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Radiological Protection Considerations as to the Crash of Nuclear-powered Satellites

Statement of the German Commission on Radiological Protection

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Stellungnahme der Strahlenschutzkommission

In the event of any doubts about the meaning, the German original as published shall prevail.

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1 Introduction

The power supply of space satellites, depending upon their mission and power demand, is provided by chemical batteries, solar cells, radionuclide batteries or nuclear reactors. The two latter contain radioactive substances which may lead to a considerable radiation exposure of the population in case of irregular course of a mission. The USA and the USSR are using these nuclear power supply systems.

For example, about two reconnaissance satellites with nuclear reactors on board are launched anually by the USSR at present. By the end of their mission they are intended to be boosted up into a so-called parking orbit of 800 km altitude, where the satellites are supposed to stay for about 300 years in order to ensure radioactive decay to small residual values before returning to earth.

Lifting up into the parking orbit did not succeed in all cases in the past.

In addition, the increasing number of residues from satellites in the parking orbit (800-1000 km altitude) may cause potential collisions of parking satellites with these residues, depending upon their particle size, with a probability of up to 50 % within 300 years' time. Five to 50 years after such a collision a hit satellite or fragment thereof will return to earth prematurely.

An example of satellites powered with radionuclide batteries is the research satellite Galileo which was launched for an interstellar mission by the USA in October 1989 with a radionuclide battery on board.

The United Nations' Space Committee has been attempting for a number of years to prepare recommendations which would permit to accept the use of nuclear-powered satellites, if adhered to.

The SSK (Commission on Radiological Protection) has been asked by the Federal Ministry of the Environment, Nature Conservation and Nuclear Safety to evaluate nuclear power supply systems used for space missions from the view of radiation protection.

2 Criteria for Evaluation of Potential Radiation Exposure from Nuclear-powered Satellites

The Commission on Radiological Protection recommends to evaluate the potential radiation exposure from nuclear-powered satellites on the basis of the radiation protection principles laid down by the ICRP for normal operations (ICRP Publication 26) and for irregular courses (ICRP Publication 40).

Regarding military uses of satellites a distinction has to be made between reconnaissance satellites and space weapon systems. The following considerations cannot apply for the latter, which require the use of high performance reactors (1000 kW) due to their high power demand. The use of these weapon systems cannot be justified by the principles of radiation protection.

2.1 Normal operations

The recommendations of the ICRP as given in ICRP Publication 26 are based on the following three principles of justification, optimization and dose limitation:

A: No practice shall be adopted unless its introduction produces a positive net benefit (justification)

Satellites are used today for the following purposes:

- meteorological and environmental observation,
- telecommunications,
- basic research, and
- military reconnaissance.

Application of the ICRP principle of justification for these uses of satellites leads to the following considerations:

Uses of satellites for the purposes of meteorological and environmental observation, telecommunications and within the scope of research tasks is of considerable benefit. However, the power demand for these applications often is not so high as to require nuclear power; in such cases alternative energy systems should be used preferably. For interstellar missions, too, the question arises of whether it would be possible to develop energy systems other than Pu 238 batteries as presently used, e.g. particularly long-lived chemical batteries or radionuclide batteries containing less radiotoxic nuclides.

The use of military reconnaissance satellites may be justified by the desire to exclude surprise attacks on a state's own territory. However, since the power demand for such reconnaissance missions may be covered by solar cells as well, the use of reactors for this purpose should be avoided in favour of alternative power supply systems.

The assessment of net benefit in space missions generally is very difficult, particularly since those benefiting from such missions usually are not identical with the group of individuals affected by the potential consequences of the mission. Only an international committee therefore would be in a position to justify the use of nuclear-powered satellites in each individual case.

If the satellite is intended to return to earth according to plan, the mission should in any case be planned so as to ensure that potential residual risk would only affect the country by which the mission was performed.

B: All exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account (optimization)

If the use of a given nuclear-powered satellite is justified, the design of the system must be optimized. In this respect a distinction has to be made between the protection feasible at the source, e.g. by mechanically and thermally safe encasement of the nuclear aggregates on the one hand, and the selection of the orbital altitude to be reached by the end of the mission, in order to ensure considerable activity decay, thus prividing direct protection of man on the other hand.

In cases of applications involving far reaching or even global potentials of damage, great importance must be attached to the type and efficacy of safety requirements.

