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MODELING OF SPACECRAFT INTERACTION WITH ENVIRONMENT

At ITM (NASU&NSAU) investigations of various aspects, processes and phenomena related to spacecraft environment interactions are carried out in plasma electrodynamic facilities. The results presented illustrate the efficiency of physical modeling to solve the problems formulated.

В ИТМ НАНУ и НКАУ на плазмодинамическом стенде проводятся исследования различных процессов и явлений, характеризующих взаимодействие КА с околоспутниковой средой. Представленные результаты демонстрируют эффективность физического моделирования для решения поставленных задач.

Active life and service life of spacecraft (SC) and their subsystems are dependent on the accuracy of prediction of variations in structural material and element properties under a long action of factors of space and the environment. Despite great experience related to operating spacecraft in various orbits, prediction of their service life remains a non-trivial problem. The complexity and high cost of full-scale experiments give no way of considering it as an acceptable means to study in details individual types of spacecraft-environment interactions, and it is impossible to identify their contributions in integral characteristics of the action on spacecraft. Thus to build models of interactions, to predict the consequences of a long action of space factors on structural materials and elements, physical modeling plays a special role.

Degradation of solar arrays power. Basic factors of influence of the environment on high-orbiting spacecraft are as follows: ionizing radiation, thermal cycling in a vacuum, radiation electrization, plasma jets of electric propulsion engines (EPE) of spacecraft, destruction, sublimation, and gassing of materials and coatings, contamination of operated systems surfaces and solar ultraviolet (UV) emission [1].

For simulating the long impact of ionizing radiation, when degradation of spacecraft materials and the solar array (SA) power losses are predicted, the equality of equivalent fluences of electrons for particles solar arrays penetrating through the protective coating on the photovoltaic converters is the basic condition: $F_e^{(M)} = F_e^{(H)}$ (the indices M and H correspond to simulation and orbit, respectively).

The equality of the number N and amplitude $\Delta T = T_{\max} - T_{\min}$ of thermal cycles in orbit and on the test bench is the condition of equivalence of thermal-cycling impacts: $N_M = N_H$, $\Delta T_M = \Delta T_H$.

The equality of fluences $F_{eh}^{(M)} = F_{eh}^{(H)}$ and energies $W_{eh}^{(M)} = W_{eh}^{(H)}$ of energetic electrons in orbit and on a test bench is the condition of modeling radiation electrization of SC structural materials and elements: $3 \le W_{eh} \le 20$ keV [2].

The equality of specific charges ($q_M = q_H$) and energies ($W_{iM} = W_{iH}$) of uniform ions transferred by an electric propulsion jet onto the SA surface is the condition of modeling the interaction of electric propulsion plasma jets with SA and SC external surface materials in orbit and on the test bench.

The equality of values and dependences of the integral coefficient of absorption of the solar radiation $\alpha_s^{(M)} = \alpha_s^{(H)}(t)$ is the condition of successful numerical simulation and physical modeling of the influence of contamination of solar

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arrays protective glasses (t is the SC operation time, duration of the effects of the environment).

Changed electric power of SA is a result of an integrated action of many factors of the near-satellite environment in SC operation in orbit. The integral characteristic of the SA rated power drop $P(t)/P_0$ is approximated by the relation [3] (P_0 is the SA power initial value)

$$\frac{P(t)}{P_0}=\sum_{i=1}^{n}k_i\left(1-\frac{P_i(t)}{P_0}\right), \tag{1}$$

where k_i is the coefficient of proportionality which takes into account the influence of separate factors and the effects of overlapping, and n is the number of factors, $P_i(t)$ – electric power degradation due to factor i alone, $P(t)$ – value of electric power at the time t. The value of the coefficient $0 \le k_i \le 1$ and the number of n – factors are determined by contribution of each factor for a particular spacecraft.

