

NEAR EARTH SPACE POLLUTION AND SAFETY OF SPACECRAFT LONG-TERM OPERATIONS

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ABSTRACT

In this paper problems of near-Earth space pollution effects on a long-term spacecraft's operations are considered. The following issues are addressed in more details:

- potential space debris sources are discussed as well as mechanisms of debris generation;
- numerical experiments are performed on investigation of debris particles interaction with space objects, and initial parameters of exploded-propellant-tank-fragments motion are estimated;
- mathematical model of a "spacecraft-space debris" system is developed taken into account active spacecrafts, large passive orbiting bodies, and small particles of different sizes located on near-Earth orbits as well as various mechanisms of debris generation.

1. INTRODUCTION

The space debris problem has been widely discussed in last few years. Scientist's concerns are based on well established facts. More than 30-year period of space exploration has resulted in launching of nearly 19000 objects into near-Earth space. Their major part was destroyed during reentry but more than 7000 objects are still located in low near-Earth orbits with total mass of a few thousands of tons. But this number involves only those objects which could be detected by modern observational means. For example, fragments with sizes less than of 10-20 cm can not be detected on orbits with 500-1000 km altitude. The most part of space debris particles were originated from satellite bodies which have been destroyed due to some accidents.

The problem of space pollution has many other aspects besides space debris danger but corresponding effects are usually small comparing to natural background fluctuations and they will not be considered here. Topics which will be discussed and investigated later include an analysis and simulation of space debris sources, a methodology for estimation of consequences of a man-made space pollution, and a study of near-Earth space "fragility" (that is, a danger to a long-term safe spacecraft operations). We consider as being of great importance issues connected with a study of remote consequences of upper stages accidents on orbits and of not unprobable military conflicts in space. For example, a deployment of an ABM space echelon and its activation would result in destruction of many upper stages, anti-missiles explosions, etc. The military conflict may come to the end in few months (if not in few weeks) but the near-Earth space would be absolutely

closed for productive human activity for many hundreds of years.

2. ANALYSIS OF SPACE DEBRIS SOURCES. MECHANISMS OF ITS GENERATIONS

Predictions of space pollution dynamics were developed elsewhere (Refs.1-5). They imply that a debris "population" which is necessary for a start-up of a fragment-multiplication "chain reaction" is 2-3 order of magnitude higher than that observed now; a critical situation is expected in 20-60 years if rates of space exploration would be maintained (Refs.1,2,6).

An important aspect of a space debris study is analysis of debris sources and mechanisms of its generation as well as correct description of multiplication dynamics for man-made orbital objects.

The spacecraft is really a complicated combination of screens, shields, wires and devices which are distributed inside a body of spacecraft itself along with large volumes of empty space. So it might be incorrect to estimate a scale of destruction on a base of only an energy input as this is made in (Ref.1) (it might be a correct but rather approximate approach for solid bodies). A real picture of high-speed fragment interaction with a spacecraft would look in other way. At impact speeds exceeding 10 km/s an intense shock wave is formed (its front pressure can be as high as few Mbar). Materials of projectile and barrier are melted in contact area and could be even evaporated partly in a depression wave. But a linear size of an area destroyed as a result of collision is only of 3-10 projectile's size (that is, it does not exceed 10 cm). At long distances from contact area shock waves are attenuated and lose their energy on free surfaces, producing no more destructions of spacecraft constructive elements. A barrier's material is scattered partly in the direction opposite to the projectile's one, a mass of this part is about of few times higher than projectile's mass. These are mostly small (with sizes lower than 0.1 cm) particles although sometimes larger particles may be broken off. These small fragments are not of direct hazard to other spacecrafts but they have to be taken into account when erosion effects of small particles on space objects are considered. Total destruction of a spacecraft after collision with a small fragment might be observed if this fragment would hit a propellant tank of the spacecraft and would initiate propellant detonation; the other option is that a fragment size would be comparable with the spacecraft's one.

