Harnessing of the power of the solar wind particles captured in the Van Allen belts

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ABSTRACT

The feasibility of constructing a high-voltage electric generator (HEG) transforming kinetic energy of particles of the radiation belts into electric power is considered. The maximum specific power of the generator is theoretically evaluated for particular cases of setting it inside the natural radiation belts of the Earth (ERB) and in polar region. It is demonstrated that from the viewpoint of weight parameters, the suggested design of HEG is quite competitive with power sources of low-thrust spacecraft operating on conventional principles.

1 INTRODUCTION

A power plant providing for power supply of operation of onboard service devices and science and technology instrumentation is one of the main elements of any spacecraft. As of now, designing the power plants transforming the natural energy of space medium into power supply is the most promising line of development of space power engineering. Power sources of this type include first of all various converters of electromagnetic radiation of the Sun (semiconductor photoelectric cells, thermoelectron, thermoionic, and thermoelectric converters). Along with manufacturing the power plants that use the energy of electromagnetic radiation of the Sun, people in our country and abroad make research into development of the concepts of radically new space electric power generators based on utilizing other types of energy available in space medium: energy of the Earth's magnetic field [1], energy of the solar wind plasma [2], and so on.

The radiation belts of the Earth and other celestial bodies belong to the carriers of natural energy density comparable with the energy flux density of the solar electromagnetic radiation. In this paper, a principal feasibility of an electric generator converting kinetic energy of particles of the radiation belts and polar region into electric power is considered. The maximum specific power of the generator is theoretically evaluated for a particular cases of setting it that mentioned above.

2 THE PHENOMENON OF STRONG ELECTROSTATIC CHARGING OF A SHIELDED BODY IN THE FLUX OF CORPUSCULAR RADIATION: PRINCIPLE OF OPERATION OF A HIGH-VOLTAGE POWER GENERATOR

It is well known that any body in open space is charged to a certain electric potential φ_p due to interactions with cosmic plasma, with fluxes of high-energy charged particles, and also with photoemission fluxes and fluxes of secondary particles emitted by the body surface. In equilibrium, the value of this potential is determined by the condition of balance of charging currents. Under usual conditions the potential of a body in the space medium does not exceed a few volts. For example, the potential of a satellite in the near-Earth space (NES) varies from negative values of order of some tenths of a volt (in low near-Earth orbits (LNO) with an altitude of several hundred of kilometers) up to positive values of about a few volts (in high near-Earth orbits (HNO) passing at altitudes of tens of thousand-kilometers) [3]. However, in some special cases a body can be charged up to considerably higher potentials. For example, when a satellite moving along HNO finds itself on a shadowed part of the orbit inside rarefied high-temperature plasma of the plasma sheet, it can be charged to negative potentials of ~(1–10) kV [4]. Finally, strong electrostatic charging (SEC) of a body to negative potentials of order of (10–1000) V is possible when this body is immersed into intense electron fluxes of natural origin (the fluxes of auroral electrons, electron fluxes of the radiation belt, the fluxes of photoelectrons from sunlit conjugate region of the ionosphere on a shadowed segment of the orbit). The smallness of the rate with which negative electric charge sinks from a body due to photoemission and space plasma flows onto it is the necessary condition of strong electrostatic charging of the body in the flux of high-energy electrons. Especially favorable conditions for SEC of a body by corpuscular fluxes are set up in the case when it is fully protected against solar shortwave radiation and space plasma by a special shield whose thickness is less than the mean free path of high-energy particles in its material. High-energy particles (in the case under consideration they can be represented by both electrons and protons), decelerating inside the matter of the body, should charge it up to a certain potential U relative to the shield whose neutrality is maintained by charged particles incoming from the ambient plasma. As will be shown below the maximum voltage U between the body and the shield can reach $\sim \bar{\varepsilon}_r / e$ (where $\bar{\varepsilon}_r$ is the mean energy of particles of the corpuscular flux) and turns out to be very significant at large $\bar{\varepsilon}_r$. The obvious application of the SEC phenomenon in a shielded body is the use of electric potential U between the inner body and the shield in order to produce electric current J_1 in the appliance load inserted between them. This current produces power $P = J_1 U$ on the load. In this case the system will operate as a high-voltage electric generator (HEG) converting the kinetic energy of particles of a corpuscular flux into electric power.

As a first step in studying the efficiency of the above method of generation of electric power in space, let us make a preliminary estimate of possible HEG power for the case, when the corpuscular fluxes producing the SEC phenomenon are represented by protons and electrons of natural radiation belts of the Earth.

