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Spacecraft-Generated Plasma Interaction with High-Voltage Solar Array

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Calculations are made of the effect of interactions of spacecraft-generated plasmas and high-voltage solar array components on an advanced solar electric propulsion system. The plasma consists of mercury ions and electrons resulting from the operation of ion thrusters and associated hollow cathode neutralizers. Because large areas of the solar array are at high potential and not completely insulated from the surrounding plasma, the array can, under some conditions, collect excessive electron currents. Results are given for the parasitic currents collected by the solar arrays, and means for reducing these currents are considered.

Nomenclature

d = thickness of the sheath separating surface of the array from the plasma
f = fraction of solar cell area occupied by exposed metallic interconnector
I = total parasitic current collected by solar array
I_{MPP} = array current at peak power
j = plasma thermal electron current density
J_B = ion current from a single thruster
L_P = length scale on which plasma density varies
L_V = length scale on which array potential varies
m = electron mass
M_n = mass of neutral mercury atom
n_n = neutralizer-generated plasma density
n_x = charge-exchange-generated plasma density
N_T = number of operating thrusters
$\dot{N}_n$ = rate of production of plasma by a neutralizer
$\dot{N}_x$ = rate of production of charge-exchange ions by one thruster
q = electron charge
r = radial distance from beam axis
r_b = radius of ion beam
T_e = electron temperature
T_n = temperature of neutral species
v_n = mean thermal velocity of neutralized ion
v_r = mean radial velocity of Hg ion
v_z = mean axial velocity of Hg ion
$\bar{v}$ = mean thermal velocity of plasma electron
V = voltage on array
$\bar{V}$ = area average of voltage on solar cell surface
V_{MPP} = array voltage at peak power
w = width of solar cell array
w_{eff} = effective width of solar cell array for electron collection
z = axial distance from thruster accelerating grids
z_l = axial half-extent of charge-exchange ion production volume
ϵ = ratio of effective collection width to geometrical width of array
σ = measure of axial spreading of radially expanding plasma

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Introduction

THE purpose of this paper is to assess the effect of interactions of spacecraft-generated plasmas with high-voltage solar array components on the performance of an advanced solar electric propulsion (SEP) system proposed for the Halley's Comet rendezvous mission. The spacecraft-generated plasma consists of mercury ions and neutralizing electrons resulting from the operation of ion thrusters and associated hollow cathode neutralizers.

Problems associated with the interaction of plasmas and high-voltage solar arrays have been studied by Kaufman[1] and by Herron et al.[2] Because large areas of the solar array are at high potential and not completely insulated from the surrounding plasma, the array can, under some conditions, collect exessive electron currents from the plasma. Estimates of the magnitude of such currents are presented in the following sections of this paper. The principal elements in estimating spacecraft-generated plasmas are 1) the rate of production of plasma, 2) the quantitative description of the plasma as it expands away from the space region within which it is generated, and 3) the rate at which solar array com-

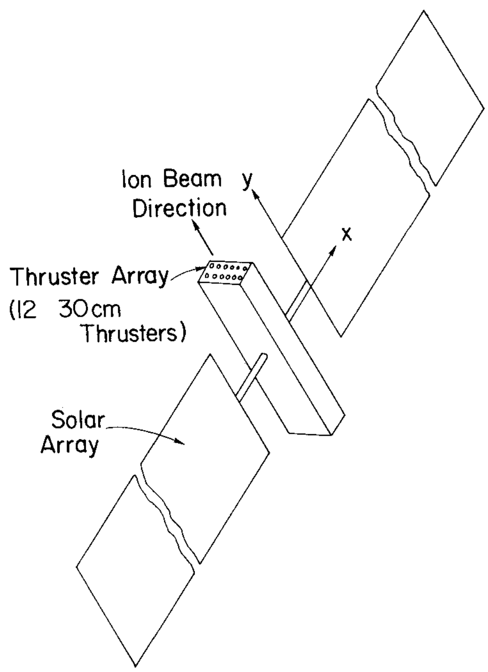


Fig. 1 Schematic illustration of spacecraft configuration.

ponents extract charged particles as a function of array voltage with respect to the plasma.

