ESTIMATE OF RADIATION SAFETY OF EMERGENCY ATMOSPHERIC REENTRY OF RADIOISOTOPE THERMAL GENERATORS USED FOR SPACE APPLICATIONS

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ABSTRACT

In estimating radiation safety of radioisotopic thermoelectric generators (RTG) for space applications, principle 3b of the "Principles relevant to use of nuclear power sources in outer space", adopted by the United Nations in 1992, is applied. This principle implies that the system of protective shells around the radioisotopic material in the event of emergency re-entry and impact on the Earth's surface should guarantee that the radioisotopic material does not enter the ambient medium. This allows complete cleanup from radioactive matierial of the re-entry region by rescuing the nuclear power source. Another fundamental principle is principle 3c, which implies that the radiation exposure of individuals should be limited to 1 mSv/year.

Safety is evaluated for all stages of RTG exploitation and all possible associated emergency situations during its storage, transportation, operations at the launch pad, accidents at the launch pad (ingress of the RTG to the burning propellant of the launcher), and emergency re-entry in the atmosphere.

Estimating the RTG safety during emergency re-entry is the most complicated problem. Our approach to solving this problem is described in the present paper.

Normally, the structure of the radioisotopic heat unit (RHU) is designed to sustain the worst possible atmospheric re-entry conditions. If such an RHU structure cannot be developed, the problem becomes substantially more difficult and requires either calculation of the formation, fragmentation, and scattering of radioisotope particles in the atmosphere and multipoint deposition of particles onto the Earth's surface or, if the ampoule containing the radioisotope would be cracked or destroyed during the impact, estimation of the admissible level of radioisotope concentration on the ground with allowance for diffusivity, atmospheric turbulence, wind velocity, and sedimentation rate of aerosols. After that, the radiation hazard and the radiation level are evaluated. If these figures are within the legal norms, the RHU structure might be approved.

1. INTRODUCTION

This paper describes an approach to radiation safety of radioisotope thermal generators (RTG) and radioisotope heat units (RHU) for space applications, based essentially on methods developed and used in Russian space missions.

The approach is based on the use of essentially two restricting and normative documents: the UN principles on the use of nuclear power sources in outer space adopted in 1992 [1], and the Russian radiation safety norms (NRB-99) [2], which were prepared on the basis of recommendations of the International Commission on Radiological Protection (ICRP) and International Atomic Energy Agency (IAEA).

2. SCOPE OF ACTIVITIES

A defence-in-depth approach to safety is of paramount importance for space missions involving radioisotope power sources.

This paper describes first the identification of worst-case conditions by analysing all phases of an RHU/RTG containing spacecraft, from the launch pad to orbital disposal. In further steps the associated hazards are estimated. Realistic case studies then demonstrate the implementation of the approach.

In seeking the worst case of atmospheric re-entry from the viewpoint of the maximum radiation hazard[1], all phases of orbital insertion of an RTG-containing spacecraft have been examined: from the launch pad to the moment the spacecraft leaves the near-Earth orbit. Such an analysis has to be performed for those particular launchers and boosters that are planned to launch a real spacecraft with an RTG. These activities require large amounts of input information:

- Probability of launcher and booster failure for various reasons (complete absence of thrust, thrust lower than the nominal value, failure of the attitude control system, etc.) at all stages of orbital insertion;

[1] Probability of some hazardous radiation-induced effect on a person or his/her descendants

- Probability of fire or explosion of the launcher at the launch pad;
- Particular structures of the launcher, booster, spacecraft, and nuclear power source (size, thickness, position), list of all materials used and their properties, centres of mass, moments of inertia as functions of time, aerodynamic characteristics of the entire system and individual elements, etc.

We performed such an analysis for emergency re-entry and disintegration of the launcher stages, spacecraft, and RTG in the case of launcher or booster malfunction at different steps of orbital insertion. We also evaluated the probability of radioactive fuel release. If the radioactive fuel release was possible during the emergency re-entry, we calculated the formation of a cloud of fuel particles from a point source or a dust-forming source:

- From the moment the particles reach the equilibrium sedimentation state, the final size of fuel particles in the cloud and the cloud parameters are evaluated. For this purpose, extensive computational statistics of autonomous flight of particles with allowance for their heating, melting, and chemical interaction with components of the atmosphere, and fragmentation of melted particles (as random processes with certain laws of distribution of parameters) should be involved;
- The motion of the cloud formed and sedimentation of particles with allowance for the local wind pattern should be estimated;
- Propagation of radioactive aerosols in the surface layer, and the area and concentration of possible radioactive contamination of the Earth surface should be evaluated.

