pumped by two 0.8-m oil diffusion pumps (with LN_2-cooled baffles), providing a background pressure in the range $1\text{-}6 \times 10^{-6}$ T with the thruster operating.

The ion thruster used in these experiments was a 900 series, Hughes 30 cm mercury thruster with SHAG (small-hole accelerator grid) optics. Because of the SHAG optics, the ion beam output of the thruster was equivalent to that from a J-series 30 cm ion thruster. The thruster was operated and throttled as recommended for a J-series thruster by the NASA Lewis Research Center (LeRC).[8] The thruster was not operated in a completely "floating" mode; rather, to insure effective neutralization by the hollow cathode neutralizer, the neutralizer was biased approximately 14 V negative with respect to the ground (the facility potential). Using this arrangement, the neutralizer emission current was made equal to the beam current. However, it should not be assumed that electrons from the tank walls do not contribute to neutralization. Complete neutralization is best verified by running the system in a completely "floating" mode. Operating conditions for the thruster were a 1 A beam current, 1.1 kV screen grid voltage, −0.35 kV accelerator grid voltage, 32 V discharge voltage, 8.0 A discharge current, and 0.95 propellant utilization efficiency.

Two probes were used to characterize the charge exchange plasma[3]: a cylindrical Langmuir probe and a retarding potential analyzer (RPA) probe. Both probes were mounted on a rail, which was placed in the chamber so that it was parallel to the thruster beam axis. At each location, measurements were made of the cylindrical probe collected current vs angle, plasma and floating potentials, and ion energy spectrum.

Computer Model

The following is a brief description of the theory and operation of the simulation.

Axial symmetry was assumed so that the problem could be reduced from three dimensions to two. In the region exterior to the beam, three basic physical conditions were assumed to hold for the ion population and/or the plasma as a whole. The first was the continuity of the ion current

$$\nabla \cdot j = 0 \tag{1}$$

where j is the ion current density. The barometric equation was also used to relate plasma density to local potential V

$$n = n_{0,\mathrm{ref}} \exp\left[(V - V_0)/\kappa T_e \right] \tag{2}$$

where V_0 is the potential at the reference density $n_{0,\mathrm{ref}}$ and T_e the electron temperature in the region exterior to the beam. Finally, the energy conservation for singly charged ions was represented by

$$|v| = \left[|v_0|^2 - 2e(V - V_0)/m_i \right]^{1/2} \tag{3}$$

where v is the ion velocity and m_i the ion mass. As a boundary condition at the beam edge, the ions were assumed to have acquired the Bohm velocity required for a stable sheath

$$|v_0| = |v_b| = (\kappa T_{eb}/m_i)^{1/2} \tag{4}$$

where T_{eb} is the electron temperature in the beam.

The computer code generated a numerical solution to these equations. Boundary conditions included the charge-exchange current density exiting the beam as a function of the distance from the grids, the geometry and potentials representing the spacecraft surfaces, and the zero potential outer boundaries far from the region of interest.

Ion trajectories for the assumed laminar plasma flow were calculated from equations of motion consistent with Eqs. (1-4). A set of self-consistent trajectories, densities, and potentials comprised the results of the simulation. This set was generated in a single pass with only local iteration and has been found to agree quite well with an available closed form solution for a simplified geometry.

In addition to the detailed plasma properties, a trajectory plot was generated using the computer model. This plot is reproduced in Fig. 2.

Comparison of Computer and Experimental Results

The experimental and computer model flow angles for the charge-exchange plasma are compared in Table 1 for a radial distance of 48 cm. The agreement is best in the position range from −10 to +10 cm downstream of the ion-optical plane (±5 deg). At 10-30 cm downstream, the experimental flow angle was 5-18 deg greater (toward the downstream direction) than that of the computer model. A comparison was possible only to −20 cm in the upstream direction, but the experimental flow angle was −5-12.5 deg relative to the computer results in the −10-20 cm range. The comparison was limited to −20 cm in the upstream direction due to the effects of facility-produced charge-exchange ions.

