Spacecraft Plasma Environment: Forming, Modeling and Impact Effects

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Ekaterina M. Tverdokhlebova[1] , Anatoly G. Korsun[2], Flur F. Gabdullin[3], Michail Yu. Kurshakov[4]
Central Research Institute of Machine Building (FGUP TsNIImash), Korolev, Moscow region, 141070, Russia

and

Andrey B. Nadiradze[5]
Moscow Aviation Institute (MAI (GTU)), Moscow, Russia

Abstract: This paper studies the processes that are responsible for forming of SC plasma environment. The most important of them for the long-life SCs are defined: these are the plasma plumes of electric thrusters, secondary plasma generation and mass backflow to the SC surface. The main physical differences of plasma dynamics in the vacuum chamber and in space that make ground modeling of aforementioned processes difficult are given. The mathematical models of SC plasma environment forming used in the software are reviewed. The effects of plasma-SC interaction that should be considered when developing the long-life SCs are studied.

Nomenclature

$a=a(x)$ = transverse dimension of a plume
$\mathbf{B}$ = magnetic induction
e = electron charge
$\mathbf{E}$ = electric field
J = total flux
j = current density
fi = potential drop
m = mass
M = Mach number
n = normal
n = concentration
$\dot{N}$ = total ion rate
$q = q_e + q_i$ = rate of secondary ion generation
$q_e = \sigma_e n_n n_1 u_1$ = charge exchange velocity
$q_i = \langle \sigma_e C_e \rangle n_n n_e$ = ionization rate
$Q_{s \to sc}$ = flux coming from source to scattering volume [g/(cm^2·sec)]

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[1] Chief of Lab, Laboratory of Applied Plasma Dynamics, tverdokhlebova@tsniimash.ru .
[2] Senior Scientist, Laboratory of Applied Plasma Dynamics, korsun_ag@mail.ru .
[3] Senior Scientist, Laboratory of Applied Plasma Dynamics, mkurshakov@yandex.ru
[4] Senior Scientist, Laboratory of Applied Plasma Dynamics, flur.gabdullin@gmail.com.
[5] Professor, Space Propulsion Dep (208), nadiradze@mai.ru.

$\mathbf{r}, \varphi$ = spherical coordinates
s = parameter of magnetic interaction
S =area
t = time
T = temperature
u =velocity
V = volume
x, y, z = Cartesian coordinates
ε = ion energy
λ = mean free path
σ = plasma conductivity
“0”,”k” = initial and finish value
“s”,”sc”,”d” = source, scattering volume, detector
"i","e" = ion and electron components

I. Introduction

The high velocity flows exhausted from an electric thruster create the specific plasma environment of a spacecraft (SC). These flows generate electric fields near the SC and currents shorting via the plasma environment, ionosphere or over the SC’ surface.

The other sources of plasma environment are the flows of gases and vapors emitted by the SC support systems. The significant part of neutral gas flow is ionized under the influence of cosmic space factors that results in SC plasma environment change. Such sources of gas flows are:

- all types of liquid or gas propellant jet engines;
- leakage of gases and vapors during airlock operations and technological disposals of water;
- continuous leakages of gases from a SC and gassing of surface materials that forms SC’ outer atmosphere (SCOA).

Relatively high electric and thermal conductivity of plasma in ionosphere, SC environment and thruster exhaust causes the effective interaction between all of three types of plasma by means of the transfer of electric currents and heat. Interaction processes begin directly close to the SC, where the spacecraft by itself takes a part in these processes, and continue up to distance much more then the SC dimensions. As a result the additional electromagnetic torques are created and the thermal and corpuscular flows coming to the SC surface are generated.

Plasma environment characteristics are determined both by the parameters of initial gas and plasma flows and by the parameters of their interaction with the cosmic space factors. Such factors as the terrestrial magnetic field, ionosphere flow running over a SC and solar radiation have the most significant influence on plasma dynamics and ionization processes. The large-scale plasma formations arise near a SC as a result of interaction with given factors. They have different forms and specific distribution of the parameters such as concentration, velocity and temperature of charged components, self-consistent fields and currents. Moreover, the characteristics of plasma environment of the same origin will differ in case of high orbit or low orbit where the shares of cosmic space factors are different.

Low orbital automatic spacecrafts, such as satellites for the Earth remote sensing or the weather viewing, are equipped as a rule with liquid propulsion and have short-term active life, 3-5 years. Basically, the natural cosmic factors have an influence on the environment of these SCs. Taking into account that more than 30 countries have their own satellites for the Earth remote sensing, the assessment of cosmic factor influence became a standard procedure during developing of such SCs. The following factors contribute in the environment forming: a) raking of the ambient plasma up due to elastic collisions and charge exchange of ionosphere ions O_2^+, O^+, N_2^+ with released atoms, and b) released gas ionization by atmospheric molecules O_2, N_2, and oxygen atoms O which incident upon with the energy of relative orbital motion of about 8 kmps[1]. Additional influence effects related to the plasma environment arise when the engines operate and the cosmic factors ionize their jets. This influence can be most significant for high-latitude and high-elliptic orbit spacecrafts. These SCs experience periodical and differential charge accumulation that is removed by engine starting with spark arc breakdowns.

Low-orbit manned space stations – SkyLab, MIR, ISS and future ones. The main distinctions of these SCs are large overall dimensions, low orbit altitude, presence of pressurized compartments, regular gassing. There is always dense own outer atmosphere near the manned space stations. Under the influence of ionizing space factors the own outer atmosphere is partly ionized. As a result a space station is surrounded by plasma environment with time- and space-dependent parameters. Besides periodical changes there are impulse changes of plasma environment parameters that take place when onboard plasma systems such as ISS plasma contactor run and gases outflow. Currently the behavior of plasma environment is studied in many countries, mainly the ones that take part in ISS program. By now it is known for sure that plasma environment interact actively with the onboard systems and station surface, [2].

