ESA Contract No. 4000135477/21/NL/GLC/my

Executive Summary Report (ESR)

Pu-238 Production Feasibility Study

20 June 2022

R. Van Parys	B. Spindler	B. Spindler
Written	Verified	Validated

Introduction

This document is the executive summary report (ESR) in relation with ESA Contract No. 4000135477/21/NL/GLC/my "PU-238 Production Feasibility Study".

Space missions operating in the inner solar system usually rely on photovoltaic solar cells as primary power source. However, these photovoltaic cells are not appropriate for all space missions, either because the solar radiation is too weak to produce sufficient power within the limitations imposed by today's solar cell technology and spacecraft mass and volume limitations, or because the timespan to be bridged by the batteries is too long (e.g. lunar or Martian nights).

Therefore, nuclear power systems have been deployed for heat (Radioisotope Heater Unit or RHU) and electrical power generation (Radioisotope Thermoelectrical Generator or RTG). Both systems do not rely on fission energy, as is common in nuclear power reactors on earth. Instead, radioactive decay is the primary energy source.

In previous ESA activities, two radioisotopes have been selected for nuclear power systems in space missions: Plutonium-238 (Pu-238) and Americium-241 (Am-241). Both isotopes are mainly produced in nuclear reactors today.

The Pu-238 isotope, already established as a space power source in the US and Russia, has a preference for several reasons:

- it has the highest power density making an extremely light and compact power source possible;
- there are few penetrating gamma radiations which makes it relatively easy to handle;
- it has a convenient half-life of 87.7 years, which is largely compatible with all envisaged space missions.

On the other hand, Am-241 has a greater availability but a lower power output.

The previous ESA activity assessed the costs associated with Pu-238 production to be undesirably high, while the level of investment for producing Am-241 in kilogram quantities was seen as realistic in the context of ESA programmes at that time. However, new information on the chemical separation and irradiation indicated that the previous estimates regarding cost of production may be outdated. With the aim to consolidate the options and decisions regarding the choice of radioisotopes for European RHUs and RTGs, this study will therefore investigate the feasibility and cost of the production of Pu-238 in the BR2 reactor at the SCK-CEN nuclear site in Belgium, using precursor material from the French reprocessing operations at La Hague.

Even though Pu-238 is being produced in nuclear fuel today, its relative concentration with respect to the other plutonium isotopes is very small (maximum a few percentages), whereas it is required by the technical specifications of the RTG and RHU to have a concentration of at least 82.5% of Pu-238. Therefore, the production of Pu-238 will proceed via neutron irradiation of Neptunium-237 (Np-237), which is created as a by-product in nuclear fission reactors and is currently located in the waste stream of the PUREX process in the La Hague fuel reprocessing facility. Bombarding Np-237 isotopes with neutrons in a nuclear reactor will produce temporarily Np-238 which will decay to Pu-238 in a few days.

This Pu-238 production feasibility study was performed by Tractebel, with Orano and SCK-CEN as subcontractors, in request of ESA. It looks at the technical possibilities to produce this isotope in Europe without relying on non-European partners. The cost and lead-time for setting up a Pu-238 production chain is evaluated.

Technical feasibility

The study shows the feasibility of extracting sufficient quantities of neptunium-rich (predominantly the isotope Np-237 with the longest half-life) regular waste stream from the La Hague (France) reprocessing facility operated by Orano. The extracted waste stream solution, which is a nitrate solution, will subsequently be purified by selective ion-exchanging resins and retrieval of neptunium by elution. This will result in a neptunium nitrate solution with a concentration of at least 1.35 g neptunium per liter, respecting purification requirements prescribed by the further processes at SCK-CEN.

The purified neptunium nitrate solution will then be transported from La Hague to the SCK-CEN site in Mol (Belgium) in a dedicated transport cask, which is still to be designed, licensed and manufactured. It is anticipated that such a cask will contain about 100 l of solution.

At the site of SCK-CEN, the front end operation starts from the neptunium nitrate solution provided by Orano and the neptunium nitrate recycled from subsequent process steps. In order to ease the neptunium handling, a separation of the decay product protactinium-233 (Pa-233), responsible for highly energetic gamma radiation, will be performed prior to the conversion to neptunium oxide (NpO_2) powder. The NpO_2 targets for irradiation in the reactor will be manufactured and different target designs are still open for consideration.

The neptunium targets will be irradiated in the high neutron flux reactor BR2 on the site of SCK-CEN. In this feasibility study it is assumed that 3 irradiation cycles, their typical length being about 28 days, will lead to an optimum compromise between a higher amount of Pu-238 bred on the one hand and a higher quality of the resulting plutonium vector (i.e. relative concentration of Pu-238 with respect to other plutonium isotopes) on the other hand. Afterwards, the irradiated targets need to be cooled between 12 and 24 months in the reactor pool for fission product decay and for reduction of Pu-236 isotope concentration to reduce heavy gamma radiation.

The cooled irradiated targets are subsequently dissolved in nitric acid whereafter the resulting nitrate solution is separated by solvent extraction techniques into a plutonium, a neptunium and a waste stream. The neptunium stream is purified and reused in the front end for target fabrication and the waste stream is stored and evacuated as high activity waste, its volume being small though.

