



The long History of Promises by Accelerator-driven Systems

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Abstract. The concept of using accelerator-driven systems (ADS) to transmute high-level radioactive waste has recently regained attention. In such systems, selected radionuclides are converted into other (radio)nuclides through nuclear reactions, particularly fission. ADS couple an external neutron source to a subcritical reactor, offering greater flexibility in fuel composition. Although the idea dates back several decades, no systems have yet been implemented.

5 We argue that the core technological concept remains largely unchanged from earlier proposals and therefore inherits many of the same challenges – notably high costs and engineering complexity. We examine the potential role of radioisotope production as an additional revenue stream beyond electricity generation and waste incineration in more detail. We find that proponents' claims are unlikely to materialize at scale.

1 Introduction

10 *"Electricity is but the fleeting byproduct from nuclear reactors. The actual product is forever deadly radioactive waste"* is a frequently cited statement by Michael Keegan from the Coalition for a Nuclear-Free Great Lakes in Canada (NIRS, 2026). While the term "forever" is subject to interpretation, it is widely acknowledged that high-level radioactive waste must be managed over unprecedented time spans. Despite broad consensus among scientists and practitioners that deep geological repositories represent the most viable option for final disposal, progress in their implementation has been slow. To date, only
15 Finland has entered the trial operation phase of a deep geological repository (Kraev, 2025).

Against this background, the concept of Partitioning and Transmutation (P&T¹) repeatedly gains attention in the context of radioactive waste management. The approach is based on separating spent nuclear fuel into different material streams (partitioning), enabling the recycling of fissile and fertile materials, while reducing the inventory of selected long-lived radionuclides — primarily minor actinides — through irradiation (transmutation). This is generally expected to reduce the long-term radiotoxicity of the remaining material for final disposal. However, despite several decades of research and development, industrial-scale
20 implementation of P&T fuel cycles has not yet been realized.

Within the range of proposed transmutation technologies, ADS are often considered the most flexible option. They consist of a subcritical core that multiplies neutrons supplied by an external source, typically generated via spallation reactions. A schematic overview of an ADS is shown in Figure 1. The main safety advantage of an ADS is that the core remains subcritical:

¹Abbreviations: ADS - Accelerator-driven System; ATW - Accelerator-driven Transmutation of Waste, EA - Energy Amplifier; IAEA - International Atomic Energy Agency; MA - Minor Actinides (mainly Neptunium, Americium, Curium); P&T - Partitioning & Transmutation;

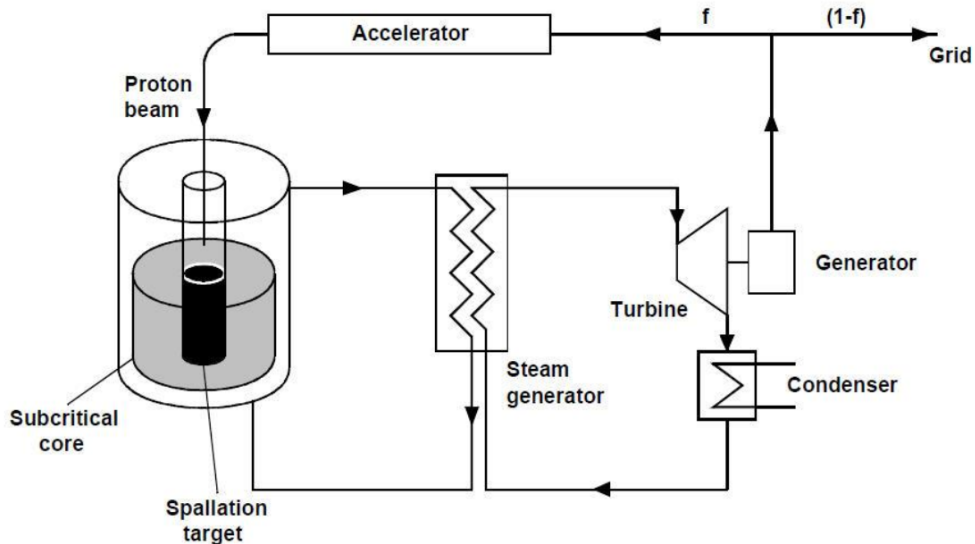


Figure 1. Schematic of an accelerator-driven system (ADS). Particles from a particle accelerator strike a spallation target (black), producing neutrons that multiply in the subcritical core (gray). The thermal power produced in the subcritical core and spallation target is removed by the primary coolant and transferred, via a steam generator, to a secondary loop and then converted into electricity through a turbine-generator set. A fraction of the electricity f is used to operate the facility, especially the accelerator. The remaining electricity is exported to the grid. (Figure source: Xenofontos (2018))

25 it only multiplies the neutrons supplied by the external source and cannot sustain a chain reaction. The neutron population in the core is therefore controlled by the strength of the external source, which can be rapidly reduced or stopped by shutting down the particle accelerator.

