THE ANALYSIS OF CONSEQUENCES FOR SOME DANGEROUS SCENARIOS OF PROBABLE COLLISIONS BETWEEN SPACE DEBRIS AND RUSSIAN NUCLEAR POWER SYSTEMS (RORSAT)

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ABSTRACT

Russian satellites equipped by nuclear power systems (NPS) ceased to be active and turned into category of space debris from 12 to 30 years ago. However, until now these systems constitute radiological hazard in the case of their re-entry to dense layers of the Earth atmosphere. Besides, beryllium and its oxides, lithium hydride and uranium as NPS materials constitute chemical hazard. These circumstances demand analysis of the consequences in the case of NPS re-entry. Brief results of such analysis are given in the present paper.

1. INTRODUCTION

There are 31 Russian NPSs on orbits with altitudes from 750 to 1000 km at present. 29 NPSs have thermoelectric conversion system and two NPSs have thermionic conversion system. For three NPSs ("Cosmos 1670, 1677 and 1900") imperfect core separation from the reactor should not be ruled out, since free-flying cores of these satellites are not identified until now. If it is so, for 16 NPSs the cores are in the reactors and for 13 NPSs the cores are removed from the reactors and placed on autonomous orbits.

2. CONDITIONS AND PROBABILITIES OF DE-ORBIT

NPS active stabilization system has not operating long ago. Gravitational stabilization tends to turn the satellite axis along orbit radius vector. If the reactor will get a bash of large space debris (SD), the one can be destroyed. If a massive part of NPS structure will get a bash, the NPS can has the decelerating impulse sufficient for its descent from initial orbit. In this case the reactor can remain undestroyed.

In order that the NPS will be entered into dense atmosphere layers at the next circuit at once after impact, its collision with sufficiently large SD fragment is necessary. Inasmuch as the probability of such events is too small, their analysis is of little interest. The case, when the NPS partially destroyed goes to elliptical orbit after decelerating impulse, is more probable.

The collisions NPS with SD fragments can result in a broad circle of consequences. In the paper are considered only those of them, which cause a consequence when NPS will be shifted onto elliptical orbit with lifetime about 50...60 years. On the one hand, the probability of such event is already significant, and, on the other hand, during such times the radioactivity of nuclear fuel Radioactivity decreases due to radioactive decay. To a moment of an entrance NPS into dense atmospheric slices the quantity of radioactivity will be determined by a sum of times from a moment of cutoff of the reactor up to a moment of collision with SD and lifetime on elliptical orbit after collision. If to assume, that such collision NPS with SD will happen in 2010, the soak period (if to take into account life time on elliptic orbit) will be 80...100 years. This time was taken for calculation of radioactivity of nuclear fuel.

The collisions between spacecraft and SD were assumed as absolutely inelastic. Average values of interaction relative velocity ($\overline{V}_{rel} = \overline{V}_0 - \overline{V}_{SD}, \overline{V}_0$ - NPS velocity on initial orbit) and corresponding angles between velocity vectors of SD and of spacecraft were used for the calculations. Initial inclination of NPS orbit is i = 65 degrees. After impact, as a rule, NPS motion around center of mass has a rotational nature, and that defines its ballistic factor.

The decelerating impulse directed against tangential component of NPS velocity on initial circular orbit with altitude h_0, moves NPS to elliptic orbit with apogee $h_\alpha = h_0$ and perigee $h_\pi = h_0 - \Delta h_\pi$. The perigee altitude h_π and, therefore, parameters of the SD with which the collision must occur are determined by the values of lifetime adopted above (50…60 years).

Under the conditions indicated above the mass of the SD fragment (m_{SD}), collision with which will move NPS to the orbit with lifetime 50…60 years can be determined.

The estimates of mass and size for steel SD moving NPS, assembly of fuel rods and the spacecraft along with NPS onto an elliptical orbit with lifetime about 50 years are shown in Table 1.

We assume destruction is catastrophic one, if in an outcome of collision not less than 10 % of mass of the target is transformed into debris. In table 2 are listed SD fragments parameters and probabilities of collision followed by catastrophic destruction of the reactor or the fuel assembly. The distribution of SD in near-Earth space according [1] was used to calculate the probabilities of collisions.