If conditions of modeling are fullfilled in testing the influence individual factors on fragments SA silicon solar arrays, it will be derived calculated and experimental dependences of the SA power drop on the time of operation of GEO spacecraft and Global Position System (GPS) high-orbiting spacecraft constellation by using the relation (1). Fig.1 shows the calculated and experimental dependence $P(t)/P_0$ which characterizes an integral action of the near-satellite environment in geostationary orbit (GEO). The measured values of $P(t)/P_0$ correspond to SA with the silicon conductivity of 10^2 ohm^{-1}m^{-1} and the thickness of the protecting glass (fused quartz) of 0.3 mm. On Fig. 1 it was used the following indications: 1 – is the relation (1); satellite measurements: 2 – Intelsat-IV, 3 – Western Union F1, F2, 4 – Telesat Anik F1, F2, 5 – Tacsat, 6 – averaged data in GEO, 7 – ATS-5, 8 – IDSDS, 9 – LES-6.

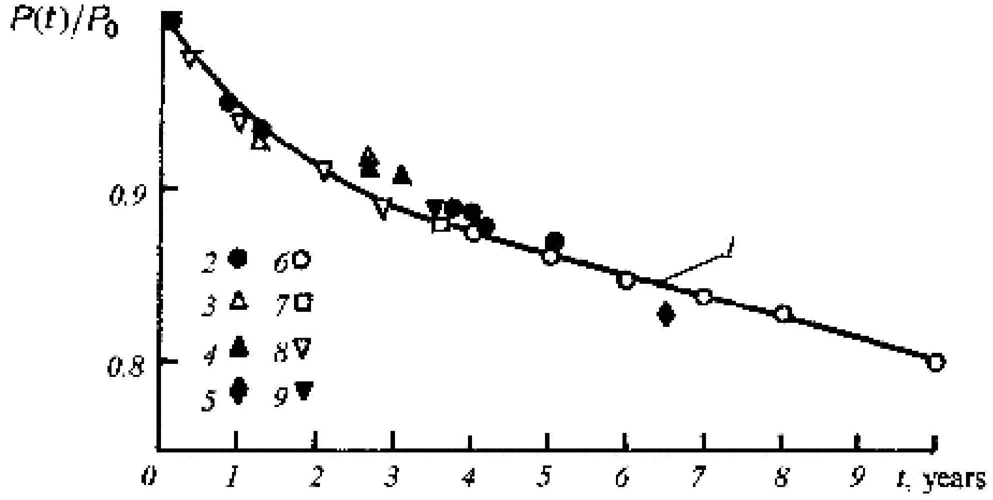

Fig. 1

The data of Fig. 2 for GPS satellites in a high circular orbit also confirm the correctness of the procedure of estimating the influence of integral actions of the environment factors on SA with the use of the relationship (1) and of numerical and experimental dependences $P_i(t)/P_0$ characterized by the influence of separate factors. On Fig. 2 it was used the following indications: 1 – integral effects of ionizing radiation, contramination and thermocycling (1); satellite measurements: 2 – GPS SC 13-17 block II, 3 – SC 18-21 block II, 4 – SC 22-40 block II, 5 – SC 1-6 block I.

Radiation electrization of spacecraft leeward surfaces. Spacecraft radiation electrization in a polar ionosphere in the Earth's shadow results from two effects of the environment: irradiation by fast auroral electrons with energies from 1 to 35 keV (captured in radiation belts of the Earth) and the flow of a cold ionospheric plasma. If the concentration of positive ions near the SA body surface is $N_{iW} \le 10^4$ cm^{-3}, negative charges up to a voltage of 1 kV are accumulated on dielectric surfaces [1]. The effects and consequences of high-voltage differential charging are the most hazardous for the leeward surfaces of extended structural elements of electrodynamically large satellites ($R/\lambda_d \ge 10^2$) and also for small bodies in the nearbody wake (R is the characteristic size of a spacecraft, $\lambda_d = \sqrt{kT_e/4\pi e^2 N_e}$ is the Debye screening length of the undisturbed plasma, k is the Boltzmann constant, e is the electron charge, T_e, N_e are the temperature and the concentration of electrons in a cold plasma).

