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## The Journey of PULSAR, PU-238-coupled dynamic power system for SpAce exploRation and beyond.

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*PULSAR (PU-238-coupled dynamic power system for SpAce exploRation and beyond) is a research and innovation project funded by the European Commission between 2022 and 2024. The aim of this project was to establish building blocks for the development of Radioisotope Power Systems (RPS) fueled by Pu-238 with European technologies and standards. Radioisotope Power Systems (RPS) is a key enabling technology for space exploration of locations hidden from the sun for prolonged periods, or of deep space, where the sun cannot deliver sufficient power to spacecrafts. This project has brought together leading stakeholders in the field of space and nuclear. PULSAR consortium includes nine partners: Tractebel (coordinator), SCK CEN, CEA, JRC, Airbus DS, ArianeGroup, UBFC-UFC, INCOTEC and ARTTIC. The paper provides a presentation of the project achievements and how the partners consortium was organized along the project. Future prospect and expected challenges are presented based on the hypotheses assumed in PULSAR.*

### I. INTRODUCTION

Space power production relies on two main technologies: solar power and nuclear power. The specific power of solar arrays is directly proportional to solar irradiance, which diminishes with the square of the distance from the sun. Over recent decades, significant advancements have been made in photovoltaic cell efficiency under low light conditions and in their resistance to space radiation at low temperatures. Despite these improvements, nuclear-powered Radioisotope Thermoelectric Generators (RTG) remain superior and more attractive than solar panels and batteries when solar irradiance is not available or insufficient. Solar panels also face challenges during prolonged eclipses, such as the 14-

day nights on the Moon or dust storms on Mars that can obscure the sun for days and deposit dust on the panels, or for high-power surface mobility applications. Consequently, nuclear power systems have been utilized for heat (Radioisotope Heater Unit or RHU) and electrical power generation (Radioisotope Power System or RPS), either by direct thermal to electric conversion (RTG) or by dynamic conversion when the thermal power is first converted to mechanical and finally to electrical power. These systems do not rely on fission energy like terrestrial nuclear reactors but convert the heat from radioactive decay into electricity. However, RPS technology remains niche, and Europe currently lacks its own RPS solution and dedicated industrial isotope production chain for space applications. Previous ESA activities identified two radioisotopes for space mission nuclear power systems: Plutonium-238 (Pu-238) and Americium-241 (Am-241). Am-241 is a by-product in spent fuel from nuclear reactors while Pu-238 is obtained from irradiation of Neptunium targets. Pu-238, already used as a space power source in the US and Russia, is preferred for several reasons:

- It has the highest power density (0.56 W/g for pure Pu-238), enabling a very light and compact power source.
- It emits few penetrating gamma radiations, making it relatively easy to handle.
- It has a convenient half-life of 87.7 years, suitable for all planned space missions.

Therefore, Pu-238 was chosen as the primary fuel for the PULSAR project. To address technological gaps and external dependencies, the PULSAR project aims to establish end-to-end Pu-238 production in Europe and design a dynamic RPS using a Stirling engine for higher conversion efficiency than past RTGs<sup>1</sup>.

The PULSAR consortium, led by TRACTEBEL, a Brussels-based international nuclear engineering consultancy part of the ENGIE group, includes key European nuclear and space sector actors: Belgian Nuclear Research Centre - SCK CEN, French Alternative Energies and Atomic Energy Commission - CEA, European Commission Joint Research Centre (JRC), Airbus Defence & Space, ArianeGroup; a leader in Stirling engine research, UBFC - Université Bourgogne-Franche-Comté and its affiliated UFC, Université de Franche-Comté; and two consultancies specializing in innovation and technology transfer, INCOTEC - Innovación Eficiente and ARTTIC.

This paper presents the project’s organization, scope definition through various tasks, and an overview of achievements. Future prospects and expected challenges are discussed based on PULSAR’s envisaged roadmap assumptions.

## II. PULSAR OVERVIEW

### II.A. Scope description

PULSAR’s technical scope is divided into four work packages: Pu-238 production and processing (WP1), heat source architecture and Stirling converter (WP2), RPS engineering (WP3), and market assessment (WP4).

The two last work packages, WP5 for Dissemination, communication, and exploitation, and WP6 for Project management, are common to Horizon Europe projects.