This subcritical configuration enables the use of fuels with comparatively high minor actinide fractions (up to $\approx 40,0\%$ in some design studies), whereas in critical reactors the fraction is usually limited to a few percent due to safety and feedback
30 constraints.

While ADS have been extensively studied from a technical perspective, fewer studies systematically examined the persistence of underlying design assumptions and the robustness of associated economic claims.

We argue that current ADS concepts do not constitute a fundamentally new technological solution, but largely reproduce design principles and system assumptions that have been discussed for decades, together with their associated challenges.
35 Building on a historical overview and an assessment of the current state of development, we identify key technical and systemic constraints that remain unresolved.

Furthermore, we assess recent efforts to broaden the value proposition of ADS by incorporating additional revenue streams beyond electricity generation and waste transmutation. Using radionuclide production as a case study, we evaluate the credibility of such claims and their potential contribution to the overall economic viability of ADS facilities.



40 2 History of ADS for Transmutation

The basic technical parts of ADS – high-energy proton accelerators, spallation targets to produce neutrons, and subcritical multiplying assemblies – were developed separately.

45 Already in 1940, three possible ways of particle acceleration had been demonstrated (Bryant, 1992). The idea of coupling particle accelerators to subcritical assemblies emerged at Livermore National Laboratory and Chalk River Laboratory shortly after World War II (Lucia and Grisolia, 2024). The goal was the production of fissile material using neutrons generated from a spallation source. This option drove research in the following decades (Pistner et al., 2023, p.284).

50 An interest in ADS for energy production and waste transmutation increased in the late 1980s and early 1990s. In the U.S., Bowman et al. developed the idea of using an accelerator-driven neutron source for commercial nuclear energy production and transmutation of fission products and actinides (Bowman et al., 1992). Bowman's 1998 review provided one of the first systematic quantitative assessments of ADS for nuclear waste transmutation, comparing thermal and fast ADS cores and establishing reference ranges for subcritical multiplication factors ($k_{\text{eff}} \approx 0.95\text{--}0.98$) and achievable actinide destruction rates under various fuel-cycle assumptions (Bowman, 1998). The U.S. *Accelerator Transmutation of Waste (ATW)* program starting in the mid 1990s examined high-current linear accelerators (typically 1 GeV, 10–30 mA) coupled to subcritical systems optimized for transmutation of minor actinides and selected long-lived fission products. It emphasized high overall actinide destruction 55 fractions under multiple recycling schemes (Beller et al., 2001).

The U.S. Department of Energy published a *"Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology"* in 1999 (DoE, 1999). This was three years after the National Academy of Sciences had already stated that "[n]one of the dose reductions seem large enough to warrant the expense and additional operational risk of transmutation" (NRC, Committee on Separations Technology and Transmutation Systems, 1996).

60 At CERN, Rubbia et.al. proposed the *Energy Amplifier (EA)*, a fast-spectrum, lead– or lead–bismuth-cooled subcritical reactor driven by a 1 GeV proton beam with currents in the order 10 mA (Carminati et al., 1993; Rubbia et al., 1995). The shift from a thermal to a fast neutron spectrum was expected to improve transmutation efficiency and to enhance fuel utilization through the breeding of additional fissile material. One of the claimed features of the EA was that criticality accidents, one major cause of nuclear accidents, would be suppressed (Rubbia et al., 1995).

65 Later, detailed system studies indicated that limited actinide recycling in thermal reactors provides only a comparatively small benefit for repository utilization. A quantitative assessment for the U.S. Yucca Mountain reference repository showed that limited recycling of plutonium and minor actinides in pressurized water reactors increases the allowable repository loading by only about a factor of two compared to once–through disposal (Wigeland et al., 2007). This can be considered in relation to the efforts required to implement such a cycle and the expectations associated with transmutation fuel cycles.

70 The EA and ATW concepts triggered a series of international scenario analyses by the International Atomic Energy Agency (IAEA) and OECD Nuclear Energy Agency (NEA), which formalized ADS terminology and compared ADS-based transmutation strategies with once-through and fast-reactor-based closed fuel cycles (NEA, 2006, 2002; IAEA, 2004, 1998). These studies generally position ADS as dedicated burner systems within broader P&T strategies rather than stand-alone power



75 technologies (NEA, 2006, 2002; IAEA, 2004, 1998). They indicated that recycling and fissioning all plutonium can reduce the long-term radiotoxicity of high-level waste by about an order of magnitude relative to once-through operation, and that additional efficient burning of minor actinides in fast-spectrum systems (including ADS) could, in principle, further reduce long-term radiotoxicity and decay heat by factors exceeding 100, provided very high overall destruction fractions and separation efficiencies are achieved (Salvatores, 2005). Some of those studies also mention the relevance of fission products.