High-orbit geostationary SCs (communication and navigation satellites) are characterized by the longest active life, unpressurized design and are often equipped with electric propulsion. When the engines are stopped a density of the own outer atmosphere at the end of positioning stage is extremely low. But when the engines are switched on (the time of switching runs into tens of minutes) not only the pressure rises, including the pressure in equipment bay, but the concentration of charged particles rises as well. That means that the plasma environment actively forms.

Deep space spacecrafts are the smallest group of SCs. The measures of protection from the deep space factors and the measures that provide protection of the equipment from artificial plasma environment are mostly the same. But, it is possible to get a problem in this case also, that is causes by an EP use. The EP having the low thrust operates very long time. A navigational support takes a long time also and the direction of an observation coincides with the direction of a plasma exhaust. The plasma plume keeps own electron structure over a several hundreds and thousands meters when the neutralized space factors absent. The presence of the large-scale plasma formation impacts on the radio signal propagation, in spite of the plasma formation is radio transparent in whole.

This short review shows that the geostationary orbit (GSO) satellites, which are long-life and supplied with EP device, are the most open to the plasma environment influence.

The analysis of the earlier conducted calculations and experiments shows that the interaction effects combination may be also conventionally divided into the following groups: damaging, interfering, potentially positive, neutral. It goes without saying that SC developers are mostly interested in the effects, which can influence the mission feasibility on the whole or shorten the expected SC operation duration. Therefore the assessment of one or another effect in the given mission should be made already in the SC designing phase and while defining the requirements to location and composition of onboard sensors.

II. Sources of SC plasma environment forming

A number of space factors influence a spacecraft (SC) after its launching: ultraviolet emission of Sun, incident flow of atomic oxygen, space radiation and in addition to that the SC's own outer atmosphere. SCOA is formed due to SC' weight loss during an operation of a propulsion system, due to surface and volume gas exhausting, due to gas leak from an enclosed modules and so on. The pressure in SCOA increases by orders of magnitude during the operation of propulsion system [3]. During an operation of electric propulsion system and a short time after its switch off the composition of a SCOA changes due to forming of ion back flow of secondary plasma from the accelerated (primary) jet. This change concerns substantially an increase of a share of ionized components in SC environment; the ion backflow of secondary plasma forms a peculiar SC's plasma environment. Electric features of environment determine a magnitude and a distribution of electric currents flowing over the complex "plasma - spacecraft". In addition SCOA can essentially influence on a kinetic of physicochemical processes taking place on surfaces with the participation of atomic oxygen and SC' material vaporization products.

The number of processes causes the plasma environment forming:

- Mass transfer from a source to the receptor direct;
- Gas release from the SC surface materials;
- Gas exhaust from engines or drain systems;
- Sputtering of the SC outer surface under the impact of high-energy ions or high-velocity solid particles;
- Dispersion of particles on the both the ionospheric flow or the gas jet;
- Gas chemical transformation in a volume or over a surface;
- Gas condensing and adsorptions on a SC surface.

The plasma flow generated at an EP operation interact active with the spacecraft' surface and with particles of an SC environment

A. The primary plasma of an electric thruster jet

The plasma of Hall' thruster plumes is almost completely ionized (ionicity is more than 0.95). Generally, the energy of accelerated ions is much more than electron temperature and ion energy spread, therefore, Mach number is considerable ($M^2>>10$). Plasma flow is well focused, i.e. it has minimal divergence. Nevertheless, the spreading of a plasma flow takes place as a rule into a conical angle of 90º. Here it is concentrated up to 90% of a flow. This value is input data for calculation of the some operating characteristic of the thruster. Remaining part of a accelerated ion flow, 10% , forms the flow periphery that spreads into angle up 180º. This part of a flow is seldom taken into account by SC designers. The different fluctuations [4] arise and intensive oscillations [5],[6],[7] are generated in the accelerating channel in the discharge zone and in the beginning of plasma plume where a beam of accelerated ions interacts with cathode-neutralizer slow plasma and with secondary plasma. A significant number of beam-plasma oscillations is equivalent to effective collisions of electrons and ions. As a result the mach more propellant go away from the central part of a flow to the periphery. The additional factor that amplify an evacuation of a propellant to the periphery is the electron temperature which is higher in an orbit than it is measured in a vacuum chamber, [8]. This factor is reviewed below. Structure elements exposed inside the periphery of an EP flow undergo by accelerated ions with energy of 50 eV and more.

B. Secondary plasma of an electric thruster jet

The secondary plasma is formed in the plume during the operation of EP. Under space conditions the flow of secondary ions is usually low in comparison with directed flow of the plume. However, total effect of secondary ion flows on long lifetime spacecrafts can be significant. Unlike EP plume which ions have narrow span of velocity vectors, the secondary ions scatter in all directions from the zone near thruster exit where they appear. Arising radial and reverse flows of secondary ions hit all nearby elements of SC which plume can not reach.