**TABLE I.** PULSAR work package breakdown and scope.

Work Breakdown Structure	Leader
WP1 – Pu-238 production and processing	SCK CEN
WP2 – Heat source architecture and Stirling converter	CEA
WP3 – RPS engineering	TRACTEBEL
WP4 – Market assessment	INCOTEC
WP5 – Dissemination, communication & exploitation	ARTTIC
WP6 – Project management	TRACTEBEL

#### *WP1 – Pu238 production and processing.*

This WP addresses the key technological challenges in establishing a Pu-238 production chain in Europe. The first part focuses on designing Np-237 targets, optimizing irradiation cycles in a high-flux reactor, and the Pu separation process. The second part involves synthesizing, characterizing, and manipulating PuO<sub>2</sub> pellets with representative microstructure. A laser welding technique for encapsulating the pellets in their cladding is also developed. The third part covers safety assessment, licensing, and regulatory framework for the radioisotope heat source to receive launch authorization. WP1 is led by SCK CEN with involvement of JRC and Tractebel.

#### *WP2 – Heat source architecture and Stirling converter*

This WP develops the PULSAR radioisotope heat source architecture to meet mission operational and safety requirements and analyzes its coupling with a Stirling engine. A review of state-of-the-art heat-to-electric conversion technologies is conducted to contextualize the PULSAR proposal. Design trade-offs are assessed, and development paths are optimized. WP2 is led by CEA with contributions from UBFC-UFC.

#### *WP3 – RPS engineering*

Future space missions will include various endeavors such as observational missions, cargo transport, planetary surface exploration, sample retrieval, and in-situ resource utilization (ISRU). The first part of this WP identifies missions that would benefit from RPS technology and defines operational and safety requirements. The second part focuses on designing the RPS, including radiator sizing, heat source integration, and Stirling engine integration. The goal is to create a comprehensive 3D model of the RPS with its engineering files (thermal, mechanical, and shielding analyses). Finally, design validity is controlled through mission system integration. WP3 is led by Tractebel with involvement of from ArianeGroup and AIRBUS DS.

#### *WP4 – Market assessment*

WP4 assesses the market potential for the PULSAR solution and the developed technological components. The application of similar Stirling converters outside space applications is also evaluated. WP4 is led by INCOTEC

#### *WP5 – Dissemination, communication & exploitation*

The primary objective of this WP is to effectively promote the innovative approach, project results, and outcomes through appropriate channels to key stakeholders, including the scientific community, industry, policymakers, and the public. The consortium also reviews the exploitation strategy to ensure optimal outcomes for all stakeholders. WP5 is led by ARTTIC.

#### *WP6 – Project management*

WP6, led by Tractebel, involves traditional project management activities, promoting partner exchanges, providing strategic decision counsel, and ensuring project progress towards objectives. WP6 also includes project governance activities with an Advisory Board comprising Euratom, ESA, ArianeGroup, Airbus, and the Belgian Federal Agency for Nuclear Control to support strategic decisions and ensure project developments meet stakeholder needs and requirements.

### II.B. Project important milestones

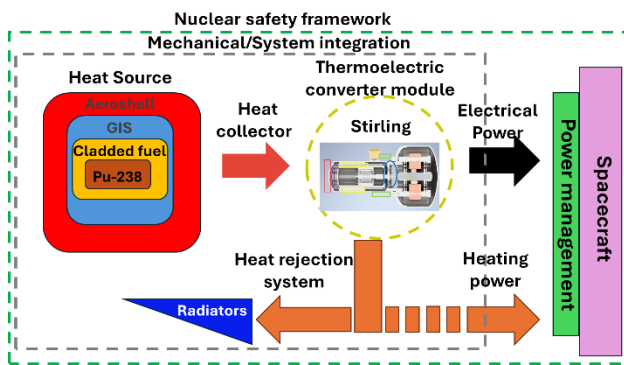
The PULSAR research project commenced in September 2022 and concluded in October 2024.

The initial progress was reviewed during the Milestone 1 meeting in March 2023, which laid the foundation for a conceptual RPS design. Milestone 2 took place in October 2023, marking the project's midpoint and providing an opportunity for a second iteration of the RPS design.