Thus, the general picture from Table 1 is one of fairly close agreement near the ion-optics plane and of an increasing difference between experimental and computer flow angles either upstream or downstream of this region. The difference between the experimental and computer results was such that the experimental values showed a larger range of flow angles: that is, closer to the upstream direction in the upstream region

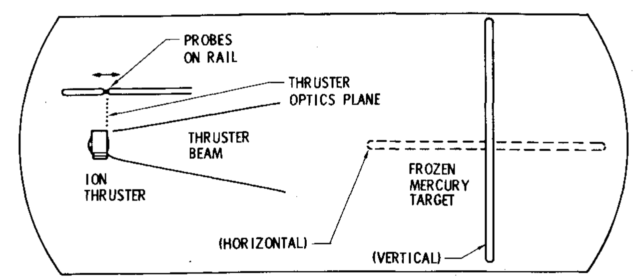

Fig. 1 Experimental arrangement (probes may move upstream or downstream of the thrust plane).

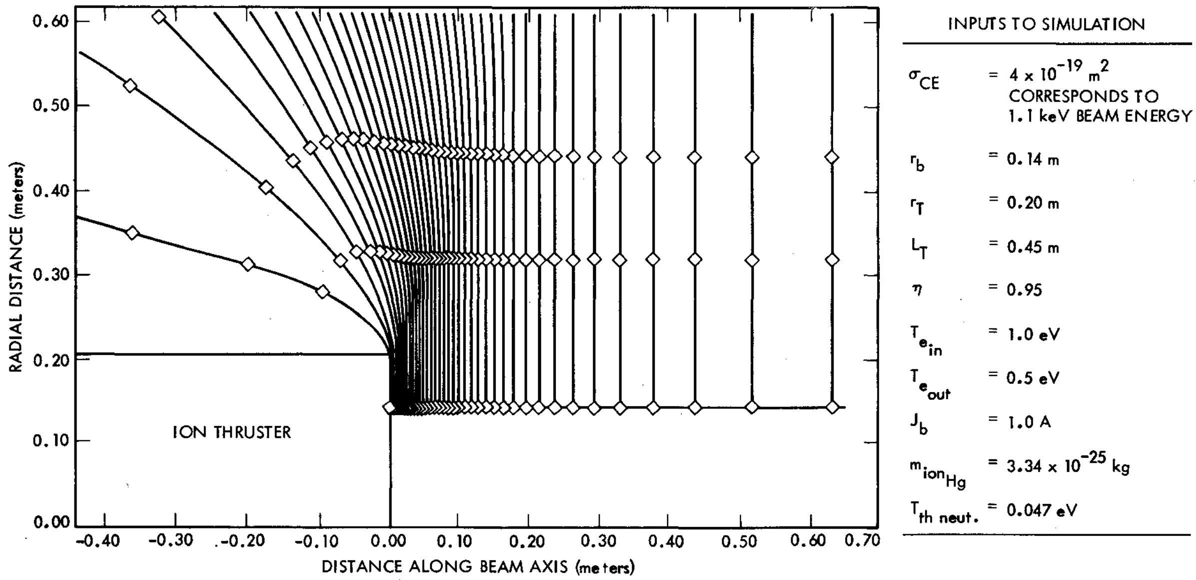

Fig. 2 Ion trajectories generated by computer model.

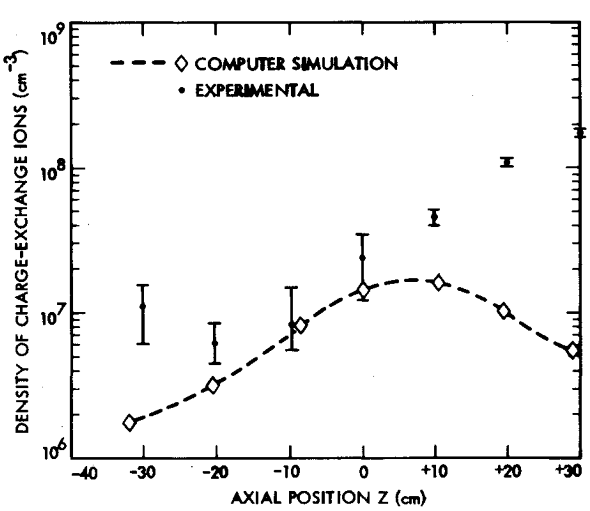

Fig. 3 Density of charge-exchange ions vs axial position.