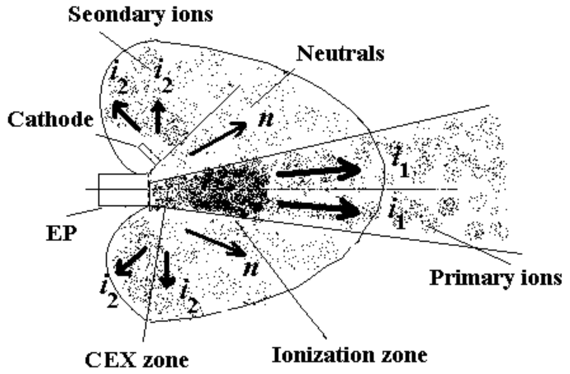

Figure 1. Zones of secondary plasma birth (i_1 –EP ion flow, i_2 –secondary ion flow, n- EP neutral flow)

Secondary plasma is formed due to charge-exchange (CEX) and ionization of neutral atoms and molecules which are contained in the EP plume. Concentration of neutrals in the zone of main flow expansion under space conditions is determined by the flows of unionized propellant from the thruster anode (5-10% of flow rate) and from the cathode neutralizer (another 10 % of flow rate) and also by the neutrals of SCOA. Concentration of atoms under terrestrial conditions during tests is determined by the facility background pressure and by the flows from the thruster. Since velocity of neutrals is almost by 2 orders of magnitude less than velocity of primary flow ions the concentration of neutrals in the zone of the secondary plasma formation is more than or of the same magnitude with the concentration of primary plasma flow. Concentration of secondary plasma ions can be less than or of the same magnitude with the concentration of primary ions. Flows of secondary plasma have a significant influence on erosion and stress of SC nearby elements, on plasma radiation near a thruster and on formation of voltage drops and currents in the SC elements.

The zone where secondary ions are formed is determined by the distance within which, firstly, density of primary flow is rather high and, secondly, electron temperature is rather great. As one can see in Fig. 1 the area where secondary plasma is generated is a rather big part of the plasma plume.

The main processes due to which secondary ions originate are electron impact ionization and CEX of high-speed ions. Productivity of these processes is determined by interaction cross-section of the particles and by their concentration. Therefore, both of these processes occur in the relatively small area of the plume where the densities of neutral and ion flows are rather high.

During scattering the secondary ions gain energy in the electrostatic field of plume where voltage drop is about 10-30 V. That voltage is generated mainly across a plume. This estimation of energy values correlates with the experimental results, [9].

III. Plasma environment modeling

The investigations of the plasma environment / spacecraft interaction may proceed in two directions: a theoretical simulation and experimental check-up.

The theoretical simulation includes: first, elaboration of a model of parameter distribution in plasma exhaust, and, second, selection of effect models (optical radiation models, erosion models, models of interaction with own outer atmosphere, radio wave scattering and so on).

The experimental simulation implies bench reproduction under ground conditions of interaction conditions maximally approximated to space conditions. Such conditions may be reproduced either in full-scale values or scaled in accordance with the similarity criterions.

A. Peculiarities of ground modeling in a vacuum chamber

The usually distances where the plasma plume interacts with spacecraft elements, for example with solar battery, is about 5 to 10 meters. But the features of plasma plume at such distance down stream can not be modeling inside a vacuum chamber. The following factors determine a difference between the electric propulsion's plume characteristics in a vacuum chamber and in space:

- Influence of plasma and gas background on the plasma plume expansion;
- Influence of conductive walls on the distribution of electrical fields and currents in a EP plume;
- Losses and transformation of thermal energy of the plasma plume electrons;
- Influence of the geomagnetic field on electrodynamic processes in a plume.

Taking into account mentioned above factors we can conclude that only measurements of plume parameters near to the thruster exit plane are reliable. Here the density of plasma plume is more than the density of background gas. To calculate the impact effects on spacecraft elements and onboard systems we have to know the plume parameters at distances 5, 10, 20m downstream. Other words, the ground measurements of parameters in the near zone of plasma plume are not enough to calculate the ion flux incoming on SC elements (solar battery, radio reflector and so on) having the dimensions more than 1,5 to 2 m, how it is shown in Ref.8.

Influence of a dense neutral background inside a vacuum chamber

The accelerated and concentrated in a thruster ion flow $\dot{N}$ is re-charged on background neutrals having a density n_n at near-field of a plume. A length of this part of a plume is in order of free pass length of an ion in background gas $\Delta x \sim \lambda_e = \frac{1}{n_n q_e}$. Except a charge-exchange, at distance of $\Delta x \sim 0{,}2$ m from an exit nozzle of thrusters like SPT-100 or D-55 a background neutrals are ionized partly. An ionization of neutrals by electron impact occurs in discharge gap of a thruster and in a near-field ("hot") zone of a plume as well where a electron temperature is great enough, $T_e \sim 10$ eV.

As a result of the two mentioned above processes a secondary plasma appears near to a thruster and scatters in a radial direction and partly backwards, [10]. The flow rate of primary ions decreases $\dot{N} = \dot{N}\exp\left(-\frac{x}{\lambda_e}\right)$. Secondary ions accelerate in a self-consistent electric field of a plume and get an energy of $\varepsilon \sim 20 \div 30$ eV.

As distinct from vacuum chamber a secondary plasma is less dense in space. Its sources are only the non-ionized in a gap propellant – Xenon (a share of neutral xenon is too little 0,01-0,05) and rather rarefied gas of a spacecraft outer atmosphere (the pressure in *"Express"* outer atmosphere was $P \sim 10^{-8}$ *mm Hg,* [11]).

Secondary plasma influences on processes of an interaction between a plume and walls of vacuum chamber or nearby structure elements of a spacecraft. Obviously, such effect is much greater under vacuum chamber conditions.