3 SPECIFIC POWER OF A HIGH-VOLTAGE ELECTRIC GENERATOR IN NATURAL RADIATION BELTS OF THE EARTH

The natural radiation belts of the Earth are extended regions of the near-Earth space that are characterized by the intense fluxes of high-energy electrons and protons trapped by the Earth's magnetic field. The electron radiation belt consists of the inner and outer radiation belts, the gap between which is located near a magnetic shell with the McIlwain parameter L = 3. Unlike electrons, protons with energies $\leq$ 1 MeV that give the main contribution to electric power produced by HEG occupy the entire region of trapping.

Let us first estimate possible values of the specific power of a HEG positioned in the NES where the flux of ERB protons is dominant. In accordance with the data of [5], this region is located on magnetic shells with L values approximately from 2.5 to 4.5.

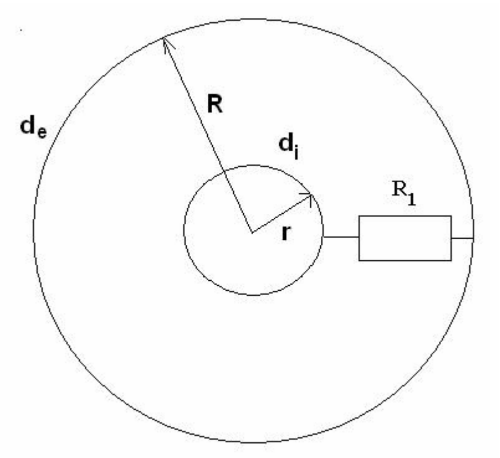

Fig.1

Let for certainty the generator be a system of two spherical concentric conducting shells. The internal shell of radius r has the thickness d_i, while the external shell of radius R has the thickness d_e which is presumed to be substantially less than the mean free path of particles of the corpuscular flux in its material. The density of materials from which the internal and external shells are manufactured are equal to ρ_i and ρ_e, respectively. A load with resistance R_1 is connected between the shells (Fig.1). Some high-energy particles of the radiation belt, passing through the external shell and electric field of the gap between the shells, are detained by the matter of the internal shell, thus imparting to it an electric potential relative to the external shell. The electric potential of the external shell is maintained close to zero due to a flux of charged particles with thermal energies from the ambient plasma. As a result, high voltage $U \sim \bar{\varepsilon}_r / e$ appears between the shells. This voltage produces electric current in the load thus developing corresponding power, i.e., the system operates as an electric generator.

So, let us suppose that high voltage U between the shells of HEG is established as a result of partial absorption of the ERB proton flux by the material of the internal shell. In the steady state, the voltage U is determined from the condition of balance of the currents charging the internal shell of HEG

$$J^{p}_{abs}(U) = J_1 \qquad (1)$$

where $J^{p}_{abs}(U)$ is the total current of protons absorbed by the internal shell material, and $J_1 = U / R_1$ is the current flowing through the load. In order to determine current $J^{p}_{abs}(U)$ let us first formulate the conditions under which a proton of energy E entering the external shell of HEG at an angle ϑ_1 to the generator's center direction is absorbed by the matter of the internal shell of HEG. In the case, when one can neglect the proton's energy loss and scattering in the process of passing through the external shell, the condition of reaching the internal shell can be written for the proton in the following form:

$$U_{eff} = \frac{M^2}{2mr^2} + U \le E = \frac{mv^2}{2} \qquad (2)$$

where U_{eff} is the effective potential energy of the proton at the moment of entering the internal shell, and $M = mvR\sin\vartheta$ is the angular momentum on the external boundary of the generator. It follows from (2) that admissible angles of entering the generator are restricted by

$$\vartheta_1 \le \vartheta_1^*(E) = \arccos\sqrt{1 - \frac{r^2}{R^2}\left(1 - \frac{eU}{E}\right)} \qquad (3)$$

If the direction of motion of a proton lies in the cone determined by condition (3), in the process of subsequent motion inside the generator the proton should reach its internal shell, and at the moment of crossing the internal shell surface it will move under the angle ϑ_2 to the normal of the surface. This angle can be found from the integrals of energy:

$$\frac{mv^2}{2} = \frac{mv^2}{2} + eU \qquad (4)$$

and angular momentum:

$$M\big|_R = mvR\sin\vartheta_1 = mvr\sin\vartheta_2 = M\big|_r \qquad (5)$$

From (4) and (5) we get:

$$\vartheta_2 = \arccos\sqrt{1 - \frac{R^2}{r^2}\frac{\sin^2\vartheta_1}{(1-\frac{eU}{E})}} \qquad (6)$$