The rate of generation of the charge-exchange ions has been studied theoretically by Poeschel et al.[3] as well as by Kaufman.[1] In particular, the results of Poeschel et al. on charge-exchange and neutralizer plasma production rates were used as input for our calculation of the interactions between thruster plasmas and solar arrays. Komatsu and Sellen,[4] having conducted extensive studies of charge-exchange plasma production and expansion from a thruster operating in a 5×11 ft chamber, assert that their results appear to confirm analytical models of charge-exchange ion production. Measurements of electron density are within a factor of 2 of the densities estimated from simple analytical models of plasma expansion.[1] The measurements, however, extend only over a small region located at about two thruster radii from the axis of the ion beam. Limited facility dimensions preclude firm conclusions regarding the density of charge-exchange plasma at large distances from the thruster and its interaction with long (~60 m) solar arrays.

Detailed studies of electron collection by a complex but small (1 ft^2) solar array have been conducted in ground test facilities by Kennerud.[5] The measurements were made for a solar panel with bare interconnectors exposed to plasmas with electron densities ranging up to about 10^4 /cm^3. For positive bias potentials ranging up to 10^4V, measured plasma leakage current was within a factor of 3 of predictions made by Kennerud on the basis of extensions of simple electrostatic probe theories. Similar experiments[6] give results in substantial agreement with those of Kennerud.

It appears that the aforementioned studies have provided a basis for predicting the interaction of spacecraft-generated plasmas with high-voltage solar arrays. Based on the preceding discussion, it also appears however that the status of theory and experiment does not justify confidence in predictions of the parasitic currents to large solar arrays and the effect of these currents on the power generated by such arrays.

In view of the limitations inherent in both theory and experiment, it is appropriate not only to estimate the effects of spacecraft-generated plasmas on solar array performance, but also to explore the sensitivity of estimates to the parameters that characterize these plasmas. Estimates of the effect of parasitic currents from spacecraft-generated plasmas on the performance of SEP systems are given subsequently. The models invoked to perform these estimates are simple variants of the models used by previously mentioned authors.

The present calculations extend previous theories by considering that the voltage along the array varies with position, rather than having a single value, and by introducing a model of plasma transport that permits wide departures from spherically symmetric expansion of the plasma cloud. In making estimates the voltage distribution on the solar panels is considered to be fixed; that is, the panel voltages are assumed not to shift as a result of collection of charged particles. The same assumption has been made in previous theoretical studies. Finally, currents collected from the solar wind environment are negligible[6-8] and are not further considered.

Statement of the Problem

Consider a spacecraft configured as a direct-drive planar array, shown schematically in Fig. 1.[3] The x-y coordinate system is fixed in the plane of the solar array. The propulsion module can be rotated about the x axis, which is directed along the long dimension of the array. Throughout most of the proposed Halley's Comet rendezvous mission, the module would be oriented such that the thruster ion beams are nearly parallel to the plane of the solar arrays; that is, they are nearly parallel to the y axis. Various orientations occur during the early part of the mission when the spacecraft is within about 1 AU (astronomical unit) from the sun. For present purposes the ion beams are considered as either parallel or perpendicular to the y axis.

The spacecraft configuration proposed for the high-voltage direct-drive systems is adequately represented by Fig. 1. The electric propulsion subsystem employs twelve 30-cm-diameter electron-bombardment mercury ion thrusters mounted in a 6×2 array, as indicated in Fig. 1. The separation between thruster centers is approximately 60 cm. Each thruster generates up to 2.5 A of beam ion current with energies in the range 1-4 kV. A hollow cathode neutralizer located on each thruster supplies electrons to the beam to neutralize the ion current and maintain charge neutrality. Each solar array is 60 m long by 8 m wide and can generate about 60 kVA of electric power at a distance of 1 AU from the sun. The inboard end of the array is at a distance of 3 m in the x direction from the centerline of the thruster assembly. The array axis is separated by 1 m in the y direction from the plane defined by the accelerating grids of the thruster. Table 1 summarizes the parameters for the direct-drive thrust system that are employed in subsequent calculations.

The conventional low-voltage systems that employ reflectors to concentrate the solar radiation (C/C systems) incident on the solar array are geometrically more complex than indicated in Fig. 1 (see Fig. 2). This added complexity, however, does not crucially impact the estimates of effects of parasitic currents on the performance of these low-voltage systems. The relevant computational parameters of this system are the same as for the direct-drive system, except as indicated in parentheses in Table 1.