One may consider the following stable sources of space debris:

- fragments of upper stages;
- launcher's or spacecraft's accidents;
- ejection of particles in the process of spacecraft engine operations;
- pyrotechnical operations, opening of covers and hatches, etc (that is, a garbage intentionally thrown away in the process of active spacecraft operations); and space debris would be generated due to testing of ASAT (anti-satellite weapons) space elements.

Some experimental data on spacecraft-constructive-elements destruction scale due to collision with space debris particles are available (Ref.3). For example, thermal-protective coating of the "Solar Max" satellite (of 2 sq.m surface area) after 4 years of operation on orbit of 570 km high, had 1900 holes and craters of 40-300 μ in diameter (Refs.2,3).

By using numerical methods of high-speed-impact investigations one may evaluate consequences of space debris particles of various mass interaction with spacecraft constructive elements.

We shall consider the following versions of interaction:

1. Impacts of particles of 0.1 and 1 cm size (speed 10 km/s) with aluminum body. Impact geometry is shown in Fig. 1a.

2. Impacts of the same particles with a propellant tank of either launcher or spacecraft. Initiation of a solid propellant detonation is considered. Threshold for detonation is determined by the value of a pressure on propellant surface comparing to critical value for detonation which are typical for specific solid propellants. Impact geometry is shown in Fig. 1b.

The corresponding results are presented in Fig. 2-4.

Fig. 2 shows that a destruction scale is of about 2-5 specific sizes of an incoming fragment; therefore, if a projectile is of 1 cm size it could not result in a complete destruction of a spacecraft.

A behind-barrier fragment-plasma flow would cause rather serious destructions of spacecraft's internal elements. Fig. 2 shows the destruction of a second barrier after an impact of a 1-cm fragment. The coloured palette to the right of the figure represents a scale of longitudinal speed V changes of projectile's and barrier's particles. It is seen that some fragments have negative V values, that is, they will be ejected into space. The mass of ejected material will be of few 1-10 grammes.

Hitting a propellant tank may result in propellant detonation and spacecraft (or missile upper stage) complete destruction onto a large number of fragments.

Fig. 3a illustrates an intensive development of propellant detonation after an impact with 1-cm-sized fragment. Pressure gauges on a casing and a solid propellant surfaces (see Fig. 1b) measure pressure changes versus time. Obtained values do exceed significantly thresholds for initiation of detonation in relevant solid propellants. Changes of a colour on Fig. 3a indicate explosive transformations. The coloured palette represents a fraction of detonated material of the propellant.

Fig. 3b shows corresponding pressure gauge readings vs time.

An impact of a 0.1-cm-sized projectile initiates a start-up of an explosive process in the propellant but in this case one can not state with confidence that the propellant will eventually be detonated since calculated pressure values correspond to an "uncertainty region" for parameters of solid propellants explosive transformation kinetics (see Fig. 4a, 4b).

Therefore, a propellant explosion on an upper stage would lead to a significant increase of space debris amount.

One has to evaluate what is a fraction of fragments (generated by an upper stage explosion on 90-130-km altitude) which will remain on near-Earth orbits. A problem of after-explosion-fragments mass-, size- and speed-distribution is rather complicated, so that reliable results could be obtained probably with a help of simulative experiments. Qualitative estimations of fragment's mass could be obtained in a following manner. An upper stage body consists of a cylindrical propellant tank and a payload section. It should be noted that a solid propellant mass exceeds considerably a mass of an empty propellant tank. Therefore, after solid propellant detonation tank casing with a thickness of 5-20 mm will be destroyed onto fragments with linear size of the order of casing thickness (and lower), that is, of 0.1-10 mm. Initial speed of fragment's motion may be as high as 2-5 km/s.

It is rather difficult to evaluate a degree of payload-section destruction (i.e. fragment masses). But one might assume that those elements of payload section which were located not so close to a propellant tank (at the distance of the order of 1 m) would not be transformed into small fragments (smaller than 1 cm) but instead some of them will be accelerated up to speed of tens or hundreds m/s in a form of rather massive fragments of rather large sizes.