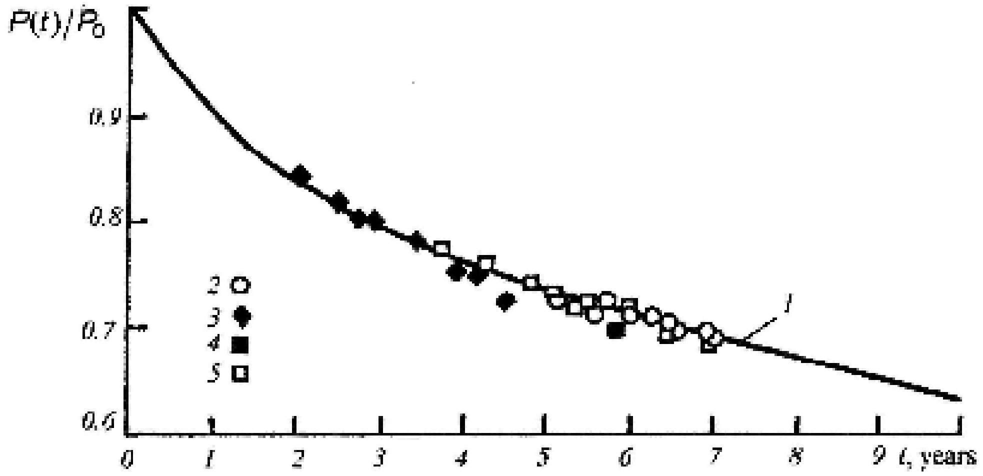

Fig. 2

Numerical simulation of high-voltage charging the SC surfaces in a polar plasma in the Earth's shadow involves a non-trivial problem of the joint solution of nonlinear Vlasov–Poisson equations for a predetermined condition of the flow around a dielectric body and current-balance equations on the irradiated surface. The values of the coefficients of interactions between the charged particles and the surface for a particular material are determined experimentally.

Physical modeling high-voltage charging in a polar ionosphere is concerned with the necessity of reproducing the current density distribution in the near-body wake, conditions of the flow around body in a supersonic cold plasma under simultaneous irradiation of streamlined surfaces by fast electrons with energies from 1 to 35 keV. The difficulties of such studies are caused by the necessity of simultaneous implementation of conditions of plasma gasdynamic and electrophysical modeling [4, 5].

Physical modeling radiation electrization in the near-spacecraft wake in a polar orbit amounts to reproducing full-scale values of the range of energy and current density of auroral electrons, an ionic current and the current of secondary ion-electron emission in facilities (by using samples of structural elements from dielectric materials and coatings). These conditions are realized in plasma dynamic facilities at the ITM in supersonic flows of the rarefied $O^{+}+O_2^{+}$ plasma with the concentration $N_{i\infty}=1.6\times10^5 - 5.7\times10^7$ cm^{-3} of charged particles and velocity $U_\infty \approx 8.4$ и 11.9 km/s. The reference models are made from an isolated aluminum plate with one side covered by a dielectric and a disk made of fused quartz with one side covered by an aluminum film.

Fig. 3 shows the equilibrium potential $\Phi_W = e\varphi_W/kT_e$ (φ_W is the surface potential) on the leeward side of the solid as a function of concentrations of fast electrons and positive ions N_{eh}/N_{iW}. Satellite measurements with F6, F7, and F13 (Defense Meteorological Satellite Program) are made in a polar orbit in the Earth's shadow while acting fast electrons with energies $W_{eh} \approx 4.2$; 10.1; 14.4 keV. On Fig. 3 it was used the following indications: 1, 2, 3 – measurements by DMSF-series F6, F7, F13 satellites; 4 – calculated values; measurements with samples (ITM): 5 – A1; 6 – carbonic plastic material; 7 – the TR-SO-11 coating; 8 – 12X18H10T stainless steel.