The voltage distribution $V(x)$ is taken to depend only on the position x along the array (it is independent of y). For the direct-drive case, an array voltage reconfiguration is performed at 2.2 AU. The two voltage configurations for the direct-drive case are given in Figs. 3 and 4, including scale factors to determine voltage distribution as a function of heliocentric distance. Figure 5 shows the voltage distribution for the C/C system. The figures also summarize assumed conditions of operation at various distances of the spacecraft from the sun.

On the basis of simple variants of previously referenced models of spacecraft-generated plasmas, parasitic currents collected by the array for the direct-drive thrust system/flat solar array and conventional thrust/concentrator solar array are estimated.

Spacecraft-Generated Plasma

The charge-exchange plasma density in space is determined from the plasma generation rate in the ion beam and the assumed manner in which the plasma expands. According to Poeschel et al.[3] (see Fig. 6), practically all of the charge-exchange ions are produced within the first few tens of

Table 1 Parameters used for results tabulated in Tables 2-5

Electron temperature	5 eV
Charge exchange ion radial energy	10 eV
Ion mass	200 AMU
r_b	0.15 m
z_l	0.20 m
Panel width w	8 m (9)[a]
Distance of panel axis from thruster plane	1 m
Minimum radius of panel	3 m (39.5)[b]
Maximum radius of panel	63 m (64.5)
Exposed area fraction f	0.1 (0.05)
Neutralizer current $\dot{N}_n$	5 mA
$\dot{N}_x$ for 2-A beam	25 mA
The calculations assume that $\dot{N}_x$ is proportional to ion current.	

[a] The quantities in parentheses apply to the C/C system.
[b] The positive voltage for the C/C systems begins at 39.5 m.

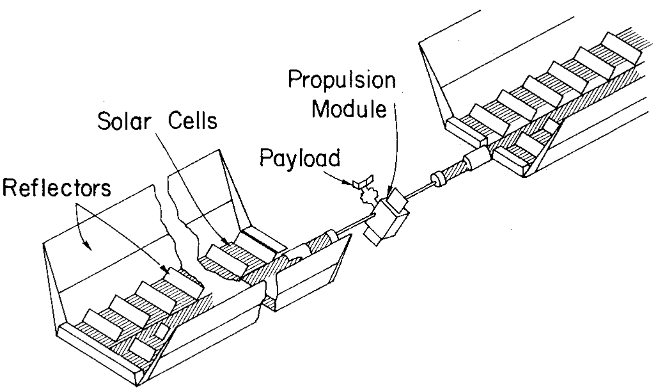
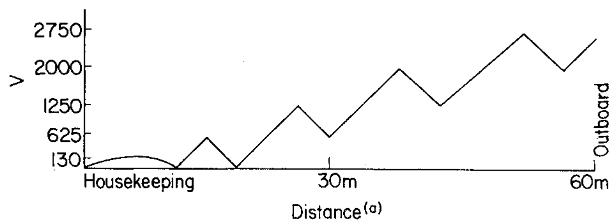


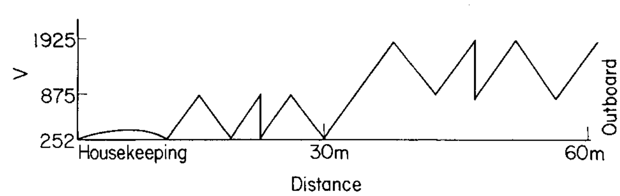
Fig. 2 Solar electric propulsion with concentrating reflectors.



AU	Thruster	J_B (A)	V_{MAX} (V)
1.0	12	2.5	2750
1.6	12	1.0	3438
	6	2.0	3438
2.2	6	1.0	3850

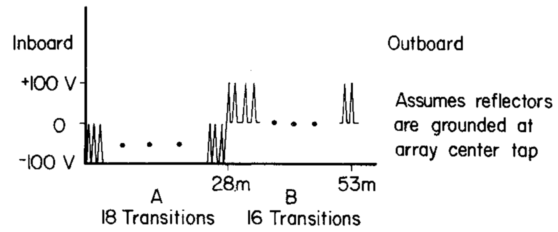
[a] From inboard end of array.

Fig. 3 Direct-drive voltage distribution – configuration 1.