These calculations are very complex and time-consuming, and require large computation power. One computational variant for emergency descent requires approximately three months of activities even if complete information about the launcher, spacecraft, and launch programme is available.

These activities are not required during an advanced development stage. Therefore, based on previous experience, the radiation hazard is evaluated only for the worst emergency variants. It was verified that the worst variants of emergency re-entry occur in the case of booster failure.

3. HAZARD ESTIMATES AND RADIATION SCHEMES

Usually, the following two types of hazard are considered:

1. Hazard of a radiation accident, which is the probability of occurrence of a situation that can lead to radiation exposure of people or contamination of the environment above accepted legal norm levels;
2. Radiation hazard, which is the probability of occurrence of some hazardous radiation-induced effect for an individual or his/her descendants (health effects).

3.1 Radiation Accident Hazard

The radiation-accident hazard is determined as

$$R = p_{\text{re-entry}} \times p_{\text{area}} \times p_{\text{exp}}, \qquad (1)$$

where $p_{\text{re-entry}}$ is the probability of emergency reentry, p_{area} is the probability of incident on an inhabited area, and p_{exp} is the probability of exceeding the radiation dose above the norm.

The statistical data on launcher or booster failure yield $p_{\text{re-entry}} \approx 10^{-2}$. More specifically, the following design estimates were obtained for individual elements of a booster: the probability of engine failure is $p_1=6\cdot10^{-3}$ and the probability of control-system failure is $p_2=4\cdot10^{-4}$.

These estimations require some additional comments. RTGs usually have long development times, and during their design and development phases, most of the detailed required data are not available (on the spacecraft structure, RTG position, angle of inclination of the orbital plane, and moreover, the moment at which the launcher or the booster will fail).

The region of possible emergency incident of the RTG/RHU is not known *a priori*. Therefore, analytical activities are performed to obtain a conventional division of the Earth surface from the viewpoint of possible consequences of emergency incidence of the RTG (Fig. 1). The RTG is potentially hazardous if it enters the human habitat, which includes the infrastructure, the land-tenure system, and the water-supply system. The infrastructure is understood to be the territories visited by people every day: houses, gardens, shops, sources of water, workplaces, etc.

Without particular details of the analysis, Fig. 2 shows the probabilities of emergency incident of the RTG on the human habitat (p_{land}, p_{water}, and p_{infr} are the probabilities of incidents onto systems of land tenure, water supply, and infrastructure, respectively). The probability of incident p_{area} for a particular angle of inclination of the orbital plane is chosen on the basis of Fig. 2.