The proton will be absorbed by the internal surface on the condition that

$$\frac{2d_i}{\cos\vartheta_2} > l(E - eU) \qquad (7)$$

where $l(E')$ is the path length of a proton with energy E' in the material of the internal shell (when formulating condition (7) it is assumed that the effects of scattering in collisions with atoms of the internal shell material can be neglected for protons passing through the HEG internal shell). Substituting (6) into (7), we get the additional restriction on the initial direction :

$$\vartheta_1 > \vartheta_1^{**}(E) = \arccos\sqrt{1-\frac{r^2}{R^2}(1-\frac{eU}{E})(1-\frac{4d_i^2}{l^2(E-eU)})}. \qquad (8)$$

Let E^* be a root of the equation $l(E - eU) = 2d_i$. In the case when $E < E^*$ and $\vartheta_1 < \vartheta_1^*(E)$ condition (7) is valid automatically. However, if $E > E^*$, the restriction on the admissible angle of entrance has the form:

$$\vartheta_1^{**}(E) < \vartheta < \vartheta_1^*(E). \qquad (9)$$

Taking these relations into account, the total current of protons absorbed by the internal shell of HEG is determined by the integral:

$$J_{abs}^p = 8\pi^2 R^2 e[\int_{eU}^{E^*}\int_0^{\vartheta_1^*}\frac{dI^p}{d\omega dE}\sin\vartheta dE d\vartheta + \int_{E^*}^{\infty}\int_{\vartheta_1^*}^{\vartheta_1^{**}}\frac{dI^p}{d\omega dE}\sin\vartheta dE d\omega] \qquad (10)$$

where $dI^p/d\omega dE$ is the differential intensity of protons of the Earth's radiation belt.

In the considered stationary mode of operation of the generator, when current J_{abs}^p is balanced by current J_1 flowing through the load, the power $W = UJ_{abs}^p(U)$ is released on the load. In this case, specific power *w* of the generator, equal to the ratio of power *W* to the generator's mass $M_g = 4\pi(\rho_i d_i r^2 + \rho_e d_e R^2)$, is determined by the formula:

$$w = \frac{2\pi eU}{\rho_i d_i \frac{r^2}{R^2} + \rho_e d_e} \times \{\int_{eU}^{E^*}\left[1-\sqrt{1-\frac{r^2}{R^2}(1-\frac{eU}{E})}\right]\frac{dI^p}{d\omega dE}dE + \int_{E^*}^{\infty}[\sqrt{1-\frac{r^2}{R^2}(1-\frac{eU}{E})(1-\frac{4d_i^2}{l^2(E-eU)})} - \sqrt{1-\frac{r^2}{R^2}(1-\frac{eU}{E})}]\frac{dI^p}{d\omega dE}dE\} \qquad (11)$$

In the particular case, when the radii of the external and internal shells are close, and the thickness of the external shell is small in comparison with the thickness of the internal shell, formula (11) for *w* takes on the simpler form:

$$w = \frac{2\pi eU}{\rho_i d_i}\{\int_{eU}^{E^*}\left[1-\sqrt{\frac{eU}{E}}\right]\frac{dI^p}{d\omega dE}dE$$
$$+\int_{E^*}^{\infty}[\sqrt{\frac{eU}{E}+\frac{4d_i^2}{l^2(E-eU)}(1-\frac{eU}{E})} \quad (12)$$
$$-\sqrt{\frac{eU}{E}}]\frac{dI^p}{d\omega dE}dE\}$$

As follows from (12), in this case the specific power of HEG does not depend on radii of its shells and is determined by the differential intensity of the proton flux at the point of HEG location in NES, by the voltage between the shells, and also by the density of the material of the internal shell and its thickness.