Influence of conductive walls on a distribution of electric fields, currents and dynamic characteristics of a plume as well

Inside the plasma plume there is a potential drop *Δfi* in radial and axial direction regarding to a flow velocity, [12]. Its magnitude is *Δfi* ~ 30V with reference to the kilowatt-class thrusters, [13]. Under influence of this electric field appearing between a plasma plume and conductive surfaces (walls of vacuum chamber or structure elements of a spacecraft) a electric current leaks through a secondary plasma.

Under vacuum chamber conditions "hot" electrons go to walls from a near-field zone, and ions from narrow accelerated beam encloses this current trough a far-field zone. As a result along the plume an electric current leaks and encloses over vacuum chamber hull.

At EP operation in space where a secondary plasma is less dense in several order of magnitude and a plume almost does not touch conductive surfaces, these currents are much less.

The technique of estimation of an intensity of these processes and also examples of calculation of shorting current under ground and space conditions are given in Ref. [14].

Losses and transformation of thermal energy of electrons in a plume

Inside a vacuum chamber and at EP operation on orbit there is an electron flow from a plume to walls, first of all it relates to "fast" electrons from a high-energetic tail of their distribution function. However, inside a vacuum chamber, where there is a dense secondary plasma and all plume is bounded by metal, this process occurs more intensive than it is in space, near to a spacecraft. These electron flow to walls are regulated by a potential jump, Δfi_E, in a thin Debye layer close to hull surface (of a vacuum chamber or spacecraft). A potential jump in turn is assigned by a balance of flows of electrons and ions all over a surface. For example, during a ground test of SPT-100 or D-55 thrusters a magnitude of potential jump is equal to $\Delta fi_E \cong 10$V. The earlier calculations of potential jump with reference to SPT-100 operation on geostationary orbit (see Ref.12) gave the magnitude $\Delta fi_E \cong 13$ to 20V in dependence on thruster design.

An experimental study of a distribution of electron temperature in the D-80 plume has shown (see Ref.13) that the heat transfer by electrons is difficult in an accelerated plasma flow. Besides, a retarding field close to spacecraft surface is higher than it is in a chamber. That is why under space conditions, where the flow of "fast" electrons to walls is not so intensive, the electron temperature in a plume should be higher that it is registered under ground conditions. Measurements made in vacuum chambers by many authors give a same value $T_e \sim 1 \div 2$ eV at distance $\Delta x > 1$m from SPT' exit nozzle. The analysis of "*Express*" flight data. [15], shows that at flow downstream $\Delta x \sim 3 \div 8$ m the electron temperature is higher and it is equal to $T_e \sim 3 \div 4$ eV.

The analysis of obtained results lets us to conclude that due to intensive divergence of plasma flow in space the rather dense ion flux will arrive to the SC elements and surfaces. Intensification of ion flux on the solar battery, for example, causes the acceleration of erosion processes, the generation of additional torque and the losses of the EP thrust as well.

B. Computing of SC plasma environment

To calculate the distribution of plasma environment parameters the software "SVI-ERD" ,[16] is developed. The software allows to evaluate the parameters of a geostationary spacecraft own ionosphere (in Russian transcription SVI) that arises at onboard electric propulsion device operation, and choice the SC assembly as well. The goal of these calculations is to create the SC design allowing to minimize the negative impact of electric thruster and to ensure the compatibility of EP with onboard system.

Knowledge of the SC plasma environment means the knowledge of the next values in a every selected point around the spacecraft: concentration and velocity vector of the each components of a SCOA.

Parameters of secondary plasma are table-fixed (concentration and velocity of neutrals, ions and electrons) concerning to the selected thruster type.

Visualization of calculation results is realized with 3D graphic method on a monitor. It is enable "zoom", "rotate", "fragment", "diapason", "value" and other option. The result can be printed or exported in a file as figures or numeric data.

Modeling of primary plasma

As a model of primary plasma plume we use the self-similar model (SSM), [17], according to that the terrestrial magnetic field influences significant on a flow configuration, [18].

The self-similar solution for the unperturbed flow can be expressed by the next relationships:

$$nu = \frac{\dot N (p - 1/2)}{\pi a^2} \frac{1}{\left(1 + \frac{r^2}{a^2}\right)^{p + 1/2}}; \quad p = 1 - \frac{1}{1 - \gamma M_0^2}; \qquad n = \frac{\dot N (p - 1/2)}{\pi a^2 u_c} \frac{1}{\left(1 + \frac{r^2}{a^2}\right)^{p}}; \tag{1}$$

$$\left(\frac{u_c}{u}\right)^2 = 1 + \frac{2}{\gamma M_0^2} \ln \frac{u_c a^2}{u_0 a_0^2}; \qquad a' = \left(a_0'^2 + \frac{4p}{\gamma M_0^2} \ln \frac{a}{a_0}\right)^{\frac{1}{2}} \frac{u_0}{u_c}.$$

In the distant part of a flow injected along the magnetic field the SSM solution can be written as:

$$n = \frac{2\dot N}{\pi a_0^2 u_0} \frac{1 - r^2/a^2}{\left(1 - \frac{8}{s_0}\frac{x}{a_0}\right)^{1/2}}, \; a = a_0 \left(1 + \frac{8}{s_0}\frac{x}{a_0}\right)^{1/4} \;; \quad s_0 = \frac{\pi \sigma_0 u_0^2 B^2 a_0^3}{2 \dot N T_0}, \; u = u_0\,; \; T = T_0 \;; \; r^2 = z^2 + y^2 \tag{2}$$

One can see that the value n changes relatively slowly downstream ($n_c \sim x^{-1/2}$). Owing to that isoconcentrales of the distant part of a flow acquire the "knitting needle" shape elongated along the magnetic field **B**.

