SPACECRAFT WITH A NUCLEAR POWER SYSTEM AND PROBLEMS OF SPACE DEBRIS

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ABSTRACT

Onboard nuclear power sources (NPS) are related to the space debris problem in terms of several aspects:

- Orbital spacecraft with NPSs themselves can be regarded as space debris and, hence, are potentially hazardous to space objects and (in the case of their incident) to ground-based objects;
- In designing and launching of new spacecraft with NPSs, they should be protected from collisions with space debris, and measures should be taken to avoid man-induced contamination of the near-Earth space.

Since the time of launching the first NPS into space, some experience has been accumulated, and techniques and codes helpful in solving population and environment safety problems have been developed.

1. INTRODUCTION

It was pointed out in the materials of Scientific and Technical Subcommittee of the UN Committee on the Peaceful Uses of Outer Space (_/__.105/_.1/ L.276/Add.1, 2004) that "…countries implementing space programs should pay more attention to the problem of collision of space objects including those having onboard nuclear power sources with space debris…"

The relation of onboard NPSs with the space debris (SD) problem has two aspects mentioned above in Abstract. The national rules of radiation safety, as well as "Principles on using the nuclear power sources in space" approved by UN in 1992, are the main documents to be guided in producing the radiation-safe space NPSs.

2. DOMESTIC OBJECTS WITH NPS REACTOR IN ORBIT

Space vehicles with NPSs have been launched in USSR from 1970 till 1988 (Tab. 1). 33 space vehicles have been launched into orbits (Nazarenko et al, 1996). Radiation safety was provided by transferring the reactor NPS after completion of the mission program to sufficiently high orbits and removal of nuclear fuel from the reactor (beginning with C-1176). This discharge was not carried out in two cases (C-954 and C-1402). As a result of aerodynamic destruction of the reactor and nuclear fuel, no considerable negative consequences were recorded.

Table 1. General satellite data

_	Cosmos	Int. No	Altitudes, km		_ __	Cosmos	Int No	Altitudes, km
1	C-367	70079001	930/1020		23	"---------"	**82043004**	890.960
2	C-402	71025001	960/1030		24	C-1372	82052001	920/980
3	C-469	71117001	945/1025		25	"---------"	**82052004**	915/955
4	C-516	72066001	925/1030			**C-1402**	**82084001**	Reentered
5	C-626	73108001	910/990		26	C-1412	82099001	905/995
6	C-651	74029001	890/960		27	"---------"	**82099005**	910/960
7	C-654	74032001	930/1015		28	C-1579	84069001	915/985
8	C-723	75024001	890/980		29	"---------"	**84069004**	910/965
9	C-724	75025001	865/945		30	C-1607	84112001	925/990
10	C-785	75116001	900/1025		31	"---------"	**84112003**	920/965
11	C-860	76103001	930/1005		32	C-1670	85064001	915/1000
12	C-861	76104001	930/1000		33	C-1677	85075001	895/1000
13	C-952	77088001	930/990		34	C-1736	86024001	940/1005
	C-954	**77009001**	Reentered		35	"---------"	**86024005**	940/990
14	C-1176	80034001	900/955		36	C-1771	86062001	930/995
15	"---------"	**80034004**	890/930		37	"---------"	**86062003**	925/975
16	C-1249	81021001	915/980		38	C-1818	87011001	790/805
17	"---------"	**81021003**	900/965		39	C-1860	87052001	920/985
18	C-1266	81037001	905/960		40	"---------"	**87052004**	905/965
19	"---------"	**81037004**	905/940		41	C-1867	87060001	790/805
20	C-1299	81081001	920/985		**42**	**C-1900**	**87101001**	**700/740**
21	"---------"	**81081004**	920/980		43	C-1932	88019001	940/1005
22	C-1365	82043001	900.975		44	"---------"	**88019004**	940/975

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Presently, there are two SCs (C-1818 and C-1867) with the thermoemission transformation system (Fig. 1) in orbits at altitude of about 800 km. 28 so-called RORSATs (Fig. 2) are situated in orbits in the altitude range of 900-1000 km, and one RORSAT (C-1900) is situated at the altitude of 700-740 km. Besides, 13 fuel element assemblies (FEA, Fig. 3) are situated at aforementioned altitudes, and 3 FEA (including that for SC C-1900) have not been detected.

