CONSIDERATIONS ON SAFETY AND EUROPEAN OPTIONS REGARDING NUCLEAR POWER SOURCES FOR SPACE

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ABSTRACT

Nuclear power sources for space (NPS) are, according to current physics knowledge, the only power source option for some classes of space missions. Europe has successfully used nuclear power sources for space exploration missions (e.g. *Huygens* lander on Titan, *Ulysses* spacecraft). While some small-scale study and development efforts have been undertaken at national level during the past 40 years, these did not go further than a study and early prototyping level.

In the light of further European integration and European ambitions in space, an independent working group involving all European institutional stakeholders has discussed options and proposed coherent European positions concerning the safety, use and development of NPS technology in Europe.

This paper presents safety aspects and options as identified by this European Working Group.

Key words: nuclear power sources, safety.

1. INTRODUCTION

The absence of hydrocarbon power sources in space and the limitations of batteries have led, since the beginning of space exploration in the late 1950s and 60s, to the development of photovoltaic and nuclear power devices; these were identified as the only options with the potential to supply sufficient energy over an extended time period.

Both technologies were developed and used in parallel, partly due to the criticality of power supply to any space mission and partly due to their complementary nature.

1.1. Definitions

The term “space nuclear power sources” or “nuclear power sources for space” (NPS) usually comprises:

nuclear fission reactors: small fission reactors that are in principle similar to terrestrial reactors but with different retained design options especially for reactor cores, cooling, moderation and control systems;

radioactive power sources (RPS): generally relatively small and currently only passive devices using the natural decay heat of radioisotopes either for thermal control (*radioisotope heating units (RHUs)*) or converted into electricity (*radioisotope thermoelectric generators (RTGs)*).

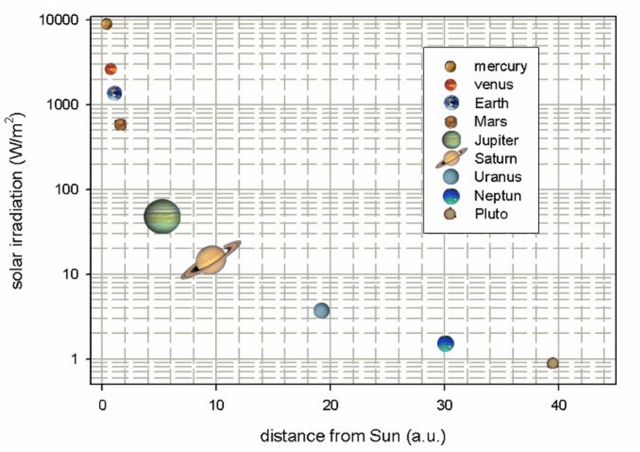

Figure 1. Semi-logarithmic graph showing the decrease of solar intensity with the square of the distance to the sun, resulting in a 60% decrease at Mars orbit and more than 95% decrease at Jupiter orbit compared to its intensity at Earth distance.

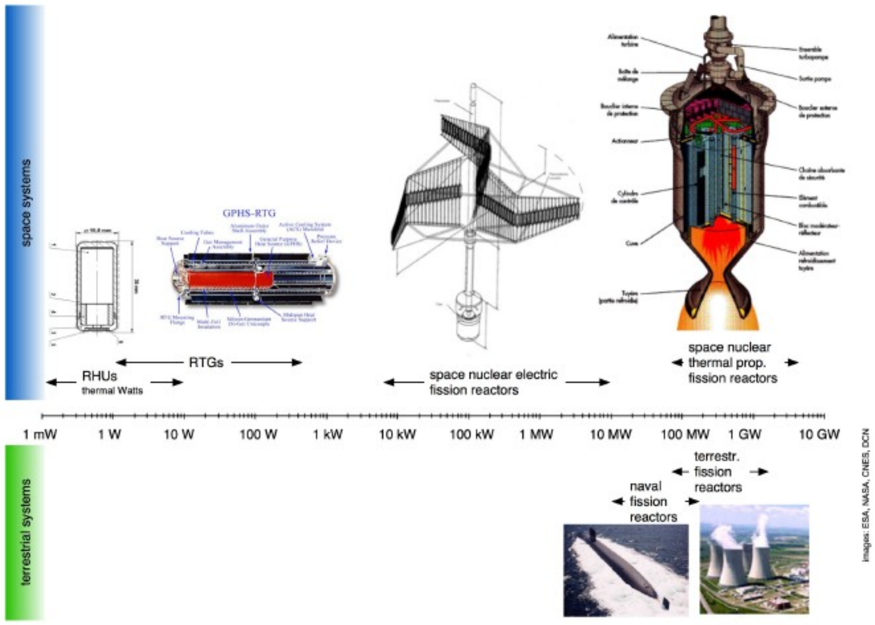

Figure 2. Power range of nuclear power sources for space applications, and comparison with standard terrestrial nuclear power applications.