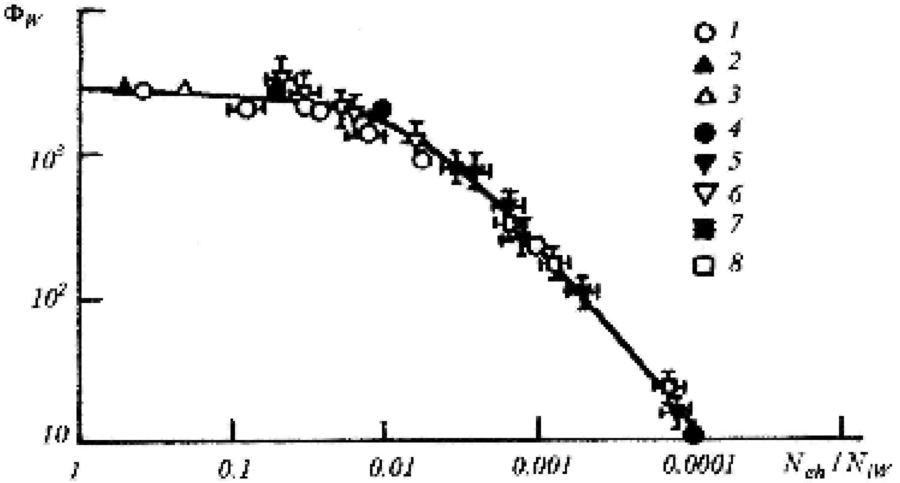

Fig. 3

The dependences Φ_W on N_{eh}/N_{iW} make it possible to predict the levels of charging the leeward surfaces of spacecraft structural elements and small bodies in their wake in a polar ionosphere in the Earth's night shadow.

Variations in spacecraft material properties under a long action of atomic oxygen. The problem of maintaining a prolonged operation of spacecraft in low and mean (200 – 700 km) orbits is closely connected with the problem of providing the durability of materials and coatings of external surfaces of structural elements to the action of atomic oxygen (AO).

The mechanism of failure of materials of spacecraft external surfaces includes at least two types of the influence: physical spluttering and chemical etching by a flux of atomic oxygen. The consequences of the AO influence on materials of spacecraft solar arrays are as follows:

– mass loss from the surface of materials;

– variations in thermo-optical properties of material surfaces (the integral coefficient of absorption of solar radiation, α_s , and integral emissivity, ε);

– reduction of electric conductivity of metal-to-metal contacts due to their oxidation;

– variations in physical and mechanical properties of materials as a results of their surface erosion.

Information about variations in the properties of materials of spacecraft external surfaces due to the action of the atomic oxygen flux may be only derived by the experiment: from the results of in-flight or benchmark tests. The equality of velocities and energies for identical types of the particles bombarding the surface is the condition of bench (physical and chemical) modeling and simulation of the action of the AO flux on the spacecraft external surfaces in orbit.

The fulfillment of the conditions of modeling in the collisionless flow around the surfaces of a solid body with a supersonic flux of partially ionized AO one can ensure modeling and simulation of the processes of physical (dynamic) and chemical interactions of the materials of external surfaces with AO in the Earth's ionosphere. Simulation of the conditions of a prolonged operation of a spacecraft in orbit suggests the performance of accelerated tests by using more intensive particle fluxes than in orbit.

Thus, in order to realize accelerated model tests of materials for external surfaces of spacecraft with the aim of determining their erosion resistance to the influence of atomic oxygen in the ionosphere, one needs to provide for:

– the flux of partially ionized AO with directional velocities of particles which are close or equal to orbital velocities in the ionosphere;

– the condition of the collisionless gas flow around the fragments of spacecraft structural elements or the samples of materials under test.

The conditions listed above are realized in plasma dynamical facilities of the ITM. Schematic of facilities is shown on Fig. 4 [7]. On Fig. 4 it was used the following indications: 1 – vacuum chamber, 2 – pumping-out system, 3 – generator of supersonic plasma current, 4 – sample (SC model), 5, 6 – diagnostic systems, 7 – cryogenic panels (LN_2), 8 – electron gun, 9, 11 – microwave systems aerials, 10 – source of ultraviolet radiation.