3. PROBABLE DANGEROUS SCENARIOS OF RE-ENTRY FOR FRAGMENTS OF SPACECRAFTS WITH NPS

The following objects can be entered to atmosphere dense layers as a result of such collisions:

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

- NPS with undestroyed reactor but with destroyed withdrawal compartment (16 NPS with thermoelectric energy conversion)
- Spacecraft with NPS ("Cosmos-1818" and "Cosmos-1867") with undestroyed reactor but with the payload partially destroyed
- Fuel rod assembly with destroyed front cover
- fuel rods, thermionic fuel elements (TFEs), nuclear fuel fragments

The radiation situation on Earth surface will be determined by quantity of radioactive fuel, which reaches the surface and by its radioactivity. The radioactivity of fuel is determined by operating time of the reactor and by soak period after stop of the reactor (80...100 years). The calculations of radiation situation on territory with radioactive fall-out were carried out under the conditional standard scheme of external irradiation of individuals by gamma-ray emission:

A) The reactor or radioactive fragment has been detected. There is random short-term irradiation on distance 1 m from the object during a day before the installation of a forbidden zone around the object

B) The radioactive fragment has not been detected. There will be continuous irradiation during a year on distance 10 m from the object with taking into account of shielding of gamma-ray emission by a building (attenuation factor is 2), by vegetation (attenuation factor is 1.3), by soil (attenuation factor is 1.7).

Calculated estimates of destruction of indicated objects during reentry were carried out. The calculations were carried out with following initial data: initial altitude H_0=160 km, initial flight path angle Θ_0=0 deg., initial attack angle α_0=0 deg. Initial angular velocity was being varied from 0.1 deg./s up to 10 deg./s.

Under descent of the reactor as a part of the NPS based on thermoelectric energy conversion the destruction of nuclear fuel occurs. Further descent of the nuclear fuel particles formed were calculated according to Monte Carlo method with taking into account the probabilistic variation of

- critical Weber's number,
- amount of daughter particles formed by each act of fragmentation of initial drop,
- degree of participation in reaction of oxidation of oxygen brought to the drop surface.

By the time when the particles bring to the mode of equilibrium precipitation the cloud stretched on altitude from 55 to 25 km and with extent in a projection on the Earth surface 120 km is generated. Size of particles in the cloud adheres to the logarithmic normal distribution: final particle diameter is in the range from 3 to 900 μ with mathematical expectation about 50 μ.

The estimates of radiological consequences due to the fallout of nuclear fuel particles on the Earth surface show that irradiation levels will not exceed permissible

Release of beryllium being part of radial and axial reflectors occurs under reactor destruction. About 1 kg of the whole beryllium mass is melted in the altitude range 45…35 km. The rest of its mass falls onto the Earth surface as undestroyed components of radial and axial reflectors. Lithium hydride being a part of radiation shield falls onto the Earth without loss of its mass practically.

There is not a radiological hazard because of re-entry of the fuel rod assembly partially destroyed.

Because of disruption of reactor or fuel assembly as result of collision with SD the fragments of nuclear fuel can appear in space. If the fragments get a decelerating impulse at the instant of their appearance then until re-entry to dense atmosphere layers these fragments are in upper layers of the Earth atmosphere a long period of time. Inasmuch as metal jacket is absent on them, oxide film can cover the particle surface.

If to assume that thick oxide film covers the whole surface of the fragment, the disks of nuclear fuel with dimensions up to 20×3 mm can reach the Earth surface. In this case radiological consequences will be dangerous (slightly more than 1 mSv per year) only for the disks of nuclear fuel from "Cosmos-1900". For other RORSATs radiation situation will be normal.

Thus, as for the NPS based on thermoelectric energy conversion only re-entry of the "Cosmos-1900" in the worst case can be radiological dangerous.

There are somewhat other situation for "Cosmos-1818" and Cosmos-1867" spacecrafts. The impact the reactor of one of these NPS with SD steel fragment with equivalent diameter more than 80 mm can lead to early TFE re-entry.

The calculation of TFE descent and destruction was carried out under the conditions facilitating nuclear fuel burning. There was assumed the following initial data:

- initial flight path angle was assumed close to zero,
- minimum initial spin relative to transverse axis (0.1 degree/s),
- zero initial attack angle (longitudinal axis coincided with velocity vector).

TFE jacket fails to the altitude 80 km. After jacket melting (with taking into account of all factors favorable to maximum TFE destruction) autonomous descent of the emitter and/or emitter with collector is possible.

Nuclear fuel in the course of descent loses no more than 10 % of initial mass and the rest reaches the Earth surface. Probable irradiation dose due to TFE emitter for standard irradiation procedure (item B) can be up to 3 mSv; that must be considered as exposure of an individual under the conditions of radiation accident.

