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SPACE RADIATION EFFECTS SIMULATION METHODS

SINP MSU Preprint – 2003 – 9 / 722

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УДК
ББК

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Abstract

Experimental and computer methods for simulation of space radiation effects on spacecraft materials and devices are discussed. The main principles of laboratory radiation testing of spacecraft materials and principles of computer modeling of space radiation effects are covered.

Brief description of several accelerators used in Russia, and at SINP MSU in particular, for radiation testing of the spacecraft materials and devices is given. Several Russian mathematical models and software tools used for analysis of the radiation impact on spacecrafts are described. Information on complex space experiments, where the space radiation parameters and effects are measured simultaneously onboard the space stations MIR and ISS, and onboard the Russian geosynchronous spacecraft is given. Some results of experimental studies and computer modeling are presented.

Л.С.Новиков

МЕТОДЫ ИМИТАЦИИ ВОЗДЕЙСТВИЯ КОСМИЧЕСКОЙ РАДИАЦИИ

Препринт НИИЯФ МГУ – 2003 – 9 / 722

Аннотация

Обсуждаются экспериментальные и компьютерные методы имитации воздействия космической радиации на материалы и оборудование космических аппаратов. Рассмотрены основные принципы лабораторных радиационных испытаний материалов и принципы компьютерного моделирования радиационных эффектов.

Дано краткое описание некоторых ускорительных комплексов, используемых в России, в частности в НИИЯФ МГУ, для радиационных испытаний материалов и оборудования космических аппаратов. Описаны некоторые российские компьютерные модели и программы, используемые при изучении радиационных воздействий на космические аппараты. Приведена информация о комплексных космических экспериментах, в которых одновременно измеряются параметры космической радиации и эффекты ее воздействия, на борту орбитальной станции «Мир» и Международной космической станции, а также на российских геостационарных ИСЗ. Приведены некоторые результаты экспериментальных исследований и компьютерного моделирования.

1. Introduction

The effects of space radiation on spacecraft materials and devices are one of the main reasons of arising of the spacecraft operation failure and life-time reduction. Main components of the space radiation are: the Earth's radiation belts (RB), galactic cosmic rays (GCRs), solar proton events (SPEs), hot magnetosphere plasma (HP).

The total energy range of electrons and ions of the space radiation is exceedingly wide: from 10^3 up to 10^{21} eV that produces various radiation effects both on the spacecraft surface, and inside the spacecraft. It is possible to classify all appearing radiation effects into effects of the total dose and effects of the dose rate. The typical illustration of the first type effects is degradation of solar cell, optical glass, thermo-control coatings. The examples of the second type effects are radiation conductivity of dielectrics and semiconductors and radiation luminescence of materials. The brightest manifestation of such effects is single events upsets (SEUs) in modern electronic devises.

Information on the space radiation effects can be obtained using the following three ways:

1. on-board experiments in space;
2. ground-based radiation testing;
3. mathematical modeling.

The space experiments may provide the most reliable information. However, it is difficult to obtain the necessary full database both on the space radiation features and on the appearing effects in spacecraft materials and devices in such experiments. Besides, space experiments are very expensive. So the main amount of information is obtained using the ground-based radiation testing of the spacecraft materials and devices, as far as the mathematical modeling.

In turn, two approaches are possible in the ground-based testing:

1. reproduction of the space radiation features (the ion composition, energy spectra, angular distribution, intensity) in laboratory equipment as exactly as possible;
2. radiation testing under the following simplifications:
    - usage of monoenergetic electron or ion beams instead of fluxes of particles with distributed energy spectra,
    - change of the charged particle fluxes with x-ray or gamma-radiation;
    - increase to the radiation intensities by a factor of 10^2-10^3 compared to conditions in space for reduction of the tasting time.

Evidently, the first approach specified above is very difficult to realize technically, and the second approach requires enough serious scientific ground, i.e. detailed knowledge of physical mechanisms of the radiation effects to avoid the wrong results.

Mathematical modeling of the radiation environment effects allows to take into account the real features of the space radiation, spacecraft design peculiarities, properties of used materials and equipment. But in this case also, it is necessary to use the physical data on mechanisms of the radiation effects.

The above problems are considered in this paper.

2. General principles of the space radiation effects study

The scheme of study of the space radiation environment effects on the spacecraft materials and devices is presented in fig. 1

The starting points for problem setting and choice of the study methods are:

- models and standards of space radiation (1);
- types of orbits and the spacecraft life-times (2);
- spacecraft design, used materials and on-board devices (3).

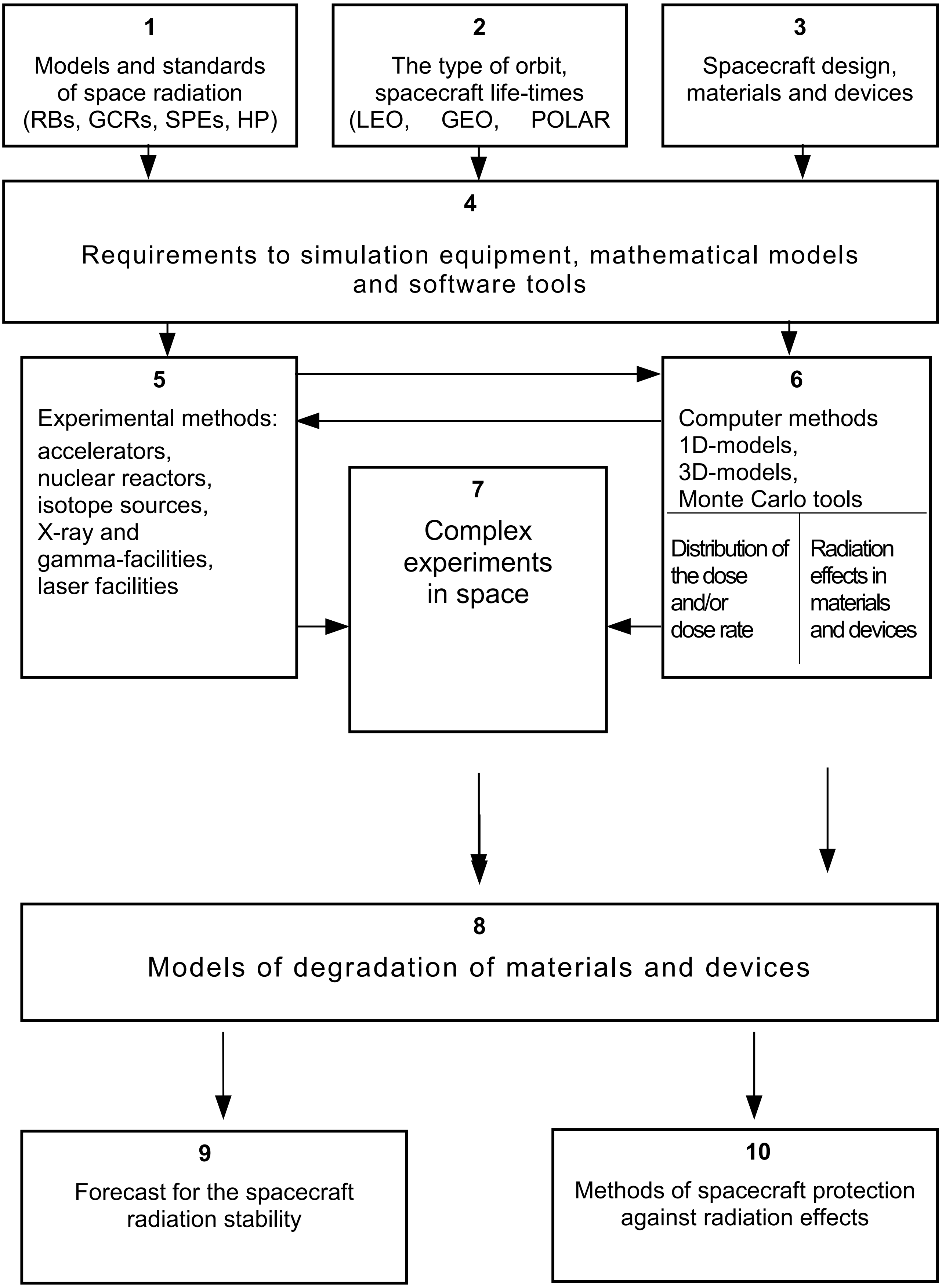


Fig. 1. The scheme of organization of the space radiation effects study

In terms of the starting points above, requirements to laboratory testing equipment, mathematical models and software tools, which must be used for the space radiation effects modeling, are formulated (4). Then, the most suitable experimental methods and equipment (5) and/or mathematical models and software tools (6) are chosen taking into account the requirements.