Figure 2 illustrates the change of plasma dynamics. Initial part of the plume expands very intensive, according to Eq.(1). At some distance from the thruster exit nozzle the pressure of a terrestrial magnetic field is getting more than the gas-dynamic pressure inside the plume. The expansion in lateral direction becomes slower. The forward motion of plasma is not limited. The plasma plume maintains own structure rather long downstream that is obeyed by Eq.(2).

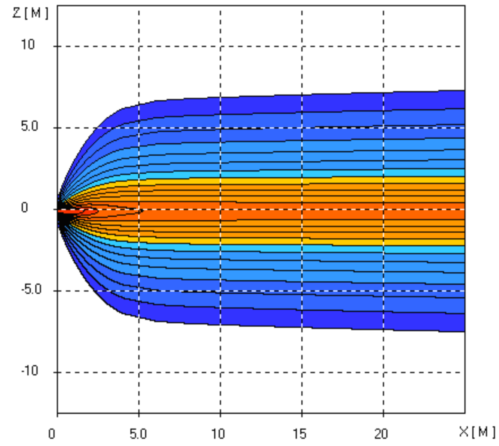

Figure 2. SPT-100 plasma plume expansion limit under GSO condition

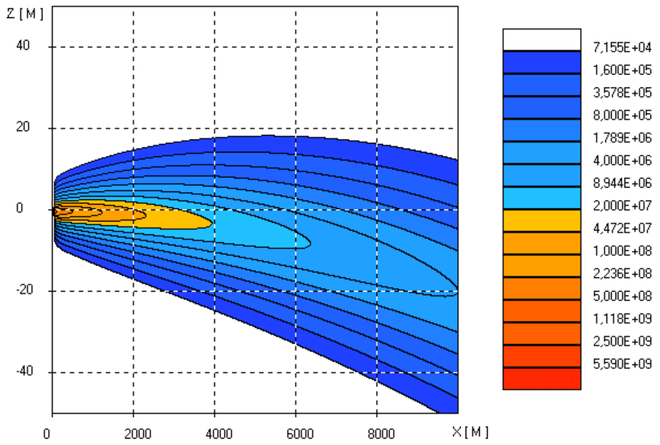

Figure 3. SPT-100 plasma plume curvature under GSO condition

As a rule the correction impulse is in the “north-south” direction. Plasma follows the magnetic lines and bends forward to Earth. At the distance more than 10 km downstream the curvature of EP plasma plume became noticeable. Concerning to equatorial orbit the shift of the plasma flow axis is hundreds meter to Earth. Figure 3 illustrates the configuration of isoconcentrales at distant part of SPT-100 plume created on a geostationary orbit.

Modeling of secondary plasma

Basic processes, responsible for birth of secondary ions, are the ionization of neutrals by electron impact and also charge exchange between fast ions and neutrals. Efficiency of the processes depends on the cross-sections of interactions and also on concentration of particles. Therefore, the both processes happen within a rather small initial zone of a jet where the density of both (neutral and ion) flows is rather high.

If the density of secondary plasma is comparable to the density of a primary beam, the secondary plasma distorts the potential distribution in a primary beam. For such case **CFSP** software has been developed. The description of CFSP software is presented in Ref.10. In the code the secondary plasma parameters are calculated in continual approximation.

A system of continuum equations, [19], that takes into consideration secondary ions generation and also corresponding dissipative processes is as follows:

$$\nabla n_2\vec{u}_2 = q$$

$$mn_2(\vec{u}_2\nabla)\vec{u}_2 = -\nabla(n_2T_2) - \frac{n_2}{n_e}\nabla n_eT_e - m(\vec{u}-\vec{u}_n)\nabla n_2\vec{u}_2 \quad \frac{3}{2}n_2\vec{u}_2\nabla T_2 + n_2T_2\nabla\vec{u}_2 = \frac{m(\vec{u}_2-\vec{u}_n)^2}{2}q - \frac{3}{2}(T_2-T_n)\nabla n_2\vec{u}_2 \qquad (3)$$

Secondary plasma expands almost spherically with a small energy of directional motion $\frac{mu_2^2}{2e} \sim 20 \div 30V$ and with ion temperature $T_{i2} \sim 10$eV. The energy distribution for secondary ions is the Maxwellian, whose spectrum is shifted on the value of velocity of the ions. Such kind of distributions are generally used to derive a continuum equation from kinetic relationships [20]**.** The continuum description of processes in the accelerator channel takes into account the birth and acceleration of ions, and so gives the energy distribution of ions close to the experimental ones (see in Ref.10).

Modeling of scattered flow

To determine the value of scattered flux coming to the given it needs to integrate all of fluxes scattered into a volume (hemisphere) that is visible from this detecting surface and limited by the length of molecule free pass as well. By dividing of this volume on elementary units, the scattered flux incoming from the elementary unit with volume dV_{sc} on the surface with area S_d can be expressed as:

$$S_d dJ_d = Q_{s\to sc} \cdot e^{-|\mathbf{r}_{sc}-\mathbf{r}_s|/\lambda} \cdot \frac{dV_{sc}}{\lambda} \cdot \frac{S_s\cos(\mathbf{n}_d, \mathbf{r}_{sc}-\mathbf{r}_d)}{4\pi(\mathbf{r}_{sc}-\mathbf{r}_d)^2} \qquad (4)$$

