
Safety of radioisotope power sources for space missions

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Abstract:

Nuclear power sources (NPS) have been widely used in space missions. They are needed for deep space missions to the outer planets as well as many kinds of planetary surface missions. At present, launches with NPS onboard can be carried out by the U.S. and Russia, as these countries have established a corresponding safety framework and approval process. A European nuclear safety approach would be a prerequisite for the launch of future European missions with NPS on board from the Guyana Space Center in Kourou. Within this context, a study for outlining the possibilities for a “European Space Nuclear Safety Framework” (ENSaF) has been carried out by co-operation of members from space industry, nuclear industry and four European TSOs. Some of the main results consist of the outline of a viable safety evaluation approval process with international participation on the European level. The foundations for corresponding nuclear safety goals which account for specific hazards of a space mission with NPS on board are also presented.

1 INTRODUCTION

Nuclear power sources (NPS) have been widely used in space missions over the past decades. In principle, NPS can be divided into two classes:

- Nuclear fission reactors for propulsion and power supply
- Radioisotope thermo-electrical generators (RTG) and radioisotope heat units (RHU)

While nuclear fission reactor technology is not used in current research space activities, radioisotope heat and power sources are playing an essential role in many ongoing and planned missions. This contribution will refer to the latter kind of NPS.

Radioisotope thermo-electrical generators (RTG) and radioisotope heater units (RHU) have been extensively used in U.S.A., Soviet and Russian space missions. For example, NASA deep space missions Galileo, Ulysses, Cassini and New Horizons have relied or still are relying on RTG as power sources. Apart from deep space missions to Jupiter and beyond, radioisotope heat sources have been used in planetary surface missions to maintain functions of surface probes and equipment under extreme temperature conditions. As an example, the Mars rovers of recent NASA exploration programs employ RHUs for maintaining sensitive electronic parts at proper temperatures while electrical power is provided by solar panels.

While the use of RTG and RHU for many types of space missions seems indispensable for the near future, there are some safety aspects which are unique to the use of such radioactive sources, as they are operated in extremely hazardous environments. In particular, this is the case during launch and early flight phase of a spacecraft with NPS on board. A proper safety approach for licensing of NPS use in spacecrafts and launch approval

which accounts for the special hazards is thus essential. While a framework for licensing and approval of such launches has been established in Russia and the U.S.A., there is no possibility to launch European missions from the Guyana Space Center in Kourou at present. Consequently, all European missions employing NPS would need to be launched under U.S. or Russian control at the moment.

Europe therefore would need to develop its own capacity for carrying out space missions employing NPS from Guyana Space Center in Kourou. The establishment of a proper technical, administrative and legal framework would have to deal with all issues related to the development, transport, handling, inspection, launch, use and disposal of NPS.

Within this context, a study for outlining possibilities for a “European Space Nuclear Safety Framework” (ENSaF) funded by the European space Agency (ESA) has been carried out in which members from space industry, nuclear industry and four European Technical Safety Organizations (TSOs) worked together. One of the tasks focused on the drafting of general space nuclear safety goals which could provide a reference in the safety review and approval process.

This paper addresses the specific safety issues associated with the use of NPS in space missions and gives an overview over the safety approach including safety goals and criteria which could be used on the European level.

2 TYPES OF RADIOISOTOPE SOURCES FOR SPACE MISSIONS

Radioisotope power sources for space application are mainly based on Plutonium 238 in oxide ceramic form as heat source. Pu-238 combines a high output of thermal energy from its decay with a half life sufficiently long for space missions in which a service lifetime of several years is required. Being predominantly an emitter of alpha particles (with some low gamma and neutron background due to impurities), shielding of Pu-238 sources can be provided without heavy structures. Moreover, high thermal power density is achievable by Pu-238 heat sources. The most important material properties of Pu-238 are summarized in the table below.

Material Properties of Pu-238	
Specific activity [TBq/g Pu-238]	0.63
Half-time of decay $T_{1/2}$ [a]	87.7
Specific thermal power P_h [W/g Pu-238]	0.5
Ratio activity/thermal power [TBq/W]	1.26

At present, RTG and RHU designed for space missions stem from U.S. and Russian production. An example for a powerful RTG from U.S production is the one used for the 1996 Cassini Mission to Saturn. It is shown in Figure 2.1

The radioisotope content of such an RTG is contained in 18 modules. Each of these so-called General Purpose Heat Sources (GPHS, Fig. 2.2) contains about 600 g of PuO₂ with 69% Pu-238, about 14,5% other Plutonium isotopes, 4,5% actinide impurities and about 12% Oxygen.