AU	Thrusters	J_B (A)	V_{MAX} (V)
2.2	6	2.0	1925
2.6	6	1.33	2040
	4	2.0	2040
3.4	4	1.0	2195
	2	2.0	2195
4.5	2	1.25	2291

Fig. 4 Direct-drive voltage distribution – configuration 2.



		THRUSTER		
AU	Thrusters	V_{MPP} (V)	I_{MPP} (A)	J_B (A)
1.0–1.8	8	200	133	2.0
4.4	2	350	20.4	1.6

Housekeeping occupies two inboard panels (two voltage transitions)

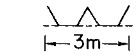


Fig. 5 Voltage distribution on array with concentrating reflectors.

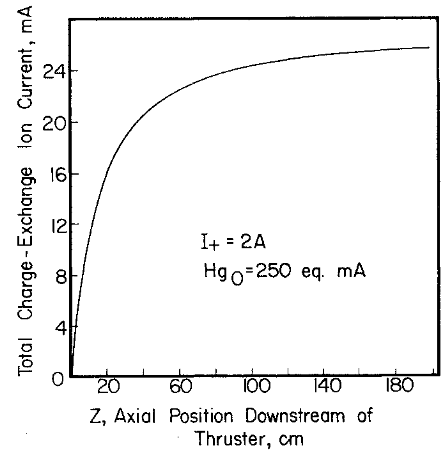


Fig. 6 Total charge-exchange ion formation.

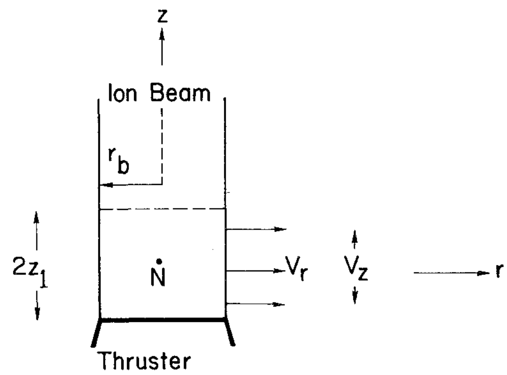


Fig. 7 Geometry for modeling charge-exchange ion plasma.

centimeters downstream from the thruster. The ordinate in Fig. 6 is the total charge-exchange ion current generated from a single thruster in the interval from $z=0$ to a distance z downstream from the thruster. Approximately 75% of the charge-exchange ions are formed within a downstream distance equal to one thruster diameter (30 cm). They emerge from the ion beam with a predominantly radial drift velocity (perpendicular to the beam axis) corresponding to an energy of about 10 eV. The emerging charge-exchange ions will also have velocity components parallel to the beam axis, caused either by the velocity distribution of neutrals or by the presence of small axial components of electric field. The mean axial velocity is denoted by

$$v_z = \sqrt{8kT_n/\pi M_n} \tag{1}$$

Assume, therefore, that the charge-exchange plasma spreads axially as it moves radially and for definiteness, take the axial density profile at a given radial point to be Gaussian. The beam spreading becomes effective, however, only for radial distances $(r-r_b) > (v_r/v_z)z_l$ sufficiently large compared to the axial dimension of the production volume (see Fig. 7). A model for the charge-exchange plasma density that exhibits these features is

$$n_x(r,z) = [\dot{N}_x \exp(-z^2/\sigma^2)/2\pi^{3/2} r v_r \sigma] N_T \tag{2}$$

where

$$\sigma = z_l + (r - r_b)(v_z / v_r) \tag{3}$$

Moreover, the integral of Eq. (2) over z reduces to the conservation law for the cylindrically symmetric radial expansion of particles away from an axial source.

The neutralizer also contributes plasma from which the array may draw electrons. Assume that this plasma expands spherically with velocity given by the mean thermal velocity v_n of neutralizer ions and a total current ranging from about 1 to a few milliamperes. Particle conservation requires that

$$n_n = (\dot{N}_n / 4\pi R^2 v_n) N_T \tag{4}$$

where

$$R^2 = r^2 + z^2$$

Equations (2) and (4) assume that the total spacecraft-generated plasma density is proportional to the number of operating thrusters, an assumption that is valid for thrusters that are sufficiently far apart. Calculations[3] indicate that about 75% of the total charge-exchange ions generated by one thruster are formed within a downstream distance of one thruster diameter (30 cm). Moreover, the considered thruster array has centers separated by at least 60 cm, a separation large enough that the density of neutrals near a given thruster is dominated by the neutral efflux from that thruster. Thus it is justified to neglect the effects of neutral efflux from one thruster passing through the ion beam of neighboring thrusters.