After the division of both the left and right parts in Eq.(4) by the value S_d and the integration by the all scattering volume, the next equation came out to describe the flux of SCOA component incoming on surface-detector as a result of scattering:

$$J_{\mathrm{d}} = \iiint Q_{\mathrm{s}\to sc} \cdot e^{-|\mathbf{r}_{\mathrm{sc}}-\mathbf{r}_{\mathrm{s}}|/\lambda} \cdot \frac{\cos\left(\mathbf{n}_{\mathrm{s}},\mathbf{r}_{\mathrm{sc}}-\mathbf{r}_{\mathrm{d}}\right)}{4\pi\left(\mathbf{r}_{\mathrm{sc}}-\mathbf{r}_{\mathrm{d}}\right)^2}\frac{dV_{\mathrm{sc}}}{\lambda} \qquad (5)$$

The flux from a source, $Q_{\mathrm{s}\to sc}$, is described by the next expression

$$Q_{\mathrm{s}\to sc} = \sum Q_{\mathrm{s}} + \iint_{S_{SC}} \frac{I\left(\mathbf{r}_{\mathrm{s}}\right)\cos\left(\mathbf{n}_{\mathrm{s}},\mathbf{r}_{\mathrm{sc}}-\mathbf{r}_{\mathrm{d}}\right)}{\pi\left(\mathbf{r}_{\mathrm{s}}-\mathbf{r}_{\mathrm{sc}}\right)^2} dS_{\mathrm{SC}} \qquad (6)$$

This expression includes both the sum of all fluxes from individual sources such as thrusters, drain holes and so on, and the integral describing the fluxes coming from SC surface. The magnitude of a flux from surface unit assembles both a gas emission flux and a reflected flux.

The model of scattered flow is described more detail in Ref. [21]

Calculation results

Figure 4 and Figure 5 demonstrate the modeling results concerning the parameters of a SCOI formed during SPT-100 operation under the GSO conditions. One can see on the Figures that the panels of solar arrays (SA) are almost immersed into plasma with density level of $n_e \cong 10^{14}$ m^{-3} . Moreover the energy of particles bombing the SA panels exceeds the value of 50eV. Ionized environment with such density level exerts a noticeable erosion and forces influence on a SC due to both a dynamic impact of hypersonic ion flow and electrostatic effects taking place on the SC elements which are under a floating potential relative to the ambient plasma.

All of SC elements, which are getting into the plume zone, will be sputtered by high-energy ions of SPT' plume. From point of view of mechanical damage of these SC' elements the ion-beam sputtering is unsubstantial. But, the sputtered materials can deposit on other surfaces causing a change of their functional features. In the first place it relates to both a changing of optical features of cover surfaces of photo detectors and star trackers and a changing of reflection coefficient of thermal covers. The sources of SCOI are the plume particles and the particles scattered from SC' surfaces. As a result a pressure in SC environment increases by an order of magnitude almost – from 10^{-8} up to 10^{-7} mm Hg..

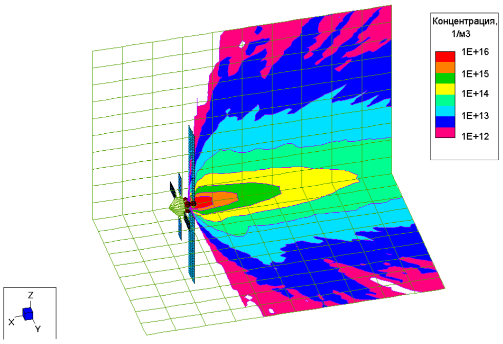

Figure 4. Distribution of primary ions in SC environment, *n_e, m^{-3}*

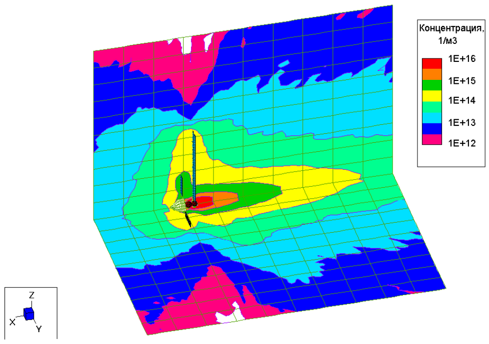

Figure 5. Distribution of primary, secondary and sputtered ions in SC environment, *n, m^{-3}*

IV. Impact Effects

The objective value of primary analysis of the scale of probable EP plume effects on a spacecraft consists in an early identification of the most critical effects for the mission implementation. It makes it possible already in the item designing phase to work out the strategy of neutralizing negative aftereffects by technical and organizational measures (e.g.by an operation cyclogram modification of EP and other onboard systems) as well as to define a necessary volume of additional investigations.

The interaction effects combination may be also conventionally divided into the following groups: damaging, interfering, potentially positive, neutral.

Irreversible negative processes such as erosion or scattering relate to the damaging effects. Negative effects, which disappear at the thruster switch-off, i.e. radio communication interference may be attributed to the interfering effects. The potentially positive effects may include the phenomenon of static charge drop on the spacecraft surface during onboard plasma source operation. One can for example consider the availability of an ionized track behind a satellite with its EP operating as a neutral effect. In certain cases the length of a track may be of several tens or hundreds of kilometers.