Therefore, when evaluating a fraction of fragments remained in near-Earth orbits, one can suppose that a propellant tank of the upper stage is destroyed after propellant detonation onto fragments of 1-10 mm sizes (with total mass of these fragments being about 100-1000 kg) which will move with a speed of 2-5 km/s.

It should be noted that most frequent mode of fragment's interaction with a spacecraft body will be erosive actions of many small particles (with sizes less than 0.1 mm). We identify an erosion action as a kind of impact which results in crater formation rather than making a hole in spacecraft shell. An example of erosion action was given earlier in reference to the "Solar Max" satellite. It is very difficult to take these action into account in a correct way since there are no definite criteria of spacecraft's functional damage. We shall assume that small particle's "mortal" fluence is equal to 1000 impacts per square meter. We have no experimental confirmation of this particular value, but if, for example, each square meter of solar panels were hit by 1000

small (of 1 mm size) particles, then about a half of panel surface would be deteriorated.

3. MATHEMATICAL MODEL AND DISCUSSION OF COMPUTING RESULTS

We have developed a rather straightforward mathematical model of space debris multiplication in order to evaluate dynamics of a "spacecraft-debris" system taking into account most important debris sources and their generation mechanisms. This model is based on a set of non-linear differential equations for the following variables:

N_{ob} - total number of large-sized (> 1 m) orbital objects;

N_{af} - total number of active satellites in orbits;

n - number of space debris small particles (of 0.1-1 cm size, or larger) which are able to make holes in satellite shells or to initiate propellant detonation;

n_e - number of space debris small particles (< 0.1 cm) which are able to produce only erosion effects at interactions.

But this system of differential equations involves a lot of parameters and coefficients which are a major source of uncertainty in calculations. Among them are the following ones:

A - number of new spacecrafts launched per year (in fact, this is a difference between launched spacecrafts and reentered ones per year);

v_1 - frequency of n -population fragments collisions with a vulnerable surface area of spacecraft S_{y1} ;

v_2 - frequency of n -population fragments collisions with a vulnerable surface area of spacecraft engine section (propellant tank) S_{y2} ;

v_e - an effective coefficient of erosion damage to a spacecraft ;

β, β_e - coefficients which are connected with a generation of $n(\beta)$ and $n_e(\beta_e)$ -populations after explosions of second and third stages engines (Ref.1);

γ, γ_e - average numbers of $n(\gamma)$ and $n_e(\gamma_e)$ -population particles ejected into space during an annual operation of a single spacecraft engine (parameters of typical engine with a solid propellant are used);

χ, χ_e - average number of $n(\chi)$ and $n_e(\chi_e)$ -fragments which are generated by spacecraft's engine explosion.

S_{y1} - total area of a spacecraft vulnerable units;

S_{y2} - propellant section area;

S_{ye} - average spacecraft area subject to erosion effect.

As stated above v_1 and v_2 are the collision frequencies of particles on a vulnerable spacecraft area. The calculation of these coefficients was done in such a way. The probability of impacting a spacecraft by a given number of particles could be calculated proceed from Poisson law supposing that the probability of the fact that one or more particles will hit the spacecraft can be found by the expression:

$$P = 1 - \exp(-n_p S_y)$$

where n_p - particle surface density; S_y - spacecraft vulnerable area; n_p - can be calculated by the formula:

$$n_p = n_k \cdot V_0 \cdot \Delta t,$$

where n_k - particle concentration in a considered space volume;

V_0 - particle velocity (a mean value of relative velocity of particles and spacecraft motion is considered);

Δt - time period when at least one particle of P - probability impacts the vulnerable area.

Then the desired collision frequency v is defined by the expression:

$$v = V_0 \cdot S_y \cdot n / (-\ln(1-P)).$$

A method of statistical modelling of erosion particles impact on a spacecraft was used to determine v_e .