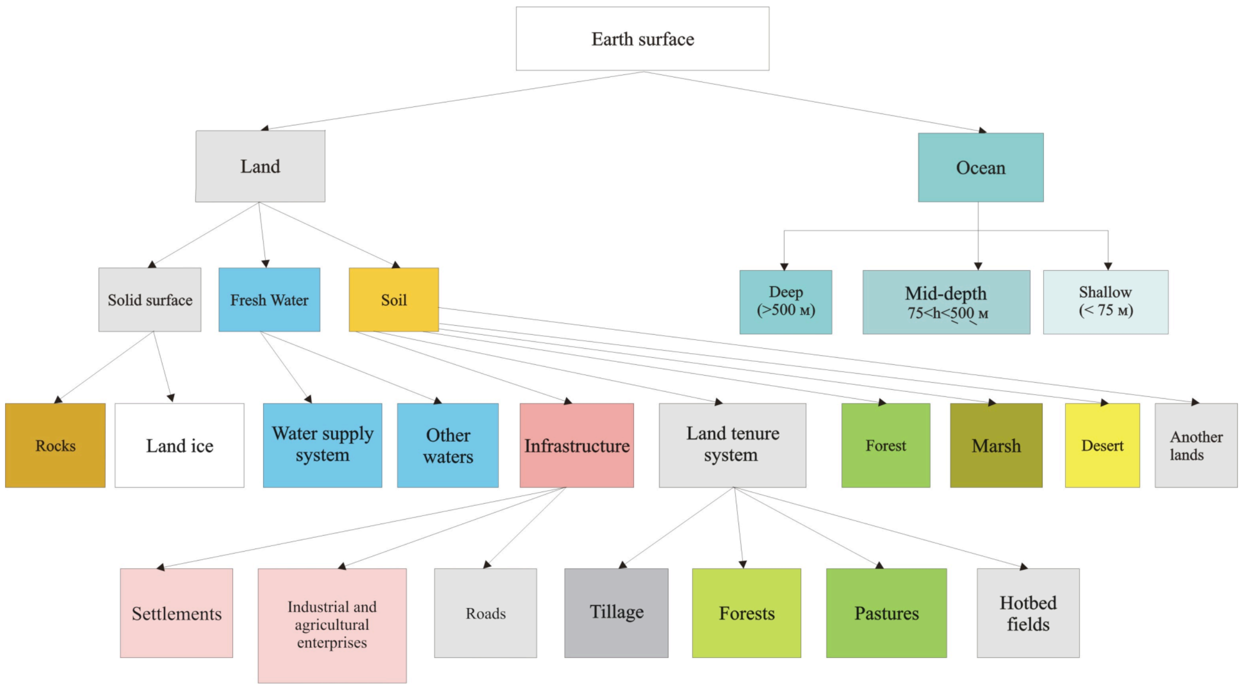

Figure 1: Conventional ficision of the Earth surface

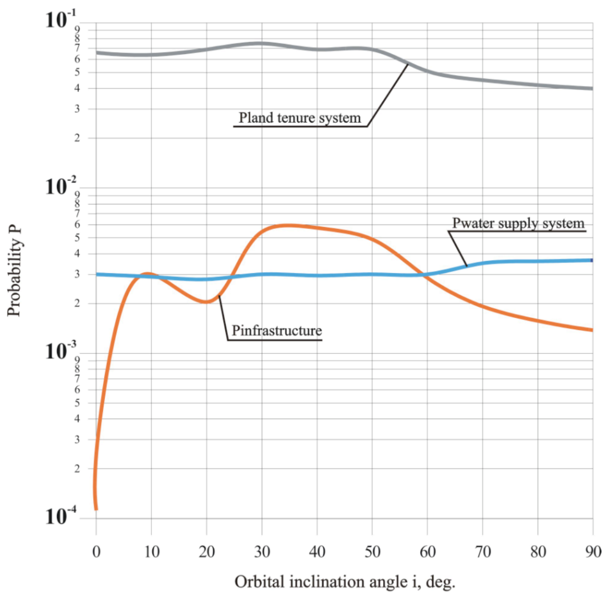

Figure 2: Probability of incident into human inhabited areas

The parameter p_{exp} is a quantity to be calculated for each particular source of radiation. The amount of calculation needed is especially large if it is necessary to estimate isotope burning during the emergency descent, formation of the dusty wake of particles, afterburning of particles, and deposition or expansion of the cloud of particles.

Another labour- and time-consuming case is isotope propagation in the near-Earth layer for the case that the isotope-containing shell is cracked/broken by the impact with the Earth's surface. The radiation hazard can turn out to be acceptable in this case, but a large number of numerical and experimental activities are needed to determine and validate this hazard.

Therefore, it is desirable to have an RHU structure such that the isotope-containing ampoule retains its integrity under the worst conditions of emergency descent and impact with the Earth's surface. Possible radiation is calculated for two radiation scenarios:

1. exposure from a distance of 1 m over 24 hours until the RTG is rescued by the search personnel, if the RTG is accidentally discovered by the population;
2. exposure from a distance of 10 m over one year if the RTG is found and the search terminated.

3.2 Radiation Hazard

The radiation hazard takes into account the consequences of irradiation of human beings, i.e. the health effects.

Determining the maximum value of the individual radiation hazard, and hence using appropriate simplifications, we obtain the expression for the maximum radiation hazard under stochastic radiation [2]

$$R_{\max} = p_{\text{reentry}} \times p_{\text{area}} \times Q \times T \times r_E \times \frac{1}{L^2} \quad (2)$$

where p_{reentry} and p_{area} were defined previously, Q [Sv/h] is the effective dose rate at a distance of 1 m from the source, T [h] is the time of the possible action of the dose, L [m] is the distance from the source of radiation, and r_E is the hazard coefficient, which takes into account health damage in the form of reduction of adequate lifetime on average by 15 years per stochastic effect (e.g. cancer or severe hereditary diseases).

The safety norms [2] define the following limits for exposure of population:

$r_E = 7.3 \cdot 10^{-2}\ 1/_{\text{man-Sv}}$ for $E < 0.2$ *Sv/year*;

$r_E = 1.5 \cdot 10^{-1}\ 1/_{\text{man-Sv}}$ for $E \geq 0.2$ *Sv/year*

(E is the individual effective dose rate).