Construction of the reactors placed at "Cosmos-1818" and "Cosmos-1867" is more resistant considerably to thermal effect than the construction of RORSAT reactor. Preliminary estimates of destruction (refining calculations will be carried out during this year) show that TFEs, moderator disks, axial and radial reflectors (i.e. reactor core practically) can reach the Earth surface having activity about 17 Ci after soak period during 100 years. Then the irradiation dose calculated according to conventional irradiation procedure (item A) for individual persons from population constitutes 250 mSv; that must be considered as population exposure under the conditions of radiation accident. Under calculating irradiation dose the self-absorption of gamma-radiation inside the core (self-absorption coefficient is equal to 5.0) was taken into account. It is assumed that subcritic of the reactor in the case of its surrounding and filling with water or with wet sand is ensured.

Certainly, the probability of irradiation for individual persons of population by radioactive object containing nuclear fuel will not be determining only by probability of collision with SD fragments on orbit (table 1 and 2). It also will be determining by probability to fall out into man's habitat. The last one varies from $2 \cdot 10^{-3}$ (infrastructure) up to $3 \cdot 10^{-2}$ (land utilization system).

The calculation shows that exceeding of irradiation dose from fragments of "Cosmos-1818" or "Cosmos-1867" containing nuclear fuel is possible even within 150…200 years of soak period. With allowance for the adopted lifetime on elliptical orbit after collision (50…60 years) the probability of collision in 100 years will be close to maximum probability of appearance of dangerous nuclear fuel from "Cosmos-1818" or "Cosmos-1867" in man's habitat and equal to $4 \cdot 10^{-4}$.

4. CONCLUSIONS

There are dangerous scenarios of probable interaction between fragments of SD and NPS with thermionic and thermoelectric energy conversion. Realization of these scenarios will lead to exceeding permissible irradiation doses for individual persons of population.

Maximum probability of realization of dangerous scenario (in 100…150 years) is equal to $4 \cdot 10^{-4}$. Only collisions with "Cosmos-1900, 1818 and 1867" are dangerous.

Calculated according to standard irradiation procedure (item A) irradiation dose will be able reach 250 mSv. It must be considered as exposure for population under the conditions of radiation accident. In such situation Russian national and international documents envisage the necessity of monitoring trajectory parameters of satellites "Cosmos-1900, 1818 and 1867". In the case of detecting of changing their orbits and/or of destruction of objects, it is necessary to supply:

- Forecasting of time and area of a possible reentry and possible regions of a falling of fragments NPS with nuclear fuel
- Notification of the competent authorities of a potential situation in the impact region
- Search, discovery and removal of radioactive dangerous objects
- Organization of radiation monitoring at the impact site and, where necessary, clean-up of ra-
- Examination and counting of members of the public located in the impact zone of the object and fragments and evaluation of possible individual radiation doses, assistance to the public being provided where necessary

5. REFERENCES

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Table 1 – Target and Striker Parameters

Object	Target				Steel striker				Impact probability		Transfer orbit	
	Mass, kg	Area for impact F, m^2	Ballistic factor at f/m * mode σ_x, m^2/kg	Altitude h, km	Mass m, kg	Conventional diameter d_c, mm	Average relative impact velocity V_{rel}, m/s	Impact angle γ, degree	TPF**=1		h_α, km	h_π, km
									Over 100 years	Over 1 year		
NPS based on thermoelectric conversion	1254	1.95	$6 \cdot 10^{-3}$	950	≥ 15.6	≥ 153	12410	115	With one of 16		950	440
									$3.2 \cdot 10^{-2}$	$1 \cdot 10^{-4}$		
Fuel rod assembly	53	0.02074	$3 \cdot 10^{-3}$	950	≥ 0.7	≥ 55	12410	115	With one of 13		950	400
									$0.2 \cdot 10^{-2}$	$7.8 \cdot 10^{-6}$		
SC with NPS based on thermionic conversion	3090	7.7	$5.8 \cdot 10^{-3}$	800	≥ 25	≥ 180	12540	114.5	With one of 2		800	470
									$1.4 \cdot 10^{-2}$	$53 \cdot 10^{-6}$		

* f/m – free molecular

** TPF – technical policy factor

Table 2 - Target and Striker Parameters under Catastrophic Destructions

Object	Target		Steel striker		Impact probability	
					TPF=1	
	Area for impact F, m^2	Altitude h, km	Mass m, kg	Conventional diameter d_c, m	Over 100 years	Over 1 year
Reactor of NPS based on thermoelectric conversion	0.265	950	≥ 0.15	≥ 33	With one of 16	
					$7.9 \cdot 10^{-2}$	$2.95 \cdot 10^{-4}$
Fuel rod assembly	0.08975	950	≥ 0.045	≥ 22	With one of 13	
					$2.15 \cdot 10^{-2}$	$8 \cdot 10^{-5}$
Reactor of NPS based on thermionic conversion	0.31	800	≥ 2.1	≥ 80	With one of 2	
					$0.27 \cdot 10^{-2}$	$1 \cdot 10^{-5}$