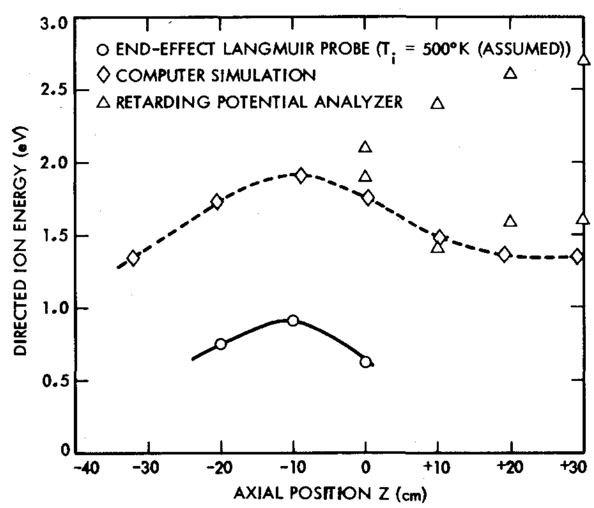

Fig. 4 Directed energy of charge-exchange ions vs axial position.

and closer to the downstream direction in the downstream region.

The charge-exchange plasma properties of density and directed-ion energy are shown in Figs. 3 and 4 for the experimental and computer results. The computer results generally showed lower densities and high directed-ion energies. All of these differences are consistent with a higher than experimental value of the electron temperature assumed for the computer model. The value assumed was 1.0 eV.. The electron temperature in the ion beam was not measured. No careful or accurate measurements of the electron temperature were made in the charge-exchange plasma region, but the results of some preliminary measurements indicated values of 0.2-1.0 eV (in the 0 to -30 cm region). These measurements were made using the end-effect Langmuir probe. However, in the same region, electron temperature calculations made using measured values of the plasma and floating potential and $T_e = e(V_p - V_f)/6.1$ indicate an almost constant electron temperature of the order of 0.3 eV. See Ref. 1 for a complete discussion of the measurements of electron temperatures in both the beam and charge-exchange regions of several thrusters, including the 30 cm. In this review paper, Carruth concluded that a direct measurement of T_e has not been made in either the charge-exchange plasma or the plasma beam of a modern 30 cm thruster.

The experimental and computer results agree within a factor of three for the plasma properties in Figs. 3 and 4 over the -10 to $+10$ cm range. If correction is made for a rough factor of two difference in the electron temperature, the difference decreases to less than a factor of two for these plasma parameters.

The ion energy shows agreement by about the same factor of two or three outside of the -10 to $+10$ cm range. The plasma densities, however, show a greater difference, with the experimental density up to 7 times greater at -30 cm and up to 30 times greater at $+30$ cm. The thruster charge-exchange ions in the experiment are not monoenergetic, but have a spread in both ion energy and flow direction.

The charge-exchange ions from the thruster, which are the ones of interest for space simulation, have their greatest density near the thruster. Facility contributions to the total density of the surrounding plasma became more important farther from the thruster. The data of Fig. 3 show the ion density from the end effect probe results. In the upstream regions (-10 and -20 cm), the probe results were corrected for the contribution of facility produced-ions (see Ref. 2 for more details), but in the downstream regions (0-30 cm) it was assumed that the end-effect probe measurement (which showed a single well-defined peak) was due only to the thruster charge-exchange ions. The high plasma density in the downstream regions makes the applicability of the theory used by Sanmartin[9] to reduce the data questionable.[2] At −30 cm, the ion density shown in Fig. 3 is thought to be due mainly to facility-produced ions.The experimental and computer results show the same general shape over the −20-0 cm range. The higher experimental values are again probably due to the electron temperature being assumed too high for the computer calculation. Outside of the −20-0 cm range, any discrepancies between the computer and experimental results may be due to the presence of facility ions (upstream and downstream) and the inapplicability of Sanmartin's theory to calculate the ion density. Furthermore, it must be pointed out that Sanmartin's theory is directed for an ion population that has a unique and singled directed energy (and flow direction).