It should be noted that after missile explosion at 120 km height (with missile velocity of 6 km/s, and fragment speeds of 2-5 km/s) about 10-20% of total missile's mass remains in orbits of 200-2000 km height (in form of rather small fragments).

A missile explosion at 500 km height resulted in about 60-80% of missile mass remaining in orbits of 200-2000 km height (in this case propellant mass is lower than spacecraft's mass so that fragment's speed was supposed to be about 100-1000 m/s.

The equation system is:

$$dN_{ob}/dt = A - v_2 \cdot N_{ob}$$

$$dN_{af}/dt = A - v_1 \cdot N_{af} - v_2 \cdot N_{af} - v_e \cdot N_{af}$$

$$dn/dt = \beta \cdot A + \gamma \cdot N_{af} + v_2 \cdot \chi \cdot N_{ob}$$

$$dn_e/dt = \beta_e \cdot A + \gamma_e \cdot N_{af} + v_2 \cdot \chi_e \cdot N_{ob}$$

$$v_1 = \alpha_1(n) \cdot n$$

$$v_2 = \alpha_2(n) \cdot n$$

$$v_e = \alpha_e(n) \cdot n,$$

This system of equations was solved in three specific cases:

Case A - spacecrafts on orbits with height H (200 km $< H < 2000$ km); following coefficients were chosen:

$A=100$; $\beta=70$; $\beta_e=7000$; $\gamma=1.2...2$; $\gamma_e=10^4$; $\chi=10^4$; $\chi_e=10^6$; $\alpha_1=8.4 \cdot 10^{-11}$; $\alpha_2=9 \cdot 10^{-12}$; $\alpha_e=5.3 \cdot 10^{-13}$; $N_{af}=N_{ob}=2 \cdot 10^3(t=0)$; $n=5 \cdot 10^4(t=0)$; $n_e=3 \cdot 10^6(t=0)$.

Case B - spacecrafts are in mostly populated orbits (800 $< H < 1000$ km); following coefficients were chosen:

$A=20$; $\beta=70$; $\beta_e=7000$; $\gamma=2.8$; $\gamma_e=10^4$; $\chi=10^4$; $\chi_e=10^6$; $\alpha_1=7.7 \cdot 10^{-10}$; $\alpha_2=8.2 \cdot 10^{-11}$; $\alpha_e=4.8 \cdot 10^{-12}$; $N_{af}=N_{ob}=486(t=0)$; $n=10^4(t=0)$; $n_e=6 \cdot 10^5(t=0)$.

Case C - sharp increase of space debris. Spacecrafts are in orbits with 800 km $< H < 1000$ km. Total number of fragments $\Delta n=5 \cdot 10^7$ is injected in 20 years period. Total mass of fragments is estimated in nearly 50 tons. This amount could be launched by five "Proton" launcher, for example, or by a single "Energiya"-like rocket.

Fig.5 (Case A) shows that for 60-70 years effects of space debris are negligible, and number of active

spacecrafts is about the same as total number on large bodies in orbit. Later on, space debris multiplication processes will result in relative decrease of N_{af} comparing to changes of N_{ob} . Lastly, after 160-180 years spacecrafts will be more frequently destroyed then new satellites will be launched. Therefore in this particular case after certain characteristic period of time (about 180 years) "spacecraft-debris" system makes transition into new qualitative state when fast exponential multiplication of space debris prevails a rate of new satellite launches resulting in a decrease of active satellite number in orbits.

As it was noted before, lower values of some coefficients made some favourable effect on characteristic time but qualitatively the general dynamics of system does not changed.

Fig.6,7 (Case B) show results of calculations for most populated orbits with $H = 800-1000$ km (Refs.1-5). It is seen that characteristic time has decreased (down to about 120 years).

Instability of a "spacecraft-debris" system in aspect of long-term safe spacecraft's in-orbit operation can be demonstrated in a following way (Case C).

