

The RocketRoll Project

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Abstract

The RocketRoll project explores the feasibility of Nuclear Electric Propulsion (NEP) for space applications, focusing on European technological capabilities. Led by Tractebel with a consortium comprising CEA, Airbus D&S, ArianeGroup and Frazer Nash, the project aims to propose a scalable NEP demonstrator for deployment by 2035. A design selection process based on global NEP projects and emerging technologies resulted in a helium-xenon gas-cooled reactor with a closed Brayton cycle conversion system, operating at 1150 K turbine inlet temperature. This low-power (100 kW) demonstrator serves as a proof-of-concept, paving the way for future high-power (>600 kW) applications. The long-term goal is to reduce the specific mass of the nuclear power generator, enhancing competitiveness against solar and chemical propulsion systems. The project also highlights terrestrial synergies, identifying cross-benefits in the terrestrial nuclear sector. Safety considerations are central to the design, with strict compliance with nuclear safety standards, starting the reactor only after reaching orbit, and mitigation strategies for potential re-entry risks.

The RocketRoll project marks a foundational step in European NEP development, emphasizing technological innovation, scalability, and cost-effectiveness. While challenges remain, continued research, collaboration, and investment could position Europe as a leader in nuclear space propulsion, facilitating long-duration deep-space exploration and enabling manned Mars missions in the future.

1. Introduction

The RocketRoll (**P**reliminary **E**uropean **R**e**C**on on **N**uclear **E**lec**T**ric **P**ROpulsion for Space **A**pp**L**ications) project, initiated under ESA Contract No. 4000140561/23/FR/KR, explores the feasibility of Nuclear Electric Propulsion (NEP) for space applications, focusing on European technological capabilities. Led by Tractebel with a consortium comprising CEA, Airbus D&S, ArianeGroup and Frazer Nash, the project aims to propose a scalable NEP demonstrator for deployment by 2035.

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The project also highlights terrestrial synergies, identifying cross-benefits with high-temperature materials, TRISO (Tristructural Isotropic fuel particle) fuel technology, closed Brayton conversion, and heat pipe systems, which are under development in the terrestrial nuclear sector. Safety considerations are central to the design, with strict compliance with nuclear safety standards, starting the reactor only after reaching orbit, and mitigation strategies for potential re-entry risks.

Preliminary performance assessments indicate that, at current European launcher capacities, Solar Electric Propulsion (SEP) remains preferable for low-power lunar missions. However, NEP is projected to be essential for deep-space missions beyond Mars, where solar energy is insufficient and high-power, high-specific impulse thrusters are required. Market viability is contingent on advances in in-orbit refueling, propulsion reusability, and launch vehicle capabilities.

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2. Design Selection

A comprehensive review of the state-of-the-art in NEP design, based on past and present NEP projects worldwide, along with an assessment of emerging technologies, has enabled a balanced selection of minimum risk technologies that are feasible within Europe. Given that the NEP demonstrator will be a low power prototype, the chosen technologies shall be scalable to higher power outputs in the future. This scalability ensures that further development will not require restarting the R&D process, thus allowing for a seamless transition to more powerful applications.

The selected **minimum risk design** consists of a highly-enriched uranium (HEU) fuelled helium-xenon (He-Xe) gas-cooled reactor, operating in direct cycle with a closed Brayton convertor at 1150 K turbine inlet temperature. While the low-power design may not meet most operational use-cases, this Nuclear Electric Propulsion configuration serves as an attractive mid-term solution for proof-of-concept, limited to around 100 kW of electrical power output. A schematic representation of such a design is shown in Figure 1.

However, to be competitive with other propulsion technologies, it will be required to **reach higher powers**, well above 600 kW.

Looking ahead to the **more distant future**, the absolute emphasis in research and development should be on the **reduction of the specific mass** (i.e. the mass per power output) of the nuclear power generator, as this factor significantly influences the overall feasibility and attractiveness of the nuclear electric propulsion solution.

By reducing the specific mass of the nuclear power generator, several important outcomes can be achieved:

- **Expanding use-cases:** broadening the range of selectable use-cases for nuclear electric propulsion;
- **Enhancing competitiveness:** increasing vehicle power and/or allowing the useful payload mass to increase;
- **Transition from high to low-enriched uranium:** counteracting the potential increase in reactor and shield mass.

The main leverage for lowering the specific mass of the nuclear power generator is the further increase in reactor outlet temperature. The higher turbine inlet temperature will increase the radiator temperature, lowering considerably its mass. At the same time, the increased turbine inlet temperature will increase the efficiency of the power generator.

However, this higher temperature will require to make intensive use of refractory materials which are still in the research and development phase.