In total, the RTG produces about 3.8 kW thermal power at the beginning of its design lifetime which is converted into 290 W electrical power by thermoelectric conversion. Its total weight is about 56 kg at a length of 1,14 m. The total content of radioactive material is 10,9 kg PuO₂ with an activity of about 4900 TBq (132500 Ci).

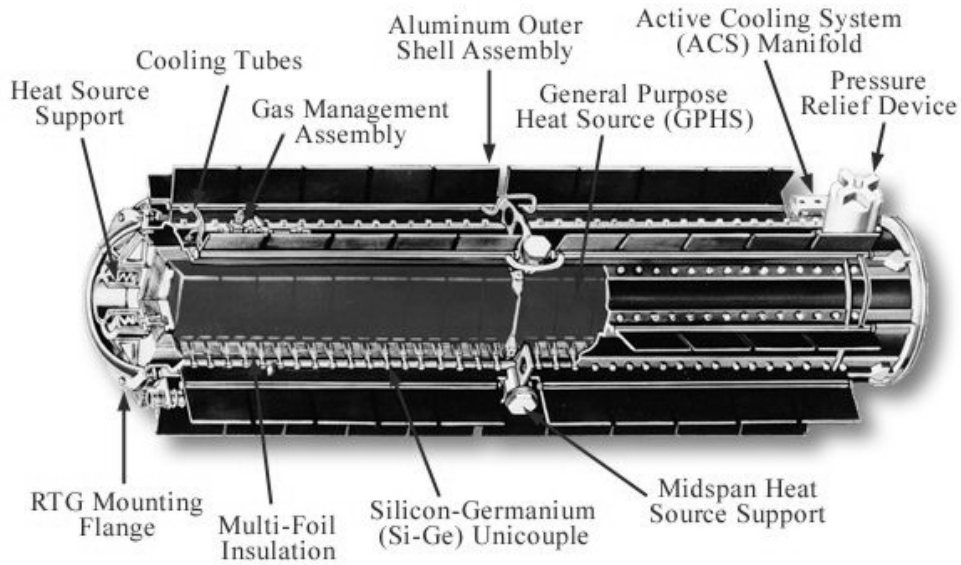


Fig. 2.1: RTG from U.S. production used for Cassini mission. Image source: U.S Department of Energy.

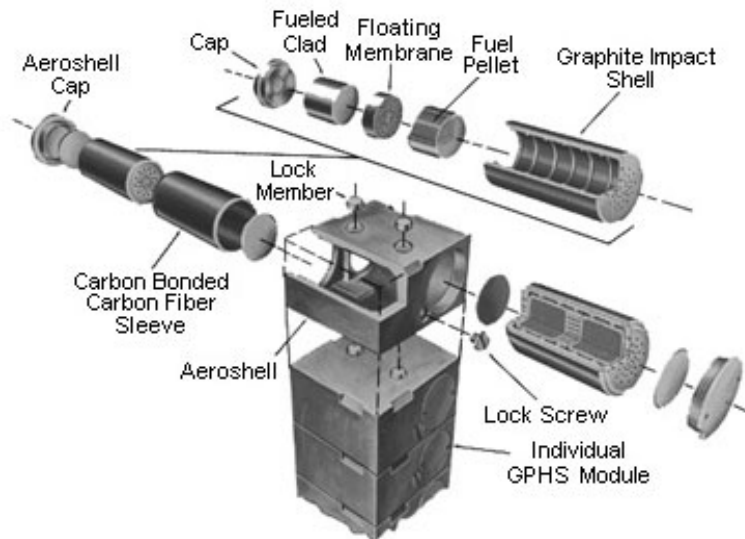


Fig. 2.2: General Purpose Heat Sources (GPHS). Image source: U.S Department of Energy.