The conditionally of such a division is that with the change of space mission type or even in its separate phases the character and scale of one or another effect may alter and be transformed from the neutral into interfering or damaging wise versa. So for example the long ionized track formation behind a spacecraft in orbital flight does not present at a first glance a direct danger for its system. However, the characteristic dimension of such a track of GEO spacecraft is hundreds of kilometers. Though the terrestrial magnetic field on GEO is not strong, just this field determines the primary exhaust plasma distribution. If the jet velocity vector matches the magnetic induction vector direction, then the forming track has a strongly elongated form along the field line. Following the field line the track bends towards the Earth surface (see Fig.3). Availability of a large-scale ionized non-uniformity on the trajectory near the spacecraft may bring about undesirable effects:

- radio communications impact. Basically the whole exhaust volume is radio transparent. But due to large dimensions and large gradients of the electron density (in the direction lateral to the exhaust axis) the radio waves refraction in the exhaust may be sufficient even causing communications disruption[22];
- effects on optical sensors. The incident Sun light is dispersed in the plasma volume in all directions including the S/C direction. The luminescence intensity angular distribution peak corresponds to the direction towards the plasma flow.

It goes without saying that S/C developers are mostly interested in the effects, which can influence the mission feasibility on the whole or shorten the expected S/C operation duration. Therefore the assessment of one or another effect in the given mission should be made already in the S/C designing phase and while defining the requirements to location and composition of onboard sensors.

A. Erosion effects

Erosion of cover materials of satellites is one of the most undesirable factors taken place at EP operation. Erosion processes can cause the degradation of mechanical, optical or electrical features of SC materials, the destruction of thin-film coat and number other effects leading to the changes of functional characteristics of SC surfaces. That is why the erosion is one of the key problem, which should be analyzing at EP integration process on a SC.

Plume erosion effects, as a rule, initiate simultaneously several processes:

- sputtering of structural elements (solar batteries, optical devices, radio antenna reflectors) being within the plasma plume zone;
- functional surfaces pollution (solar batteries, sensors, thermal cover) of the spacecraft with thruster working channel erosion products;
- SC structural element spraying products deposition on the SC functional surfaces;
- change of the coating structural, physical and chemical properties under ion flow effects.

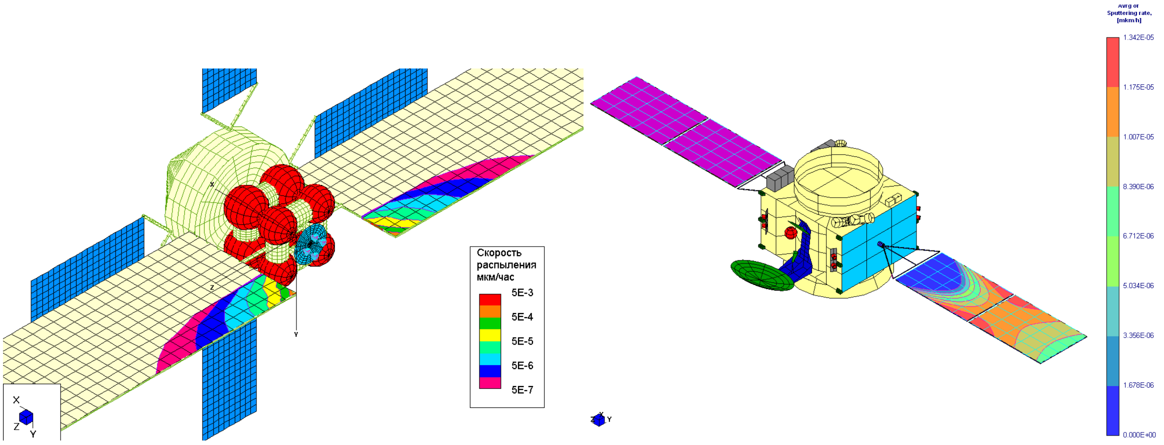

Figure 6. Erosion rate of solar battery. Examples of calculation results.

Here the standard problem is the necessity of minimizing solar battery degradation and thermal protecting contamination.

To calculate and analyze force and erosion impacts of plasma plumes exhausted from electric thrusters on SC surfaces and structure elements we have developed the software "Plasma-SEV"[23]. Software was used at evaluation of impact effects concerning satellites "KazSat", "Dialog", "Express" and so on.

The calculations of plasma environment erosion impact are shown on Fig.6 relative to some satellites.

The plasma plume force effects are manifested as a formation of extra torques and propulsion system thrust losses. The torques formation may be conditioned, first of all, be variation of the total thrust vector value and direction during simultaneous operation of two or more engines, and secondly, be fall of a plume portion on the SC structure protruding elements (these may be solar batteries, thermal screens .radio antenna reflectors and other large-scale elements of the SC structure). EP thrust losses and as a consequence SC motion disturbances are conditioned by the same reasons.

Significant electromagnetic forces and torques may also be produced during electric current generation by the plasma plume in the SC structure conducting elements when the spacecraft flies in the ionosphere.

When plasma flow touches the SC' structure elements, its surfaces are bombarded by ions Xe^{+} and Xe^{++} having energy up 300 and 600 eV respectively. Such energetic and heavy ions , even at glancing angle of incidence, give up to the SC body that surface like as light atoms array (*Al, Si, O*) almost all own energy and impulse, [24,25]. Therefore the values of the all accommodation coefficients are equal 1 or close to 1. As a result of force impact the torques are being created. Plasma-surface contact causes the Debay layer creation inside the plasma volume close to the surface. This layer is characterized by the charges separation and the potential drop.

B. Electromagnetic Effects

The electromagnetic effects form the widest and most significant group of plasma plume / SC interfering effects. Here the main effect types are the two interference types: electromagnetic interference in the feed circuits and electromagnetic interference in ether.

The interference produced by the thruster itself manifest themselves as modulated noise generation in the wide frequency band, whose amplitude may grow with the current discharge increase and thruster power. The interference of the kind influence mainly the radio equipment operation. The methods of eliminating the first type interference of an EP should comprise the probability of a spontaneous transfer of the EP in the impulse regime of power consumption exceeding the rated value. Such operational peculiarities characteristic in particular of the most widely used SPT at present govern the enhanced requirements to a power supply which should prevent onboard power supply skipping. These impulses grow both during one firing cycle in one to one and half hour of operation and in several hundreds hours of the total running time.