Experimental and mathematical methods are often used together, and complement each other: choice of parameters of laboratory equipment is done using the results of mathematical modeling, and results of laboratory studies of radiation effects are input data for computer modeling.

The complex experiments in space (7) in which the features of the space environment, radiation condition inside the spacecraft and radiation effects in various materials are studied simultaneously, are organized taking into account the results of both laboratory testing and mathematical modeling.

The database obtained using all methods is used for creation of models of material and device degradation in various conditions (8), and for development of spacecraft reliability and life-time forecasting methods (9) and recommendations on spacecraft protection against the radiation effects (10).

For estimation and forecasting of the spacecraft radiation stability, special expert systems which contain computer databases on radiation conditions in various spacecraft orbits and on typical radiation effects are developed. Such systems may have the channels for reception of the real-time information on the near-Earth space environment condition from satellites (solar wind velocity, interplanetary magnetic field, charged particle fluxes and others), and from the ground observation facilities (the geomagnetic indexes, solar electromagnetic radiation, neutron monitor data etc.). In the last case, the expert systems can work in mode of real-time and give the recommendations on operative spacecraft control.

Taking into account the variety of space radiations acting upon spacecraft and complexity of processes, running in tested materials and elements of the spacecraft equipment, testing is conducted using the special techniques:

- the most weak segment which defines the limit of the radiation stability is noted in the material or device under investigation;
- one (sometimes two-three) component of space radiation, causing most critical radiation damages of the investigation object are selected taking into account the spacecraft orbit type and life time;
- the most important physical processes causing material and the equipment elements degradation are revealed;
- criteria of change of the space radiations by monoenergetic beams, and change of radiations of the given types by radiations of other types are chosen and proved (the criteria may can be the uniform distribution of the absorbed dose on thickness of irradiated sample of material, similar type and concentration of radiation defects appearing in the material);
- in terms of division of the total dose effects and the dose rate effects, reduction of the test time due to increase of irradiation intensities compared to conditions in space are proved. Here it is taken into account that under high irradiation intensity the following processes can occur: radiation heating of the test sample of material, radiation-stimulated diffusion, radiation defect annealing, cascade radiation processes.

The mean parameters of the various space radiation components are presented in Table 1. In terms of these parameters, it is possible to formulate the requirements to experimental equipment and mathematical methods for study of the radiation effects. Note that hot magnetosphere plasma energies of electrons and ions of which lie in the interval of 10^3-10^5 eV, is not considered often as factor producing radiation effects in the spacecraft materials and equipment. However, contribution of charged particles with energy in the interval above in the value of dose absorbed in thin surface layers of material, may be significant in some cases. Besides, hot magnetosphere plasma causes the spacecraft charging. Methods for laboratory and mathematical modeling of the spacecraft charging are similar to ones used for the modeling of the radiation effects.

Table 1

Mean parameters of particles fluxes of galactic cosmic rays, solar proton events, Earth's radiation belts and hot magnetosphere plasma

Type of corpuscular radiation	Composition	Energy of particles, MeV	Flux, $m^{-2}s^{-1}$
Galactic cosmic rays	protons He nuclei heavy nuclei	10^2—10^{15} (for all nuclei)	$1{,}5 \cdot 10^4$ $1 \cdot 10^3$ $1.2 \cdot 10^1$
Solar proton events	protons	1 – 10^4	10^7—10^8
The Earth's radiation belts	protons electrons	1—30 >30 0,1—1,0 >1,0	$3 \cdot 10^{11}$ $2 \cdot 10^8$ $1 \cdot 10^{12}$ $1 \cdot 10^{10}$
Hot magnetosphere plasma	protons electrons	10^{-3} – 10^{-1}	10^{11} – 10^{14}

The more detailed description of various components of the space radiation, models and standards of space radiation, space radiation effects on material and devices, as well as methods of radiation environment effect study are presented in [1-4].

3. Laboratory equipment for radiation testing of materials and devices

The main types of equipment used for the ground radiation tests are specified in fig. 1. For these purposes, various charged particle accelerators are broadly used: electrostatic accelerators, linear accelerators, cyclotrons etc.

3.1. SINP MSU ion and electron accelerators

At choice of accelerators, one should take into account the range of energy and the intensity of the space radiation simulated (see Table 1). The parameters of some ion accelerators, used in SINP MSU for radiation testing of spacecraft materials and devices, are presented in Table 2. By means of these accelerators, simulation of the Earth's radiation belts effects on spacecraft is produced. Note that acceleration of electrons and micron and submicron size hard particles is produced on electrostatic generator EG-8 (the Van de Graaff generator) also for simulation of the impact of micrometeoroids and space debris particles on spacecraft [5,6].

In the last years, race-track microtron and several linear electron accelerators were designed in SINP MSU for acceleration of electrons up to energy of 70 MeV, and for lower energies correspondingly [7,8]. These accelerators are used both for solution of fundamental problems, and for simulation the space radiation effects on the spacecraft materials and devices. The main parameters of the electron accelerators developed are presented in Table 3.

Block diagram of the universal linear accelerator, parameters of which are specified in Table 3 is presented in fig.2.

Table 2

Parameters of SINP MSU ion accelerators

Type of accelerator	Accelerated particles	Energy of ions, MeV	Maximum current, μA
120-cm cyclotron	p, α-particles	7,5 20,0	20
Electrostatic generator EG-8	p, α-particles	1-3,2 2-6,4	20
Cascade generator CG-500	p, α-particles	0,1-0,5 0,2-1,0	100

Table 3

Parameters of SINP MSU electron accelerators

Type of accelerator	Energy of electrons, MeV	Maximum current, мА
Microtron	10 - 70	40
One-section linear accelerator	0.6	50
Two-section linear accelerator	1.2	50
Universal linear accelerator	1.2 1.7 2.3	10

The accelerator involves the following main elements: electronic gun (EG) producing energy of the electron beam up to 100 keV; three accelerating sections with standing wave (AS1-AS3), rotary 15° magnet (M1), magnetic mirror (M2).