1.2. Power level range of nuclear power sources

Fig. 2 shows the approximate power level range of different nuclear power sources (from small RHUs emitting mW_{th} to nuclear thermal propulsion reactors in the GW_{th} range) and the comparison with terrestrial nuclear power sources (surface and submarine reactors).

1.3. General use of nuclear power sources in space

For interplanetary exploration beyond the Earth' distance from the Sun, solar power quickly reaches its limits (Figure 1), leaving radioisotope devices as the only possible power source for a whole range of missions: RPS were used on all past and current interplanetary spacecraft to Jupiter and beyond as well as on-board most planetary landers. [28, 29, 4, 9, 2, 14, 11, 13, 12, 19, 7, 15]

The first "nuclear battery" was presented to the public in 1959. The first US space mission involving an RTG was the *Transit 4a* spacecraft launched in 1961; 24 further missions into Earth orbit as well as into interplanetary space and to planetary surfaces followed.

While the US have focussed their effort right from the start of space activities on radioisotope power sources, the Soviet space nuclear programme has given priority to the development of space fission reactors, of which over 30 have been flown in the last 40 years. All of these have been used on experimental and defence related satellites in low Earth orbit. [28, 17]

1.4. European space science and exploration perspectives

Europe will continue its knowledge-driven scientific discovery missions into the Solar System. For the timeframe 2015-2025, the European space science community will focus on studying the evolution of the Solar System, missions to the outer Solar System (Jovian satellites, Trans Neptunian Objects (TNO), boundaries of the heliosphere), and missions aimed at answering key questions related to the origin and evolution of life (e.g. old rock formations on Mars). [6]

Europe is currently developing its approach to space exploration. Although the plans are not yet finalised, the first phase programme will include robotic landers on the martian surface (*ExoMars*), possibly followed by a mission to return soil samples from the Red Planet. Europe will probably continue its cooperation with international partners, with the intention of extending human presence to the Moon and beyond. [5]

Based on current physics knowledge and past experience, Europe will need to use radioisotope power sources for its missions to the outer Solar System. Europe will also very likely need radioisotope heating units and possibly radioisotope thermo-electric generators for longer lasting lunar and Martian surface missions. Extended human presence on the Moon or Mars might require the constant power range delivered currently only by nuclear reactors.

2. INSTITUTIONAL EUROPEAN APPROACH

Based on the facts that

- Europe is likely to need nuclear power sources as essential elements for its planned space missions,
- Europe is currently fully dependent on its partners for their supply and launch, and
- activities involving nuclear power sources for space involve stake-holders outside the traditional space sector,

ESA has approached the European Commission in 2003 in order to reflect together with institutional stake-holders on the options for Europe in this area.

2.1. European Working Group on Nuclear Power Sources for Space

The *European Working Group on Nuclear Power Sources for Space* was established and mandated in spring 2004 to deliver a strategy level assessment of the European situation and options and make high-level recommendations within one year.

The working group concluded its work in March 2005 with a 30-page report. The presentation of the present paper was agreed upon by the group during its last meeting and largely reflects the options and safety aspects as identified by this working group.

2.1.1. Methodology

The EC-chaired working group comprised 31 members from seven European countries (including new EU Member States), including all large European countries involved in space and nuclear energy activities, in addition to the European Commission and ESA. Members were mainly from institutions in the space and nuclear energy sector in Europe.

Space and nuclear industry as well as academia were consulted during the elaboration of the report and provided written and oral input in the form of technical presentations.

The working group held eight meetings and operated on a consensus basis. The final report was adopted by consensus by all members. Its findings and recommendations constitute the basis for the ongoing ESA activities in this field.

3. RELEVANT EUROPEAN COMPETENCE

Europe does not start from zero when engaging in space nuclear power source activities: Europe has developed and maintained a well-functioning institutional and industrial nuclear base, made early prototypes and in-depth studies on NPS for space already in the 1960s and gained experience on their integration and use during the *Ulysses* and *Cassini/Huygens* missions.