4. HAZARD ESTIMATE PROCEDURE

The first objective is to create an RTG structure that retains the integrity of the isotope-containing ampoule with a sufficiently high degree of confidence under the worst variants of re-entry and impact with the Earth's surface, not releasing the isotope under any foreseeable conditions. In this case, it is possible to estimate the radiation hazard by assuming a point source in the form of a sealed ampoule containing the isotope.

For the case that it is technically not possible to create an RTG structure that retains the integrity of the isotope-containing ampoule in the worst variants of re-entry and impact onto the Earth surface, the hazard of possible exposure of population will have to be estimated under conditions of local release of the isotope and be compared with radiation safety norms, i.e., the problem will become much more complicated.

If the so calculated radiation hazard for the worst-case conditions does not satisfy the norms, the RHU structure is rejected.

The following procedures are used to estimate the radiation safety of the RTG during its emergency re-entry:

- Computational analysis of booster operation in emergency situations to find the initial parameters of the worst variants of atmospheric re-entry. The worst variants are understood as re-entry trajectories on which the RTG/RHU experiences the highest thermal and mechanical loads.
- Computation of centred and mass-inertial parameters of the spacecraft, its elements, RTG, and RHU. Choice of thermophysical properties of materials.
- Computation of aerodynamic characteristics of the spacecraft, its elements, RTG, and RHU for all flow regimes from free-molecular to continuous.
- Computation of descent ballistics and dynamics, normally, for the autonomous descent of the RHU, following the "worst-case" principle, computation of the corresponding parameters for the worst re-entry variants (heat flux at the stagnation point, dynamic pressure, etc.).
- Determination of the laws of distribution of heat fluxes over the surface of the descending object with allowance for dynamics of motion around the centre of mass, i.e. determination of local heat flux coefficients needed to compute the thermal state of the object.
- Definition (theoretical or experimental) of criteria of retaining the isotope-containing ampoule integrity during its descent (heating) and impact with the Earth's surface.
- Computation of temperature fields during the descent. Analysis of the isotope-containing ampoule integrity.
- Computation of temperature fields before the impact with the Earth's surface and determination of the impact velocity.
- Computation of the impact and analysis of the isotope-containing ampoule integrity.
- Estimation of radiation hazards and comparison with legal norms.

The last point can have two variants:

- computation of radiation hazards for an intact isotope-containing ampoule.
- Computation of radiation hazards for an isotope-containing ampoule that lost its integrity.

The second variant has two subvariants. In the first subvariant, the ampoule is destroyed during its descent. This is possible in the case of re-entry with a high velocity because of malfunction of control at the acceleration part of a fly-by trajectory. It is necessary to compute the formation of nuclear fuel particles in the atmosphere, motion, fragmentation, and afterburning of particles, and the expansion of the cloud of particles. For this purpose, one uses a code that describes the physical essence of phenomena and defines the initial data as a set of random quantities. Using a generator of random numbers (e.g. the Monte Carlo method), we ensure N implementations of the descent of the cloud of particles, which yields a statistically reliable histogram of the size distribution of particles in the cloud and the deposition area. After that, the radiation hazard is estimated.

In the second subvariant, the isotope-containing ampoule loses its integrity after the impact with the Earth's surface. Then it is necessary to estimate the near-Earth concentration of the isotope from a continuous point source, while taking into account the radioisotope release rate (mSv/h), with allowance for diffusivity, atmospheric turbulence, wind velocity, aerosol sedimentation rate, etc. We compute the volume concentration of the isotope at various distances from the source and estimate the radiation hazard.

5. EXAMPLES OF RADIATION SAFETY ESTIMATES

The number of results computed for radiation safety estimates for RTG/RHU emergency descent is too large to be described in one paper, so we give only some examples of radiation safety estimates for an RTG design delivering 1 W_{el} under study under the agreement No. 03-53-4490 INTAS-CNES [3] as well as for a potential high-power RTG delivering several 100 W_{el} [5].

Ideally, an RTG/RHU structure is designed to retain the integrity of the isotope-containing ampoule under conditions of the worst variants of descent and impact onto the Earth surface. **The worst case method** [4]:

- simplifies computations and almost excludes erroneous results in safety estimates and
- takes into account (normally exceeds) tolerances of physical quantities (e.g. material properties) and computational errors.