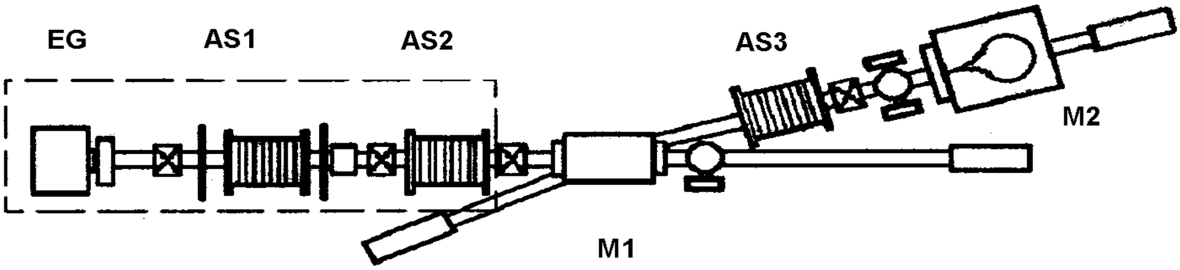


Fig. 2. Block diagram of the universal electron accelerator

The accelerator has three outlets with various beam energies - direct outlet with maximum beam energy of 1.2 MeV, outlet at the angle of 15° to the main beam direction with the beam energy up to 1.7 MeV and outlet at the angle of 336° with the beam energy up to 2.3 MeV. The beam is monoenergetic with error of 5%, long-time stability of the beam energy is 1%, stability of the beam current is 10%. The beam current is checked by means of Faraday cylinder that provides the measurement of true value of the electron flux on the target. In the accelerator, the beam scanning is possible that provides the irradiation of surface 500*50 mm^2 at the flux unevenness better than 5%.

For study of the radiation environment effects on the spacecraft materials and devices, special experimental chambers were designed where test objects and detectors for the charged particle beam parameter measurement and for registration of the appearing effects are placed.

In fig. 3, the scheme of experimental chamber which is used in SINP MSU cyclotron is presented. In fig. 4, the scheme of similar chamber used in SINP MSU cascade generator CG-500 [9] is shown.

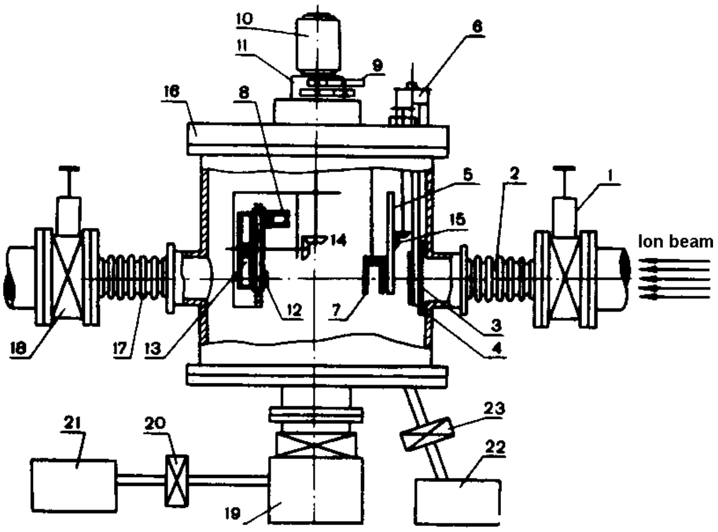


Fig. 3. Scheme of experimental chamber in SINP MSU 120-cm cyclotron: 1,2,17,18,19-23 – vacuum system elements; 3 – diaphragm; 4,6 – electromagnet gate; 5 – disk with thin metal films; 7 – collimator; 8 – Faraday cylinder; 9-11,14,15 – disk rotation mechanism; 12 – sample; 13 – cooler; 16 – removable flanger

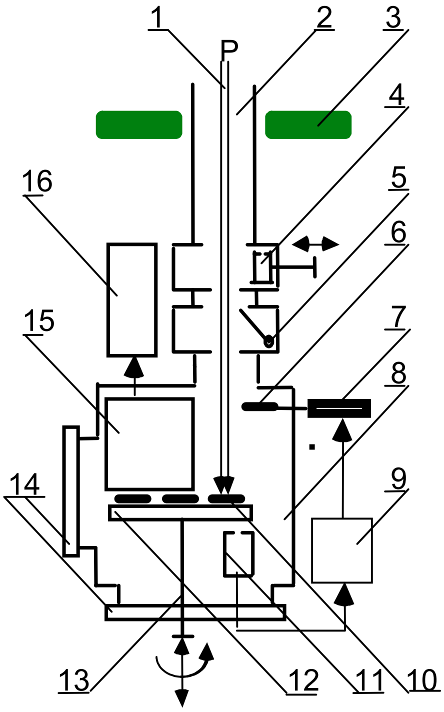


Fig. 4. Scheme of experimental chamber used for the proton beam effect tests: 1 – proton beam, 2 – proton guide, 3 - declining electromagnet, 4,11 – Faraday cylinders, 5 - vacuum valve, 6 - small flag-damper, 7 - solenoid, 8 - vacuum chamber, 9 – beam monitoring block, 10 - tested samples, 12 - disk for the tested samples mounting, 13 - rod for the disk rotation, 14 - flanges of the chamber, 15, 16 – blocks for the sample parameters measurement

3.2. Accelerators in other Russian research centers

The studies of the space radiation effects on spacecraft materials and devices are conducted in Russia in various scientific centers using electron and ion accelerators. As examples, parameters of several electron and ion accelerators used for radiation tests [9,10] are presented in Table 4.

Table 4

Parameters of several Russian electron and ion accelerators used for radiation testing of materials and devices

Type of accelerator, research center	Accelerated particles	Particle energy, MeV	Flux, $m^{-2}s^{-1}$
Linear accelerator, IMET RAS	electrons	2	10^{15} - 10^{16}
Microtron, IMET RAS	electrons	30	10^{12} - 10^{13}
Betatron, Tomsk polytechnical university	electrons	6	10^{12} - 10^{13}
Linear injector, IHEP Centre, Protvino	protons	30 70 100	10^{13} - 10^{14}

For study of SEUs in microelectronics elements, big heavy ion accelerators, which work in Joint Institute of Nucleus Studies (JINR) in Dubna [11] are used. Isochronous cyclotron U-400 gives the beams of ions with atomic masses from 4 up to 100 and maximum energy up to 25 MeV/nucleon. The maximum ion beam intensity is $2\cdot10^{14}$ s^{-1}. Beams of Kr27+ and Ar16+ ions with energy 1 Gev/nucleon are obtained on the Nuclotron accelerator, and works aimed at Fe22+, Fe23+, Fe24+ ion beams are conducted.

3.3. Production of the charged particles beams with distributed energy spectra in accelerators

As mentioned above, one of the methodical problems of the space radiation effects simulation is substitution of the space ion and electron fluxes with broad energy spectra with monoenergetic accelerator beams. Some technical methods exist for solution of this problem in accelerators which enable to get fluxes of particles with energy spectra similar to ones in space.

In SINP MSU 120-cm cyclotron, a stopping plate of variable cross-section (see fig. 5) placed on the way of primary monoenergetic beam was used to obtain the beam of protons with broad energy spectrum. Profile of the plate, characterized by width of elements of structure M and height R, is evaluated in terms of the necessary energy spectrum parameters. In fig. 6, differential energy spectrum of protons after passing of 6.5 MeV proton beam through the plate of variable cross-section is shown together with the space proton spectrum as an example. The method of the plate of variable cross-section finds its application for simulation radiation tests of various elements arranged on spacecraft external surface (thermo control coatings, silicon photovoltaic cells etc.).

Similar method is used for transformation of monoenergetic electron beams (E~1-10 MeV) into beam with broad energy spectrums.

