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Implementation of the guidelines from the international safety framework for nuclear power source applications in outer space for ESA space missions - Preliminary Nuclear Launch Safety Authorisation Process (NLSAP)

Conference room paper submitted by the European Space Agency (ESA)

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I. Toward the first European RPS (Radioisotope Power System) development and mission

Since 2009 ESA is developing technology, processes and capabilities in the field of radioisotope power sources based on Americium Oxide (Am241) as source isotope, identified as an attractive alternative to the use of Plutonium-238 (Pu238).

In 2018, the development of a RPS launch capability from French Guiana Space Centre started under the title "Launch Safety and Authorisation Process" (LSAP) with a strong emphasis on building a robust nuclear safety objectives and methodology demonstration, in close collaboration with the French Space Agency CNES.

ESA Member States decided at the ESA Council Meeting at Ministerial level in November 2022, to start a technology development component as part of the ESA General Support Technology Programme (GSTP), titled ENDURE (EuropeaN Devices Using Radioisotope Energy). It aims to develop Am241 based RHUs compatible with the planning for the Rosalind Franklin mission to be launched in 2028 from the United States of America, and a European lunar mission to be launched in the early 2030s from French Guiana. The project thus aims at developing a nuclear safety process compatible with both the US and European nuclear launch safety requirements.

* A/AC.105/C.1/L.412.

The methodology is addressing for each component of the Launch System their technical Nuclear Safety contributions to ensure the Nuclear Safety objectives of the space mission (the Radioisotope Power Source design & definition, the spacecraft, the Ariane 6 launcher, and the launch base). Such approach aims at building a robust authorization framework with the relevant Nuclear authorities, complying also with the ESA's Fundamental Safety Objective as specified in the ESA safety policy on the use of nuclear power sources, which is to protect people and environment in Earth's biosphere.

II. Specific regulatory framework of Nuclear Power Source (NPS) space missions

The ESA safety policy on the use of nuclear power sources has been issued in 2018 as ESA/ADMIN/IPOL-INSR (2018)1, as reported in document (A/AC.105/C.1/2019/CRP.10). The ESA Space Transportation safety framework for NPS space applications has been drafted, based on the guidance provided in the Safety Framework for Nuclear Power Source Applications in Outer Space and using best practices reflected in the national safety frameworks of states with experience in using space NPS. The U.S. regulations, expertise and standards are constituting important benchmarks for this task.

The first European missions with RPS are foreseen to be launched from Europe's spaceport in French Guiana. From 2018, preliminary contributions from LSAP activities have contributed to the preliminary nuclear safety Launch objectives and methodology in complement to the ESA safety policies and standards.

The preliminary nuclear safety process to authorize a RPS launch from Europe is considering the following alternative application situations, listed in order of preference and priority:

(a) Development of a new RPS, based on Americium Oxide source isotope (Am241), aiming at delivering an end-to-end autonomous European operational capability,

(b) Use of an existing RPS (Am241 or Pu238) from international providers,

(c) Design of a European RPS based on Pu238 radioisotope.

The Nuclear Safety launch process presented below is focusing on the application case a), the development of a new RPS.

III. Nuclear Safety methodology for a launch with a new design RPS

The preliminary European nuclear safety process is performed through a combination of deterministic and probabilistic objectives, to be implemented for a launch from the European Launch Space Centre in French Guiana. It relies on:

- Demonstration that the rationale for the use of space nuclear power source application has been appropriately justified, assessing the risks towards population and the environment. For this reason, space RPS missions should ensure that the rationale for each space RPS application considers alternatives and is appropriately justified.
- Implementation of the principle of "defence in depth" which takes into account the occurrence of technical and human failures and the definition of four defence lines to face these failures and to mitigate their consequences (prevention of incidents, monitoring and recovery actions, consequences mitigations, and management of accidental situations).

- Interposition of nuclear safety barriers between radioactive materials inside RPS and workers, public and environment. Depending on studies of hazard sources that may jeopardize the identified safety barriers, nuclear safety functions are defined to ensure the safety of the subsystems involved in the launch system.

The deployment of the methodology all along the development of the space mission is sequenced as follows:

(a) Definition of Nuclear Safety Objectives at mission level,

(b) Identification and classification of the Representative Accidental Scenarios by a preliminary risks assessment from the Launch and its concept of operations,

(c) Characterisation of the accidental environments of the accidental sequences,

(d) Allocation of the nuclear safety requirements to each subsystem,

(e) Build-up of a nuclear safety demonstration plan at system and subsystem levels,

(f) Demonstration of the “as designed” system nuclear safety performance for the systems,

(g) Demonstration of the “as built” system nuclear safety performance for the Nuclear Safety flight authorization.

a. Fundamental Nuclear Safety Objectives for the targeting envelop mission

In order to capture the fundamental Nuclear Safety Objectives into operative engineering requirements, nuclear safety goals are defined according to the mission as followed:

- Quantify radioactive objectives to determine tolerable thresholds of injury to workers and the public health.
- Set of acceptable radiological dose rate limits regarding the occurrence probability of situations or radiological dose rate limits regarding accidents categories (normal, incidental, accidental, or beyond design).
- Define qualitative nuclear safety objectives as high-level principles: justification principle of the use of RPS, application of the As Low As Reasonably Achievable (ALARA) principle, criticality risk as uncontrolled chain reaction, and management of accidental situations.

b. Identification and classification of the Representative Accidental Scenarios (RAS)

The system risks analysis consists in characterizing, for each life cycle phase of the launch and orbital mission, risks induced or aggravated by RPS that could result in non-compliance with the Nuclear Safety Objective.