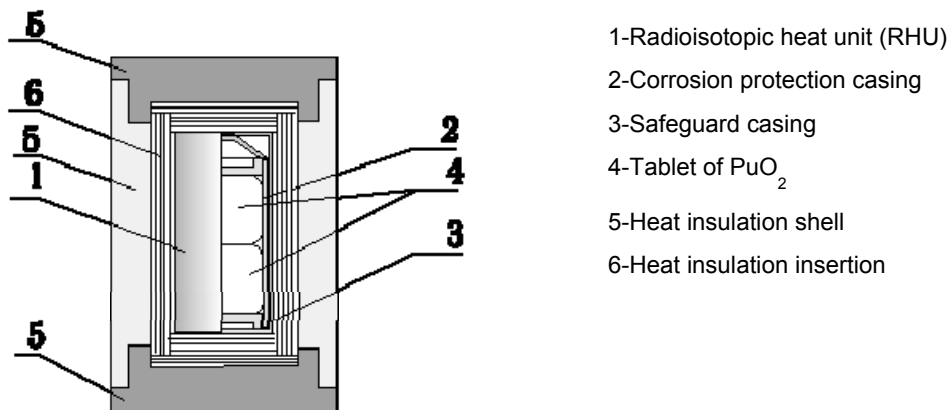


Fig. 2.3: "Angel" RHU from Russian production. Image source: BIAPOS.

Another example for a smaller RTG/RHU module is given in Fig. 2.3. This Type of RHU/RTG is produced in the Russian Federation. This RHU contains up to 23 g PuO₂ with a total activity of 9.6 TBq, producing about 8.5 W thermal power. It can also be used together with a thermoelectric converter as RTG with electrical power of up to 1 W.

3 SPECIFIC SAFETY ASPECTS FOR NPS USED IN SPACE MISSIONS

During their life time, NPSs undergo a lot of handling procedures which are comparable to the use of sources for other practices. Those activities are covered by existing safety requirements for such sources in general. There are, however, some safety aspects which are unique to the use of NPS in space missions.

3.1 Specific hazards to the use of NPS in space missions

Unique safety aspects are associated with the proximity of the radioactive material to hazardous substances in the pre-launch phase, during launch and early flight phase. The probability for a failure of the launcher with subsequent accidental conditions imposed on the NPS is relatively high compared to other activities with radioactive sources. Specific hazards for the use of NPS in space missions may be associated with the following events (e.g. cf. [1]):

- Falling of payload from the launcher followed by explosion/fuel fire
- Falling of launcher from launching pad followed by explosion/fuel fire
- Mechanical impact followed by fuel fire after failure in launching phase
- Accidental reentry from suborbital or orbital flight path

Such events may be associated with extreme loads such as:

- Explosion overpressure
- Fragment impact at very high velocity
- Fuel fire (e.g. up to more than 3000°C if exposed to solid propellant fuel)
- Friction heat upon accidental reentry
- Mechanical impact on ground after reentry
- Long-term exposure to corrosive environment (e.g. submersion in sea water)

The design of NPS for space mission has to withstand these loads so that releases of radioactive material can be prevented with a high degree of confidence. However, according to environmental impact assessments for past U.S. missions (e.g. [1]), event sequences which can lead to significant release of radioactive material cannot be ruled out completely. For these sequences, the need and feasibility of measures to reduce their probability as well as to reduce the consequences should be considered.

3.2 Safety design features of present RHU/RTG technology for space missions

RTG and RHU for space missions are designed to withstand extreme accidental conditions during launch and in the first flight phase. In order to withstand such conditions, multiple barriers exist to prevent the radioactive material from being spread into the environment.

- The first barrier consists of the ceramic PuO₂ matrix, which has low solubility in water, high melting point and is designed to fracture into large, non-respirable parts upon mechanical impact.

- The second barrier consists of a metallic cladding (often Iridium) with low chemical reactivity, high melting point and high resistance against breakup by mechanical impact.
- The third barrier consists of the graphite impact shell, often reinforced by carbon fiber and designed to absorb mechanical and thermal loads during reentry, impact and fire exposure.

Another important design feature is the modular structure of larger RTGs. In case of accidental reentry, the structure disintegrates into modules with small dimensions and weight in order to minimize terminal velocity and surface heating.

3.3 Safety-related measures for accidents with possible releases

For some event sequences, the possibility of significant releases cannot be excluded by virtue of the source design. For example, in the pre-launch and early launch phase, accidents with mechanical impact due to failure of the launcher on or near ground and subsequent exposure to propellant fuel fire could lead to significant release of PuO_2 . In order to reduce the probability of such a scenario, in some missions ejection mechanisms are foreseen to separate the spacecraft with NPS from the launch vehicle and eject it to some distance from the assumed positions of larger amounts of propellant fuel [1].