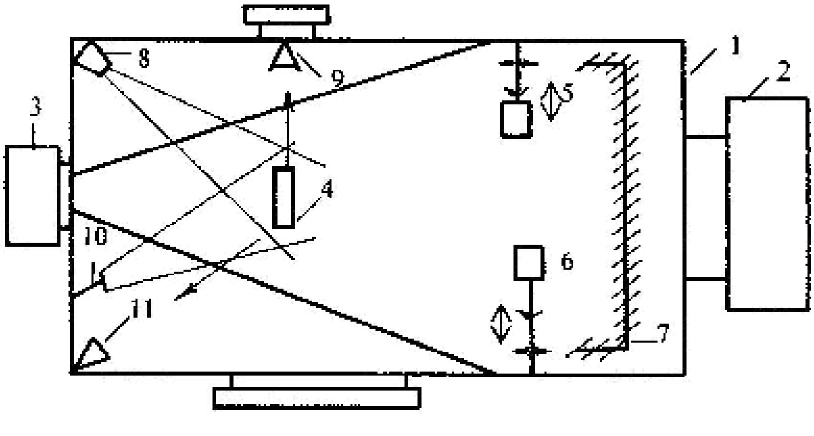

Fig. 4

Samples of tested materials (four ones, simultaneously) are mounted on a frontal (relative to a free-stream flow) surface of a two-section thermostat cooled by the running water and liquid nitrogen. The thermostat of 115×115 mm in dimensions is arranged on a movable platform of a lower coordinate-measuring gage.

Investigations in kinetics of the process of interaction of atomic-molecular oxygen plasma, for example, with a polyimide film testify that molecular oxygen is inert and takes no part in chemical reactions. All chemical reactions are limited by one stage: reaction with oxidizer (atomic oxygen). In this case, the velocity relation of gas release for products of chemical etching (CO_2, CO, H_2O and H_2) remains constant.

Fig. 5 presents the dependence of variations in the polyimide film thickness Δx (x_0=0.040 mm) on the integral fluence of atomic oxygen F_O. On Fig. 5 it was used the following indications: 1 – ITM's measurements at AO flux velocity of (8.3±0.5) km/s, 2 – irradiation of the PM-A film by diffusely scattered particles with thermal velocities of 2.24 km/s, 3 – Mir Orbital Station (the PM-1E film, $\delta \approx 0.040$ mm, exposure time t_H= 28 and 42 months), 4 – dependence $\Delta x = R_e \cdot F_O^{\beta_x}$ ($\beta_x \approx 1.0$, $R_e \approx 2.6 \cdot 10^{-24}$ cm^3/Oatom). The dependence $\Delta x = R_e \cdot F_O^{\beta_x}$ (R_e is the volume coefficient of material losses, β_x is the coefficient), presented in Fig. 5, points to the fact that the mechanism of chemical etching the atomic oxygen film has the overwhelming influence. Losses in mass of the PM-A polyimide film, owing to the action of the atomic oxygen flux, is illustrated by Fig. 6. On Fig. 6 it was used the following indications: 1 – ITM measurements, 2 – Mir OS (the PM-1E film, $x_0 \approx 0.040$ mm), 3 – Mir OS (the PM-1E film, t_H= 28 and 42 months), 4 – Mir OS (the PM-1E film, $x_0 \approx 0.080$ mm, t_H= 1036 days), 5 – HF-plasma, 6 – dependence $\Delta m = Y_0 \cdot F_O^{\beta_m}$ (for the PM-A film $\beta_m \approx 1.0$, $Y_0 \approx 4.2 \cdot 10^{-24}$ mg/Oatom).

An increase of the diffuse component of emission (the degree of roughness of the film) is the result of the atomic oxygen impact on the surface of exposed samples. A slight however stably recorded increase of emitting capability of materials in the infrared range ε is a consequence of such changes. The integral coefficient of solar radiation absorption in a visible part of a spectral range of wave lengths increases. Data of Fig. 7 provide support for this. On Fig. 7 it was used the following indications: 1 – ITM, 2 – Mir OS (1036 days, the film thickless is 0.08 mm), 3 – satellite averaged measurements, 4 – approximation $\Delta\alpha_s = 1 \cdot 10^{-27.5} \cdot F_O^{1.3}$.