Using formula (12), let us calculate the specific power of HEG whose internal shell is manufactured from aluminum foil with a thickness of 0.5 to 8 microns. In this case the current of protons absorbed by the internal shell of the generator is determined by the flux of low-energy protons with energies ≤ 1 MeV whose differential intensity flux near the equatorial plane is described by the exponential function [5, 6]:

$$\frac{dI^p}{d\omega dE} = \frac{I_0^p}{E_0}\exp(-\frac{E}{E_0}), \qquad (13)$$

where I_0^p is the total flux of protons per unit solid angle. In order to determine the values of I_0^p at various magnetic shells, let us take advantage of the data about proton fluxes in NERB in the plane of geomagnetic equator presented in [9] for the maximum phase of solar activity. The dependence of energy E_0 in (13) on the McIlwain L-parameter we approximate by the power-law function, $E_0 \sim L^{-3}$ [5, 6]. For L = 5 energy E_0 = 120 keV [6]. Eventually, in order to specify the dependence of the path length of a proton in the internal shell material on its energy E', we take advantage of an analytical approximation of function $l(E')$ presented in [7].

4 RESULTS OF CALCULATIONS OF HEG SPECIFIC POWER FOR A CASE SETTING IT INSIDE NATURAL RADIATION BELTS OF THE EARTH

Let us consider thus obtained results of calculating the specific power of HEG whose location in NES is characterized by values of the L-parameter from L = 2.5 up to L = 4.5. First of all we notice that, as one could expect based on calculation data obtained, at a fixed location in natural ERB the specific power of HEG with a given thickness of the internal shell varies with changing operating HEG voltage nonmonotonically, reaching the maximum

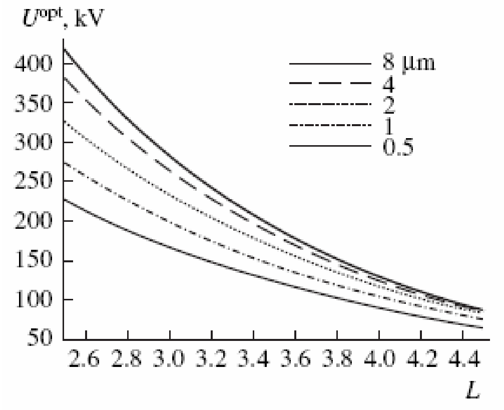

Fig. 2

value w^{max} at a certain operating voltage of HEG, optimal for its given location in NES. For the considered values of the thickness of the HEG's internal shell (from 0.5 to 8 μm) optimum operating voltages U^{opt} decrease monotonically with increasing L-parameter (see Fig. 2). The calculated L-dependences of maximum specific powers of HEG for different values of the thickness of the generator's internal shell are presented in Fig. 3. As is seen from this figure, at a fixed thickness of the internal shell the power w^{max} varies nonmonotonically with increasing L-parameter, reaching the largest value at a certain optimal (for the considered value of d_i) location of HEG in natural ERB. The limiting value of the specific power of HEG, equal to 3.3 W/kg, is reached at 1 μm thickness of the internal shell for a location of the generator on the magnetic shell L = 3.3.

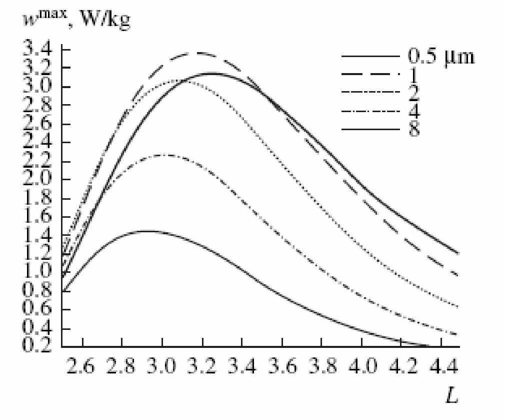

Fig. 3

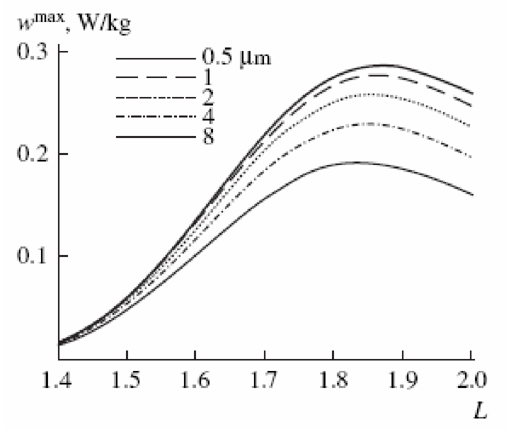

Fig.4

Now let us consider the issue of possible values of the HEG specific power in NES regions where the flux of ERB electrons is dominant. In accordance with the data of [5] these regions are located on magnetic shells with $L \le 2$ and $L \ge 5$. As in the case considered above, in order to determine the HEG specific power, we take advantage of formula (12). One should have in mind that estimates obtained in this way are approximate, since, unlike the case of protons, the effects of scattering of electrons during their passage through generator's shells can play an important part when HEG is charged by the flux of ERB electrons. These effects were not taken into account in derivation of formula (12).