80 Europe emerged as a focal region for ADS development, with the Belgian MYRRHA concept as the most advanced example. Initially conceived as a 40 MW_{th} experimental facility driven by a 350 MeV, 5 mA proton accelerator, MYRRHA evolved into a lead–bismuth eutectic-cooled fast-spectrum ADS with a 600 MeV, up to 4 mA linac (2.4 MW beam power), designed as a multipurpose research facility for materials irradiation, fuel testing, ADS dynamics experiments, and transmutation studies (Abderrahim et al., 2001; Bruyn et al., 2015). Within the EU’s 6th and 7th Framework Programmes (2002-2013), two reference designs building on MYRRHA were developed: The *MYRRHA-FASTEF* core as an experimental demonstrator and the
85 *EFIT* (European Facility for Industrial Transmutation) as a conceptual 400 MW_{th} industrial ADS dedicated to minor actinide transmutation (Artioli et al., 2008; Mansani et al., 2012; Sarotto et al., 2013). None of these systems has been realized so far.

90 Taken together, this historical development suggests a considerable degree of continuity in the central design logic of ADS, namely the combination of a high-power accelerator, a spallation target, and a subcritical multiplying system (Figure 2). While design details and intended applications have evolved over time, many of the underlying concepts remain comparable. Contemporary ADS concepts thus build on earlier approaches, with several of the challenges identified in early studies continuing to shape ongoing research efforts.

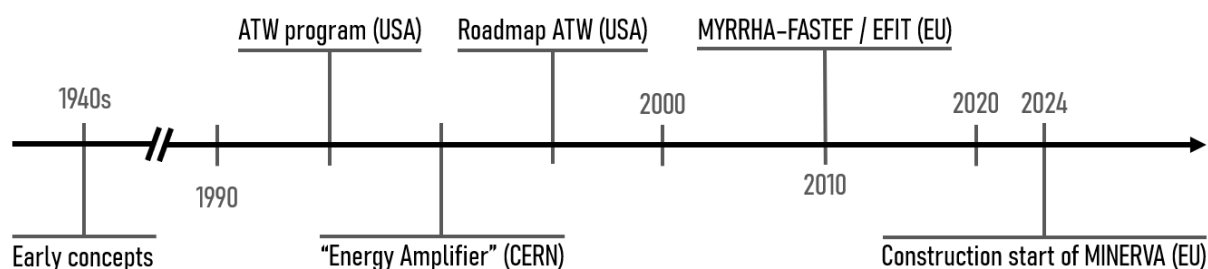


Figure 2. Timeline showing the evolution of accelerator-driven systems (ADS). In the 1940s, basic concepts of ADS were demonstrated. In the 1990s, the USA developed the Accelerator Transmutation of Waste (ATW) program, and a corresponding Roadmap was published, while at CERN, the Energy Amplifier (EA) was proposed, shifting from thermal to fast neutron spectrum reactors. Since the new millennium, European projects like MYRRHA and EFIT emerged, leading to the start of construction of MYRRHA’s reactor part MINERVA. To date, no industrial-scale systems have been implemented.



3 Current State of Development

There are several approaches to assessing a technology's readiness for deployment. The most widely used is the Technology Readiness Level (TRL), originally developed by NASA. Pistner et al. (2023) discuss different approaches and their applicability to nuclear systems in detail. In their study, ADS are assessed as being in the "applied research" phase: key components (high-current accelerators, megawatt spallation targets, fast cores, advanced fuels) have been demonstrated individually, but not yet as a fully integrated, industrial-scale power or transmutation plant (Pistner et al., 2023; Abderrahim and Giot, 2021). Existing spallation neutron sources for research operate at a maximum level of a few MW and validate spallation target concepts. Industrial ADS transmuters would require neutron sources in the 10–20 MW range and long-term, high-availability operation that has not yet been demonstrated in an integrated ADS configuration (Pistner et al., 2023). To date, no prototype ADS has operated anywhere in the world, and development remains limited to research facilities, experimental setups, and conceptual designs rather than integrated industrial-scale systems.