3.1. Well-functioning European industrial and institutional nuclear base

A number of Member States of the European Union and ESA have developed world-renowned expertise in nuclear power systems in general. Terrestrial nuclear power plants deliver 35% of the European electricity need. Europe has developed and partly implemented the full nuclear fuel cycle and successfully operated a large variety of different nuclear power plant designs. [10]

3.2. Early European work on NPS for space

In parallel to the US and Russian efforts for the development of nuclear power sources for space, Europe has started research and development efforts for both radioisotope power systems and nuclear fission reactors. These have resulted in early prototypes of radioisotope thermo-electric generators, including nuclear fuelled testing during the 1960s and advanced studies on space fission systems in the late 1960s/early 1970s and late 1980s/1990s. [17, 20, 18]

Until now, however, these activities have been very country-dependent and thus quite “fragmented” across Europe.

3.3. RPS application experience in space

European industry and agencies gained some experience with the application of radioisotope power sources in space during the two co-operative space missions with the US: *Ulysses* and *Cassini/Huygens*. For both missions, however, the radioisotope power sources were provided and taken care of by the US partners and both missions were launched from US territory and on US launchers following US launch approval processes. [2, 11]

According to US and Russian experience and backed up by European studies, nuclear power sources for space require development times of the order of at least a decade. The European Working Group on Nuclear Power Sources for Space therefore recommends eventual development decisions to be taken as far in advance as possible, while keeping design choices relatively flexible and recognising that likely application scenarios may well change.

4. PROPOSED EUROPEAN APPROACH TO NUCLEAR SAFETY IN SPACE MISSIONS

Since about 50 years, western Europe has accumulated a very high degree of expertise in operating nuclear installations in a safe and reliable manner. During that time, European nuclear institutions and industry have developed and implemented very high safety standards, that have led to excellent nuclear safety records.

The use of nuclear power sources for space missions needs to follow similar high safety standards and establish within the concerned parts of space industry and space agencies the same strong nuclear safety culture that is governing the nuclear industry.

Safety needs to be and is of primary importance for all activities involving nuclear power sources. Following the IAEA general nuclear safety objectives, a defence-in-depth strategy needs to be followed to protect individuals, society and the environment by establishing and maintaining effective defences against radiological hazards.

The prevention of the exposure of humans and the biosphere to harmful levels of ionising radiation is also treated by the International Commission on Radiological Protection (ICRP) and dealt with by the EC Directive 96/29/Euratom. [3]

Besides safety, security as well as non-proliferation aspects need to be considered.

The European Working Group on Nuclear Power Sources for Space therefore recommends to "*try to expedite the establishment of binding international safety standards and their subsequent implementation at European level. If such international standards cannot be established successfully within a reasonable timeframe, a common European regulatory framework should be elaborated with the aim of ensuring maximum safety and security in all activities related to the use and launch of nuclear power sources.*"

4.1. Approach to radiation hazard

Radioisotope sources and nuclear fission reactors for space present different types and levels of hazard. The radiation hazard is related to the possibility of release of radioactive material. In fission reactors for space, radioactive material is gradually produced only after its activation. Radioisotope power sources, in contrast, are based on isotopes generally produced in and extracted from terrestrial fission reactors.

Radiation hazards specific to the use of nuclear power sources for space missions can be divided into three categories:

Launch hazards: The accidental release of radioisotopes during accidental launch conditions is prevented in the case of reactors by launching a cold, non-critical Uranium core (almost no radioactive fission products present), and in the case of radioisotope devices by adding protection layers that are able to withstand all foreseeable accidental conditions. Reactors are furthermore designed to prevent the possibility of accidental criticality. Radiation hazards caused by possible additional neutron sources or the dispersal of fuel debris require to be managed by the above-mentioned defences.

In-space hazards: In space, humans and spacecraft are exposed to higher natural levels of radiation than on Earth, taken into account as an operational constraint. Radioisotope sources do not present any significant additional hazard in space. Shielding and distancing protects humans and materials from additional radiation from fission reactors.

Re-entry hazards: Radioisotope sources are enveloped with several protecting layers that are able to withstand all foreseeable accidental re-entry conditions. Nuclear reactors are either operated in or put into a safe orbit in the case of a malfunction or at end of life.

4.2. Prevention and mitigation of accidents

Along with the gradual increase of international safety, radiation and environmental protection standards over the last 50 years, safety requirements for the use of nuclear power sources in space have changed over time.

During the 1960s, a period of multiple atmospheric nuclear bomb test explosions, radioisotope sources were designed to break up in the upper atmosphere in case of re-entry and dilute to then-acceptable levels. Now safety measures prevent the release of radioisotopes under any foreseeable accidental conditions. During all past accidents with radioactive power sources, the prevention and mitigation measures worked as foreseen.