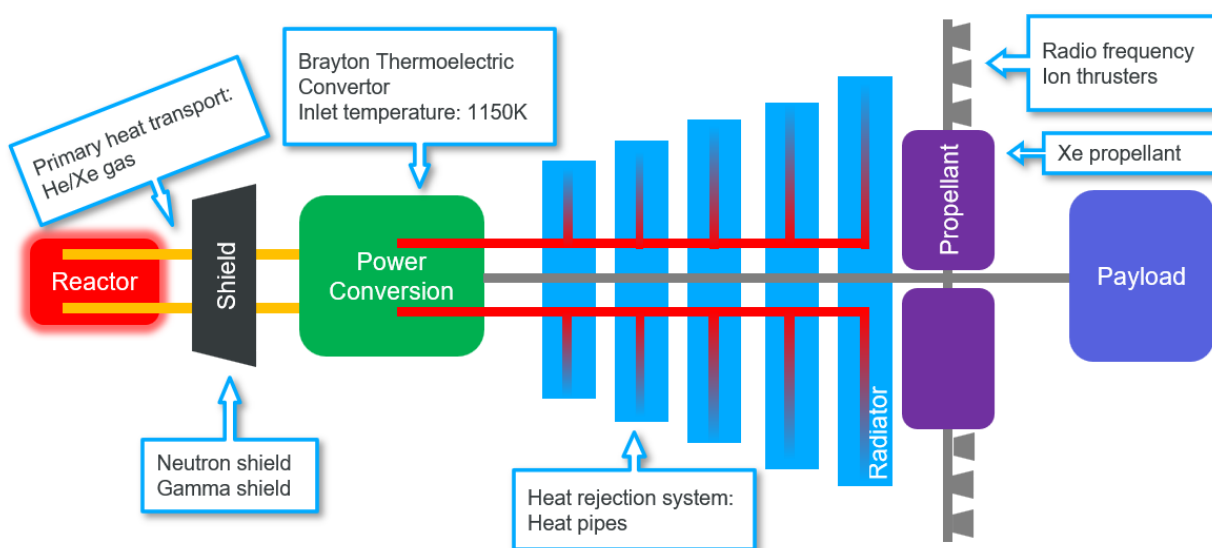


Figure 1: Schematic representation of a Nuclear Electric Propulsion vehicle

The different technological choices that were made by the project for the demonstrator NEP can be justified as follows:

- **Heat to electric conversion system:** static conversion systems might be very reliable but they have generally a low efficiency and are difficult to scale up to higher powers. Therefore, a more classical Rankine or Brayton convertor is a better choice for higher power devices. The Brayton convertor was the final choice because the behaviour of the two-phase flow in zero gravity for Rankine convertors needs to be better understood first;
- **Radiator:** a fully passive heat pipe system, relying not on gravity but on capillarity, is the obvious choice for ultimate heat sink in space;
- **Fuel type:** in the nuclear sector there is a huge experience in UO_2 fuel, while the more fissile dense uranium nitride (UN) fuel would be a good alternative in the future. The fuel form depends on the final reactor design, but a kind of TRISO particles embedded in a ceramic matrix, as used for high-temperature gas-cooled reactors on Earth, would be a possible choice compatible with the high temperatures envisioned;
- **Moderator:** In a fast reactor design, no moderator is used, but when going for a thermal reactor design a moderator is required to slow down the neutrons. The high temperature reactor design will be a challenge for this typically light material. The use of Yttrium hydrides could be considered;
- **Reflector:** a reflector surrounding the core is required to maximize the number of neutrons remaining in the reactor core. A light beryllium material would be an excellent choice;
- **Control and protection:** for the control of the core power, different systems exist: inserting/extracting control rods, rotating control drums or movable reflectors. The control drums offer simpler control mechanisms and are more compatible with the compactness of the design;
- **Primary heat transport:** whereas liquid metals have the advantage of being a low pressure system, there are several challenges related to their use: the corrosion issue and the requirement to thaw the liquid prior to its use in space. Therefore a gas heat transport system, at relatively high pressure up to 30bar, would avoid these issues even though it is a less efficient heat transport medium;
- **Radiation protection:** the radiation shield protects the equipment and payload from neutron and gamma radiation. Neutron energy is reduced by light materials and LiH would be a good candidate. Gamma radiation is shielded by high-density heavy material, where tungsten is the obvious choice due to the combination of high melting point, excellent structural resistance and good shielding performance;
- **Thrusters:** an electrostatic European designed thruster technology was selected because of its design maturity, while in the future electromagnetic thrusters could be considered;
- **Propellant:** the propellant gas compatible with the currently selected thruster technology was a xenon gas. Future thrusters should aim for using cheaper and more widely available propellant gases.

3. Terrestrial Synergies

Even though the general principle for a nuclear power source in space and on Earth is the same, there are fundamental differences between space reactors and terrestrial reactors due to different drivers and constraints.

Space reactors are designed to operate in the vacuum of space, often in extreme temperature variation, radiation from cosmic rays, and micro gravity. Micro gravity affects fluid flow and heat transfer. On Earth, there is access to water and air for cooling. Space reactors need to rely on radiative heat dissipation for ultimate cooling.

Space reactors must be compact and lightweight due to the constraints of launching them into space. Terrestrial reactors have more extensive shielding (e.g. concrete) because weight is not a limiting factor, whereas in space reactors shielding is often directional, focusing on protecting the spacecraft and its astronauts.

While terrestrial reactors are designed for regular refuelling with maintenance, space reactors designed for long-duration missions are non-refuellable and need to be very reliable in the absence of any maintenance.