We first make an estimate of possible values of the HEG specific power in the inner radiation belt of the Earth on magnetic shells with values of *L* from 1.4 to 2. We approximate the differential intensity of the electron flux by an exponential function similar to (13) with E_0 = 200 keV for L = 1.4 and $E_0 \sim L^{-2}$ for $L > 1.4$ [5]. In order to determine the values of I_0^e on various magnetic shells let us make use of the data on the flux of ERB electrons in the plane of the geomagnetic equator presented in [5] for the phase of maximum solar activity.

The optimal operating voltage U^{opt} for the considered values of the thickness of the HEG internal shell (from 0.5 up to 8 μm) monotonically decreases with increasing *L*-parameter. Figure 4 presents calculated L-dependences of maximum specific powers of HEG for various values of the thickness of the generator's internal shell. As is seen from Fig. 4, at a fixed thickness of the internal shell the power $w^{\max}$ reaches its largest value at a certain optimal (for the considered value of d_i) location of HEG in the inner electron radiation belt of the Earth. The limiting value of the specific power of HEG, equal to 0.29 W/kg, is reached in this case at the internal shell thickness of 0.5 μm for the generator's location on the magnetic shell $L = 1.9$.

Finally, let us estimate possible values of the specific power of HEG in the outer electron radiation belt of the Earth. For determination of the differential intensity in this case we have used experimental data of [8]. As follows from the calculation data obtained, in this case the specific powers $w^{\max}$ monotonically decrease with increasing thickness of the HEG internal shell from the maximum value equal to $2.9 \cdot 10^{-2}$ W/kg at d_i = 0.5 μm down to $w^{\max} = 1.4 \cdot 10^{-2}$ W/kg for d_i = 8 μm.

5 DISCUSSION OF RESULTS FOR ERB

The results of the above estimation of possible values of the specific power of HEG which transforms into electric power the kinetic energy of particles of the natural radiation belts demonstrate that maximum values of the generator's specific power (up to 3.3 W/kg) can be realized in the case when the generator is placed in the gap between the inner and outer radiation belts. In this region the flux of protons of the ERB substantially exceeds the flux of energetic electrons. Maximum values of the HEG specific power are smaller than the above limiting value by an order of magnitude in the inner electron radiation belt and by two orders of magnitude in the outer electron belt. Notice for comparison that the specific power of available systems of power supply for small satellites is within the limits 1–3 W/kg [9] at a total power of ~50–100 W. Thus, the HEG construction under consideration turns out to be quite competitive (at least in the region where the flux of ERB protons dominates) with the power sources for small spacecraft that operate using traditional principles. Moreover, in those special cases when a source of electric power should provide for generation of electric power at the output voltage of tens and hundreds of kilovolts (for example, energy supply of operation of ion engines or onboard accelerators of charged particles) it is preferable to use HEG, since electric power is produced by HEG directly at high primary voltage, which makes it unnecessary to use additional devices of voltage rise.

However, one should have in mind that the above estimates of the specific power of a high-voltage electric generator are a first step in studying the circle of science and engineering problems associated with the development of HEG. First of all, evaluation of possible influence of various currents of charge leakage through the high-voltage vacuum gap on the process of HEG charging is among these problems. Discharge currents and currents of secondary electron emission are basic currents of this type. In the case when HEG charging is caused by the flux of ERB protons, one can neglect the contribution of discharge currents to the process of charging, provided that their density is $\leq 10^{-8}\, A/m^2$. As is shown by the results of *in situ* experiments on charging a conducting shielded body onboard satellites of the *Kosmos* series [10–12], the density of discharge leakage currents at voltages below 100 kV does not exceed $\sim 10^{-9}\, A/m^2$, i.e., it is smaller than the above limiting value by at least an order of magnitude. However, the necessary small values of discharge currents, $\sim 10^{-9}\, A/m^2$, are achieved only in the case of pre-burning high-voltage currents with a density of $\sim 10^{-2} - 10^{-4}\, A/m^2$ and duration of tens of minutes. As is shown by evaluation, when the generator operates in the NES region with predominance of the flux of ERB protons, the current of secondary electrons with energies of ~1 eV can have substantial influence on the process of HEG charging. These electrons are generated in the material of the HEG external shell when high-energy protons penetrate into the space between the shells. In this case, for cutting off the extraneous current of secondary electrons, one should include into the HEG construction an additional grid positioned near the inner surface of the external shell of the generator. This grid must be kept under a small negative potential of order of a few volts. When the generator operates in the electron radiation belts of the Earth, the current of secondary electrons generated when ERB electrons enter the internal shell of HEG can be a factor hindering from creation of high voltage between the HEG shells. However, one can demonstrate that, due to smallness of the coefficient of secondary electron emission at energies typical for ERB electrons, this current can be neglected in the case under consideration.