The project concluded with the publication of several public reports as part of the Dissemination, Communication & Exploitation activities, covering the main topics addressed throughout the project. Notably, significant public reports included one on Safety Assessment Licensing and Regulations for Europe and another on Exploitation and future valorization prospects.

A final PULSAR workshop was held on October 2024, where ESA and EURATOM – European Commission policymakers were invited to discuss the potential benefits for Europe in developing such independent technology.

### III. PROJECT ACHIEVEMENTS ON TECHNOLOGY DEVELOPMENT



**Figure 1. Technology bricks involved in PULSAR RPS.**

The PULSAR project has tackled all the different technology bricks and regulatory aspects of the development of a dynamic RTG, based on European know-how and standards. A scheme of the elements involved is represented in Figure 1..

1. Heat Source (HS) module, which is further segmented in three technology bricks:

- 1.1 Pu-238 production and processing
- 1.2 Cladded fuel (238-PuO<sub>2</sub> pellet + cladding)
- 1.3 HS architecture (protective layers: Graphite Impact Shell, insulation and aeroshell)

2. Thermo-Electric Converter (TEC, being the Stirling engine)

3. Heat rejection system (connecting elements and radiating surfaces)

#### 4. Structural RPS assembly and spacecraft integration

In addition to these technology bricks, power management distribution, control and monitoring of the power source are considered important features for the final product which need to be integrated with the spacecraft requirements. As a parallel process to the development, it is important to consider that a nuclear safety framework needs to be updated and harmonized to be able to create the opportunities to launch the RPS from European territory. PULSAR project has contributed to progress on the TRL of each technology brick listed and on setting a comprehensive view of the nuclear safety framework.

#### III.A. Pu-238 production and processing

Pu-238 is the preferred radioisotope for RPS application because of its high-power density, the almost absence of penetrating gamma radiation and its relatively long half-life of 87.7 years. Even though Pu-238 is part of the Pu-isotopic vector build-up of power reactors fuel, its relative concentration with respect to the other plutonium isotopes is very small (maximum a few percentages). A concentration of at least 82.5% of Pu-238/Pu is required for an RPS. This high isotopic concentration is obtained by neutron irradiation of Np-237. A preliminary study on the feasibility of Pu-238 production in Europe funded by ESA in 2021 proposed a roadmap for Pu-238 production<sup>2</sup>.

The main steps for Heat Source Pu-238 production are:

- Identification of an available Np-237 source i.e., from spent nuclear fuel streams, extraction of the nuclide, purification and increasing its concentration for easier and safer transportation.
- Manufacturing of neptunium targets, including neptunium-247/protactinium-233 separation, neptunium liquid-to-solid conversion and neptunium target fabrication.
- Neutron Irradiation of NpO<sub>2</sub> targets.
- Chemical reprocessing on irradiated neptunium targets, i.e., separation and purification of plutonium and neptunium from each other and other fission products.
- PuO<sub>2</sub> pellets manufacturing
- Clad the PuO<sub>2</sub> pellets

#### III.A.I. PULSAR ACHIEVEMENT

Within the PULSAR project, SCK CEN has achieved significant advancements towards the Pu-238 production particularly in the areas of neptunium target manufacturing, neutron irradiation, and chemical reprocessing. Notably:

- Optimization studies of the target geometry and irradiation conditions have been performed and several trends regarding the Pu-238 yield and the quality of the Pu vector as a function of target geometry and irradiation conditions have been identified. Two irradiation scenarios using reflector channels at BR2 have been proposed, with a calculated production rate of 418 g and 378 g of Pu-238 per year (TRL2)<sup>3</sup>.
- The conventional Savannah River Site (SRS) oxalate conversion route described in the open literature by US has been reproduced at laboratory-scale<sup>4</sup>. Moreover, modifications of the SRS oxalate conversion flowsheet as well as more advanced conversion routes such as external gelation process to produce NpO<sub>2</sub> kernels have been investigated. The goal is to identify and solve challenges in designing Np targets for liquid-to-solid conversion step. Within all the studied processes, a yield between 84 and 91 wt.% was achieved and free-flowing NpO<sub>2</sub> materials has been obtained. This will facilitate the further pelletization step. The PULSAR project has successfully achieved TRL3 for the neptunium conversion process<sup>5</sup>.
- Solvent extraction in continuous process has been identified as the preferred method for separating neptunium and plutonium from fission products and from each other based on literature study. In PULSAR, distribution ratios as a function of nitric acid concentration were determined for Np(IV), Np(V) and Np(VI) and Pu(III) and Pu(IV) with three solvents (a TBP-based solvent, N,N-diethylhexylbutyramide (DEHBA), and N,N-diethylhexylisobutyramide (DEHiBA)) (TRL2)<sup>6</sup>.