The experimental and computer values of ion energy are shown in Fig. 4. In the −20-0 cm range, the two values show the same qualitative variation. As discussed previously, the absolute level of the computer values is higher by a factor of about two. Figure 4 shows values of the directed-ion energy as measured with a retarding potential analyzer probe (RPA). Results using this probe were obtained only in the region 0-30 cm due to the large angle between the RPA and the flow directions at positions upstream of the thruster. (The RPA was always pointed in the radial direction.) From Fig. 4, it can be seen that qualitative agreement is good in the 0-10 cm range, but that the average value of the RPA results increases with increasing axial distance. However, quantitative agreement in the whole range is good, being within a factor of two or better. The RPA results shown in Fig. 4 show two distinct values for the ion energy. Since this is a rather anomalous result, the following explanation is offered: the voltage, at which the collected current vs retarding grid potential curve has a point of inflection, gives the most probable ion energy. Two points of inflection then give rise to two values for the most probable velocity and indicate the presence of two ion populations. A tentative explanation of this effect might be the existence of the charge-exchange ions produced by the thruster and those produced by facility effects, but further measurements are needed to confirm this hypothesis.

Discussion

Considering the arbitrary nature of the electron temperature assumption for the computer model, the experimental and computer results are in close agreement for axial locations near the ion-optics plane. The effects that need to be discussed are those that occur farther upstream and downstream.

Ion Density

Considering first the ion density in the upstream region, to the extent that the data from the end-effect probe could be corrected for background ions, the experimental and computer results are again in good agreement. Further upstream than about −20 cm, the techniques used did not permit separation of the thruster charge-exchange ion density from the background plasma in the facility.

In the downstream direction, the experimental values of density were far greater than the computer values. This difference is believed due primarily to the divergence of the experimental ion beam.

The computer model beam was assumed to be perfectly collimated, so that potential differences within the beam gave initial velocities to charge-exchange ions in precisely the radial direction. The experimental ion beam, similar to most real beams, showed significant divergence. This experimental divergence introduced axial variations of ion density at a given radius, which through the barometric equation, produced axial components of electric field. (See Ref. 1 for a discussion of the barometric equation and the effect of density of variations on plasma potential.) The charge-exchange ions from the thruster that were directed upstream tended to come from the ion beam quite close to the ion optics (a small fraction of an ion beam radius). On the other hand, the charge-exchange ions that were directed downstream tended to come from the ion beam at a larger distance downstream (typically one ion beam radius or more). The beam divergence will therefore have only a small effect on the charge-exchange ion trajectories that leave the beam close to the ion optics. But those charge-exchange ions leaving the ion beam further downstream can experience significant acceleration in the axial (beam) direction. For example, a charge-exchange ion formed near the center of the ion beam will be subjected to a predominantly axial acceleration. In general, the closer to the beam axis that a charge-exchange ion is formed, the greater the component of axial velocity that will be attained before escaping from the ion beam. The magnitude of this effect will depend on the degree of ion beam divergence. Therefore, the experimental effect shown in Fig. 3 cannot be considered as general.

Table 1 Comparison of flow angles ($R = 48$ cm from axis of thruster)

Position (from optics) z, cm	Experimental flow angle, deg	Computer model flow angle, deg
30	18	0
20	10	0
10		0
0	−16	−16
−10	−33	−28
−20	−54	−41.5

Most of the experimental increase in the charge-exchange ion density in the downstream direction is thus felt to be due to the effects of ion beam divergence. Some of the increase may also be due to propellant neutrals from the ion beam returning to increase the local neutral density. Because the experimental and computer results are in excellent agreement close to the plane of the ion optics, it is felt that this enhanced neutral density is significant only further downstream.

The upstream region is probably more important, because in a properly designed spacecraft the downstream region is best avoided to reduce the direct deposition of sputtered material from the ion optics. In this upstream region, the facility effects have been shown to be significant in that the end-effect probe results indicate the presence of two distinct ion peaks. In Ref. (3), these two peaks were identified with both the thruster- and facility-produced exchange ions. The major effect of the background ions on the thruster charge-exchange ions is to reduce (through the barometric equation) the potential variations in the surrounding plasma. From the background facility ions, then, one would expect fewer charge-exchange ions to be turned in the upstream direction.