6 RESULTS OF CALCULATIONS OF HEG SPECIFIC POWER FOR A CASE OF SETTING IT INSIDE POLAR REGION

Another place for HEG location can be a polar region where there are intense electron fluxes (these are named fluxes of auroral electrons). Results of numerous studies show that there are mentioned below features of these fluxes: 1) a strong time variation of total fluxes; 2) a strong dependence of auroral electrons location on geomagnetic conditions; 3) complex energy spectrum is describable by presence of some local maxima; its values can be changed significantly with time; 4) the energy of first maximum is about 1 keV and second one is situated inside a interval from 15 keV till 20 keV; 5) maximal total electron fluxes are more than ERB fluxes; 6) altitudes of observation of maximal fluxes are substantially less than ones for other cases [13].Experimental studies of auroral electrons fluxes which took place during Defence Meteorological Satellite Program permitted to deduct a approximate expressions of auroral electrons distributional functions as a combination of some Maxwellians [14]. Basing on these functions we have evaluate maximum specific power of the generator $w^{\max}$ for various values of the thickness of the generator's internal shell (Fig. 5). The obtained data show that if the generator is situated in auroral electron zone specific power can exceed 100 W/kg for the thickness of 100 nm. If the thickness is less than 100 nm our evaluations prognosticate higher efficiency. However in this case we

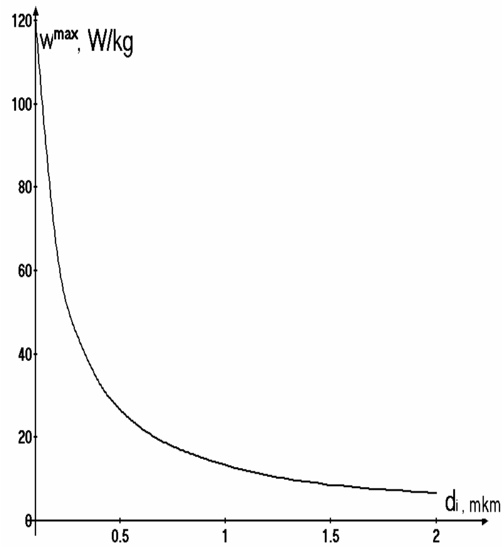

Fig.5

have to use improved methods of electron path length calculations in the material and modeling of charging process.

7 CONCLUSIONS

For the case of setting HEG inside the natural radiation belts of the Earth results of our calculation show that the largest values of the HEG specific power are 3.3 Wt/kg. Maximum values of the HEG specific power are smaller than the limiting value by an order of magnitude in the inner electron radiation belt and by two up to orders of magnitude in the outer electron belt.

For the case of setting HEG inside the auroral zone results of our calculation show that specific power can exceed 100 W/kg.

In its weight characteristics the HEG construction considered above turns out to be quite competitive with the power plants for small spacecraft operating on conventional principles. This is especially true for those special cases when the power supply should provide for electric power generation at the output voltage of tens and hundreds of kilovolts.

Side by side with studying the influence of leakage currents through the high-voltage vacuum gap on functioning of HEG, further substantiation of the suggested concept of power supply should include investigations of the problem of maintenance of the stiffness and stability of the generator construction, and calculations of its strength characteristics.

In conclusion, we emphasize that the Earth is not a single planet in the solar system with radiation belts. The powerful radiations belts (far exceeding in their particle density the Earth's radiation belts) have been found in the vicinity of Jupiter. The existence of radiation belts is established for Saturn and Uranus. At the same time, at large distances from the Sun the specific power of conventional electric power sources based on converting the energy of solar electromagnetic radiation into electric power becomes insignificant. Therefore, one cannot exclude that the principle of getting electric power in space considered by us may turn out to be especially efficient in creating electric generators designed for power supply of space probes in the vicinity of giant planets of the solar system.

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