A broad portfolio of low- and medium-power ADS-related experiments (FEAT, TARC, MUSE, YALINA, MEGAPIE, TEF-P, etc.) has provided data on source-driven reactor physics and target behavior, while industrial-scale concepts such as EFIT (400 MW_{th}) remain at the conceptual-study level and have not progressed to licensing or construction (Pistner et al., 2023). MYRRHA (Belgium), a multi-purpose research facility, not a commercial plant, is the most advanced ADS project worldwide. The construction of MINERVA, the reactor part in the MYRRHA ADS, started in 2024 and is currently planned to be commissioned in 2036 (myrrha aisbl/ivzw, 2026a). Accelerator reliability is identified as a central technical bottleneck. For MYRRHA, safety and availability requirements limit beam interruptions longer than 3 s to less than 10 times per 90-day operating cycle (Vandeplassche, 2011). Such performance levels have not yet been demonstrated in an integrated ADS environment (Pistner et al., 2023; Abderrahim and Giot, 2021).

Even though one of MYRRHA's stated applications is nuclear waste treatment, it should be noted that this does not refer to the actual treatment of radioactive waste. One purpose of MYRRHA is to conduct experiments using fuel with high minor actinide content. Most of the reactor elements use once-recycled MOX-fuel (Sarotto et al., 2013).

Other countries such as China and Japan are conducting limited research on ADS (Kurata et al., 2002; Yan et al., 2017; Wang et al., 2016; Sasa, 2015; Liu et al., 2025; Fu et al., 2025; Liu et al., 2025, 2024). All of these projects are in the applied research state at best (Yee-Rendón, 2022). Overall, current activities remain focused on component validation, experimental facilities, and conceptual design studies rather than on prototype operation or industrial deployment.

4 Assessment of Transmutation Systems

Already in 1996, it was stated that P&T cannot "eliminate" the need for a final repository for high-level radioactive waste (NRC, Committee on Separations Technology and Transmutation Systems, 1996). The assessment of transmutation systems is therefore not only a question of the theoretical performance of an irradiation facility but also of system-level constraints across the entire fuel cycle. In this context, it is important to distinguish between theoretical radiotoxicity-reduction potentials and repository-relevant performance indicators. Repository capacity is typically constrained by factors such as decay heat and waste



125 volume, rather than by radiotoxicity metrics alone. This is also acknowledged by proponents of P&T systems (Abderrahim and Giot, 2021). This is particularly relevant for fuels with high transuranic contents, as considered in ADS concepts, which are associated with higher decay heat and may therefore affect repository design and capacity constraints.

Partitioning and transmutation do not eliminate the need for geological disposal, nor do they fundamentally alter repository design requirements under limited recycling schemes. The dominant limitation arises from the need to dispose of the final
130 generation of recycled fuel, in which transuranic elements are concentrated, thereby largely offsetting the gains achieved through process waste separation.

Several studies were published at the end of the 1990s that assessed systems for transmutation more critically (Liebert et al., 1999; Husson and de Montgolfier, 1999; Birraux, 1997). These studies identified significant challenges and development risks. Among the well-known and, to date, unresolved issues is the problem of proliferation. As already mentioned above, the origin
135 of ADS lies in the motivation to produce fissile materials. Many high-energy accelerators were further developed in U.S. weapons laboratories after the end of the Cold War (Frieß and Liebert, 2018). But the more important proliferation risk is the fact that almost every implementation of a transmutation fuel cycle requires separating the fissile material from the spent fuel, thereby removing the radiation barrier that provides self-protection and makes the material difficult to handle.

Another crucial aspect that remains unclear is whether the required separation efficiencies can be achieved. For example,
140 in 1998, the IAEA assumed a separation factor of 1:10,000 (corresponding to a separation efficiency of 99.99%) (IAEA, 1998). The separation efficiency is crucial for the overall efficiency of the transmutation system: the losses during each cycle accumulate in the material that needs to be sent to final disposal.

Assuming ten recycling steps in a transmutation scenario and a continuous supply of spent fuel entering the separation facility, even with a separation efficiency of 99.99% per step, about 0.1% of the initial inventory of the target radionuclides
145 would enter the waste stream.

An OECD/NEA Study of 2018 showed only limited progress on the availability of processes for spent fuel treatment ending in separated material streams (NEA, 2018). Today, as summarized in Table 1, the efficiencies envisaged for potential transmutation scenarios have not yet been achieved at the laboratory scale. With an efficiency of 99.9%, as reached by most laboratory processes, losses in the separation step already amount to approximately 1% of the initial inventory. This must be considered
150 in relation to the ton-scale initial inventory, as even 1% represents a significant quantity of material.

Other development risks include achieving sufficient accelerator availability in continuous operation, demonstrating the safe operation of metal-cooled subcritical systems, and the practical feasibility of the spallation targets (Englert et al., 2024; Frieß et al., 2021).