The altitude range of 800…1000 km is characterized by the maximum level of technogeneous (man-induced) contamination. There are two types of unexpected consequences at NPS collisions with SD:

- emergency situation which can lead to radiation hazard to the Earth population;
- formation of new space debris particles.

To evaluate the damage from mentioned unexpected consequences it is necessary to determine the probability of spacecraft collisions with SD particles of various-size, as well as to estimate the consequences of these collisions. The technique for estimating the probability of SC collision with space debris, based on the domestic model, is outlined in details in the normative document (RF GOST R, 2005), as well as in some papers (Nazarenko, 2002, 2003). The appropriate software is available.

In some works of American specialists (Kessler, 1995, Kessler et al, 1997) the opinion was expressed, that, being in orbits, the Russian space vehicles with NPSs represent a source of formation of a plenty of small particles ~ 1 cm in size. It was declared that these particles were formed as a result of sodium-potassium coolant leakage from NPSs at the instant of separation of fuel elements assemblies (Fig. 4). The number of particles of such type with total mass of about 30 kg was evaluated as about 80,000.

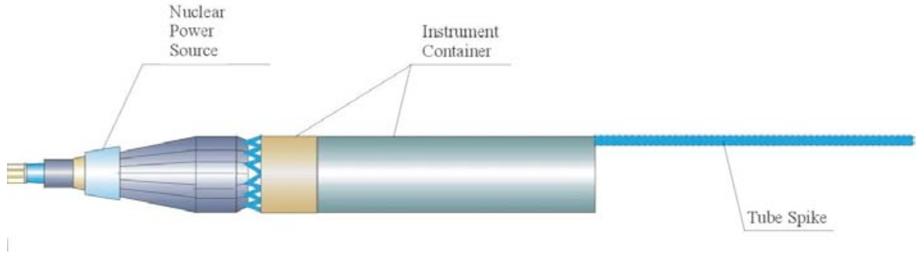

Figure 1. Spacecrafts Cosmos-1818, 1867

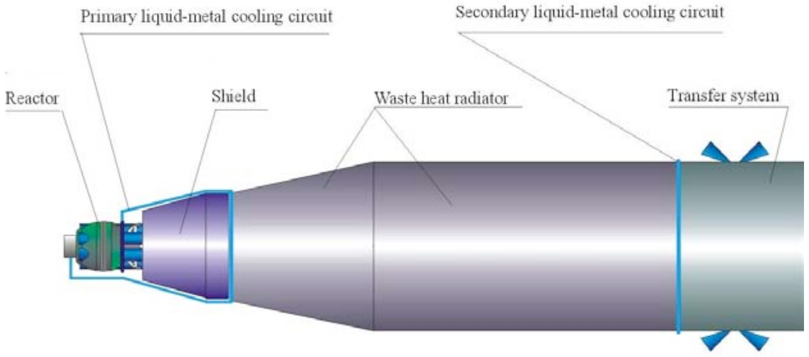

Figure 2. Space reactor system

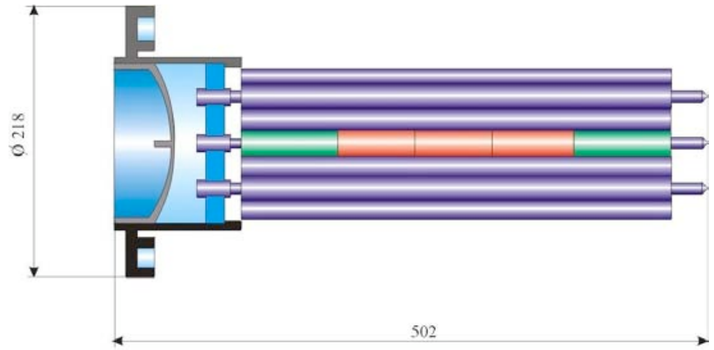

Figure 3. Fuel element assembly

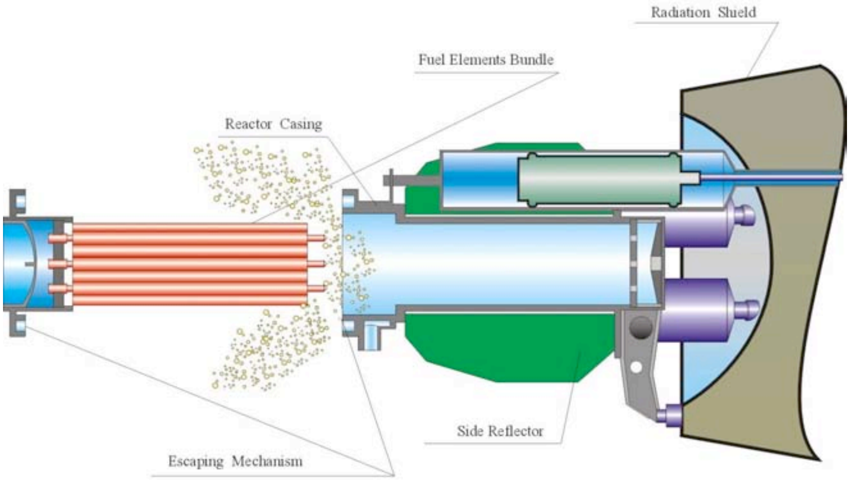

Figure 4. Scheme of escaping for fuel element assembly

At interpreting these estimates one should have in mind that the estimates of the current distribution of SD spatial density could differ several times. This is testified by Fig. 5 (Beltrami et al, 2004), which provides the comparison for different models..

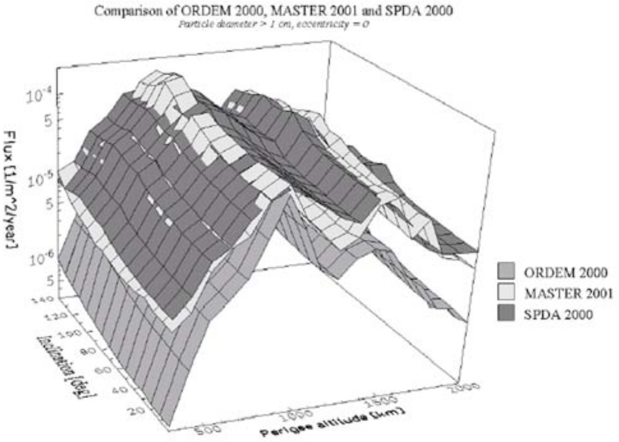

Figure 5. Flux of particles larger than 1 cm, e=0