Satellites are deployed onto orbits with $H = 800-1000$ km and they ejected particles which could destroy other various satellites in these orbits (for example, small fragments with a mass of about 1 gramm). This sharp increase of space debris will result in more fast destruction of active functioning spacecrafts (one may vary a "kill time" by changing an amount of ejected fragments).

This situation is easily simulated at numerical solution: one needs only preset a given n-value at a given time.

Fig.8,9 show dependences of active satellites number (N_{af}) in 800-1000-km-height orbits on time as well as corresponding n-dependence. Fig.9 shows that a number of active satellites begins to reduce immediately after completing of a pollution operation. Therefore, long-term existence of active satellites in these orbits is impossible under these conditions.

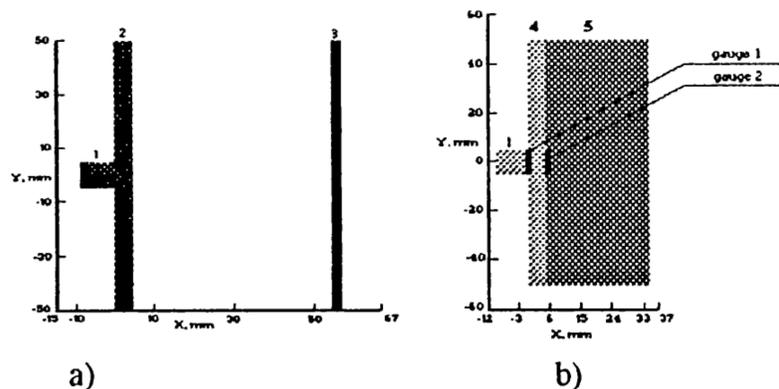


Fig.1. a) Barriers simulating the spacecraft's outer shell and its inner assembly; b) Barriers simulating housing of a ballistic missile stage and a solid propellant. 1 - projectile (Al); 2 - shell (Al); 3 - inner assembly (Al), 4 - missile housing (Al); 5- solid propellant. Initial impact speed - 10 km/s.

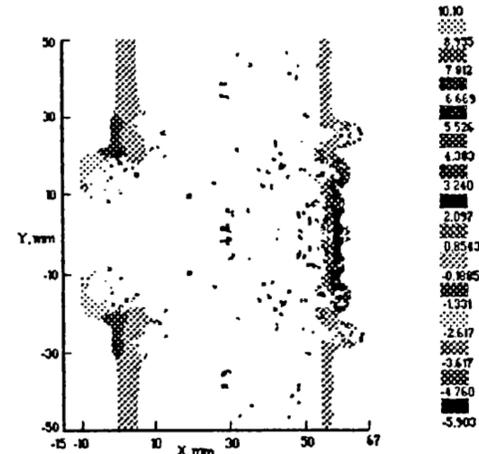


Fig.2. Destruction of spacecraft's inner assemblies at $t=7.3 \mu s$. Particle size - 1 cm, impact speed - 10 km/s.

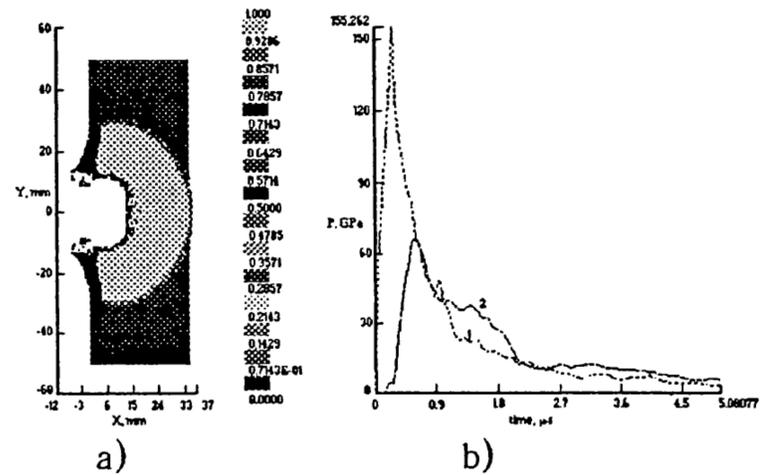


Fig.3. (a) Development of solid propellant detonation, (b) pressure gauges readings; projectile's size - 1 cm, initial impact speed - 10 km/s, $t = 4 \mu s$.