### III.B. Cladded fuel

The PuO<sub>2</sub> powder needs to be pressed and sintered into cylindrical pellets which can be successively cladded. The pellets production process is composed of at least two different operations:

1. Granule production.
2. Pellet production.

Obtaining the right microstructure with an adequate ratio of void between the grains is important as this makes it possible to sustain the build-up of internal pressure created by the accumulation of alpha particles (helium nuclide) from Pu-238 decay. The final microstructure is the outcome of the different operations which include chemical reaction for oxalate precipitation, oxide conversion, oxygen exchange, milling processes, pressing processes, several steps of sintering with different atmospheres and temperatures. All these processing steps need to be optimized in order to reach a final pellet with

the right microstructure and Theoretical Density (TD) in the range of 82 to 86%<sup>7</sup>.

Plutonium oxide needs to be contained and shielded in a first layer (cladding) before being integrated in the Heat Source module. This cladding is particularly important to ensure radioprotection and to confine fines of Pu<sup>8</sup>. The cladded fuel must remain sealed one year after impact on Earth ground or sea following any sequential scenario<sup>9</sup>. NASA has developed its own iridium alloy (DOP26) to satisfy the safety and operational requirements. DOP26 is not available in Europe and manufacturability of such metallic alloy needs to be developed.

#### III.B.I. PULSAR ACHIEVEMENT

In the PULSAR project, JRC have investigated in the Fuel and Materials Research laboratory both pellets and cladding manufacturability to develop a European know-how.

Pellet: in PULSAR the synthesis and characterization of PuO<sub>2</sub> pellets with representative microstructure have been investigated with Pu-239. The process to obtain pellets in the JRC facilities PuO<sub>2</sub> from reactor-grade plutonium with tailored microstructure and density mimic well the results obtained in the open literature by US (TRL 3)<sup>10</sup>.

Cladding: in PULSAR, the feasibility of using laser welding technics for the iridium encapsulation has been studied and tested in the JRC laboratories. Due to a lack of materials (DOP26 is not commercially available and iridium is very expensive), the few welding tests carried out are not sufficient to conclude on the feasibility. In addition, the composition for the iridium tested differs from that of DOP26 and may not be sufficient to produce good weld (TRL 2)<sup>11</sup>.

### III.C. Heat source architecture

The cladded PuO<sub>2</sub> pellets need to be protected under additional layers in order to:

1. Protect the cladded fuel in case of launch accidents (explosions, fireball, and ultimate impact on ground.
2. Protect the cladded fuel in case of atmospheric re-entry, by thermally isolating the cladding and creating an ablative barrier.

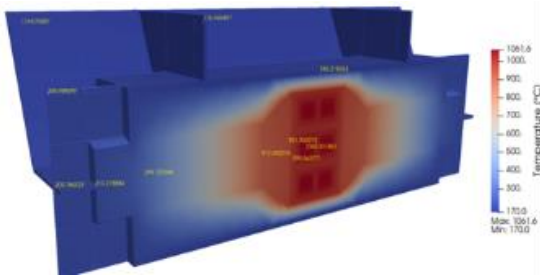
The final architecture of the Heat Source module should contain the cladded fuel and the protective layers stacked together to adapt the power request and interfaced with the thermoelectric converters in an efficient way.

#### III.C.I. PULSAR ACHIEVEMENT

In PULSAR, CEA tackled the functional analysis, architecture proposal, selection of reference operating

scenarios and definition of design criteria for the HS of a European RPS with Stirling converters. A preliminary design of a European RPS HS module has been proposed based on thermal modeling (CEA) using the same properties as the graphite materials used by the GPHS and integrated in the RPS structure and thermally coupled with the Stirling converter<sup>8</sup>. Thermal-mechanical calculations for nominal and accidental calculations were performed to map the temperatures in the module (Figure 2)

The re-entry ablation and peak temperature has been modelled for a SEPCARB 360 (ArianeGroup) aeroshell.