In our opinion, the above mentioned number of particles is a hypothesis only and is not 100% confident (Nazarenko, 1996). The matter is that, presently, there are no technical means allowable to determine the national belonging of small particles of space debris. Objects larger than 10…20 cm in size are subjected to cataloguing. The number of objects of smaller size is evaluated statistically on the basis of local measurements and experiments. In particular, according to the data of modern space debris models, the number of particles larger than 1 cm in size equals 250,000…300,000, about 80,000 of which lie in the altitude range of 800…1000 km. So, the considered hypothesis is equivalent to the statement that the Russian satellites with NPSs in the altitude range 800…1000 km are the only source of formation of all objects larger than 1 cm in size. We can not agree with this statement, just because in the considered altitude range at least 20 explosions of space vehicles and launch vehicles took place (JSC 62530, 2004), as a result of which a great number of small debris has formed. This hypothesis is not confirmed also by the results of chemical analysis of 1000 largest craters on the surface of American satellite LDEF. Traces of Na and K were observed in two craters only (Kessler et al, 1997). Nevertheless, there is a grain of truth in the considered hypothesis, i.e. the leakage of sodium-potassium coolant from NPS is possible. However, no sufficiently confident information about this process is now available.

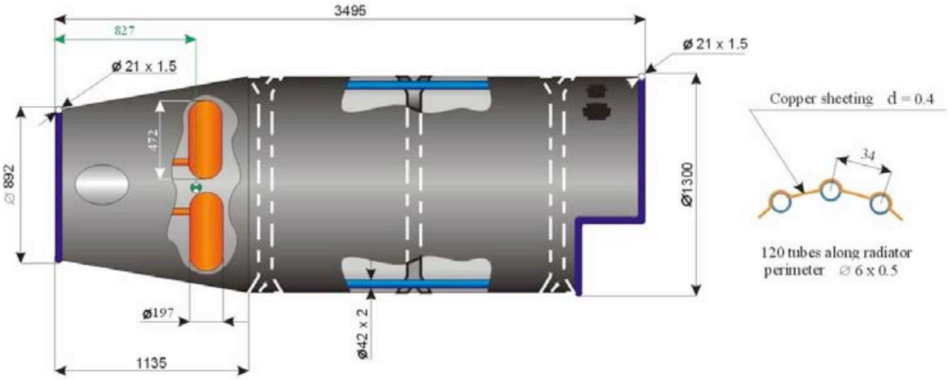

Figure 6. Calculation scheme of NPS radiator

The second (emitting) contour of RORSAT's heat-carrier (a coolant) can be a potential source of Na-K particles. In our report (Grinberg et al., 1997) it was shown that the basic force causing Na-K ejection at the second contour depressurization is the centrifugal force (Fig. 6). Multiple observations of the character of RORSAT motion have shown that its angular velocity decreases twice every three years. The analysis has shown that now the heat-carrier ejection is possible only at depressurization of a rear collector and for two SCs only (C-1900 and C-1932, Fig. 6).