Even if these technological challenges are resolved, the question of the benefit of minor actinide transmutation remains open.
155 While early concepts considered the transmutation of both minor actinides and certain fission products, more recent proposals tend to focus on minor actinides. This is sometimes justified by the claim that minor actinides are especially relevant to assessing the hazard of a final repository, in contrast to the relevance of fission products when assessing risk (Stanculescu, 2013). However, it is precisely this risk—and thus the long-lived fission products—that is most pertinent to the safety assessment of a final repository (Schmidt et al., 2013). The focus on minor actinide reduction via fission leads to an increased produc-



Table 1. State of the art in separation efficiency. The listed efficiencies should be seen in relation to the assumed value of 99.99% in IAEA (1998).

Process	Target elem.	Efficiency	Data source	Reference
PUREX	U, Pu	99.88%	Industrial Operation	IAEA (2008)
DIAMEX	An & Ln	99.8%	Laboratory	Modolo et al. (2007)
i-SANEX	Am, Cm	99.9%	Laboratory	Wilden et al. (2022)
EURO-GANEX	Am, Np, Pu	99.9%	Lab (Hot test)	Lyseid Authen et al. (2022a)
CHALMEX	Am	99.9%	Laboratory	Lyseid Authen et al. (2022b)
Advanced TALSPEAK	Am, Cm	99.9%	Laboratory	Wilden et al. (2017)
HPLC	Am, Cm	96-97%	Laboratory	Bosbach et al. (2022) Zsabka et al. (2023)
TODGA-based	Am, Ln	99.97%	Laboratory	Bosbach et al. (2022) Sasaki et al. (2022)
PhenCN-based	Am, Cm	>99.9%	Laboratory	Bosbach et al. (2022)

160 tion of long-lived fission products in the final waste stream (Frieß and Liebert, 2018, 2022). This aspect is not captured when
 considering radiotoxicity alone. Nevertheless, Council Regulation (Euratom) 2025/1304 explicitly identifies "*radioactive waste
 165 minimisation and reducing the radiotoxicity of this waste*" as eligible areas for funding.

5 Motivations for ADS Systems

The main motivation for Rubbia and his colleagues in proposing their concept of an ADS, dubbed "*Energy Amplifier*" (EA),
 165 was to design a system for energy production (Rubbia et al., 1995; Carminati et al., 1993).

Bowman et al. (1992) already made "*waste transmutation*" a more prominent part of their design. This idea persisted,
 even though the potential benefit for final disposal of high-level radioactive waste have been continuously questioned in the
 literature (NRC, Committee on Separations Technology and Transmutation Systems, 1996; Frieß et al., 2021; Schmidt et al.,
 2013).

170 Producing electricity using nuclear power plants is generally associated with relatively high costs compared to other forms
 of electricity generation: "*The prospects for the expansion of nuclear energy remain decidedly dim in many parts of the world.
 The fundamental problem is cost*" was stated in a famous MIT study (Buongiorno et al., 2018). This did not change, even
 if storage as needed by volatile renewables is taken into account (Lazard, 2025; CSIRO, 2024). Nuclear projects in Western
 countries are typically only bankable if governments provide financial risk mitigation or support mechanisms (Weibezahn and
 175 Steigerwald, 2024).

This issue becomes more pronounced when considering fast ADS: as a rule of thumb, metal-cooled fast reactors are esti-
 mated to be about 20-40% more expensive than light water reactors (Mooz and Siegel, 1979). The BN-800 had 20% higher
 cost than the VVER-1200 (WNA, 2021).



180 Studies on the economics of the back-end of the nuclear fuel cycle indicate that fast reactors represent one of the more costly options considered (NEA, 2013). Exact cost estimates remain difficult due to the limited number of fast reactors in operation (Braun, 2012). In addition, the particle accelerator represents a substantial cost component (Rubens, 2024). Its size, which is a major driver of cost, is determined by the required particle energy (Kirchner et al., 2015, p.86). Consequently, developer are exploring additional revenue streams by expanding the range of potential products. One declared option is the production of radioisotopes.

185 More recent designs, such as the ADES facility promoted by Emerald Horizon propose the provision of process heat for hydrogen production in addition to electricity generation, while aiming to avoid the production of transuranic waste (Mueller, 2024). The START facility from Transmutex offers not only transmutation of already existing high-level radioactive waste but also process heat, district heating, and radioisotope production (Houben et al., 2025). The similarity of these concepts to earlier designs is not coincidental: Federico Carminati, who was part of the team developing the EA, is the founder of Transmutex.

190 **6 Production of Radionuclides**

Radionuclides have various applications in medicine, industry, and research. In medicine, they are central to diagnostic nuclear imaging (e.g., single-photon emission computed tomography (SPECT) using technetium-99m and positron emission tomography (PET) using positron emitters such as fluorine-18) and to targeted radiopharmaceutical therapies, where radioactive compounds deliver cytotoxic radiation to tumors while enabling patient-specific dosimetry and treatment planning (NEA, 195 2019; IAEA, 2020).