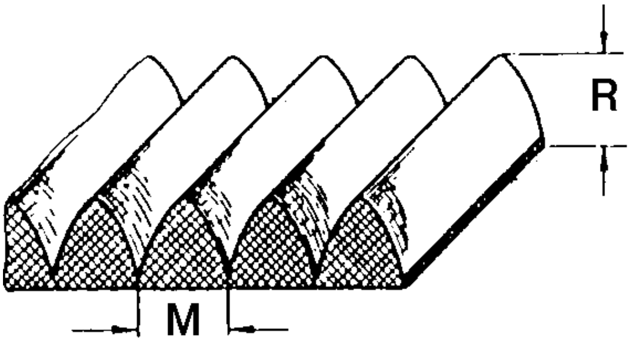


Fig. 5. Schematic outline of the stopping plate of variable cross-section, characterized by parameters M and R

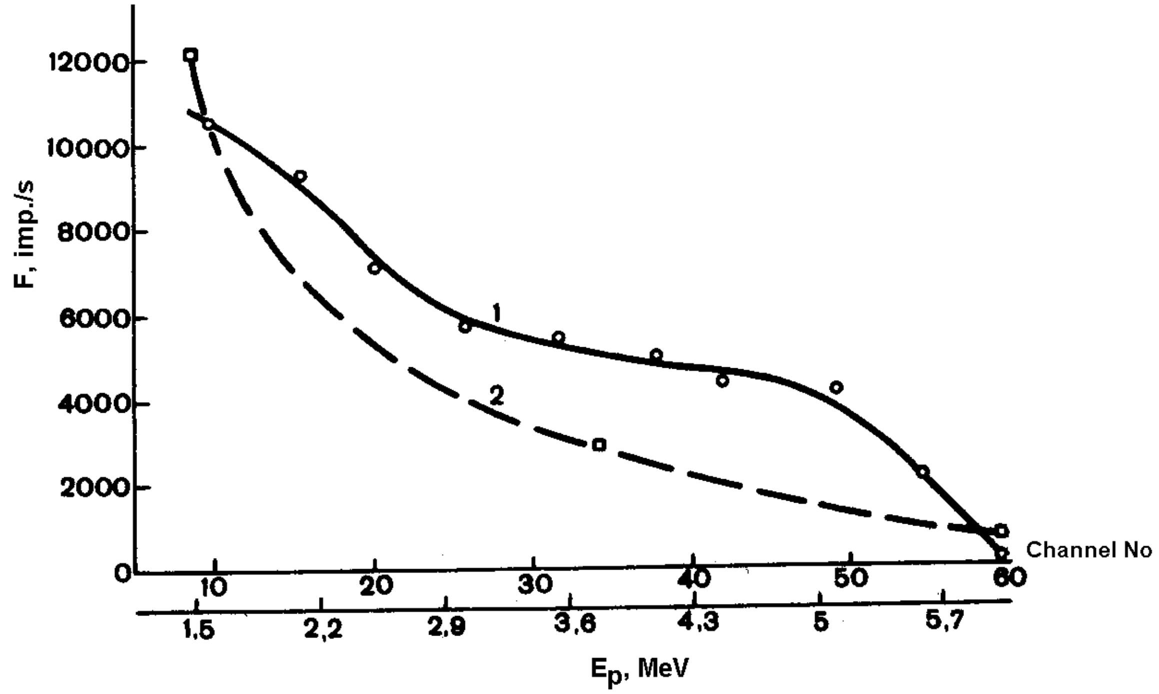


Fig. 6. Energy spectrum of protons with initial energy of 6.5 MeV after passing through the stopping plate of variable cross-section (1) in comparison with energy spectrum of the Earth's radiation belt protons (2)

The method for production of electron beams with distributed energy spectrum in betatron was developed in Tomsk Polytechnical University [10]. Special computer program which controls the process of electron bunch exit from betatron is used in this method. One can form the necessary spectrum selecting energy and amount of electrons in each bunch. In fig. 7, the spectrum of electrons obtained using the method described compared to the Earth's radiation belt electron spectrum is shown.

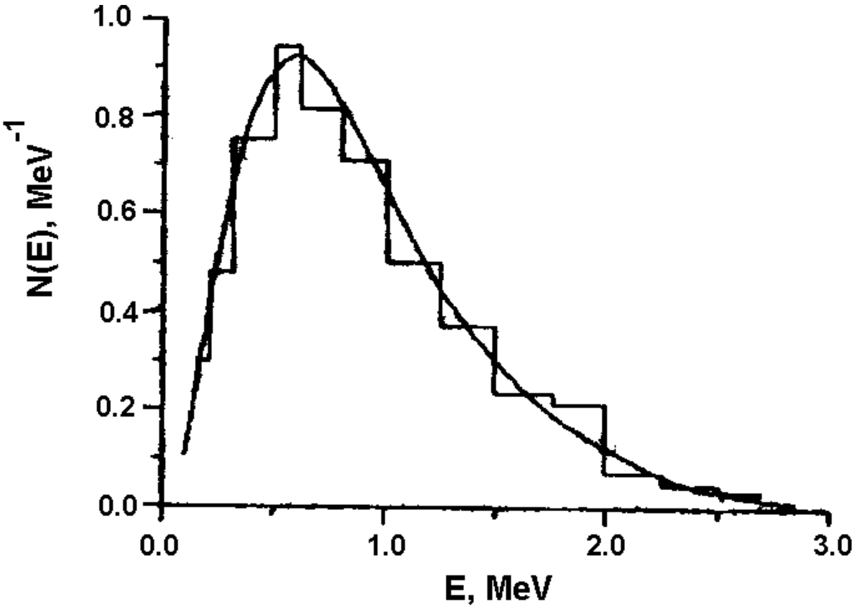


Fig. 7. Results of modeling of the distributed electron spectrum on betatron (histogram) in comparison with the Earth's radiation belt electron spectrum (monotonous curve)

3.4. Simulation facilities of other types

For simulation of the radiation environment effects on the spacecraft materials and devices, isotope sources, x-ray, gamma and laser facilities can be used instead of the charged particle beams. In Table 5, parameters of several facilities used in SINP MSU, FCI [9] and in NIIP [12] are presented.

Table 5

Facilities for radiation testing of the spacecraft materials and devices

Facility type, research center	Type of particles	Energy, MeV	Main parameters
Isotope facility: Co^{60} (SINP MSU)	gamma-radiation	1.25	Dose rate 1 –3 R.s^{-1}
Isotope facility: Co^{60} (Obninsk branch of FCI)	gamma-radiation	1.25	Dose rate 10^2-10^3 R.s^{-1}
Isotope facility: Tl^{204} (SINP MSU)	Electrons	0.25	Flux: 10^7-10^8 cm^{-2}s^{-1}
Isotope facility: Sr^{90} – Y^{90} (NIIP)	Electrons	0.7 – 0.9 (mean energy)	Flux: 5.10^4-6.10^8 sm^{-2}s^{-1}
Isotope facility: Cf^{252} (NIIP)	α-particles, fission fragments	6.1 50 – 130	Isotope activity: 2.2 Bc
Laser facility (NIIP)	photons	λ=1.08 μm	Energy in impulse ~50 mJ, impulse length ~10 ns

4. Computer methods of modeling

Mathematical modeling of the space radiation effects is developed in two directions:

- computation of the radiation dose and/or dose rate distribution in the spacecraft materials and elements of equipment, in particular in complex models describing the main design features of the spacecraft;
- computation of material or device parameter changes induced by the radiation effects.

In this work, we concern the first direction mainly.

4.1. Models with simple configuration of protective shield

For computation of the absorbed dose value in various depths in target and beyond various shields, a great amount of analytical and numerical models taking into account the energy and type of the impact particles, shield and target types of material, as well as the shield geometry is created. Specially for calculation of the space radiation doses, the SHIELDOSE program [13] which considers the effect of isotropic electron and proton fluxes with distributed energy spectra on the object was developed. In the program, computations may be done for three shield geometries (slab shield, semi-infinite, spherical). The program contains the database on electron and proton energy losses created in terms of Monte Carlo modeling of processes of interaction of particles with materials.