The values of ε measured in an atomic-molecular oxygen flux at various fluences of atomic oxygen in ITM's facilities are presented in Table 1.

Table 1 – Infrared emissing ability of the PM-A film

F_O, cm^{-2}	Emissivity coefficient ε	
	Before exposure in flux	After exposure in flux
$1.16 \cdot 10^{20}$	0.550	0.550
$3.67 \cdot 10^{20}$	0.550	0.560
$4.9 \cdot 10^{20}$	0.550	0.560
$1.27 \cdot 10^{21}$	0.550	-*)
Note:	* The sample is failured, the failure time is equivalent to $t_H \approx 3.8$ years in orbit with $h \approx 700$ km under conditions of maximal solar activity.	

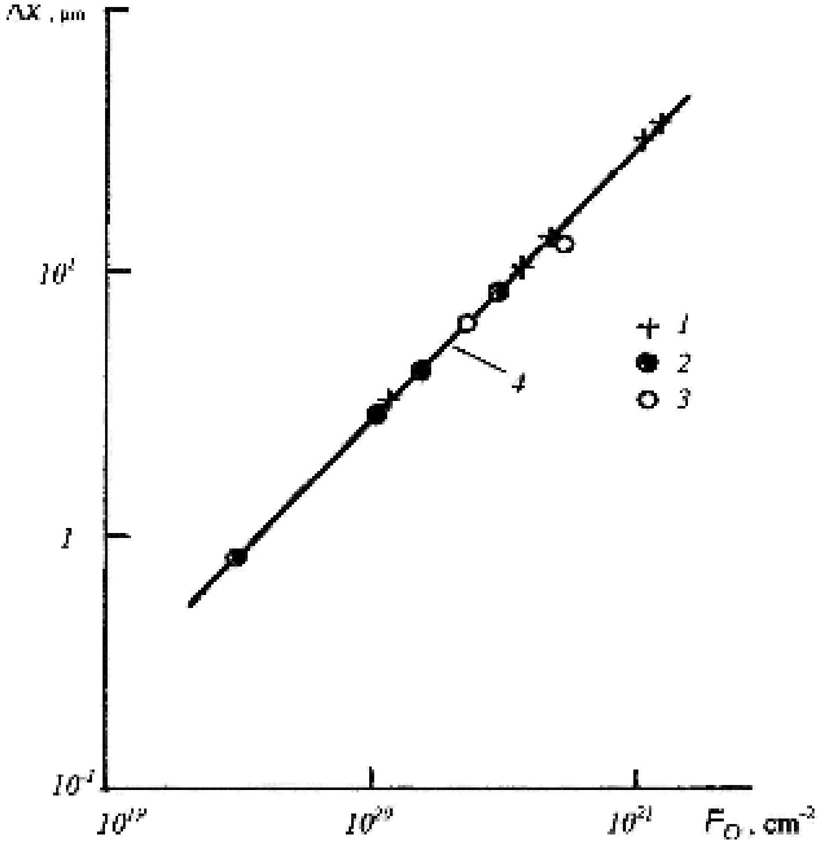
ΔX , μm
10¹
1
10⁻¹
10¹⁹
10²⁰
10²¹
F_O , cm⁻²
4
+ 1
● 2
○ 3