In industry, radionuclide sources are widely used for non-destructive testing and process control, such as industrial radiography to inspect welds and castings, gauging devices to measure thickness, density, or fill levels, and well logging to characterize subsurface formations, as penetrating radiation can probe sealed systems where optical or mechanical sensing is impractical (Moussa et al., 2025; Pant et al., 2022).

200 In research and academia, radionuclides function as tracers to quantify transport, mixing, residence times, and reaction pathways in complex systems, supporting both laboratory experiments and field studies across chemistry, biology, environmental science, and engineering (Moussa et al., 2025; IAEA, 2020).

There are two principal methods of producing radioisotopes: either by irradiation of targets or by the extraction of fission products from spent nuclear fuel.

205 Examples of radioisotopes that are produced by irradiation are Lutetium-177, which is used in targeted radionuclide therapy, and Molybdenum-99/Technetium-99m for nuclear imaging. Technetium-99m has a half-life of 6 hours, which makes direct transport over longer distances highly challenging. Therefore, a so-called "*Technetium-99m-Generator*" is supplied, in which Molybdenum-99, with a half-life of 66 h, serves as a parent nuclide. Lutetium-177 has a half-life of 6.6 days.

210 These physical decay properties illustrate the limitations on transport and, consequently, on market structure. In addition, these materials are subject to strict transport regulations while simultaneously having to meet pharmaceutical quality standards.



The second way of production is the separation of radioisotopes produced during the nuclear fission process from irradiated nuclear fuel. Examples are Caesium-137 and Strontium-90. These isotopes are generated by the fission of fissile material during reactor operation.

215 While both power and research reactors produce such isotopes, commercially relevant quantities are obtained primarily through the reprocessing of spent power reactor fuel. Separating them from irradiated fuel requires facilities capable of handling highly radioactive material.

Consequently, the number of suppliers is limited, and those are located in countries with large-scale nuclear programs. This results in a geographically concentrated supply structure and potential geopolitical dependencies.

220 Strontium-90 is primarily used in industrial applications such as thickness gauges and calibration devices, while also serving niche functions in medicine and research (Pant et al., 2022; Salem and Thurston, 2006; Chakravarty, 2012). Its half-life of approximately 29 years makes it suitable for long-term applications and international trade. However, as a high-activity radioactive source, its production, transport, and disposal are subject to stringent regulatory control under international radiation protection and nuclear security frameworks, and price transparency is limited compared to conventional commodities (IAEA, 2018). The global market for Strontium-90 is estimated to range between US\$10-200 million, with projected growth to US\$12-225 250 million by 2032. Estimates vary substantially depending on methodology and data availability (24chemicalResearch, 2025; Intel Market Research, 2025; Synorah Systems, 2026). Purity levels and chemical form vary according to application requirements. Based on available estimates, reported prices range between US\$10,000-50,000 per GBq (24chemicalResearch, 2025; Intel Market Research, 2025).

230 The first group of radionuclides does not necessarily have to be produced in a nuclear research reactor; alternative production routes, such as a cyclotrons, are also available. Nevertheless, the prospect of generating revenue and thereby reducing the burden on public finances is frequently cited as a justification for incorporating radioisotope production into research reactors (NEA, 2019; European Commission, Joint Research Centre, 2021; Krásny and Belko, 2025).

235 The research reactor FRM-II in Munich, Germany, was also presented as a facility for isotope production (Gerstenberg and Waschowski, 1997; Axmann et al., 1997). It provides radioisotopes for diagnostics and therapy and is considered to contribute to mitigating supply shortages in Europe (ENS, 2022).

The BR2 research reactor in Mol, Belgium, supplies medical isotopes to the market, and its successor MYRRHA is also intended to do so (myrrha aisbl/ivzw, 2026b). Originally oriented as a commercial project, it is argued that the shift towards a transmutation facility was driven in part by the aim of scaling up the project, and aligning it with the European research landscape (Brookhuis, 2023).

240 The Belgian government announced in 2018 that it would cover 40% of the costs (Dalton, 2018). Six years later, work on the first phase of MYRRHA started (WNN, 2024). Commissioning of user facilities is now planned to start in 2030 (SCK CEN, 2026). As of 2026, the project continues to "seek international partners and investors" for the following phases (myrrha aisbl/ivzw, 2026c).