4.2. Engineering models for complex designs

Various engineering models are used for more exact calculation of the radiation dose and/or dose rate values. In these models, equivalent thickness of the shield may be computed for any point inside the spacecraft. To compute the equivalent thickness, the rays are traced from the selected point to surface elements into which the spacecraft surface is split, so the total mass of shielding materials is computed for each ray. The absorbed dose value in the considered point is computed by integration over the all surface elements, to which the space radiation falls, taking into account the shielding masses for each ray.

Engineering models allow to consider the objects of very complex design and, at the same time, they are simple enough, allow to conduct the calculations using personal computers of medium productivity and do not require the high personnel qualification.

Fig. 8 shows the geometric model of fragment of the Russian segment of ISS which was built for calculation of the absorbed dose distribution using the engineering computer code RDOSE, developed in SINP MSU [14,15]. The structure of this code is presented in fig. 9.

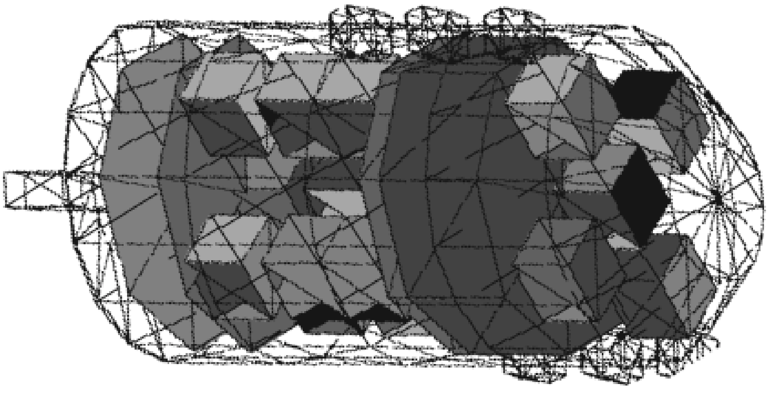


Fig.8. Geometric model of fragment of the Russian segment of ISS

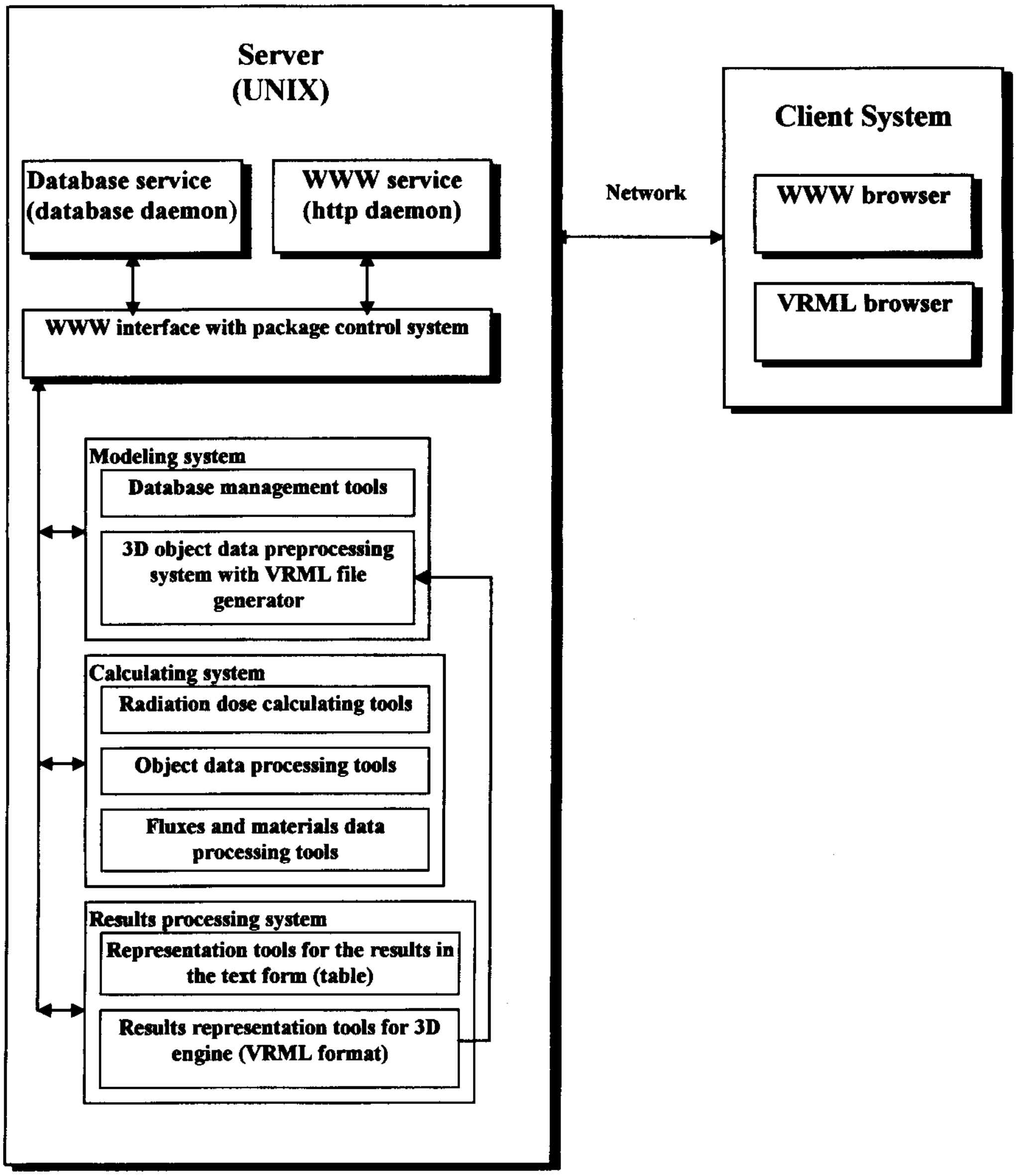


Fig.9. Structure of the RDOSE code

4.3. Application of the GEANT computer code

Universal computer code which is built in terms of the Monte Carlo method enables to solve the problems of the absorbed dose computation in objects of high degrees of complexity is the GEANT code. The code was developed originally in CERN for solution of high energy physics problems [16]. The code enables to describe the configuration of irradiated object in considerable details, and, besides, it contains extensive databases on processes of interaction of particles and quanta with various materials that enables to make the exact calculation of the absorbed dose distribution in spacecraft materials and devices. This code enables to simulate the influence of various ions, including heavy ions, on spacecraft, as well as investigate the processes of secondary neutron production in the spacecraft materials. The latter is particularly important for the low Earth orbit spacecrafts with big mass, e.g. for ISS [2].

The wide possibilities of the GEANT code and great amount of programs included in the program package make difficulties for the code application. Unlike the engineering codes above, which can be used by designers and engineers, the GEANT code requires highly skilled personnel and is used typically in scientific centers.

In SINP MSU, two versions of the code - GEANT 3 and GEANT 4 - were used for test computations. It was found that the code enables to compute the absorbed dose distribution in complex models of real spacecrafts using modern high power personal computers and workstations in short time enough (several or several tens of minutes).

The great potential of the GEANT code makes it suitable and productive for solution of problems connected with analysis of radiation processes in spacecraft materials. In SINP MSU for instance, the code was applied for calculation of distribution of the internal electric charge in dielectrics taking into account the internal electric field [17].

4.4. Computer modeling of spacecraft charging in hot magnetosphere plasma

The mathematical methods for modeling of the radiation effect in objects of simple and complex design are applicable, to considerable extent, for modeling of spacecraft charging in hot magnetosphere plasma. Same principles, as at building of models for the purpose of the absorbed dose computation, are used to construct the spacecraft geometric models in this case. Besides, algorithms, principles and methods of equations systems solution in both cases are similar also.