Following the accidental re-entry of an active Soviet nuclear fission reactor in 1978 (*Cosmos-954*, [8]), prevention and mitigation measures were implemented for all space nuclear power sources and agreed upon at international level in the United Nations General Assembly Resolution 47/68 in 1992. [26]

The operation of nuclear power sources in Earth orbit also needs to consider the interaction with orbital space debris. In particular for a spacecraft with a nuclear power source on board, it is necessary to increase the orbit up to a "sufficiently high" Low Earth Orbit consistent with the UN Principles Relevant for the Use of Nuclear Power Sources in Outer Space. [26] In its report the *European Working Group* recommends considering both the nuclear and the orbital debris conditions when defining the sufficiently high orbit for spacecraft with NPS.

5. POTENTIAL EUROPEAN SAFETY FRAMEWORK

The establishment of a European safety framework for the use of nuclear power sources for space needs to be seen within the frame of the ongoing work within the "Working Group on the Use of Nuclear Power Sources (NPS) in Outer Space" of the Scientific and Technical Subcommittee of the UN Committee on the Peaceful Uses of Outer Space (COPUOS). [21, 22]

The proposed European approach thus might take into account three main inputs:

European safety standards and procedures: It is proposed to base the approval process for the launch of radioactive material in general, including those ones used in NPS, on the existing and working European quality control and safety procedures. (ESA) Furthermore it seems reasonable to use existing European (and international) standards and procedures for production, handling, transport and operation of radioactive materials. (Euratom, IAEA, practices of nuclear industry)

US and Russian standards and procedures: Both the US and Russia have extensive experience in the development, launch, operation and use of nuclear power sources (and of significant quantities of radioactive material) and have over the years developed well-functioning approval processes.

International UN standards and procedures: Along with participating European states, ESA is supporting the ongoing work at UN level (COPUOS - IAEA) aimed at establishing an international framework. Therefore it seems appropriate to take the progress and preliminary results of the COPUOS working group into account as much as possible right from the beginning.

In order to avoid potentially difficult compromises and subsequent changes at a later stage, this implies on the one hand participation in the international process in order to take into account existing ESA quality control mechanisms; and on the other hand, ensuring that the development of European standards for nuclear power sources are in line with the drafted international framework/standards.

Given that space activities in general and those involving nuclear power sources in particular are of inherently global nature with potential global consequences, it seems to be of general interest to ensure that these activities are conducted with similarly high minimum safety standards wherever they are conducted. This is especially true since the number of states able and likely to use nuclear power sources in space is likely to increase.

European member states and ESA[1] are therefore working towards the adoption of high and possibly binding international safety standards that could ideally be translated into European regulations.

[1] as an observer

In practical terms, since the UN standards/framework are not expected to be in a relatively mature state before 2008 at the earliest, an alignment with US and Russian procedures would certainly contribute towards a high degree of coherence with the UN standards/framework to be adopted around 2010.

5.1. Possible European actors

Based on the US and Russian procedures, the launch approval for nuclear power sources seems to involve essentially five types of entities:

- Space entity
- Nuclear entity
- Environmental protection entity
- Political entity
- Civil protection and emergency response entities

While the US Department of Defence also plays a role in the approval process, it is not clear at the present stage whether such a role will be of importance for a European process.

5.1.1. Space Entity

ESA seems to be the most appropriate European entity for the part of the process covered by NASA in the USA. Given the importance of national space agencies and especially the role of CNES at the European Spaceport in French Guiana, a more detailed analysis of the optimal distribution of tasks and responsibilities among European space agencies seems necessary.

5.1.2. Nuclear Entity

There are several good reasons to follow the US and Russian example and assign the purely nuclear aspects of the launch of NPS to a specialised entity outside the space agencies.

In the US, the *Department of Energy* and the *Nuclear Regulatory Commission* (until 1974 together within the *Atomic Energy Commission*) are mandated with the "development, use and control of nuclear energy"[2]. Right

[2] *Atomic Energy Act* of 1954, as amended in NUREG-0980 and *Energy Reorganization Act* of 1974 separating the regulatory aspects and creating the *Department of Energy*.

from the very first attempts to use nuclear energy in space up to the recent developments of new RTGs, the US DoE played the central role. [28, 30, 29]

In Europe the situation seems to be slightly more complex, with nuclear regulatory authorities at national level, some development and co-operation at European level under the frame of the *Euratom* treaty, and ongoing attempts to harmonise safety and regulatory aspects at restricted European level (e.g. the Western European Nuclear Regulators' Association WENRA[3]).