**Figure 2. Computed temperature field inside the PULSAR Heat Source.**

### III.D. Stirling engine

The thermoelectric converters play a crucial role for the RPS as they transform the thermal energy in electrical power available for the final client system (spacecraft, rover or other devices). Thermoelectric converters for RPS can be separate in static systems and dynamic systems. Historically, RPS for space used static conversion with thermoelectric materials, which have a typical efficiency in the range 5-8%. In comparison, a Stirling engine (coupled with its electromechanical converter) could theoretically achieve much higher conversion efficiency (20%, maybe up to 40%) with a relatively high specific power for the anticipated power range of PULSAR RPS. A higher efficiency means that a smaller mass of radioactive material has to embark for the same useful electrical power. This is very favorable: limiting the time for production, lower source term for nuclear safety, reduced weight<sup>12</sup>.

The Stirling engine operates on the principle of the temperature difference between a heat source and a heat sink. The main components of the Stirling engine are:

1. Hot side chamber (called expansion volume).
2. Cold side chamber (called compression volume).
3. Piston.
4. Displacer.
5. Heat exchange interfaces.
6. Regenerator for efficient heat management.

The efficiency of the Stirling engine depends mainly on the temperature difference between hot and cold chambers, as well as all the associated heat and friction losses. Developing a Stirling engine meets several challenges, spanning from theoretical to practical implementation. The main challenges are:

1. Heat transfer efficiency: achieving high-efficiency heat transfer between the engine's hot and cold chambers with the external heat source and heat sink, while minimizing thermal losses.
2. Regenerator design: the regenerator is crucial for increasing the efficiency by storing and reusing heat between the expansion and compression phases. Designing an effective regenerator that maximizes efficiency without increasing the engine complexity, cost or weight is a major challenge.
3. Material selection: the selected materials have to demonstrate high thermal resistance to withstand high temperatures at the hot head and low temperatures at the cold head. Moreover, they have to be able to withstand cyclic mechanical stresses over long periods of time.
4. Sealing and leakage: maintaining leak-tight seals in high temperature environment is fundamental to avoid loss of efficiency. The materials itself have to be impermeable to gas release.

#### III.D.I. PULSAR ACHIEVEMENT

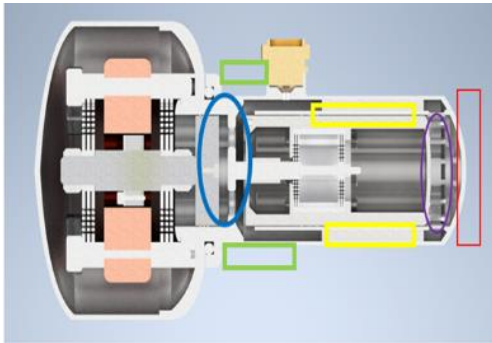
A preliminary design of a Stirling engine for space application has been elaborated by UBFC-UFC (Figure 3). The proof-of-concept and functional verification (TRL 3/4) have been evaluated by modelling analysis<sup>13,14</sup>.

The results obtained from different simulation software have been compared, giving more confidence on the validity of the modelling : in-house software (UFC) and professional software SAGE (UBFC). New arrangements for the metallic springs have been designed. The optimal operating range is found to be :

- Frequency range = 30 Hz to 40 Hz
- Pressure range = 50 to 70 bar
- Cold source temperatures : 50°C to 200 °C

A comparative analysis of the Stirling RPS developed in PULSAR against other radioisotope conversion technologies has been performed. The Stirling converter appears to be the most promising technology for overcoming efficiency and scalability limitations of thermoelectric systems. While integration challenges and reliability improvements remain key areas of focus, it is felt

that future Stirling converter R&D should prioritize robustness over performance optimization<sup>15</sup>.



**Figure 3. Illustration of the free piston Stirling engine design for the PULSAR project. Color code: red, heater; violet, expansion space; yellow, regenerator; green, rejector; blue, compression space.**

### III.E. RPS mechanical integration

The RPS design and mechanical integration starts from the definition of requirements and constraints for the space mission<sup>16</sup> and safety constraints<sup>9</sup>. It encompasses the mechanical design of the RPS assembly, with sub-assemblies for integration of the Heat Source at the latest stage. The mechanical integration is supported by studies validating thermal and radiation shielding, structural design in all operating modes.