In SINP MSU, the computer code COULOMB was developed for modeling of real spacecraft charging in hot magnetosphere plasma [18, 19]. This code works with three-dimensional models of real spacecraft, which are built of elementary geometric figures: sphere, cylinder, cone, parallelepiped etc. The total number of such figures in the model achieves 150-200. For calculation, the spacecraft model surface is discretized into surface elements, for which local primary and secondary electric currents and potentials are computed. The total number of the surface elements in the model achieves 15 000. For calculation of electric field and electron and ion motion trajectories in vicinity of the model, the three-dimensional grid which cells are adjusted with surface elements of the model is built.

5. Complex space experiments

The ground-based laboratory testing of the spacecraft materials and devices and the computer modeling of the space radiation effects provide the base for optimization of instruments and program of complex space experiments, in which the parameters of the space radiation and the radiation effects are measured simultaneously. In SINP MSU in collaboration with RSC ENERGIYA, two experimental equipment complexes SPRUT-VI and SCORPION were developed to realize the complex experiment program [3,20]. The former of the two complexes is intended for installing on spacecraft outer surface, and the later – inside the spacecraft.

The SPRUT-VI complex comprises the set of instruments for measurements of electron, proton and more heavy ion fluxes in the wide energy range, absorbed dose, as well as the test samples of solar cells, electronic devices, optical elements and others. Measurements of the test sample parameters in flight with transmission of telemetry data to the Earth or with the data recording to on-board computer is provided. This complex worked onboard the MIR space station. The more perfect modification of this complex is intended for installation on ISS.

The SCORPION complex includes the big set of instruments for study of radiation conditions and many other parameters inside the spacecraft. The complex is intended for functioning in ISS.

For installation in geosynchronous and high-elliptical orbit spacecrafts, several experimental complexes were developed in SINP MSU. In the DIERA complex [3], the detailed measurement of parameters of the hot magnetosphere plasma, causing the spacecraft charging, and the charging effects is done. Besides, complex has instruments for measurement of the Earth's radiation belt electron and ion fluxes and the solar cosmic ray fluxes, and of the absorbed dose value inside the spacecraft. This complex was installed on several high orbit Russian spacecrafts and enabled to get extensive information both on the spacecraft charging, and on radiation effects.

6. Results of laboratory and computer modeling of the space radiation effects

In this section, some examples of the material and equipment laboratory test results, as well as the results of computer modeling of the space radiation effects are considered.

In fig. 9, the results of tests of GaAs solar cell stability against the proton irradiation obtained in SINP MSU on the 120-cm cyclotron are presented. Here, relative reduction of the cell output power is shown as function of the proton flux value.

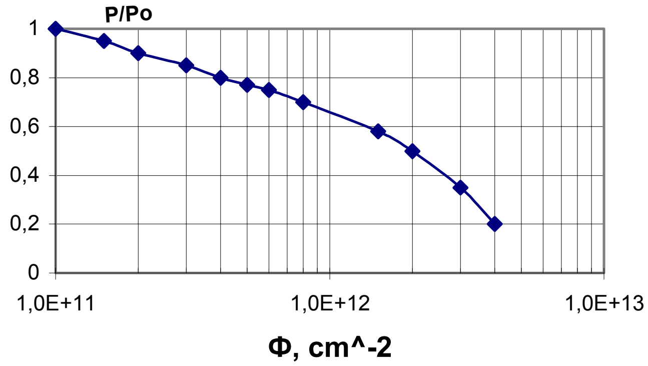


Fig. 9. Relative change of the GaAs solar cell vs. 7.5 MeV proton flux

In fig. 10, the results of testing of ceramic thermo-control coating consisting of mixture of fine-dispersed ZnO powder with fluid potassium glass in the case of 0.5 MeV proton impact are shown. Testing was run in the SINP MSU cascade generator CG-500. The figure demonstrates the increase the integral solar radiation absorption factor as function of the proton flux value.

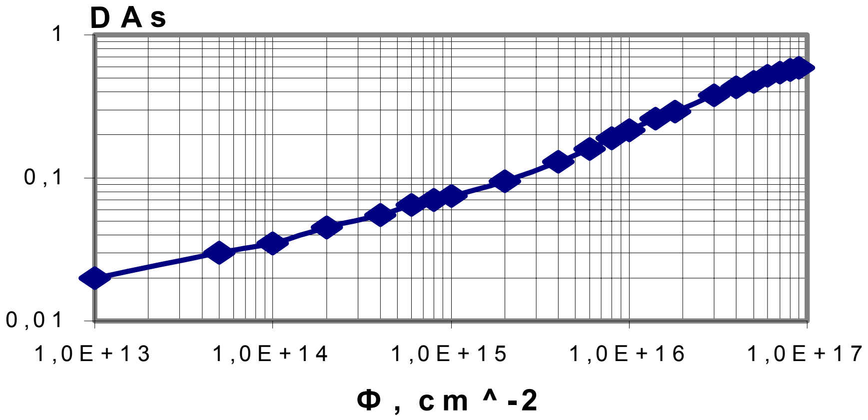


Fig. 10. Increment of the solar radiation absorption factor vs. 0.5 MeV proton flux value Φ

In fig. 11, the results of consequent irradiation of optical glass sample by 1.0 MeV electrons and by accelerated hard particles (size ~1 μm, velocity ~3 km.s^{-1}) are shown. The impacts of hard particles cause the local electric breakdowns with outcome of the electric charge to the sample surface. The size of every breakdown figure is of order of ~3-5 mms.

This result points to possibility of significant intensification of the spacecraft optical elements damage induced by the hard microparticle impacts if glass has the internal charge created by electrons of the Earth's radiation belts.

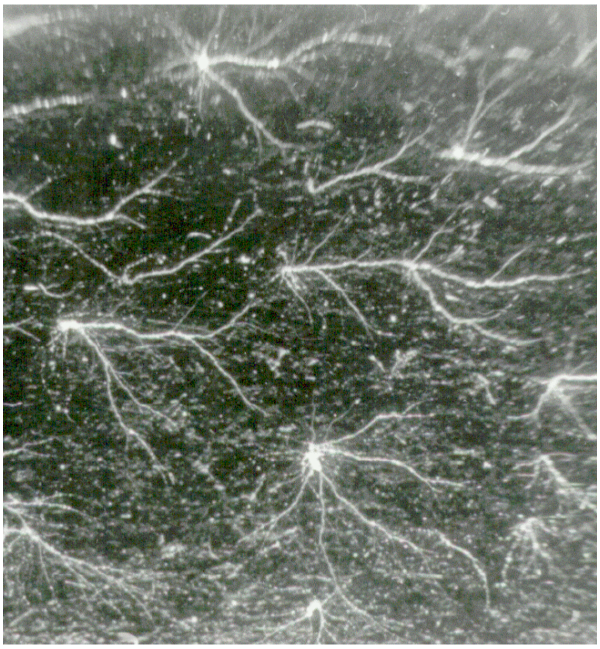


Fig. 11. Electric breakdowns in the radiation charged glass caused by the hard microparticle impacts

In SINP MSU, computer codes are used for mathematical modeling of the space radiation effects for simple objects, and for complex models of the real spacecrafts. Some results of the modeling are presented below.

Fig. 12 illustrates the influence of the shield geometry on the absorbed dose value. The data presented were obtained by means of the SHIELDOSE model [13] for geosynchronous orbit. The radiation belt electron energy spectrum was set in terms of the AE-8 model [21].