Another case in which releases cannot be totally avoided is the impact on hard surfaces after accidental reentry. Experiences with accidental reentry of satellites containing nuclear or radioactive material show that emergency planning for such an event is of pivotal importance for space missions using NPS. For this reason, IAEA has issued detailed guidance on this subject [2]. International regulations on notification, consultation and assistance to states on case of reentry of a space object with NPS on board are stipulated in a resolution by the United Nations [3].

4 SAFETY EVALUATION AND APPROVAL OF MISSIONS WITH NPS ON BOARD

In the U.S. and the Russian Federation, safety evaluation and approval processes are well established in corresponding legal and regulatory frameworks. The roles and contributions of each actor (e.g. the applicant for approval, the provider of the source, the nuclear safety authority which issues the approval and the institutions which evaluate the safety report) within the process are clearly allocated. The whole process is implemented and carried out on the national level of the launching state.

4.1 Perspectives for an approval process on the European level

Unlike in the U.S.A. and Russia, there is no European competent authority which could grant or deny permission to use NPS on the European level. Instead, production, handling and transport of the NPS up to integration into the spacecraft and launcher would be subject to the different national licensing and approval schemes in the country where the respective activity takes place. The approval decision would rest with the respective national competent authority. This also holds for activities which are unique to the use of NPS in space missions. Hence, approval for a launch with NPS on board from the radiological point of view would be subject to the decision of the respective national competent authority of the launching state (i.e. France for launches from Guyana Space Center in Kourou) and the application and approval process would have to satisfy the national regulations.

At the same time, safety-relevant activities which are specific to the use of NPS with significant activity contents in space missions and their associated hazards should include proper involvement of all European nations participating in the respective space mission, as the successful accomplishment of such a mission depends on the consensus of the participating states on the use of NPS. Still, the safety regulations of the launching state provide the mandatory basis and the national nuclear safety authority plays a central role in the approval process. In particular, the ultimate decision on launch approval will stay with the national authorities.

One option to include participating nations in the approval process would be to do the safety evaluation with international participation. Such an approach would be based on international involvement in the preparation of common safety reviews and in the discussions and preparation of common recommendations in the course of safety evaluation. This approach would have the advantage that the national competent authority could refer in its decision on an internationally coordinated and coherent review process.

The TSOs of the participating European countries could contribute to the safety assessment in a common working group. Given the considerable variety of different national standards and criteria for safety evaluation, a common reference of safety goals could provide a useful basis for the work of such a group.

4.2 General Space Nuclear Safety Goals as a common reference for safety assessment

The specification of general space nuclear safety goals (GSNSG) could be helpful to support the participation of different European authorities, TSOs and other experts in the review and commenting on safety documents provided by the applicant for the use of NPS within the approval process. For safety documents to be provided in the safety review process, GSNSG could establish a reference which may be used supplementary to existing regulations.

For defining the scope of GSNSG, it can be assumed that all protection against normal exposure as well as protection of workers are subject to existing regulations by the IAEA as well as on the European and national levels. Likewise, accident prevention and mitigation for all activities which are not specific to the use of NPS for space missions are covered by existing safety requirements. The scope of GSNSG should thus be restricted to the protection of the public and the environment against potential exposure in accident situations which are related to specific hazards as described in subsection 3.1.

In general, GSNSG should reflect a safety level which is comparable to the degree of safety required for other practices involving radioactive sources. However, comparability is not easy to achieve for the following reasons:

- Common nuclear safety goals usually refer to long-term operation of facilities with radioactive material, while a launch of a space vehicle with NPS on board is a short-term event isolated in time.
- In particular, probabilistic acceptance criteria used in nuclear regulations usually employ event frequencies which are often expressed by the (estimated) number of events per operation year. In contrast, probabilistic figures and acceptance criteria for space missions are normally expressed by number of events per mission. Moreover, probabilistic criteria do not always fit into the framework of national regulations.
- Deterministic criteria are in turn often used to require and evaluate adequate protection against a certain group of well-identified hazards. However, with respect to use of NPS in space, many hazards are mission-specific and have to be identified on a case-by-case basis.

Therefore, it seems reasonable to outline GSNSG in qualitative form based on common international safety principles. On this basis, it will be possible to check options for quantification based on internationally acknowledged regulations (which exist in particular for transport of radioactive material) or recommendations by the IAEA and/or the ICRP. By this, optimum comparability of GSNSG with safety objectives in other fields of nuclear activity can be obtained.