#### III.E.I. PULSAR ACHIEVEMENT

In PULSAR the environmental boundaries and operative conditions have been identified. The different engineering files spanned:

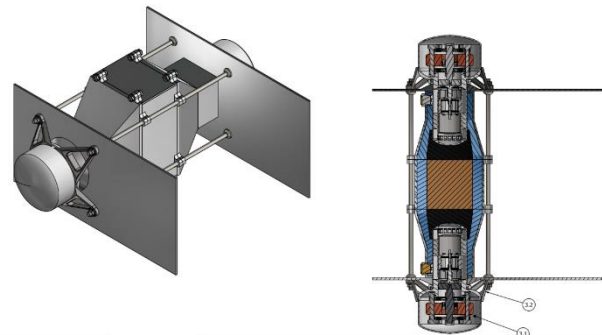
- Thermal: radiator design for heat rejection from Stirling cold side to the outer space (ultimate heat sink)<sup>18</sup>.
- Shielding: evaluation of worker's and material's protection<sup>19</sup>.
- Structural: validated resistance of RPS assembly to design conditions (pressure, loads and temperature)<sup>20</sup>.

The dynamics RPS fueled by Pu-238 is the assembly of the HS module containing Pu-238 with the Stirling engines. A complete 3D mechanical design integrating the different sub-assemblies is available and shown in Figure 4<sup>17</sup>.

A compliance check of the heat source and RPS design was conducted with the safety objectives and the launch authorization process.

The assembly developed comprises independent sub-assemblies for the heat source and the Stirling converters, allowing for the final integration of the source shortly before launch. The model will serve as the basis for further

design development, extending the scope and level of details of the engineering files, studying transient modes, failure modes, etc. to increase the Technical Readiness Level.



**Figure 4. PULSAR RPS 3D mechanical assembly.**

### III.F RPS system integration

System integration starts with identification of a target mission in order to define RPS electrical, geometry and mass constraints<sup>16</sup>. In addition, environmental requirements need to be considered. An RPS model is prepared and validated including geometry, thermal and electrical specifications. The system performances for the target mission need to be analyzed.

#### III.F.I. PULSAR ACHIEVEMENT

In PULSAR, mission specification for RPS sizing and design were issued. Then, thermal and electrical model were developed and finally, the integration of the RPS system with host spacecraft system was assessed with ADS Systema tool. Evaluation of RPS performance were assessed in a typical lunar rover mission for various cases (moon equator and polar walk). The impact of vehicle environment on RPS performance were evaluated and cold source temperature range were identified. The model weakness and required improvements for further studies were provided<sup>21</sup>.

### III.G. Nuclear safety framework

The launch safety approval and licensing process is one of the precondition to a wider uptake of the PULSAR RPS, in particular to get to social acceptance of nuclear devices launch. Regulations must allow the production of a radioactive material for space application, and a thorough licensing process with clearly defined safety requirements needs to be implemented, covering the manipulation, separation, handling, irradiation and extraction of Pu-238 and Np-237. Moreover, producing the clad fuel and its storage in quantity to be able to power a space mission, will require extra considerations and authorizations depending on the facilities and the countries involved. Finally, the use of Pu-238 powered RPS with a Stirling converter will require the regulation and safety referential of the European space launch site to be updated. It is therefore

important to tackle the whole picture of the regulatory and compliance aspects from the Pu-238 production processes, through the manufacturing of the Pu-238 pellets, its clad and integration in the Heat Source module, its transportation to the launch site and up to the launch and end of the space mission. The necessity to rely on nuclear technology will have to be assessed and approved. A set of nuclear safety files need to be compiled including:

- Handling and manufacturing activities in dedicated processing/production facilities.
- Storage of radioactive materials in any level of the production.
- Transportation to the assembly site if necessary.
- Safety requirements at the launch site and during the space missions.

This task requires considering the European legal framework and the regulations across different countries, providing a gap analysis to be able to demonstrate the compliance. Defining the nuclear safety framework is an important activity without which the RPS technology can not be developed.