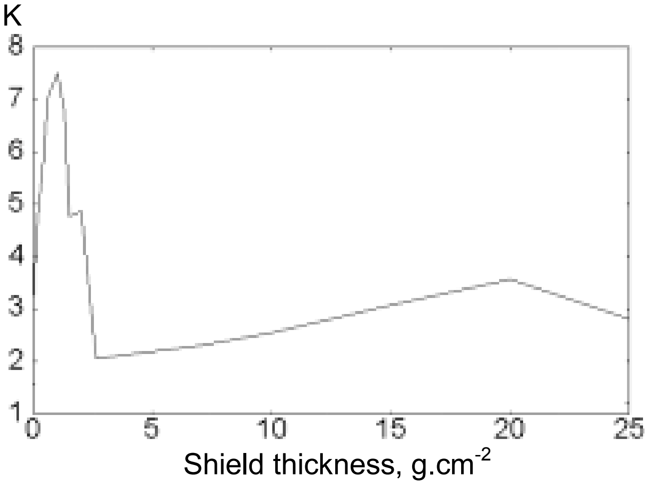


Fig. 12. Ratio of dose in the spherical shield (1/2 of the value) to dose behind the slab shield K vs. thickness of the shield in geosynchronous orbit

It was noted above that the hot magnetosphere plasma can give the essential contribution to value of dose absorbed in the thin layers of material of the spacecraft outer surface. Computation results illustrating this effect in geosynchronous orbit are shown in fig. 13.

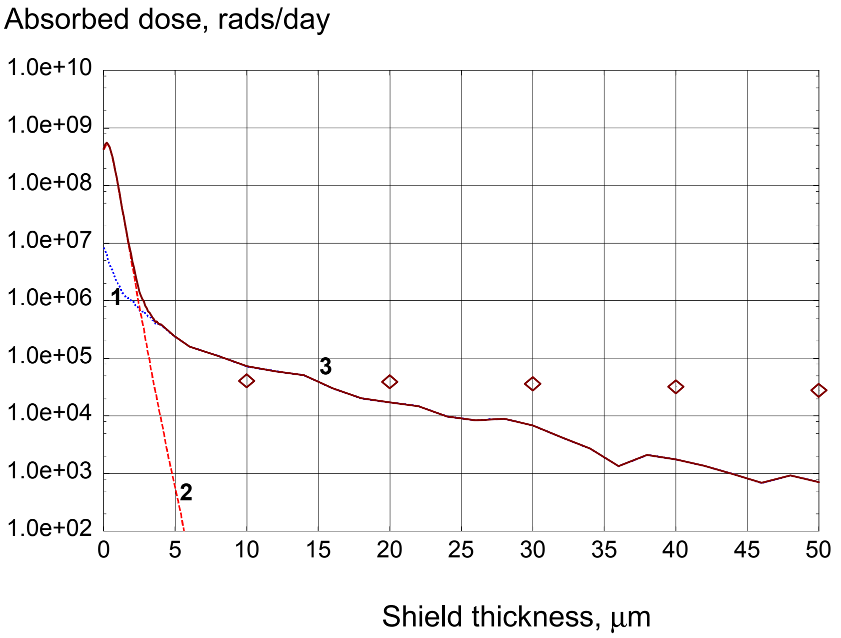


Fig. 13. The 1 day space radiation absorbed dose determined by two-temperature magnetosphere plasma particles with energy in interval 0.01-200 keV vs. shield thickness in the case of the small thickness: 1 - electron component, 2 - proton component, 3 - total. Points - results of calculation in terms of the SHIELDOSE/AE-8 models

The example of results of the three-dimensional spatial distribution of the absorbed radiation dose computation done in SINP MSU for the model of ISS Russian segment is shown in fig. 14. The calculation was made by means of SINP MSU engineering computer code RDOSE [14,15] for three-dimensional model of spacecraft shown in fig. 8. The RDOSE code was used for analysis of the radiation effects in the SOLAR PROBE spacecraft which was developed in joint US-Russian project [22].

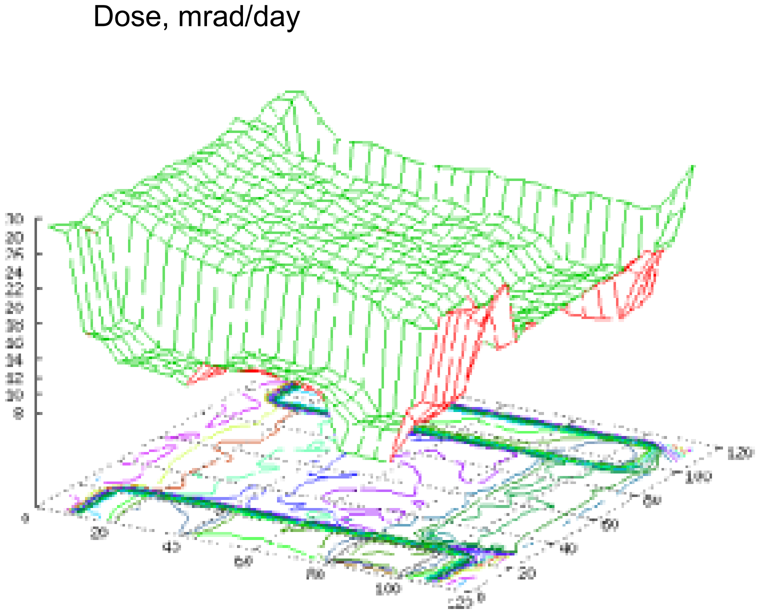
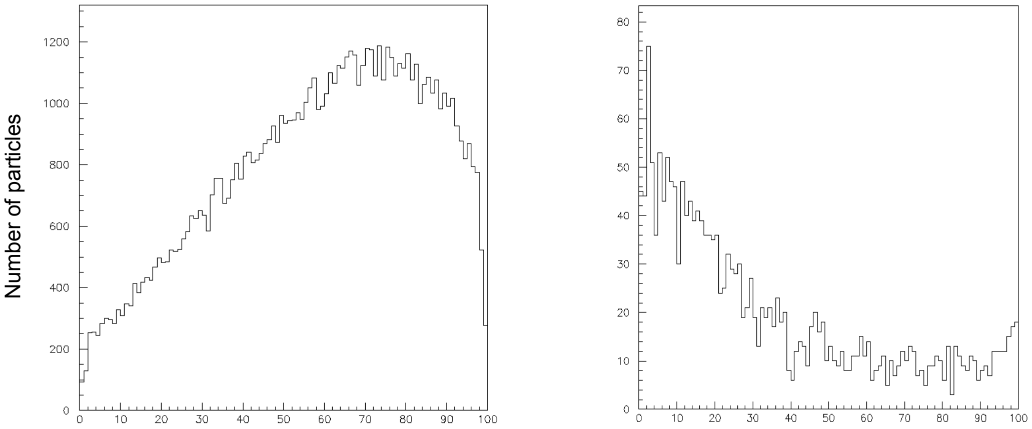


Fig. 14. Distribution of the 1 day absorbed dose of the space radiation in section of fragment of the ISS Russian segment. Dose isolines in the section are shown in the lower part of the figure

Modeling of internal electron charge in dielectrics was done in SINP MSU by means of the GEANT computer code [17]. Depth distribution of the charge in the dielectric sample was studied at various conditions of electron irradiation: monoenergetic beams in cases of normal and isotropic fall, electrons with energy spectra, typical for the Earth's radiation belt, with and without electric field created by the internal electronic charge.