The reasoning here is that regions having few ions also (through quasineutrality) have few electrons. From the barometric equation, a region with few electrons must also have relatively negative potential. The electric fields associated with this negative potential tend to deflect charge-exchange ions into such a low-density region. With the presence of a significant facility background plasma, the tendency to "fill up" such regions with charge-exchange ions will be reduced. The presence of a facility background plasma should therefore result in a lower charge-exchange ion density upstream of the thruster.

From a quantitative viewpoint, the above effect should not be large in the experimental facility used. This is because most of the deflection of charge-exchange ion trajectories normally occurs near the thruster. (See Fig. 2.) It has already been established that the environment close to the thruster should be substantially free of facility effects, because the charge-exchange thruster ions are much more dense at that location. The majority of the trajectory deflection for charge-exchange ions should thus not be influenced by the facility background.

Flow Angle

When the experimental flow angles are compared to the computer model values, it is found that the experimental values actually show more trajectory bending (more negative flow angles) in the upstream region. The difference was therefore opposite to what would be expected from the presence of a facility background plasma.

It was ncessary to look elsewhere for this discrepancy in flow angles. The computer model assumed "laminar" flow for charge-exchange ions—that is, no crossing of the ion trajectories. A related assumption was the uniformity of the charge-exchange ion energy at the edge of the ion beam. It should be apparent that different charge-exchange ions will originate in different locations within the ion beam. Their energy upon leaving the ion beam will reflect the potentials at their points of origin. The low-energy portion of the charge-exchange ion distribution will, of course, be deflected more easily than the high-energy portion. The charge-exchange ions that are deflected upstream will therefore include not only those ions leaving the beam closest to the thruster, but also lower-energy ions from further downstream. In short, the assumption of "laminar" flow cannot be strictly true.

For example, if we consider a charge-exchange ion with half the mean value of kinetic energy, the same electric fields will result in a 41% greater deflection (for small angles) than for an ion with the mean kinetic energy. From Fig. 3, the experimental upstream density at -20 cm is only about one-third of the value at 0 cm. From this low density, it appears likely that charge-exchange ions deflected upstream came almost entirely from those leaving the ion beam with less than the mean value of kinetic energy. At -20 cm the difference in the flow angle is 12.5 deg, or about 30% of the 41.5 deg deflection from the normal direction predicted by the computer model. The observed difference between experimental and computer model results in the upstream region thus appears consistent with the distribution of charge-exchange ion energy found in the experiment.

The experimental flow angles in the downstream direction also showed a large departure from the computer model values. This difference in flow angles was felt to be due primarily to the beam divergence effect discussed in connection with the charge-exchange ion density. Because the charge-exchange ion density at $+20$ and 30 cm was very large, it appears unlikely that a small fraction of lower-energy ions could play a significant role in this downstram region. Unlike the upstream region, the assumption of monoenergetic charge-exchange ions in the computer model is not felt to be important for the downstream region.

The facility background plasma should also be considered for an effect on flow angles in the downstream region. Using a logic similar to that discussed for the upstream region, the presence of a background plasma would be expected to result in charge-exchange ions following more radially directed paths. A background plasma should thus tend to reduce the difference indicated in Table 1 for the downstream region. The same would also be true of an enhanced neutral density downstream of the thruster, which would extend the region of charge-exchange with beam ions.

Electron Temperature

As discussed in connection with the data of Figs. 3 and 4, it is believed that the electron temperature in the computer model was higher in the experiment by roughly a factor of two. For the computer model, this temperature is one of the inputs, so changing it is not a serious problem. For the experimental approach, an additional effort to measure this quantity in future tests can probably be justified. A more serious problem is the electron temperature that would be expected in space.

Conclusions

The general agreement between experiment and computer model was excellent near the plane of the thruster ion optics. Most of the differences in this region appeared to be due to the assumed temperature for the computer model being about a factor of two too high.

Upstream of the ion-optics plane, the facility contribution to the background plasma was important. By proper use of the end-effect probe, it was possible to separate the charge-exchange ion contribution from this general background plasma for a distance of 20 cm upstream of the ion optics. Analysis of this charge-exchange contribution indicated that the major difference in ion density due to the difference in assumed energy distribution was less than a factor of two in this upstream region after subtracting the background plasma density. The flow angles differed by as much as 12.5 deg (about 30% of the computer model flow deflection from the normal direction).