The worst re-entry variants for the case of booster malfunction (incorrect thrust vector) are estimated by means of multiple ballistic computations with a nominal magnitude of the thrust vector directed toward the Earth under different angles to the local horizon. The specific heat flux and the heat-flux integral over the descent time are evaluated for the resultant set of trajectories.

Two re-entry variants are sought among this set of trajectories: one with the maximum specific heat flux and one with the maximum integral heat imparted to the object during its descent. These two variants are taken as a basis even though the probability of each of these two variants is less than one hundredth of the probability of other variants.

In addition, the emergency descent of an RHU rather than an RTG within the spacecraft is considered. This increases the assumed maximal thermal load on the RHU and adds additional safety margin to the design.

P_{area} is a function of orbit inclination i. For example, for i = 5°, P_{area} is equal to $6.5 \cdot 10^{-2}$ (see Fig. 2).

The sealed ampoule containing the isotope for a low-power RTG (1 W_{el}) [3] has a total radiation intensity at a distance of 1 m equal to 11.5 μSv/h. Then, for the first radiation scenario (L =1 m and T = 24 h), the dose is approx. 0.3 mSv, after which the RHU should be rescued. For the second radiation scenario (L=10 m and T =1 year = 8760 h), the dose is 1.0 mSv, i.e. in both cases, the dose does not exceed the norm of 1 mSv/year.

Thus, for the RHU structure that ensures the integrity of the sealed isotope-containing ampoule under conditions of the worst variant of descent and impact with the Earth's surface, the probability of exceeding the radiation norm is $p_{\exp} = p_{RHU} \rightarrow 0$, where P_{RHU} is the probability of destruction of the isotope-containing ampoule. Obviously, $P_{RHU} \neq 0$, but this quantity tends to zero in accordance with the worst-case theory. **The radiation accident hazard** in this case is

$$R = p_{reentry} \times p_{area} \times p_{\exp} \rightarrow 0.$$

The **maximum individual radiation hazard** for the first scenario (T=24 h and L=1 m) is

$$R_{\max} = p_{\text{reentry}} \times p_{\text{area}} \times Q \times T \times r_E \times \frac{1}{L^2} =$$
$$= 10^{-2} \times 6.5 \cdot 10^{-2} \times 11.5 \cdot 10^{-6} \times 24 \times 7.3 \cdot 10^{-2} \times 1$$
$$= 1.3 \cdot 10^{-8}$$

For the second scenario (T=1 year = 8760 h and L=10 m), $R_{\max} = 4.78 \cdot 10^{-8}$. Thus, such an RTG of 1 W_{el} can be considered as safe under all foreseeable conditions.[3]

If we consider a high-power RTG delivering some 100s W_{el} [5], and operating on Pu-238, the dose rate at a distance of 1 m from such an RTG is approximately Q = 0.65 mSv/h. For such a source of radiation, the maximum individual hazard for the first scenario of radiation exposure (T = 24 h and L=1 m) would be $R_{max} = 0.74 \cdot 10^{-6}$. For the second scheme of radiation, the radiation hazard would be $R_{\max}$ = $2.7 \cdot 10^{-6}$.

If such a source (even with the isotope-containing ampoule retaining its integrity) re-entered, this should be considered as a radiation accident. It would be absolutely necessary to find and rescue the RTG in a timely manner before the total accumulated dose might exceed radiation dose limits.

6. CONCLUSIONS

An approach to radiation hazard and safety for spacecraft with radioisotope power sources on board is presented, based on international norms, Russian experience and national Russian regulations.

Radioisotope power sources are generally designed to maintain their integrity and not release any radioisotope under all foreseeable worst-case scenarios.

It can be concluded that:

1. If after the worst variant of emergency incidences, the radiation dose from a sealed ampoule containing radioisotopes does not exceed radiation exposure limits (e.g. 1 mSv/year effective dose for the general public) and the radiation hazard is lower than the norm, such a situation need not be considered as a radiation accident. The RTG structure satisfies radiation safety requirements, but the source of radiation should be found and rescued.

2. If the effective radiation dose from a sealed ampoule containing radioisotopes after the worst variant of emergency incidence might exceed radiation protection dose limits, but the radiation hazard is lower than the norm, such a situation should be considered as a radiation accident. The source of radiation should be found and rescued, but the RTG structure could still satisfy the radiation safety requirements in case the risk of exceeding the radiation protection dose limits is extremely low.

7. REFERENCES

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