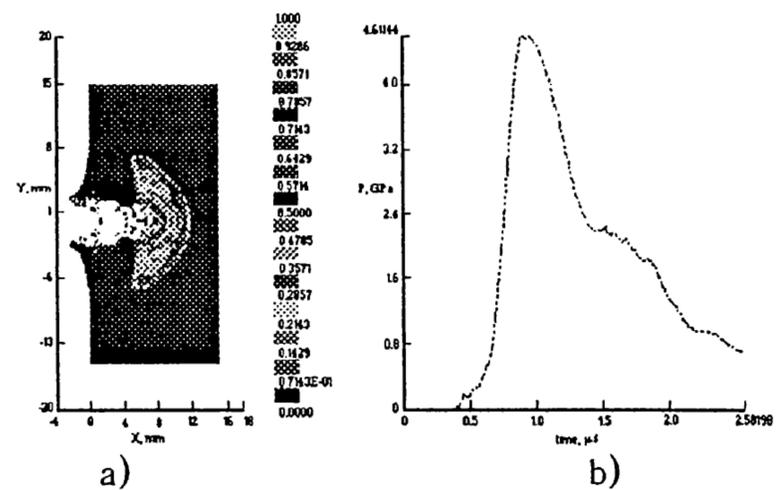


Fig.4. (a) Development of propellant explosive transformation, (b) pressure gauges readings; projectile's size - 0.1 cm, initial impact speed - 10 km/s, $t = 2.6 \mu s$.

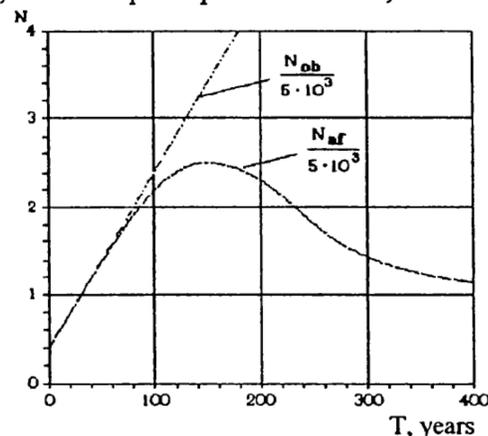


Fig.5. Number of active satellites N_{af} and total number of large bodies N_{ob} in the orbits of 200-2000 km height as a function of time (Case A).

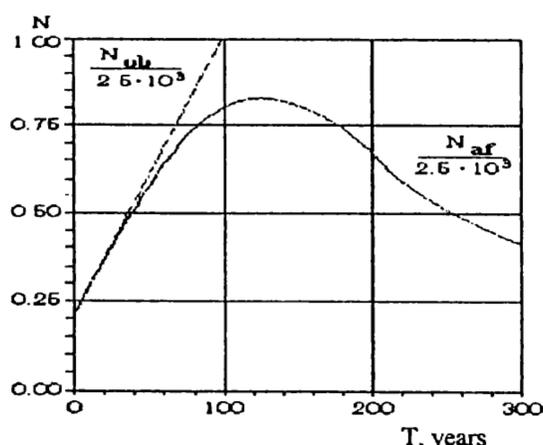


Fig. 6. Number of active satellites N_{af} and total number of large bodies N_{ob} in the orbits of 800-1000 km height as a function of time (Case B).