On ground the risk assessment is similar to the ones performed for any other nuclear installation, including nuclear specific risks such as e.g., dispersion of radioactive materials, exposure of workers and public, nuclear criticality risk.

The risk analysis during launcher flight phases and spacecraft mission until for instance lunar capture focuses on all accidental scenarios which may result in the fall back to Earth of radioactive materials, either inside RPS with intact containment barriers or after the loss of physical integrity of containment barriers of the RPS.

This analysis aims at defining accidental scenarios that could occur during the mission life cycle phases and which may have an impact on RPS, their potential triggering events, and their potential effects on RPS in terms of load environments.

Then nuclear safety Representative Accidental Scenarios (RAS) are identified by grouping together accidental scenarios that may have similar effects on RPS i.e., that may result in similar RPS accidental environments sequences. Each RAS is then characterized by the most sizing accidental sequence for RPS among all possible sequences resulting from RAS-related accidental scenarios.

The Representative Accidental Scenarios are classified according to the different possible categories of operating situations defined by the Nuclear Safety Objectives (normal, degraded, accidental, aggravated accidental, or excluded).

c. Characterisation of the accidental environment sequences

For each accidental scenarios a worse case analysis of the accidental sequence is performed in order to quantify the maximum constraints that could affect the RPS. The quantification is performed by computational modelling correlated with tests on representative samples. Lessons learnt from international testing and mission data are also used when available and relevant.

d. Allocation of the nuclear safety requirements to each subsystem

Those quantified worse cases accidental load sequences are the ones for which sufficient resistance margin of the systems barriers are to be demonstrated.

Systems barriers are spread all over the mission subsystems: the RPS, the spacecraft, the launcher, and the ground segment. They are of two kinds:

(a) The “prevention” barriers whose function is to limit the occurrence of a RAS (example: the design of the launcher flight termination system or the shielding function provided by the spacecraft),

(b) The “mitigation” barriers whose function is to limit the consequences of a RAS in terms of radiological consequences for the workers, the public and the environment,

(c) Nuclear safety requirements are defined for each subsystem (and further down to the characteristics of the subsystem components) that contributes to a “prevention barrier” or a “mitigation barrier” in order to ensure the compliance to the Nuclear Safety Objectives.

e. Build-up of a nuclear safety demonstration plan at both subsystems and system level

The demonstration of compliance with every individual Nuclear Safety requirement shall be based on a justification methodology agreed primarily with the relevant nuclear safety authorities. This agreement on the justification methodology will encompass the types of demonstration to be used (analytical, test or hybrid), the methods and tools used for calculations or tests, and the design margin levels to be sought.

f. Demonstrations of the “as designed” and “as built”

Evidence of compliance with the nuclear safety system requirements will be collected for each subsystem and flew-up to demonstrate the level of nuclear safety achieved at system level. This consolidated demonstration of nuclear safety will be provided to Nuclear Safety authorities in two steps:

i. in the Preliminary Nuclear Safety Report to be delivered at system Critical Design Review (CDR) to demonstrate the “as designed” compliance (including the environmental impact study); and

ii. in the Final Nuclear Safety Report to be delivered at System Qualification Review (QR) to demonstrate the “as-built” compliance and get the flight authorization.

g. Post accidental management

In the context of the implementation of the principle of "defence in depth", even considering all nuclear safety barriers put in place to avoid the risk of radiological material release from RPS in different launcher accidental situations, it is necessary to be prepared to deal with a radiological emergency plan to protect populations and environment.

The radiological emergency situations in safety studies have to be considered according to the different phase of the RPS life cycle. The organization and means of management of these accidental situations out of the dimensioning cases, shall adapt according to the considered phase of RPS life cycle (ground operations, near range flight or far range flight, ensuring RPS tracking and observation, environmental radiological monitoring, recovery of RPS, radiological clean-up operations, etc…).

IV. Conclusion

The Nuclear Launch Safety Authorisation Process (NLSAP) is part of ESA's ENDURE project - EuropeaN Devices Using Radioisotope Energy - to support the development a European supply of radioisotope heat and power systems for space missions building a Nuclear Safety and technological framework to authorize European launch activities for RPS powered space mission early 2030's. The NLSAP activities are managed in coordination with relevant stakeholders and nuclear safety authorities in a step-by-step approach.

In collaboration with the French Space Agency and Nuclear Safety Authorities, ESA is leading the RPS system-level design, ensuring the flow-down/built-up of the subsystem-level design and consolidating the Nuclear Safety requirements and Nuclear Safety design justifications.

The capability to launch RPS from Europe is considered an important step towards the capability of launching more powerful NPS as well as space nuclear propulsion systems.

ESA has been actively participating in drafting the international safety framework for space NPS applications and continues to fully support its guidelines, which are based on the best practices reflected in the national safety frameworks of states with experience in using space NPS. ESA is interested in a continued high level of international coordination and cooperation with the international community on safety aspects related to space nuclear power source applications, in particular through the United Nations, as well as through exchanges with ESA's safety and mission assurance trilateral partners (NASA and JAXA).