The thruster itself and its exhaust jet are ether electromagnetic interference sources. The plasma jet can distort the onboard antenna pattern, weaken the received signal intensity, frustrate the phase-modulated signal structure. As a rule, the plasma plume is radio-transparent. But due to its large dimensions and rather nonuniform structure of electron density distribution it may considerably effect the radio-wave propagation.

The dimensions of an exhaust plume of the bulk of modern EP are bigger than the SC dimensions and run into tens and even hundreds of meters. The exhaust plasma and secondary plasma contact surfaces of different exposed parts of S/C structures: solar batteries, conducing elements, sensors, reflector antennas, etc. During operating the EP generates into the plume the fields and currents shorted through conductive SC elements. Discharge current oscillations may cause:

- low-frequency interference generation by pulsating current loops in the plume and SC body;
- interference generation in the reception channel produced by pulsation of the secondary plasma flowing about the antenna reflectors.

Here one should take into account, that even at the standard stationary regime of EP operation electrostatic forces (and fields) are formed behind the barrier during S/C structure element flow-about by a hypersonic plasma flow. There may be formed a distributed potential (in accordance with the jet potential distribution) on the structure face side. In case of a solar battery having its own potential distribution and open current feeders such a contact may result in current leakage, breakthroughs and/or SB power decrease.

C. Effects on optimal equipment

Plasma jet electromagnetic radiation in a wide wavelength makes effects on UV, visible and IR optical sensors. The intensity of jet characteristic radiation at certain angles may exceed the threshold value of the optical equipment. It is possible in the directions, when the line of sight passes at low angles to the flow velocity vector and near its axis. Besides characteristic plasma emission a scattered on the plasma exhaust solar light and jet luminescence generated by the solar wind high-energy flows may, as it was stated earlier, effect appreciably optical sensors operation.

Exhausts of the bulk of modern electric thrusters are optically transparent media and do not distort light directly . However when transferring to the utilization of more powerful thrusters producing jets optically more dense one should evaluate their effects on optical equipment, since in this case the signal received or transmitted by onboard equipment may be distorted.

One should take into consideration also an additional mechanism of ionizing the substance contained in exhausts (by UV radiation, incoming ionosphere flow, etc) which also contributes to jet emission and effects on optical sensors.

D. Effects on thermal sensors

Usually the major thermal effect source by radiation is a discharge plasma and thruster working channel with a probable temperature of 1000^0C.Till now this kind of effects has not been appreciable. But if powerful thrusters and thruster clusters are used the value of total power losses may run into units and tens of kWs and it should be taken into account when selecting a radiator emitter structure. Another aspect of the problem consists in a probable jet thermal effect on the surfaces facing it.

For example, while conducting the “EPICURE” experiment, see Ref.22, they detected the plasma generator effects on the infrared vertical sensor inspire of the fact, that the shielding protected the discharge zone and the plume near zone. Besides that when plume particles lose their impulse on the adjacent surfaces there may be extra heat release changing the structure‘s equilibrium thermal regime.

E. Effects on the S/C charging

An own ionosphere formation around a spacecraft brings about a potential balancing on the SC surface and static electricity discharge. The higher is the S/C orbit the more noticeable is this effect’s manifestation.

A small initial portion of a plasma plume characterized with relatively high electron temperature, $T_{e0,}$ plays an important role in the balance of currents being collected by conductive surfaces of SC components (solar arrays SA, SC body and equipment,..). As a result of these electrons effect the SC potential becomes as much negative relatively the plume ($\Delta fi \geq$ -10 to -20V) that it becomes impossible to compensate a flow of ions on solar arrays by only means of the plume electrons having a temperature T_{ef} of ~1÷2eV. The most part of these electrons will scatter from SC surfaces. The ion current can be only compensated with the assistance of hot electrons of the initial part of plume, which have a temperature T_e of ~6 to 10 eV and come on SC body through the secondary plasma. Such separate arrival of positive and negative charges from plasma environment causes a rise of current into metal structure. The value of electrical potentials of SC conductive parts are calculated under the condition that the total current collected by each isolated part is equal to zero.

V. Conclusion

Analysis of the presented sources and processes of plasma environment forming shows:

1.The cloud of secondary plasma is always generated during EP operation and is the major part of plasma environment components especially in zones outside a line of EP sight.

2.The zone where secondary ions are formed is determined by the distance within which, firstly, density of primary flow is rather high and, secondly, electron temperature is rather great.

3.Ions of secondary plasma scatter in all directions from the place of their birth, but mainly this process takes place across the axis of primary plasma flow and in the backward direction.

4.During scattering the secondary ions gain energy in the electrostatic field of plume where voltage drop is about 10-30 V. That voltage is generated mainly across a plume.

5.The fact of plasma environment forming must be always included in preview design of a spacecraft, especially the spacecraft with long-term active life and equipped electric thruster.

The plasma environment/spacecraft interaction can causes several negative effects, degradation onboard systems and noticeable shorten the SC service life.

To calculate the plasma environment parameters and its effects on spacecraft the software “SVI-ERD” is developed. The modeling examples demonstrate visual a distribution of environment parameters and an intensity of particles and energy fluxes incoming to the selected element of SC surface.

SC design expertise using the software “SVI-ERD” let to draw up the next recommendations to solve the problem of a compatibility EP and SC.

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