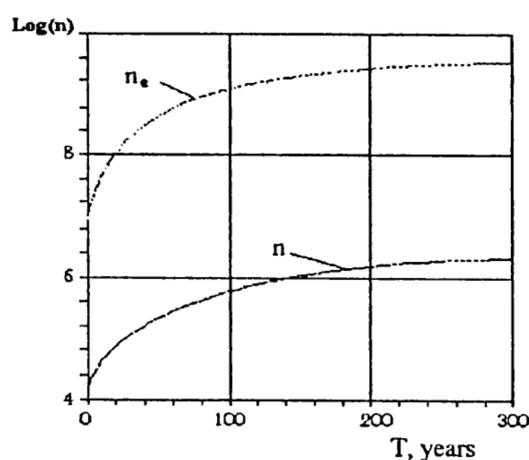


Fig. 7. Number of fragments n (with sizes larger than 0.1-1 cm) and n_e (with sizes smaller than 0.1 cm) in the orbits of 800-1000 km height as a function of time (Case B).

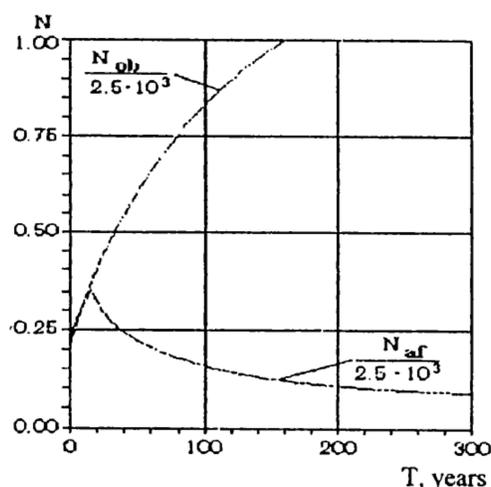


Fig. 8. Number of active satellites N_{af} and total number of large bodies N_{ob} in the orbits of 800-1000 km height as a function of time after "injection" of $5 \cdot 10^7$ fragments into these orbits (Case C).

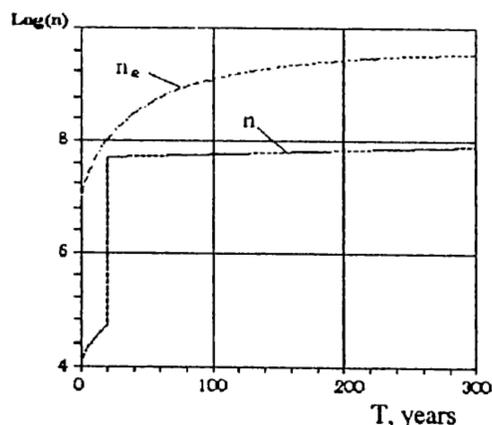


Fig. 9. Number of fragments n and n_e in the orbits of 800-1000 km height as a function of time after "injection" of $5 \cdot 10^7$ fragments into these orbits (Case C).

4. CONCLUSIONS

The presented approach to an estimation of a dynamics of near-Earth space pollution by mechanical debris is not an unique and exhaustive one. Naturally, these results have to be compared with information gained with a help of other models, which might be lucky in getting more real debris orbital distribution, in more realistic consideration of debris sources and ways of its generation. However, in our opinion, the outlined picture would not be changed, in principle, in frames of current approach to an exploitation of the near-Earth space. It seems to be true in spite of all existing uncertainties and probable significant increase of crucial characteristic time period, which will be ultimately followed by a new situation when a deployment of new satellite would not result in net increase of their population.

The main conclusion of this paper is that a developed methodology is able to attract attention to an instability ("fragility") of a "spacecraft-space debris" system which is connected with a problem of spacecraft's long-term safe operations on low near-Earth orbits. If a disturbance like injection of a large amount of fragments into an orbit is introduced then a system's qualitative state will be changed: existing and being injected spacecrafts start to be transformed into space debris. As a result there will be a danger for an effective space activity.

The other important conclusion is that a sharp increase of space debris could be generated in hypothetical armed space conflicts which would result in a great number of missiles launches as well as explosions in space. As a by-product of these military activities the near-Earth environment would be saturated by space debris to such a level which makes effective operations in the near-Earth space to be absolutely impossible for a rather long time.

5. REFERENCES

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Chapter 10

Space Debris Handbooks and Standards