C: The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission (dose limitation)

This principle of dose limitation has been further defined by the ICRP in the Statement of 1985 supplementing the ICRP Publication 26. The ICRP requires that radiation exposure basically shall be limited so as to ensure that the annual dose to members of the critical group shall not exceed a total of 1 mSv from all sources of radiation exposure (except for natural and medical exposures). This means that the dose from satellite uses may only amount to fragments of 1 mSv. If the potential exposure does not involve a relatively small group of individuals but larger population groups, the criteria applied must be much more stringent.

Additionally, reference is made to the couple of values of 10 µSv per individual and 1 manSv for the collective as given by the IAEA for practices which may be negligible with regard to radiation protection, if the radiation protection principles are adhered to (IAEA Safety Guides No. 89, Principles for the Exemption of Radiation Sources and Practices from Regulatory Control).

2.2 Irregular operations

In a situation resulting from an irregular course of a mission, the above system of dose limitation is not applicable. With regard to the planning of radiation protection measures in situations where the radiation source is not under control, the following principles are recommended in ICRP Publication 40:

(a) Avoidance of nonstochastic effects by limitation on individual dose below the thresholds for these effects.

(b) Limitation of the risk from stochastic effects, based on a balance of the radiation induced risk to health against the health risk resulting from intervention.

(c) Reduction of the collective dose equivalent as far as reasonably achievable, i.e. based on optimization of both the cost of the radiation induced health detriment in the affected population and the cost of further countermeasures.

The dose range for the limitation of individual risk, as suggested in ICRP Publication 40, is 5 to 50 mSv for the disposal of contaminated foodstuffs, or 50 to 500 mSv for the measure of evacuation or relocation. In cases of more frequent irregular courses of missions, however, only fragments of these doses can be permitted.

3 Assessment of Potential Radiation Exposures

The following is intended to give a rough estimate of potential radiation exposures, including both the possible individual dose and collective dose. These estimates are subject to great uncertainties and may only lead to indicate orders of magnitude.

However, reference may be made to the experience from the following two events:

- the crash of the satellite COSMOS 954 with a nuclear reactor on board over Canada in 1978, and
- the burn-up of the satellite SNAP-9A with a radionuclide battery on board in 1964.

3.1 Uses of nuclear reactors

Normally, the satellite is intended to be sent into a parking orbit of about 800 km altitude by the end of its mission and to re-enter the earth atmosphere about 300 years thereafter. This did not succeed in the case of COSMOS 954: the satellite returned to earth immediately after completion of its primary function an decayed into more or less large particles when it re-entered the atmosphere.

This led to a far-reaching contamination in Canada in 1978. The experience from this event may be summarized as follows:

The heavy fragments (about 100 of 20 kg at maximum each) were spread over a length of some hundreds of kilometers and over a width of some kilometers along the original flight direction. Smaller masses were increasingly influenced by drift from winds. The particulate residues of COSMOS 954 (0.1 to 1 mm in diameter; about 250 per km^2) had been transported by up to some hundreds of kilometers away from the track of impact of the heavy parts.

Considerable exposure to external gamma and beta radiation from deposited fragments or particles may be expected in persons who stayed in the vicinity of such fragments or particles for a prolonged period of time immediately after the crash, and in cases of direct body contact with the particles. Viewing the particles recovered in Canada at that time, it has been estimated that about 250 particles per square kilometer fell down there, which could cause such considerable radiation exposure.

The following local gamma dose rates have been estimated for particles from reactor fuel, including the nonvolatile fission products in 1 m distance:

Particle diameter 1 mm: 0.5 mSv/h,

Particle diameter 0.1 mm: 0.5 µSv/h.

These values apply for the time immediately after shut-down of the reactor.

The local gamma dose rates from larger fragments, corresponding to those found in Canada about 2 months after the crash of COSMOS 954, may range from 0.1 to 2 mSv/h at 1 m distance.

Although the latter values of dose rate may be expected only in rare cases of a similar course, it must be pointed out that a crash in a region of high population density may involve a very great number of persons exposed to low levels of radiation, due to the large area that might be affected and the great number of small particles.

If the satellite returns to earth only after 300 years' time as planned, the local dose rates can be assumed to decrease to about 0.1 % of the above values, due to the radioactive decay.

When evaluating the absolute numerical values it must be taken into account that a 50 kW-reactor was involved in the example given.