The probability of coolant ejection as a result of collision with a large-size SD particle ($d > 8$ mm) equals about $6 \cdot 10^{-5}$ per one year. By 2010, this probability will essentially decrease because of decreasing the angular velocity of SC rotation. So, the depressurization of the second RORSAT's contour will not result in formation of a plenty of Na-K particles.

The collision of reactor body or fuel element assemblies with SD can result in formation of radioactive SD particles. Not any SD particle can destroy a target catastrophically. The assumption is used that the NPS destroy is catastrophic, if 10 % of initial target's mass turns to splinters. For steel SD particles at collision with average velocity of about 12 km/s the critical particle size for the FEA equals about 2.5 _m, and that for the reactor body - about 3.5 cm (Fig. 7). Taking into account these estimates, the probability of formation of uranium fuel particles equals $0.8 \cdot 10^{-4}$ per one year for each of 13 assemblies, and that for each of 13 reactor bodies equals $0.2 \cdot 10^{-4}$ per one year.

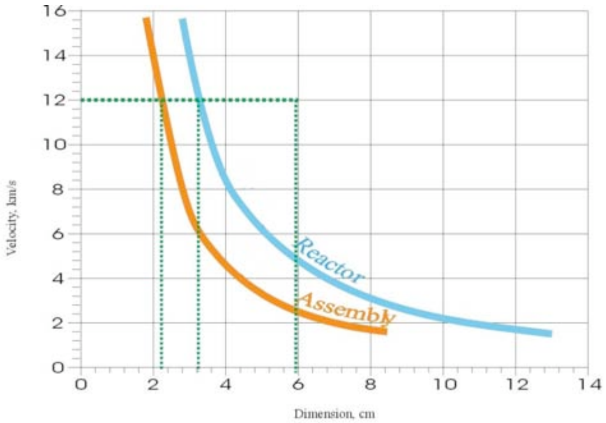

Figure 7. Limiting dimensions of steel strikers resulting in catastrophic destruction vs. collision velocity

The modeling of reentering uranium particles of different sizes into the atmosphere was performed. It has shown that the final size of particles was such, that the level of particle's irradiation did not exceed the norm (1 mSv/year), even if a cloud of particles is reentered. For orbits with inclination of 65–, the probability of particles penetration into the infrastructure, or into the system of land tenure, or into the water-supply system equals $(0.2 - 5.0) \cdot 10^{-2}$. So, the annual risk of uranium particles penetration into the mankind habitat is not greater than $0.8 \cdot 10^{-4} \times 5 \cdot 10^{-2} = 4 \cdot 10^{-6}$.

The probability of SC collision with catalogued objects, resulting in essential SC deceleration and destruction of radiation protection, equals about 10^{-6} per one year for each of 13 objects. Even in the case of collision, the nuclear fuel with residual activity will not reach the Earth surface. The modeling of reactor body reentry was performed. It has shown that at combustion the nuclear fuel forms a cloud of particles, for which the reentry does not result in excessive annual irradiation of population (1 mSv/year). So, the annual risk of uranium particles penetration into the mankind habitat is not greater than $1 \cdot 10^{-6} \times 5 \cdot 10^{-2} = 5 \cdot 10^{-8}$.

3. DESIGNING AND EXPLOITING OF SPACECRAFT WITH NPS

The perspective SCs with NPS are intended: a) for studying the deep space; b) for using as a boost for SC launching into the geostationary orbit with using a nuclear power engine (NPE, Fig. 8) or electro jet engine (EJE); c) for SC power supply during its staying in GEO. In both cases the reactor is engaged (started) only on the intermediate (parking) orbit, where SC with NPS is delivered by a rocket launcher. The probability of environment contamination by new SD particles (in the LEO region), or the probability of ejection of radioactive nuclear fuel to space environment exists only if the following three emergencies arise simultaneously:

- not engaging the engine (NPE or EJE, $P \sim 10^{-2}$),
- not stopping the reactor, which continues working in a standby mode ($P \sim 10^{-2}$),
- collision with a SD particle.