Inasmuch as the primary interest in the charge-exchange plasma concerns spacecraft interactions and the spacecraft is almost always restricted to a region upstream of the ion optics, the region downstream of the ion optics appears to be less important. The major differences between experiment and computer model in the downstream region appeared to be due to experimental effects of ion beam divergence.

The prediction of electron temperature in the space environment appears to be a major problem in either ground experiments or computer models. Until there is a better basis for predicting electon temperatures, either from continued analysis or more space experiments, the validity of ground or computer simulation wll be in question.

The electron energy in the beam and charge-exchange plasma comes from the initial temperature of the electrons as they are injected, plus their injection energy. Within the beam, electron energy is lost due to the expansion of the electron gas as an element of plasma flows downstream and expands. At the same time, conduction within the electron gas carries energy from near the injection point (the neutralizer) to the cooler downstream region. A similar process occurs within the charge-exchange plasma surrounding the thruster. At a sufficient distance from the spacecraft, the charge-exchange and beam plasmas make contact with the ambient space plasma. The space plasma thus constitutes a boundary condition to the energy balance of electrons and hence the electron temperature. As discussed by Carruth, this comprehensive problem of electron temperature in space has not been solved. It is therefore not clear to what extent the electron temperature in a ground test will agree with that obtained in a space test. In the only comparison available (SERT II), the injection energy and resultant electron temperature were quite high. As also discussed by Carruth,[1] high electron temperatures have generally been associated with low electron conductivity in the beam and charge-exchange plasmas. Thus, in the SERT II test, this low electron conductivity may have served to isolate the electron population near the thruster from the surrounding space plasma. For the lower electron temperatures typical of larger thrusters, less isolation would be expected. If the electron temperature problem is not understood in the space environment, simulation of the space environment in a ground facility can be difficult.

Acknowledgments

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS 7-100.

This paper drew from sources where large contributions were made by Ralph Carruth Jr., William D. Deininger, Raymond S. Robinson, and Shoji Kitamura. Their work is especially acknowledged.

References

[1] Carruth, M.R. Jr. "A Review of Studies of Ion Thruster Beam and Charge-Exchange Plasmas," AIAA Paper 82-1944, Nov. 1982.

[2] Carruth, M.R. Jr. and Brady, M.E., "Measurement of the Charge-Exchange Plasma Flow From An Ion Thruster," *Journal of Spacecraft and Rockets,* Vol. 18, Sept-Oct. 1981, p. 457.

[3] Carruth, M.R. Jr., Gabriel, S.B., and Kitamura, S. "Ion Thruster Charge-Exchange Plasma Flow," *Journal of Spacecraft and Rockets,* Vol. 19, Nov-Dec. 1982, p. 571.

[4] Robinson, R.S., Kaufman, H.R., and Winder, D.R., "Simulation of Charge-Exchange Plasma Propagation Near an Ion Thruster Propelled Spacecraft," AIAA Paper 81-0744, 1981.

[5] Katz, I., Parks, D.E., Mandell, M.J., and Schnuelle, G.W., "Parasitic Current Losses Due to Solar-Electric Propulsion Generated Plasmas," *Journal of Spacecraft and Rockets,* Vol., 19, March-April, 1982, pp. 129-132.

[6] Ogawa, H.S., Cole, R.K., and Sellen, J.M., Jr. "Measurements of Equilibrium Potential Between a Plasma 'Thrust' Beam and a Dilute 'Space' Plasma, " AIAA Paper 69-263, 1969.

[7] Ogawa, H.W., Cole, R.K., and Sellen, J.M. Jr., "Factors in the Electrostatic Equilibrium Between a Plasma Thrust Beam and the Ambient Space Plasma," AIAA Paper 70-1142, 1970.

[8] Staff, NASA Lewis Research Center, "30 Centimeter Ion Thruster Subsytem Design Manual," NASA TM-79191, 1979.

[9] Sanmartin, J.R., "End-Effect in Langmuir Probe Response Under Ionospheric Satellite Conditions," *Physics of Fluids,* Vol. 15, No. 6, June 1972, pp. 1134-1143.