3.2 Uses of radionuclide batteries

Normal courses of interstellar missions are not expected to cause radiation exposure of the population. Earth-orbiting satellites[1] will re-enter the earth atmosphere after long periods of time (about 1000 years), when a burn-up would involve consequences of much less severity than experienced in the case of SNAP-9A.

A malfunction during lift-off might result in a more or less small area of high contamination, if the encasement of the radionuclide battery fails. If the satellite does not reach the parking orbit and returns to earth prematurely, then a failure of encasement will have consequences similar to those experienced with SNAP-9A.

These consequences may be summarized as follows:

Due to burn-up of the radionuclide battery of SNAP-9A, about $6 \cdot 10^{14}$ Bq Pu 238 were transferred into the atmosphere. For comparison: According to UNSCEAR the atmospheric atomic bomb testings brought a total of $3.3 \cdot 10^{14}$ Bq Pu 238 into the atmosphere, leading to an effective individual dose of about 2 µSv by UNSCEAR. This leads to estimate effective dose equivalents of 4 µSv for a radionuclide battery in the order of SNAP-9A.

When evaluating these figures it must be taken into account that considerably greater radionuclide batteries sometimes are used today (the activity of the radionuclide battery of the already mentioned research satellite Galileo was about 16 times higher). Additionally, the resulting collective dose equivalents are high due to the very homogeneous distribution (in the case of SNAP-9A the collective dose is in the order of $2 \cdot 10^4$ manSv, assuming a world population of $5 \cdot 10^9$ persons).

4 Conclusions and Recommendations

The Commission on Radiological Protection points out that the power demand in uses of satellites for the purposes of

- meteorological and environmental observation,
- telecommunications,
- military reconnaissance, and
- basic research,

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[1] satellites parking near the earth atmosphere

according to the Commission's knowledge, generally is not so high as to absolutely require nuclear-operated sources of energy; therefore it is recommended to use other systems of power supply as far as possible.

For cases where the use of nuclear power is necessary though, the Commission on Radiological Protection, after having considered the radiation exposure that might occur as a result of such applications, makes the following recommendations:

4.1 In the discussion about nuclear-operated satellites, top priority must be given to the aspect of justification of the use of such nuclear power sources. An international body should be entrusted with the assessment of justification in each individual case.

4.2 In order to minimize risk, the systems should be designed according to the following recommendations:

4.2.1 Nuclear reactors

a) As a general rule, a thermally and mechanically safe encasement has to be required in order to warrant safe landing or deliberate get back.

b) The reactor must be designed so as to be put into operation only after having reached the operational orbit.

c) Subcriticality must be ensured also when dipping into water.

d) It should be examined whether the reactor, after its operation period, can be lifted up so far as to leave the earth's gravitation field.

e) If this cannot be warranted, it is recommended to have parking orbits selected as high as possible in order to attain the required decay time and reduce the risk of collision.

f) In case the lifting should fail, a back-up system should be available (e.g. recovery by a spacecraft).

4.2.2 Radionuclide batteries

a) For earth-orbiting missions[1] it should be required to dispense with the use of radionuclide batteries.

b) For interstellar missions, too, it is recommended to consider the possibility of using alternative sources of energy or, if necessary, radionuclide batteries containing less radiotoxic nuclides, viewing the risk of irregular courses.

c) The use of encasements preventing the radionuclides from being released upon return to the earth must be generally required for interstellar missions as well.

d) It is recommended to provide for systems enabling the radionuclide batteries to be located and recovered in case of malfunction during the mission.

e) With regard to those satellites with radionuclide batteries that have already been parked in high altitudes up to now, the possibility of a deliberate get-back at a later date should be considered.

[1] missions close to the earth

4.3 The Commission on Radiological Protection argues that nuclear aggregate must be constructed so as to ensure that the radiation exposure from normal courses of all planned missions together will only be in the order of fragments of 1 mSv. The Commission therefore recommends to refer to the suggestion made by the IAEA which leads to the toleration of 10 µSv per individual and a collective dose of 1 manSv, if the marginal conditions regarding radiation protection, as required by the IAEA, are observed.

Viewing the risk of radiation exposures from irregular courses of missions and the great number of persons that might be involved, the Commission on Radiological Protection requires safety systems to be designed so as to ensure that 1 mSv of individual dose is not exceeded in any cases, i.e. even in the event of irregular courses, and that such exposures are restricted to a small area.