4.2.1 Qualitative Description of General Space nuclear Safety Goals

As stated above, the specification of GSNSG should cover accidental states of the NPS which could specifically caused by their use in space missions. Like in other nuclear fields, a distinction between design basis accidents (DBA), and credible accidents beyond the design basis can be applied. For these two types of accidental states, GSNSG could be formulated in the following way:

GSNSG for design basis accidents (DBA):

- A release of radioactive material is prevented or limited by virtue of the design of the source and/or other relevant safety systems.
- It is demonstrated that either no release of radioactive material or only minor radiological consequences can occur.
- In particular, there is no need for emergency protective actions for the population such as sheltering or temporary relocation.

GSNSG for accidents beyond the design basis:

- Probability of accident is kept acceptably low.
- Reasonably achievable countermeasures are provided to mitigate radiological consequences.
- Accidents with potential early health effects are excluded with sufficient confidence.
- There is limited necessity for incisive emergency protective actions such as evacuation or permanent resettlement.

4.2.2 Options for further specification of acceptance criteria for DBA

The prime task for criteria for DBA would be to specify technical testing and qualification requirements with respect to the thermal and mechanical loads against which a source design would have to withstand. These criteria would typically include a combination of mechanical impacts, fire intensity and fire duration as well as long-term effects of adverse environmental conditions (e.g. by immersion in sea water).

Technical design criteria should account for the maximum level of safety which is reasonably achievable according to the state of the art. In order to include opportunities from ongoing technical progress and to account for mission-specific variations of relevant mechanical and thermal loads as well as types of NPS used, technical design criteria should be specified with respect to the individual mission and NPS used rather than generically prescribed for all missions in the near future.

In addition, radiological design criteria could be applied for limitation of potential exposure by virtue of the protection of the source and possibly other safety systems employed in cases where the integrity of the source cannot be achieved. In such situations, the design of the source should contribute to the limitation of the release of radionuclides (for example by virtue of the physical and chemical properties of the radioisotope matrix). One internationally

acknowledged reference for radiological assessment and corresponding criteria is given in the IAEA transport regulations [4].

4.2.3 Options for further specification of acceptance criteria for accidents beyond the design basis

Effective protection against accidents beyond the design basis is typically sought by safety measures which reduce their probability of occurrence. It will therefore be necessary to include probabilistic argument in order to evaluate the adequacy of provision against such accidents. Probability of accidents beyond the design basis should be kept acceptably low in order to provide a degree of safety equivalent to those common for other practices in the nuclear field.

The evaluation of radiological consequences for accidents beyond the design basis could be based on individual health risk. It could also include the consideration of the necessity and extent of emergency protective measures based on internationally accepted intervention levels. For example, an objective for the safety evaluation of future NPP is that incisive intervention measures such as evacuation or permanent relocation should not be required for larger parts of the public after an accident beyond the design basis [5]. An analogous safety objective could also be used in assessment of severe accidents in space missions and quantified by comparison with respective intervention criteria.

5 CONCLUSIONS AND OUTLOOK

Today, there seems to be no practicable alternative to power and/or heat supply by NPS neither for deep space missions to the outer planets nor for many kinds of planetary surface missions. Europe would need its own nuclear safety framework for the launch of missions with NPS on board in order to carry out its own independent programs in this area of space research. Within this context, possibilities for a “European Space Nuclear Safety Framework” (ENSaF) have been studied.

The drafted outline of an optional scheme for an approval process focuses on safety-relevant activities which are specific to the use of NPS in space missions and their associated hazards from accidental situations. For such an approval process, the requirement of international participation is assumed while the safety regulations of the launching state still provide the mandatory basis. International participation could be implemented in the safety evaluation process, while the ultimate decision on approval will rest with the competent national authority.

For a review process with international participation, General Space Nuclear Safety Goals (GSNSG) could provide a proper reference. Such goals have been sketched in qualitative form and could be further specified by quantitative criteria in subsequent studies.

The drafted approval process as a whole will depend on consensus by the launching state (i.e. France for launches from Kourou) as well as by the nations participating in such a mission on the European level. Such a consensus would ideally include the relevant organs of the European Space Agency (ESA), the European Union, national competent authorities, TSOs and industries in the nuclear and space technology fields. Given a broader acceptance and support by the actors involved, a distinct allocation of roles and responsibilities within the process would be the next step to implement such a framework.

6 REFERENCES

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