For a reactor, the probability of collision with large-size SD particles, resulting in formation of radioactive fuel particles, equals $2 \cdot 10^{-6}$ per one year. The total probability of formation of radioactive fuel particles equals $< 10^{-9}$ per one year.

SC with EJE (Fig. 9) has very low probability of formation of radioactive particles as well. The risk of simultaneous occurrence of three emergencies equals 10^{-11} per one year.

The formation of new SD in the LEO region as a result of radiator depressurization can take place only at simultaneous occurrence of three emergencies:

- not engaging the engine (NPE or EJE, $P \sim 10^{-2}$),
- not stopping the reactor, which continues working in a standby mode ($P \sim 10^{-2}$),
- collision with a SD particle.

The depressurization of a collector or a pipeline in a working NPS will result in ejecting coolant particles. The probability of such a collision equals 10^{-3} - 10^{-4} per one year. The total probability of coolant ejection at simultaneous occurrence of three emergencies equals 10^{-7} - 10^{-8} per one year. It will even more decrease, when the bumper protection of a collector and pipeline is applied.

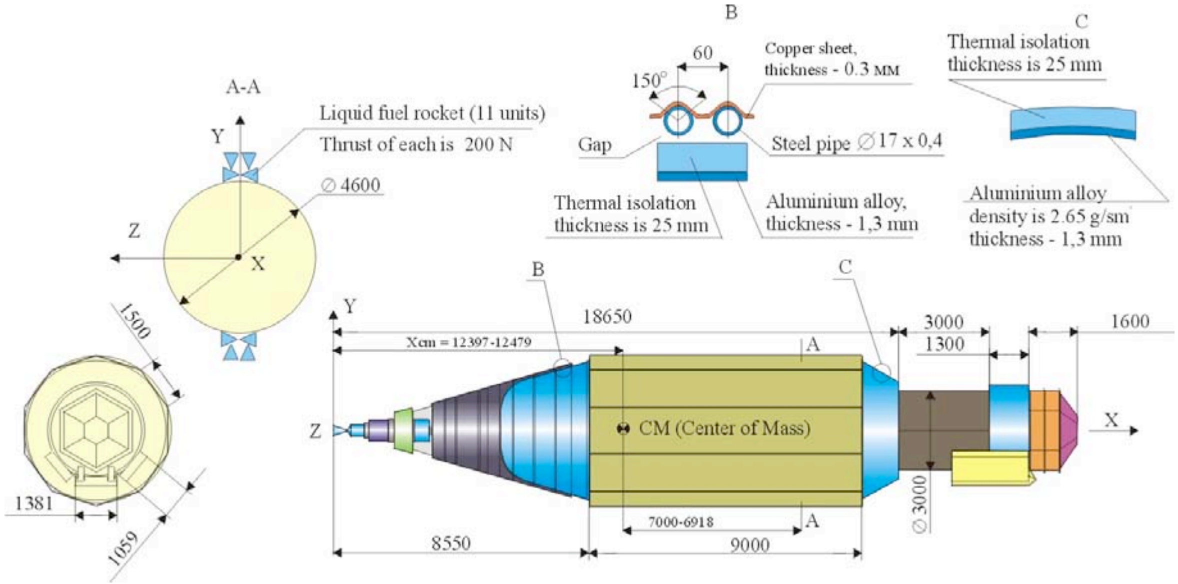

Figure 8. Spacecraft on a section of flight to GSO

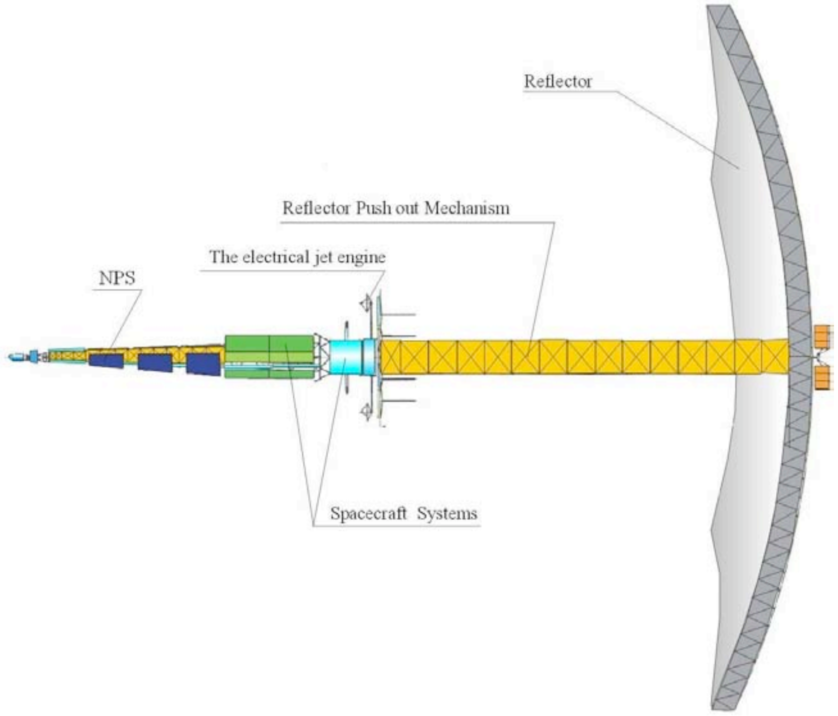

Figure 9. Spacecraft and NPS scheme

Now, the radiators are made from independent thermal pipes or with using their sectionalization. At working pipe depressurization (whose probability equals 10^{-5}-10^{-6} per one year) only 10-15 g of Na-K coolant can flow out. The total probability of coolant ejection from thermal pipes equals 10^{-9} per one year.

The calculation analysis of possible failures, including the collision with SD at all stages of space operation for a transport-power, NPS-based module, has shown that at any failure the radiation safety of human population can be provided with permissible risk equal or less than 10^{-4} per year. It is possible to essentially decrease the risk of collisions and possible damage by properly choosing the initial orbit, from which the spacecraft begins to transfer into GEO or boost to escape velocity with using backup systems, etc.

So, the possible collision of a NPS-based spacecraft with SD leads to relatively new emergency situations, where the radiation safety requirements should also be satisfied.

At the 40th Session of Scientific and Technical Subcommittee the document (The guiding principles to prevent space debris formation, 2003) of the