Finally, space reactors may use highly-enriched uranium (HEU) due to mission requirements, while this is excluded for commercial reactors on Earth to reduce proliferation risks. This, however, is still an open issue and depending on the political decisions it may be required to redesign a NEP space reactor for using high-assay low-enriched uranium (HALEU) with a maximum enrichment of 20% in the fissile U-235 isotope.

Anyhow, even though there are important differences, there still remain some potential terrestrial synergies to benefit from:

- **high-temperature materials** (superalloys and refractory materials), mainly in the research field of high-temperature gas-cooled reactors;
- **uranium nitride fuel**, which has a certain interest for terrestrial reactors as well;

- **TRISO fuel**, which is being studied intensively;
- **heat pipe technology**, which is considered for some microreactor designs on Earth;
- **closed Brayton power conversion**, having a renewed interest for coupling with small nuclear reactors;
- **control drums**, which are considered for terrestrial micro reactors as well;
- **transport of the entire fuelled reactor**, which is a regulatory challenge to be solved for some transportable micro reactor designs as well

4. Safety

The nuclear safety requirements are to be taken into account as from the preliminary design of the NEP, to include safety barriers ensuring the NEP to control the risks to the levels required for ensuring the protection of the terrestrial biosphere's population and environment. The idea is to fulfil the same Nuclear Safety Goals, a set of quantified objectives to achieve the Fundamental Safety Objectives, as those defined for the existing nuclear industry in France.

The reactors are to be fuelled exclusively with fresh uranium fuel, allowing operation only when reaching a certain defined altitude in space. This is required to keep a launching accident manageable as there will be no radioactive material inside yet.

Even so, the use-cases defined in this RocketRoll project require some attention with regard to reaching nuclear safety performance. Detailed justifications will have to be produced for the following points:

- Any application of nuclear power should properly **justify its needs**, compared to other existing alternatives;
- Use-cases having a path back to Earth, increasing the probability of an **accidental re-entry** in case of a major failure resulting in the inoperability of the propulsion system, should be justified.

5. Performance

A first comparison of the NEP demonstrator design with a Solar Electric Propulsion (SEP) design at a similar power level shows that, with the current constraints in European launcher capacity, the more mature SEP remains the best choice for Moon missions.

However, Nuclear Electric Propulsion will become interesting for high power missions (in excess of 600 kWe), which will be required for long missions with a trip duration reduction (e.g. manned flight to Mars). These missions require significant thrust with high specific impulse to limit propellant mass consumption. Certainly when going beyond Mars, in deep space, solar arrays are not sufficient any more to provide power and nuclear will be the only option.

The increase in maturity of the nuclear generator shall be synchronized with the development of high-power high-specific impulse thrusters with low erosion and using abundant propellant. Meanwhile, NEP mass performance needs to be improved significantly.

6. Market Analysis

Before introducing NEP in the future European space transport market, some key issues need to be addressed:

- The potential safety concerns from introducing NEP vehicles into an in-orbit "hub & spoke" model infrastructure;
- The future European launch capability, where a heavy launcher will be required for bringing competitive NEP systems into space;
- To be competitive with SEP, it must balance performance and recurring cost, which is difficult to estimate at this stage;
- The competitiveness for NEP compared to chemical propulsion vehicles needs to be looked at as well;
- First and foremost, the NEP system must be tested and proved as a concept;
- The potential synergies between terrestrial microreactor technologies and NEP technologies are to be exploited as much as possible in order to reduce the development costs and to obtain return on investment.

For those use-cases where there is a competition with SEP or chemically fuelled rockets, the competitiveness for NEP needs to come from their reusability for multiple missions. This requires in-orbit propellant refuelling capabilities to be further developed in parallel. At the same time, current electric thruster technologies have their erosion as a limiting factor.

7. Roadmap

The proposed NEP development roadmap is organized according to the key project phases outlined in the ECSS (European Cooperation for Space Standardization) standard [1]:

- Phase A (Feasibility) from 2025 to 2026: gathering industrial trade-offs, making some key decisions on reactor fuel and decide whether low-enriched uranium is a requirement;
- Phase B (Preliminary definition) from 2027 to 2029: designing the system for ground test, selecting demonstrator mission, designing the individual components of the NEP system;
- Phase C (Detailed definition) from 2030 to 2035: building and performing the ground test and the digital twin, developing and fabricating the individual components of the NEP system;
- Phase D (Production and Qualification) from 2036 to 2039: fabricating and assembling the actual NEP demonstration system;
- Phase E (Operations/Utilization) from 2040: launch of the NEP demonstration system.

8. Conclusion

The RocketRoll project represents a first step towards realizing the potential of Nuclear Electric Propulsion for space applications. By leveraging European capabilities and focusing on innovative, scalable technologies, it aims to position Europe at the forefront of space propulsion technology. The journey ahead is challenging, but with continued research, development, and collaboration, NEP can revolutionize space travel, enabling humanity to explore deeper into the cosmos than ever before. Together, we can turn this ambitious vision into reality, paving the way for a new era of space exploration and discovery.

References

- [1] ECSS. 2009. Space project management. Project planning and implementation. ESA, Requirements and Standards Division.