The calculations[3] conclude that for a single thruster with an ion beam current of 2 A and a neutral mercury efflux of 250 mA equivalent, the total rate of charge-exchange ion production is 25 mA. Here it is assumed that $\dot{N}_x$ is proportional to beam current over the range (1-2.5 A) of beam current of interest.

It is implicit in Eqs. (2) and (4) that the space points of interest are far enough removed from the thrusters to justify neglect of the finite separation of separate thrusters. This assumption is valid over most of the solar array, but not at the part of the low-voltage end that is removed by only 3-4 m from the thruster assembly. Accounting for the finite extent of the array would lead to decreased values of estimated parasitic currents collected by the array.

The total plasma electron current is the sum of the neutralizer and charge-exchange plasma contributions. Assuming that both components of the plasma have the same electron temperature T_e, this current is given by

$$j = (n_x + n_n) q \bar{v} / 4 \tag{5}$$

where

$$\bar{v} = (8kT_e / \pi m)^{1/2} \tag{6}$$

Positive ion currents are small and of no interest in the present context.

Electron temperatures that have been measured in thruster ion beams and in the nearby charge-exchange plasmas are in the range of a few electron volts.[1,4] Here one assumes $T_e = 5$ eV everywhere, although it is by no means clear that electrons should remain isothermal over distances of many tens of meters.

Electron Collection

Electron collection rates depend on the panel voltage distribution, the exposed metallic interconnect area, the properties of the plasma, and in general, on the geometry of the collection surface. A single cell of the array is shown

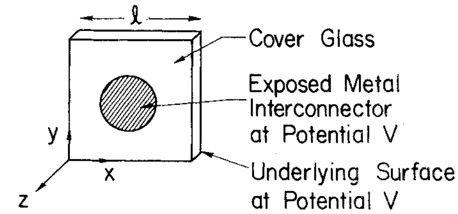


Fig. 8 Schematic representation of solar cell with exposed interconnector.

schematically in Fig. 8. Consider for the moment that the cell is one member of an infinite two-dimensional periodic array of identical elements, each with the interconnector and the material beneath the insulator at the same potential V. Except near the edge of the array, this is an excellent approximation, since the typical solar cell dimension l is small compared to the characteristic length $L_V = V / |dV/dx|$ over which the potential V varies. The spacecraft-generated plasma density and current have characteristic lengths of spatial variation $L_P = n / |\nabla n|$ which are also much greater than l, except possibly within the sheath between the cell surface and the main body of plasma.

The thickness d of the sheath separating the cell surface from the neutral spacecraft-generated plasma can be determined from the Child-Langmuir equation for plane geometry provided that its thickness is large compared to l (and small compared to L_V and L_P). For $z \gg l$, potential variations in the x and y directions are small compared with variations in the z direction, and the electric field will be very nearly equal to that which would be produced by an equipotential cell-surface at the average potential $\bar{V}$ defined by

$$\bar{V} = \int_{\text{cell}} V(x,y)\,dx dy \Big/ \int_{\text{cell}} dx dy \tag{7}$$

The sheath thickness d is then determined from the Child-Langmuir equation using the average surface potential relative to plasma ground:

$$j = 2.32 \times 10^{-6} (\bar{V}^{3/2} / d^2)\ \text{A/m}^2 \tag{8}$$

where d is in meters and $\bar{V}$ in volts. For plasma electron currents in the range $10^{-3} = 1$ A/m^2 and $\bar{V} \sim 10^2 = 10^3$ V, d ranges from 8 m to 5 cm. In any case it is typical of the high-voltage arrays considered here that the relevant sheath thicknesses are comparable to or larger than cell dimensions, and it is reasonable to consider that the plasma sees the average local array potential; even then, however, an error would occur when $d \gtrsim L_V$. If d from Eq. (8) were small compared to the cell dimensions, then there could be nonoverlapping sheaths around each exposed interconnector, and in the limit of small voltages, the current drawn from the plasma would be proportional to the interconnector area rather than the cell area. Here only the worst case, namely, in which the interconnect collects the entire solar cell's share of the plasma current, is explored.