Fig. 5

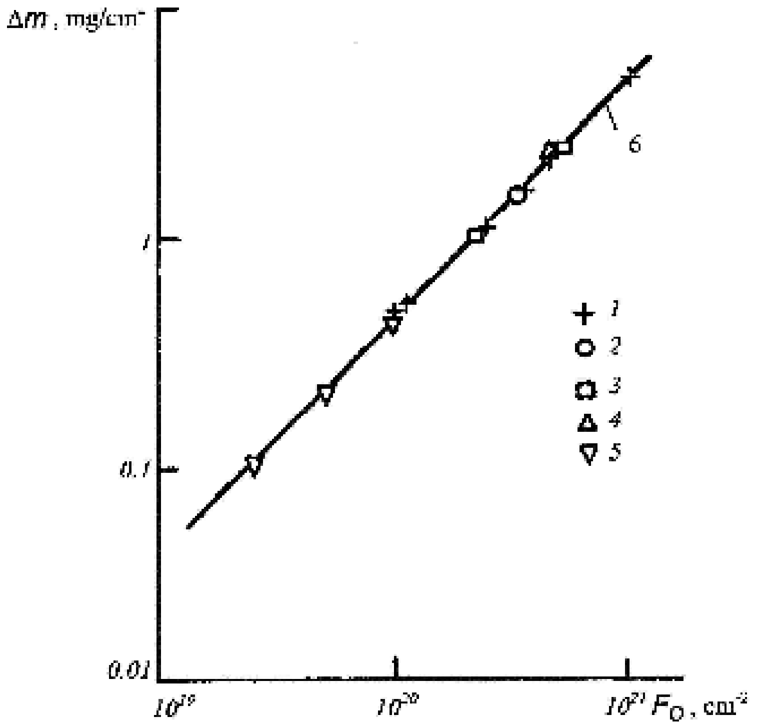
Δm , mg/cm²
1
0.1
0.01
10¹⁹
10²⁰
10²¹
F_O , cm⁻²
6
+ 1
○ 2
◻ 3
△ 4
▽ 5

Fig. 6

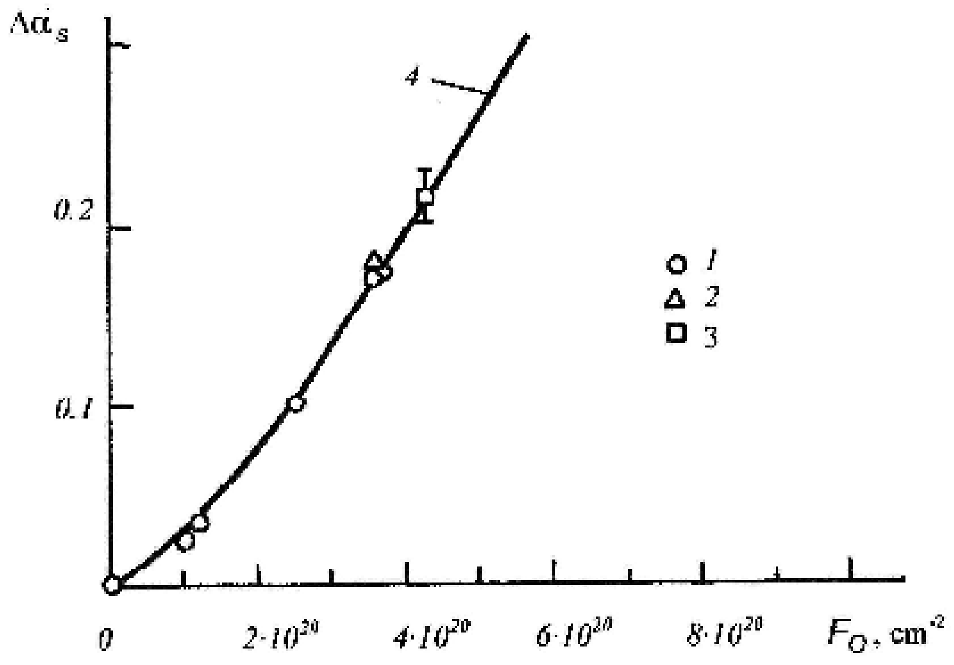

Fig. 7

The relations $m(F_O)$ and $x(F_O)$ can be used for predicting service life, material resistance to long attack by atomic oxygen in orbit, for estimating and controlling atomic oxygen fluence.

The results presented demonstrate the validity of physical modeling for predicting variations in surface properties of structural materials and elements because of a long-term action of various factors of the near-satellite environment.

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