Given the current situation in Europe related to the use of NPS in space and the recommendation of the *European Working Group on Nuclear Power Sources for Space*, it seems reasonable at this stage to first differentiate the nuclear safety aspects related to the development of NPS for space and the nuclear safety aspects related to their use.

While the first aspect is already well covered by national legislation and regulations, to a large extent following IAEA recommendations, the nuclear safety aspects of the launch and use of NPS for space are not (yet) subject to national legislation.[4]

5.1.3. Environmental Protection Entity

The role of an environmental protection entity in the approval process for the launch of nuclear power sources seems to be confined to the qualification and testing stage.

Its tasks might to include:

- Assessments of the potential environmental impact based on data provided by the space and the nuclear entity;
- Assessments of the appropriateness of (existing) civil protection measures and emergency response plans;
- Third-party involvement and information distribution to general public in close co-ordination with all other involved entities.

At European level, the European Environmental Agency (EAA), based in Copenhagen, Denmark, might play this role. [1] National environmental protection agencies would likely be involved in this process, which ideally would be fully transparent.

5.1.4. Political Entity

Space activities, and especially space activities involving nuclear power sources, are considered in international law as ultra-hazardous activities. [16] Given the special liabilities and responsibilities of states in space activities [23, 24, 25, 26, 27], the approval chain for the launch of nuclear power sources in the US and Russia also involve political entities taking the political responsibility for the launch.

In the US, the *Office of Scientific and Technical Policy* as part of the *Executive Office* of the US president is taking this political responsibility.

For the European case, two aspects to be considered are:

1. The *launching state* issue (absolute liability of launching state, joint liability in case of more launching states) and
2. The *European* character of ESA space missions with political involvement of individual Member States (e.g there were public protests in front of national ministries of ESA Member States before the *Cassini/Huygens* launch).

It therefore seems important to find a good compromise between a streamlined, efficient approval system and sufficient transparency with the involvement of all appropriate national entities.

6. CONCLUSIONS

Europe is in the process of defining its position towards nuclear power sources for space activities, a key enabling technology for European ambitions in space science and exploration and according to present knowledge the only power source option for several classes of missions (e.g. all missions to the outer Solar System). In the past, Europe has used US nuclear power sources on two collaborative missions on US launched spacecraft.

In the frame of the EC/ESA Framework Agreement, an EC-chaired institutional working working group on nuclear power sources for space analysed the European situation with respect to nuclear power sources, identified options for Europe and recommended a phased approach with clear action steps and milestones towards increased European independence in the field.

In order to enable Europe to independently launch and use nuclear power sources, a coherent European safety framework for nuclear power sources for space is required, including safety goals, the repartition of tasks and responsibilities and and efficient, streamlined and transparent European nuclear launch approval process.

Participating European states and ESA are working within the UN COPUOS *Working Group on the Use of Nuclear Power Sources in Outer Space* towards the establishment of a strong *"international safety framework for the use of nuclear power sources in outer space"*.

[3] http://www.asn.gouv.fr/international/orgintl/aoi.asp

[4] Some European States have recently passed or are in the process of establishing national space laws, with at least some paragraphs directly or indirectly applicable to the use of nuclear power sources.

ACRONYMS AND ABBREVIATIONS

ACT ESA's Advanced Concepts Team

AEC Atomic Energy Commission, former US government commission created by the Atomic Energy Act of 1946 and charged with the development and control of the US atomic energy programme following World War II, dissolved in 1974, activities integrated into DoE

CNES Centre National d'Etudes Spatiales, French National Space Agency (France)

DLR Deutches Zentrum für Luft- und Raumfahrt (Germany)

DoE Department of Energy (US)

ESA European Space Agency

IAEA International Atomic Energy Agency

ICRP International Commission on Radiological Protection

IRCU International Commission on Radiation Units and Measurements

JPL Jet Propulsion Laboratory (US)

MER Mars Exploration Rover mission (US NASA)

NASA National Aeronautics and Space Administration (US)

NPS Nuclear Power Source, in this document synonymously used for *space* nuclear power sources

RPS Radioisotope Power System (sometimes used synonymously to RTG)

RTG Radioisotope Thermo-electric Generator.
The term "thermo-electric" should not be confounded with thermoelectricity, the Seebeck-effect based mechanism used in thermocouples, but designates only the thermal to electric conversion, which might be static or dynamic

RHU Radioistotope Heating Unit

WENRA Western European Nuclear Regulators' Association

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