At a given position x along the array, the sheath thickness d permits an estimate of the effective width of the panel for electron collection:

$$w_{\text{eff}} = w + (d_l + d_2)/2 \tag{9}$$

as illustrated in Fig. 9 for the case $d_l = d_2 = d$, where the plasma is uniform over the array width.

Throughout the calculation assume the required average voltage $\bar{V}$ is taken to be $\bar{V} = fV$. This assumption, which implies that the insulator supports the full voltage drop between the solar cells and the plasma, is questionable. The actual voltage distribution on the insulator is not well known, and its theoretical determination would involve poorly un-

Table 2 Solar electric propulsion direct-drive parasitic current (beam ∥ to array)

Distance, AU	Thrusters	Configuration	Total beam current, A	Current/array, A		
				< = 5.7 deg	< = 35 deg	Spherical
1.0	12	1	30	29.1	14.1	11.1
1.6	12	1	12	13.0	7.8	6.5
1.6	6	1	12	12.4	6.2	5.0
2.2	6	1	6	7.2	4.0	3.4
2.2	6	2	12	12.1	6.1	4.8
2.6	6	2	8	8.7	4.6	3.8
2.6	4	2	8	8.2	4.1	3.3
3.4	4	2	4	4.8	2.7	2.2
3.4	2	2	4	4.2	2.1	1.7
4.5	2	2	2.5	2.9	1.6	1.3
Concentrator/conventional parasitic current (beam ∥ to array)						
1.0	8	...	16	1.8	0.49	
4.4	2	...	3.2	0.52	0.18	

Table 3 Solar electric propulsion direct-drive parasitic current (beam ∥, spherical expansion – insulated for $V \leq 500$ V)

Distance, AU	Thrusters	Configuration	Current/ array, A
1.0	12	1	1.4
1.6	12	1	0.93
1.6	6	1	0.75
2.2	6	1	0.81
2.2	6	2	0.89
2.6	6	2	0.72
2.6	4	2	0.64
3.4	4	2	0.46
3.4	2	2	0.37
4.5	2	2	0.30

Table 4 Solar electric propulsion direct-drive parasitic current (beam ∥, ∠ = 5.7 deg, 10 mA/per 2 A, 1mA per neutralizer, insulated for $V \leq 500$ V)

Distance, AU	Thrusters	Configuration	Current/ array, A
1.0	12	1	3.0
1.6	12	1	1.5
1.6	6	1	1.4
2.2	6	1	1.1
2.2	6	2	1.5
2.6	6	2	1.1
2.6	4	2	1.1
3.4	4	2	0.61
3.4	2	2	0.60
4.5	2	2	0.42

derstood mechanisms of charge transport from the insulator surface to the exposed interconnector.

Computational Results

The quantity designated in Tables 2-5 as current/array (I) is defined by

$$I = \int_{\text{array}} j(x,y)\epsilon(x)\,\mathrm{d}x\mathrm{d}y \tag{10}$$

where

$$\epsilon(x) = 1 + [\pi(d_1 + d_2)/2w] \tag{11}$$

[see Eq. (9)]. To perform the integrations, each solar cell array is divided into a rectangular grid consisting of 20 zones along the length of the array and 4 zones along the width. The dimensions of each zone (2×3 m) are small compared with the distance scale on which the density of the nearby spacecraft-generated plasma varies.

Input parameters used to obtain results given in Table 2 for direct-drive and concentrator/conventional (C/C) systems are tabulated in Table 1. The results in Table 3 also use the input parameters of Table 1, but here all portions of the array below 500 V are assumed to be insulated from the surrounding plasma. For Tables 4 and 5, the charge-exchange ion generation rate has been reduced to 10 mA per 2 A of thruster ion beam current, and the neutralizer plasma generation rate has been reduced to 1 mA per neutralizer.