Interagency Space Debris Committee (IADC) was distributed for discussion. This document contains a recommendation (Item 5.3.2) for spacecraft in near-Earth orbits: after completion of active operation, it is necessary to lower the orbit altitude down to the level providing the life-time not greater than 25 years, or to foresee direct returning to the Earth. This recommendation definitely accelerates self-purification of space environment from technogeneous debris, but is unacceptable for a NPS-based spacecraft and contradicts the acting UN principles regarding the NPS use in space. The UN principles, dated 1992, include the requirement (Item 2.1) on transferring the NPS-based spacecraft, after completion of its active mission, into a sufficiently high altitude, where the lifetime is sufficient for decaying the fission products (hundreds of years, as a rule). Moreover, the operations of separation with the purpose of decreasing the risk of radiation contamination should be permitted for a spacecraft with a nuclear power system at minimizing the number of fragments formed in the course of this operation.

For every particular system it is necessary to investigate in detail its possible failures, their risk and to take measures for providing radiation safety and for preventing the formation of new SD. The methods for solving problems of such a kind are available.

Naturally, under modern conditions the used safety providing measures should not contradict the international documents. To formulate the coordinated technical policy, it is necessary to involve domestic specialists into preparation of corresponding international documents of type (The guiding principles to prevent space debris formation, 2003, Technical paper on space debris, 1999).

4. CONCLUSIONS

1. With existing level of space contamination:

    - one should not expect additional massive formation of Na-K particles as a result of depressurization of the second RORSAT's circuit. The formation of new Na-K particles (with probability of about $6\cdot10^{-5}$ per one year) is possible only for two SCs (C-1900 and C-1932) and only with destruction of a rear collector.

    - the formation of radioactive uranium particles as a result of SD collision with one of 13 reactor bodies or with one of 13 nuclear fuel assemblies equals (0.2-0.8) $\cdot10^{-4}$ per one year. But this does not mean that particles will reach the Earth surface.

2. The IADC recommendations stated in the document "The guiding principles to prevent space debris formation" should not contradict the UN Principles of 1992 related to NPSs use in space.

3. The safety issues should be permanently analyzed when using perspective NPSs in space environment. It is important, that there are no principally insoluble problems with ensuring acceptable degree of risk of irradiation in this area.

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