The plutonium nitrate solution is then further converted into a plutonium oxide (PuO_2) powder, containing about 85% of Pu-238. The powder is pressed and sintered into cylindrical pellets, which are clad in an iridium based alloy pending transportation as a final product.

Even though the entire process still needs to be demonstrated on a laboratory scale, based on Orano and SCK-CEN experience and similar process experience world-wide, the technical process can be assumed feasible.

Process lead-time and volumes

Due to compulsory French regulatory requirements resulting from the proposed modifications of the La Hague reprocessing facility, the earliest availability of sufficient quantities of the precursor material neptunium is anticipated to be in early 2031. This time schedule is mainly determined by the fixed date of request for modification decree, which is set at mid-2025. It is supposed that the regulatory process forms the critical path, which will leave enough time for designing, licensing and manufacturing of a dedicated transport cask. Likewise, it should leave enough time for demonstration of the downstream processes at SCK-CEN and construction and licensing of the new facilities on site.

The study has a production of 300 g of plutonium per year as a working hypothesis. This production level cannot be achieved immediately since the delivered quantities of neptunium are about 135 g, which comes down to about 1 kg per year taking into account a rate of 8 transports per year. Considering a conversion ratio of about 5% (which means that 5% of the Np-237 is converted in reactor to Pu-238), the plutonium production will be limited to 50 g during the first year. In the following years, recycled neptunium from the processing of irradiated targets can be added to the delivered neptunium from Orano, increasing the yearly output of Pu-238. As such, the full capacity of 300 g plutonium production per year will be reached only after a ramping-up period which is foreseen taking up to 19 years after the first neptunium delivery. This ramping-up period can be reduced considerably by reducing the cooling time as much as possible and/or increasing the neptunium delivery (by volume and/or by concentration) during the ramping-up period. By optimizing the process in that way, a considerable reduction of the ramping-up period down to about 5 years only might be reachable. Once at full capacity the neptunium delivery from Orano can be reduced to only 3 deliveries per year.

Production costs

On Orano side, some plant modifications need to be performed as well as the construction of a neptunium purification facility and the fabrication of a new dedicated transport cask. On SCK-CEN side, three completely new facilities need to be erected: a neptunium target production facility, an irradiated target processing and separation facility and a plutonium pellet production facility. The total CAPEX investment for all this combined is estimated to be about 156 M€ (-50%/+50% accuracy).

The total yearly costs, considering a production of 300 g of Pu per year, for both Orano and SCK-CEN, is estimated to be between 8.85 and 16.35 M€ per year. About 50% to almost 75% of this recurrent cost is attributed to the cost of irradiation in reactor which is currently highly uncertain and responsible for the broad cost range. Irradiation cost will depend on the chosen target type, the available target channels in the reactor as well as on the specific reactor operation costs.

Taking both the CAPEX and OPEX into account, and considering a period of investment amortization of 40 years, the total Pu cost can be estimated to about 57 k€ per gram plutonium for the production of 12 kg of plutonium during 40 years of operation. What matters for the use of the final Pu product is the produced heat. Taking into account a plutonium heat production of 0.476 W/g, the total cost can be converted to a total average estimated cost of 119 k€ per Watt.

A comparison with a previous Areva study given by ESA as reference RD1. G. Poli, "Eurad Final Report". Areva TA, April 2010. TA-1202682, Ind. B is shown in the following table which demonstrates the proximity of Am241 cost estimations and the current updated Pu238 estimations.

	AREVA STUDY (EC 2010)		ORANO - SCK CEN - TRACTEBEL (EC 2022)
	Am241	Pu238	Pu238
CAPEX (M€)	120	400	160
OPEX (M€/yr)	12	25	9-17
k€/Watt	100-150	100-150	93-145

EC : Economic Conditions

Final considerations

A European Pu-238 production process is technically feasible even though it will require well more than 12 years after project decision to reach a full capacity of 300 g Pu per year.

There are still many opportunities for cost reductions in the estimated cost of 119 k€/W by optimizing the different process steps, e.g.:

- increasing the Np concentration of the extracted product;
- optimizing target design to achieve a high production rate at high quality;
- combining Np purification steps after Np extraction and after target irradiation in a single workshop;
- reducing ramping-up period by speeding up early Np deliveries;
- etc…

Furthermore, if the actual reactor irradiation cost can be minimized, this will have a highly beneficial impact on the total price, being for a large part determined by the cost of that step. This could reduce the Pu production cost by up to 28%.

And finally, the CAPEX costs, even though they only consist of about 25% of the total Pu cost, could be reduced considerably by taking advantage of existing facilities elsewhere in Europe that could host the front end and back end facilities for target production and processing, without having to build new facilities from scratch. This would more than compensate the cost increase due to transportations to and from the irradiation reactor.

To assist the optimizations and to fine-tune the remaining uncertainties, it is recommended to perform demonstrations on laboratory scale of the different process steps. This should be covered by a demonstration budget in the range of 3 to 5 M€. It concerns resin qualification, demonstration of production yields, demonstration of solvent extraction process, handling tests of Pu-238, etc...

It can be concluded that European production of a Pu-238 power source for space missions is worth being considered as an interesting alternative. A follow-up feasibility study should focus on process optimizations, for which there still appears to be a lot of margin, driving down costs and speeding up full capacity production. At the same time, this follow-up feasibility study could select the best site(s) in Europe suited for production of Pu-238 at minimal costs and with the highest technical chances.

*   *

*