### *III.G.I. PULSAR ACHIEVEMENT*

The PULSAR project has paved the way on the safety assessment, licensing, and regulation of the PULSAR Heat Source. The selected design aims to comply with international safety principles and IAEA guidelines. Tractebel, ArianeGroup and JRC contributed to investigate the existing nuclear safety framework and how it should evolve to make the technology and development possible. The topic addressed were:

- The assessment of the handling and processing of Pu-238 in gram quantities in a nuclear laboratory<sup>22</sup>.
- Definition of the launch phase nuclear safety requirements<sup>9</sup> and the development plan analysis for complying with the launch phase nuclear safety process<sup>23</sup>.
- Existing international and European safety regulations, licensing and gap analysis for the launch of a nuclear Heat Source from European territory<sup>24</sup>.

ArianeGroup has defined the nuclear safety requirements for the launch phase of the PULSAR RPS and has identified the roadmap for constituting the nuclear safety demonstration in the subsequent phases of the PULSAR development.

### **III.H. PULSAR roadmap**

The project proposal identified two main objectives to achieve higher technology maturity for the PULSAR RPS: establishing Pu-238 production capability in Europe and

proving the concept of a dynamic RPS powered by Pu-238. At the conclusion of PULSAR, a reflection has been done on how to organize the way forward to reach higher TRL: we outline the roadmap for future work, detailing the next steps and strategies to build upon our achievements and address remaining challenges. The development of the different technology bricks needs to take into account their integration in the final product and the necessary qualifications for the final launch phase and operational environment. We envisage that the integration with the spacecraft and its avionics occurs at a later stage while the qualification of the HS module and the Stirling engine can be performed independently. Additionally, flight qualification can be conducted in two steps: an initial flight qualification without Pu-238, simulating the heat source to reduce hazards and anticipate potential issues, followed by a second flight qualification with the radioactive source. The HS module assembly will take place at the launch site.

Technology development is assessed using the Technology Readiness Level (TRL) scale for space from ESA. Each high-level key objective is associated with a TRL to evaluate its state in dynamic RPS development. In Figure 5 a planning of the development, integration and qualification is proposed based on PULSAR assumptions. The timeline considers PULSAR achievements during the 2022-2024 project period, with subsequent steps marked as N+years, where N is the year in which the next development phase can start. Four technology bricks (Pu-238, clad fuel, HS architecture, and Stirling engine) require consistent development, which can progress in parallel. Once the mission is identified, mechanical and system integration with the spacecraft and its power management must be designed. Concurrently, nuclear safety files must be continuously updated, and the facilities involved in fuel production and TRL qualification must be adapted or designed and licensed.

In the proposed planning, considerations for each technology brick (e.g., Pu-238 production, clad fuel, HS architecture, and TEC, being the Stirling engine) are addressed. Pu-238 production is critical for the final RPS: without Pu-238 availability, the technology cannot receive final certifications. Funding to continue development at year N will allow Pu-238 production to begin within 10 years, given the assumptions in this roadmap. The development of other bricks can continue in parallel to the Pu-238 brick until TRL 6, simulating Pu-238 heat input when necessary. Afterward, obtaining Pu-238 for qualification tests is crucial. These tests should be achievable with limited amounts of Pu-238. In the PULSAR HS design, a clad fuel pellet contains 125 g of Pu-238, and a single heat source module contains 500g. Prototyping  $^{238}\text{PuO}_2$  pellets with Pu-239 and simulating hot pellet production can be developed. Consolidating the HS architecture design using European-produced materials

and manufacturing a Stirling engine with preliminary performance tests could be achieved in two years with continuous funding. Two additional years are needed to reach TRL 6 with performance demonstrations in relevant environments of cladded fuel, HS architecture design, and Stirling engine. A critical design review (CDR) is performed after component performance assessments. The next two years can focus on performance evaluation in operational conditions to increase TRL to 7. Flight qualification tests (TRL 8) are proposed in a decoupled manner: the HS module (cladded fuel + HS architecture) and the Stirling engine can be flight qualified separately to reduce risks. Once both parts are flight qualified, their design is finalized, and the HS module must be assembled with the Stirling engine at the launch pad. However, if a full RPS flight qualification with Pu-238 is required, flight qualification facilities will have to be compatible with Pu-238 presence. With this plan, the HS module and Stirling engine development bricks would be ready for in-flight testing within 8 years, while Pu-238 production could begin and ramp up 2 years later, assuming available Np feedstock and continuous investment in PULSAR RPS development. Throughout development, licensing for the envisaged amount of radioactive material must be performed and updated by facility owners.