245 Currently, the High-Flux Reactor (HFR) in Petten, Netherlands, with a thermal power of 45 MW, supplies approximately 60% of Europe's and 30% of the world's medical radioisotopes. This aging reactor is intended to be replaced by the 55 MWth



PALLAS reactor, which aims to "*secure the global production of medical isotopes*" (NRG PALLAS, 2026b). Originally planned to be commercially financed, the project is now substantially supported by public funds (NRG PALLAS, 2026a).

The Transmutex START plant, currently under design, primarily aims at the transformation of nuclear waste but also intends to generate revenue through the sale of radionuclides. While MYRRHA and PALLAS primarily emphasize irradiation-based isotope production, the START concept additionally relies on the separation of fission products from existing streams. In 2025, a detailed study of the concept, including a business case, was published. The study outlines multiple projected revenue streams and concludes that the facility could operate on a commercial basis even under a conservative scenario (Houben et al., 2025, p.174).

These projects illustrate a broader pattern in which isotope production is framed not only as a scientific objective but also as a revenue-generating component of large-scale nuclear infrastructure investments. In the following, we examine their estimated income from this revenue stream.

7 Example: Estimated Revenue from Radionuclide Production

Transmutex plans to separate Caesium-137 and Strontium-90 from spent nuclear fuel for commercial application, including potential medical use (Houben et al., 2025, p.174). In addition, radionuclides such as Lutetium-177, Molybdenum-99/Technetium-99m, Terbium-149, Actinium-224, Plutonium-238, and Gadolinium-148 are projected to be produced via irradiation (Houben et al., 2025, p.175).

The estimated turnover for irradiation-produced radionuclides is summarized in Table 22 in Houben et al. (2025, p.193). For three isotopes, no price data are provided due to limited market transparency (Houben et al., 2025, p.180).

Reported price estimates per GBq are based on email communication with private suppliers; it remains unclear whether these represent buyer or seller prices. Using the values provided, the combined annual turnover for Lutetium-177, Molybdenum-99/Technetium-99m and Actinium-225 amounts to less than EUR 15,000. This corresponds to well below 0.1% of projected annual facility revenue in both scenarios and is therefore economically negligible at the facility scale. Given the regulatory and pharmaceutical quality requirements associated with medical radionuclides (e.g., purity and quality assurance), this revenue appears limited relative to the infrastructure scale of the proposed facilities.

In the negative scenario analyzed in the study, total facility turnover is projected between EUR 250-850 million over the reactor lifetime (Houben et al., 2025, p.180). This lower revenue trajectory reflects the absence of electricity sales and more conservative assumptions regarding isotope monetization and energy-vector revenues. However, even under these assumptions, irradiation-based radionuclide production does not materially affect total revenue (Houben et al., 2025, p.188). In contrast, radionuclide recovered via reprocessing, notably Strontium-90, constitutes a major component in both scenarios.

The projected annual turnover of EUR 50–200 million therefore implies that a single facility would account for a substantial share of current global Strontium-90 market volumes (NEA, 2019). The economic viability of this revenue stream is consequently highly sensitive to assumptions regarding market absorption and long-term price stability. The financial model treats price assumptions as exogenous and does not explicitly account for potential price adjustments resulting from increased supply.