The notation "beam ∥" means that the thruster ion beams are parallel to the plane of the arrays. Calculated parasitic currents are not substantially different for other relative orientations of the ion beam direction and the plane of the array. The angles (< = 5.7 deg, < = 35 deg) labeling the "Current" columns are computed from

$$< = \tan^{-1}\sqrt{T_n/T_i} \tag{12}$$

where $T_i = 10$ eV. The effective neutral temperatures $T_n = 0.1$ eV and $T_n = 5$ eV give expansion angles of 5.7 and 35 deg, respectively, the former temperature being close to the

Table 5 Solar electric propulsion direct-drive parasitic current (beam ∥, 10 mA/per 2A, 1 mA/per neutralizer)

Distance, AU	Thrusters	Configuration	Current/array, A	
			∠ = 5.7 deg	Spherical
1.0	12	1	11.3	3.9
1.6	12	1	5.2	2.1
1.6	1		4.9	1.8
2.2	6	1	2.7	1.1
2.2	6	2	4.7	1.7
2.6	6	2	3.3	1.3
2.6	4	2	3.2	1.2
3.4	4	2	1.8	0.73
3.4	2	2	1.7	0.62
4.5	2	2	1.1	0.45

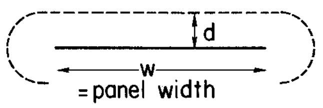


Fig. 9 Collection by an array of cells. The effective collection area is greater than the panel area.

temperature of the neutral efflux, the latter to the electron temperature.

For comparative purposes, total beam current is also listed in Table 2.

In explanation of the results for the C/C system in Table 2, the computations incorporated the following simplifying assumptions:

1) Ion curents were neglected.

2) Electron currents to the negative potential portions of the panel were neglected.

3) The entire positively biased portion of the panel was assumed to be uniform at the maximum potential (100 V at 1.0 AU; 275 V at 4.4 AU).

Finally, in all computations it is assumed that collection of parasitic currents occurs on only one side of each array.

Discussion of Effects of Spacecraft-Generated Plasmas

From the results of Table 2, one concludes for direct-drive systems that the total parasitic current passing through the low-voltage end of the array is in all uninsulated cases at least ~40% of the total beam current. The results suggest that the parasitic plasma currents may substantially impact the capability of the array to deliver the high voltage required to accelerate the thruster ions. The results in Tables 3-5 indicate that the adverse impact of parasitic currents is substantially reduced by insulating the low-voltage (≤ 500 V) portions of the array, which are near the thruster assembly and are therefore exposed to the highest plasma current densities, and by reducing the charge exchange and neutralizer plasma generation rates. Implicit in the use of insulation is the assumption that pinholes are not formed. If they are, the large pinhole currents of the kind observed by Kennerud[5] and by Domitz and Grier[9,10] for positive biases $\gtrsim 100$ V would nullify the effects of insulation.

The results presented here and the conclusions extracted therefrom are based on an analytical model which should be scrutinized by more careful theoretical analysis and/or by experiments that simulate the large length scales that are inherent in the proposed application of ion thrusters on deep space probes.

The results in Table 2 for the concentrator/conventional system invoke extreme assumptions, and in the context of the model for the spacecraft-generated plasma, represent an extreme worst case. Even so, the parasitic currents collected are a small fraction of the beam current, and are even smaller fractions of the array-generated current.

Conclusions and Recommendations

The present study indicates potential problems in the performance of high-voltage solar arrays as a result of their interaction with electric thruster-generated plasmas. The study also indicates, however, that the collection of parasitic plasma currents can be substantially reduced

1) by having low voltages on the parts of the array nearer to the thrusters;

2) by insulating the low-voltage ($\lesssim 500$ V) portion of the array (assuming that pinholes are not present in the insulation); and

3) by maintaining the charge-exchange ion and neutralizer currents at the lowest levels compatible with the mission requirements of the thruster system.

Theory is reasonably well confirmed on the spatial scale (approximately a few meters) of laboratory experiments. The theoretical foundations are not sufficiently firm, however, to permit one to confidently extrapolate the effects of spacecraft-generated plasmas to large (~60 m) solar arrays. Experiments at low Earth orbit to measure thruster interaction with a distant high-voltage surface would provide a stringent test of theoretical models.

Ground-based experiments can be performed to improve knowledge of collection of parasitic currents by geometrically complex, partially insulated surfaces at high potential. These experiments, conducted in a large plasma chamber, would include measurements of

1) sheath properties around a small (~1 m^2) solar panel exposed to various plasma environments in a large plasma chamber;

2) parasitic current through a single interconnector of a solar panel as a function of panel voltage and plasma environment; and

3) near-surface potential over a single cell of a panel as a function of bias voltage and plasma environment.

Acknowledgments

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