While developing PULSAR RPS technology bricks, nuclear safety requirements and compliance must be addressed in parallel<sup>24</sup>.

#### IV. CONCLUSIONS

The PULSAR project has successfully laid the foundation for the development of the first European Radioisotope Power System (RPS) fueled by Pu-238. Throughout the project, important achievements were realized in various technological areas, including the production and

processing of Pu-238, the development of cladded fuel, and the design of a dynamic RPS using Stirling engines. These achievements mark a crucial step towards establishing a sustainable and independent European capability in space nuclear power systems.

Through collaborative efforts, the consortium was able to address challenges in the areas of nuclear safety, regulatory compliance and production of Pu-238 by optimizing target designs, improving irradiation processes, and developing robust safety frameworks. These solutions not only advanced the project’s objectives but also set a precedent for future endeavors in the European framework.

Looking ahead, the technologies and methodologies developed during the PULSAR project hold significant promise for future space missions. The establishment of a Pu-238 production capability in Europe and the successful demonstration of a dynamic RPS provide a strong foundation for further research and development. Continued investment and collaboration will be essential to fully realize the potential of these innovations and to achieve higher technology readiness levels.

The impact of the PULSAR project extends beyond its immediate goals, offering valuable insights and advancements that can benefit a wide range of applications in space exploration and beyond<sup>25</sup>. The project’s success underscores the importance of international collaboration and the need for a cohesive regulatory framework in Europe to support the safe and effective use of nuclear power in space.

In conclusion, the PULSAR project represents a significant milestone in the journey towards sustainable and efficient space exploration. The consortium’s efforts have not only advanced the state of the art in RPS technology in Europe

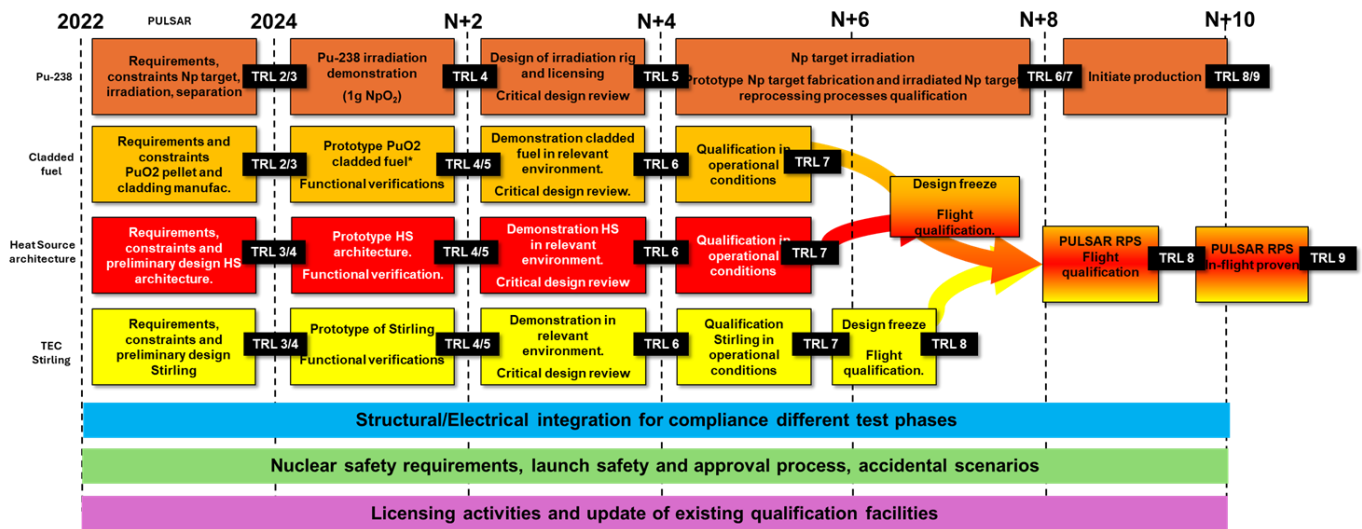


Figure 5. Proposed high level roadmap.

but also prepared the ground for future innovations that will continue to push the boundaries of what is possible in space exploration.

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