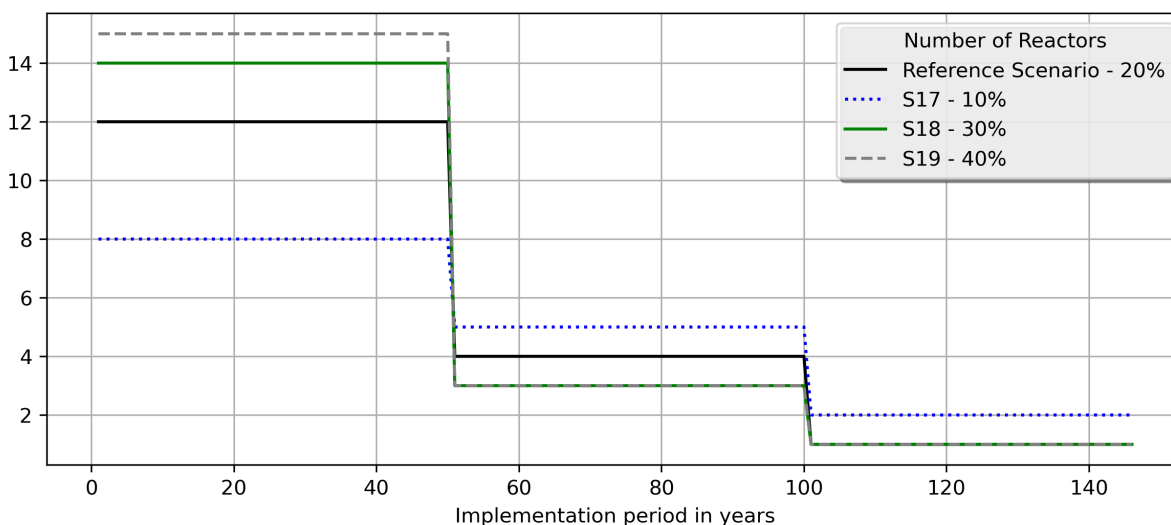


Figure 3. Number of sub-critical reactors in transmutation scenarios for different transmutation fractions. Reactor lifetime is 50 Years. The figure ends as soon the scenario with the shortest implementation period reaches the cut-off criterion. Other scenarios may last for several hundred years. The figure is taken from Englert et al. (2026). In this report, more than twenty scenarios were evaluated to assess the influence of different parameters. Scenarios *S17*, *S18* and *S19* show the influence of different transmutation efficiencies (10%, 30%, and 40%, respectively) on the reactor numbers if all other parameters, e.g., target reduction or separation efficiency, stay the same.

Houben et al. (2025) further restrict their analysis to a single facility reactor site. The scenarios, therefore, do not constitute a system-wide assessment of a transparent, reproducible nationwide system description for the treatment of the full German high-level waste inventory (HLW). Additionally, key modeling parameters and interim results are only partly documented. Additional scenario analysis has been conducted by Englert et al. (2026), which suggest that, under more conservative assumptions regarding transmutation efficiency and inventory constraints, multiple reactors would be required to process the German transuranium inventory.

One key outcome of those nationwide scenarios is the number of reactors actually needed. This number is highly dependent on the boundary conditions used in the scenario analysis. In particular, assumptions regarding transmutation efficiency significantly affect the required reactor fleet size. While parts of Houben et al. (2025) refer to efficiencies of approximately 40%, other sections implicitly assume complete transmutation. To assess the impact of the transmutation efficiency, a parameter study was conducted (Englert et al., 2026). Figure 3 presents the number of START reactors required to cover the total German TRU inventory under varying efficiency assumptions. These scenarios assume continuous full-capacity operation over a 50-year lifetime, except for the final unit in the phase-out period. The authors do not explicitly consider that the reprocessing units are designed to serve four reactors each, thus implying that it would be more economical to have reactor numbers in increments of four operating.



What is evident from the scenarios: in the first phase of a potential P&T program using the START reactor, there would
295 be around ten facilities operating. As discussed above, even one facility generates a significant share of the global market for
Strontium-90, which is seen as a potential revenue stream. It is unlikely that the projected revenues would be fully realized if
additional facilities were deployed.

8 Conclusion

*"Forty years of complex research and development has [sic] shown that ADS could provide a solution to the challenge posed
300 by spent nuclear fuels"* state Hamid Ait Abderrahim, the General Manager of the MYRRHA INP, and his colleague Michel
Giot (Abderrahim and Giot, 2021).

ADS represent a highly complex technology. In particular, within partitioning and transmutation (P&T) fuel cycles, not only
must reactor operation be reliably controlled, but advanced reprocessing and fuel fabrication technologies are also required.
Given the current state of science and technology, it remains uncertain whether all the necessary components can be developed
305 to industrial maturity.

Even if one assumes that the required technologies could be made available, the question of overall benefit remains open.
Various metrics exist for assessing radioactive waste; while they do not necessarily contradict one another, each addresses
only specific aspects of waste management and disposal. Comprehensive, system - level assessments remain limited. Those
studies would not only outline the full-scale infrastructure needed to treat a given inventory, but also systematically evaluate
310 the implications for final repositories.

This uncertainty regarding the overall effectiveness of transmutation is reflected in the trend to assign an increasing number
of additional applications to transmutation facilities in order to enhance their attractiveness. One frequently cited example is
the production of radioisotopes for potential revenue generation.

As illustrated by the example of the START facility, the promise of generating income through the production of radioiso-
315 topes is unlikely to be realized at a scale that materially affects overall facility economics. Claims of substantial economic
returns from radioisotope production should therefore be treated with caution.

More generally, it is notable that the idea of a simple technological solution to the radioactive waste problem repeatedly re-
emerges, often with only minor modifications. At the same time, progress in the search for and operation of final repositories
for radioactive waste continues to be slow. This contrast underscores the need for a careful and critical assessment of proposals
320 that present themselves as straightforward or comprehensive remedies to a fundamentally complex challenge.

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Yannick Vogt: Analysis



Code and data availability. This study did not involve the use of custom code or software scripts; therefore, no code is available.

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325 *Disclaimer.* The authors prepared the original draft, while generative AI was used solely to refine the grammar and style. The authors take full responsibility for the content.

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