The influence of the internal electric field is illustrated by the results presented in fig. 15. The results presented in fig. 15a were obtained in calculation without electric field, fig. 15b – taking into account the electric field.



a) **b)**

Fig. 15. Sample depth distribution of the number of stopped electrons in the case of 1.5 MeV monoenergy beam under normal fall of the beam: a) without the electric field, b) with the electric field value E_0=1 MV/cm. The depth of sample is shown along the abscissa axis. Sample thickness is 5 mm

Some results on the real spacecraft charging in the hot magnetosphere plasma analysis are presented in figs. 16, 17. Structure of equipotentials of the self electric field of the charged spacecraft in conditions of partial lightning of the surface by the Sun is seen in fig. 16. The arrow shows the direction of light. The numbers on equipotentials give values of potential in volts. Calculated trajectories of the surrounding plasma positive ion motion in self electric field of the charged spacecraft are shown in fig. 17.

7. Conclusion

At present, main information on radiation environment effects on the spacecraft materials and devices is obtained by the ground-based laboratory experiments, and by the mathematical modeling. The combination these two methods enables to increase the efficiency of the research.

Complex space experiments in which the features of various components of the space radiation, radiation conditions inside the spacecraft and degradation of the spacecraft materials and devices are studied simultaneously give the most reliable information on the space radiation effects. Such experiments are required for verification of results of the ground-based radiation testing. It is necessary to increase the number of the complex space experiments in spite of their difficulty and high cost.

The obtained results of studies and created methods allow to develop presently the expert systems by means of which possible to conduct the retrospective analysis of the spacecraft operation failures, to forecast the reliability and the life-time of spacecrafts, and to control the spacecraft in the real-time mode.

The further improvement and development of the methods of the space radiation effects study should take place in close international cooperation for creation of standards, computer database and in conducting the ground-based and space experiments.

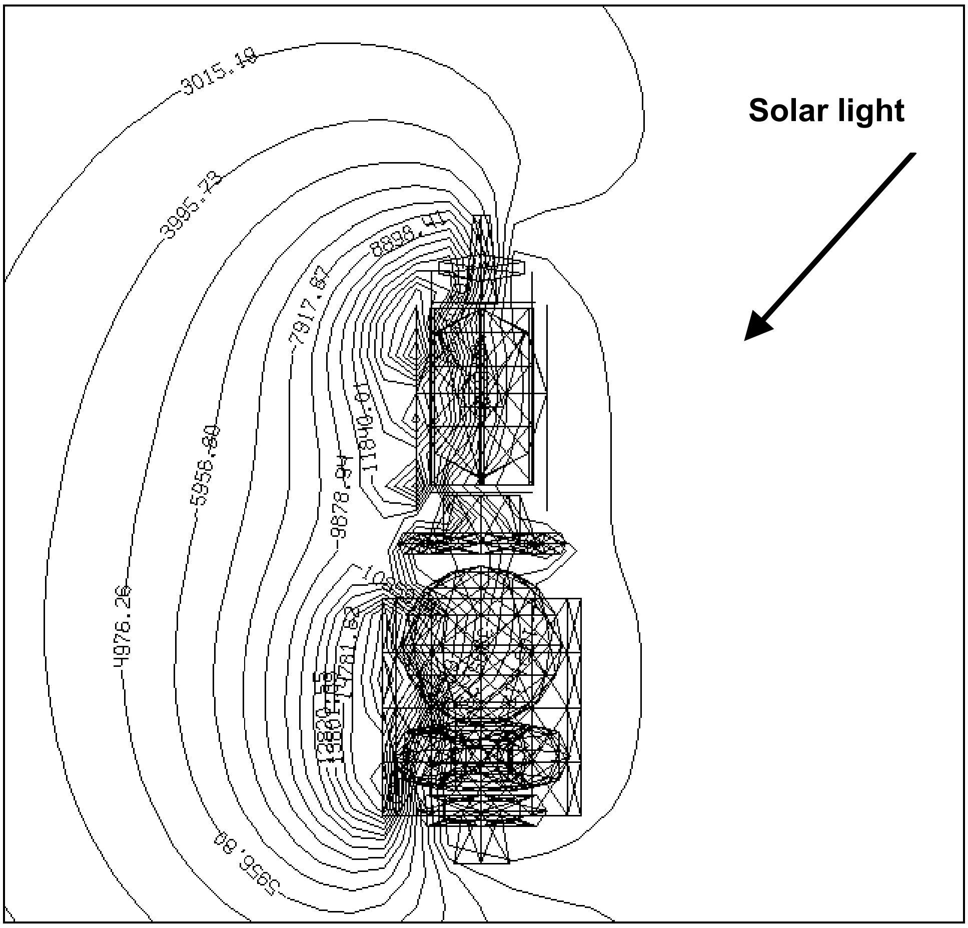


Fig. 16. Structure of equipotentials of the self electric field of the charged spacecraft in conditions of partial lightning of the surface

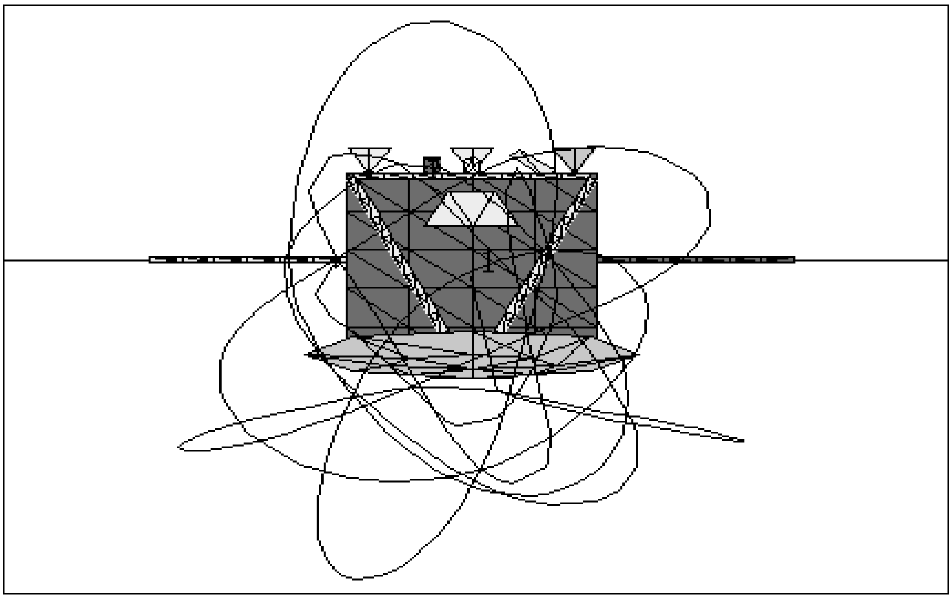


Fig. 17. Calculated trajectories of the surrounding plasma positive ion motion in self electric field of the charged spacecraft

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МЕТОДЫ ИМИТАЦИИ ВОЗДЕЙСТВИЯ КОСМИЧЕСКОЙ РАДИАЦИИ

Препринт НИИЯФ МГУ – 2003 – 9 /722

Работа поступила в ОНТИ 25 февраля 2003 г.

ИД № 00545 от 06.12.1999

Издательский отдел
Учебно-научного центра довузовского образования

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Гигиенический сертификат № 77.99.2.925.П.9139.2.00 от 24.02.2000
Налоговые льготы – Общероссийский классификатор продукции
ОК-005-93, том 1 – 953000

Заказное. Подписано в печать 26.02.2003 г. Формат 60x90/16
Бумага офсетная №2. Усл.печ.л. 1,31
Тираж 40 экз. Заказ № 348

Отпечатано в Мини-типографии УНЦ ДО
в полном соответствии с качеством
предоставленного оригинал-макета