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Scenario Analysis for Partitioning and Transmutation (P&T) in a Phase-out Scenario

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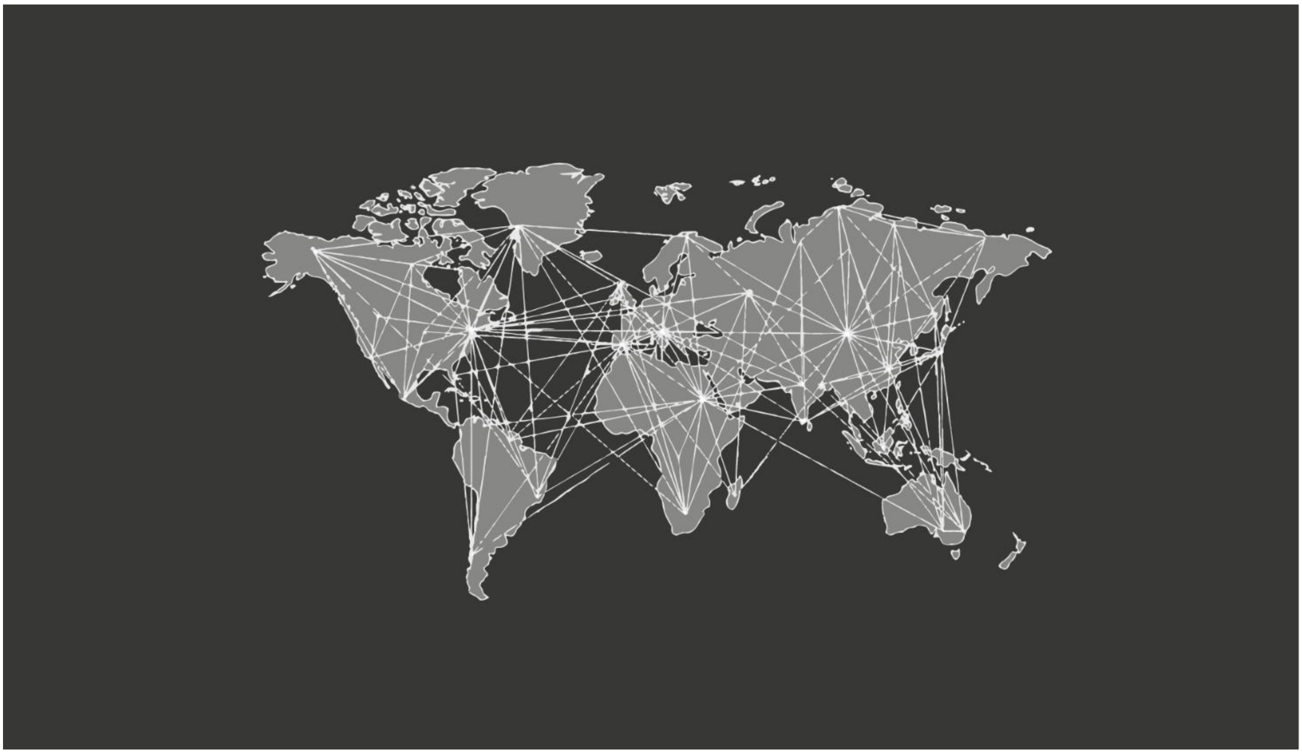

Authors

Dr. Matthias Englert
Dr. Christoph Pistner
Yannick Vogt, MSc
Dr.^{in} Friederike Friess

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Tel: +43 (1) 47654 81821
Mail: info@inrag.org
URL: http://www.inrag.org/

INRAG Office
Institute of Safety/Security and Risk Sciences (ISR)
University of Natural Resources and Life Sciences, Vienna (BOKU)
Peter-Jordan-Straße 76/I, 1190 Vienna, AUSTRIA

ZVR: 173 253 9393

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1 Introduction

In February 2025, the German Federal Agency for Disruptive Innovation (SPRIN-D) published the "Implementation Study on an Accelerator-Driven Neutron Source at the Site of a Former Nuclear Power Plant" (Houben et al. 2025), proposing an alternative waste management option. This type of radioactive waste management is often summarized under the broader term of Partitioning and Transmutation (P&T). The SPRIN-D study has been critically assessed with respect to its assumptions, feasibility, and expected benefits for Germany e.g. by the German Federal Ministry for the Safety of Nuclear Waste Management (Bundesamt für die Sicherheit der nuklearen Entsorgung 2025).

The P&T scenarios in the SPRIN-D study address only a narrow and highly constrained case. They do not provide a transparent, reproducible nationwide system description for the treatment of the full German high-level waste inventory (HLW). Additionally key modelling parameters and interim results are only partly documented. Under the explicit assumption of hypothetical technical feasibility, based on documented parameters and literature values, this INRAG study estimates what a national implementation of a P&T scenario in Germany based on Transmutex' START concept could entail.

After briefly outlining the background, we define a consistent set of scenario parameters and justifying the chosen values. We then present the modelling results, such as the number of facilities and time periods required under the stated boundary conditions, followed by a discussion of selected potential safety implications of operating a full-scale system over multiple decades. The analysis is limited to technical and system-dimension aspects.

For readers who are new to partitioning and transmutation (P&T), concise introductions to the underlying motivation, system concepts (fast reactors vs. accelerator-driven systems), and the main technical constraints are available in e.g. (Kirchner et al. 2015; Frieß and Liebert 2018; Frieß et al. 2021; Englert and Mohr 2023; Pistner et al. 2024).

2 Background

The basis of the study is a P&T overall system based on the START reactor concept developed by Transmutex and assessed in the said SPRIN-D study (Houben et al. 2025).

The basic assumption for a P&T overall system is that, with an appropriate fleet of reactors, the entire German inventory of high-level radioactive waste from LWRs could be treated. Any nationwide P&T implementation necessarily involves more than a single reactor unit, the irradiated fuel requires interim cooling, subsequent reprocessing (partitioning), and refabrication into new fuel for further irradiation and the necessary transport.

A nationwide "overall system" based on the proposed concept can be defined as a fleet of accelerator driven reactors (ADS) and associated fuel-cycle facilities that, in principle, could treat the entire German inventory of high-level radioactive waste from light-water reactors as well as the irradiated MOX fuel. Key parameters that govern the scale of the system are

- the initial inventory to be treated;
- the reactor-specific consumption rate (transmutation rate) of transuranium elements (TRU) per cycle;
- irradiation, cooling, and processing times (i.e., cycle length/time);
- partitioning efficiency (losses to waste per cycle);

- facility lifetimes; and
- the target definition for residual TRU sent disposal.

As far as possible, these parameters are taken from (Houben et al. 2025) and are placed into context using literature values and earlier German system studies (Pistner et al. 2024; Frieß et al. 2021) and will be discussed in the next section. The national inventory basis follows the current German waste inventory documentation (BMUV 2023)

For some parameters, such as transmutation rates, Houben et al. (2025) employs idealized assumptions (e.g. complete or instantaneous transmutation). Within the scope of this report, such assumptions are treated as sensitivities rather than a baseline. The primary optimization objective is a short overall implementation period, motivated by the termination of nuclear power generation in Germany and to avoid unnecessary burdens on future generations. Sensitivity scenarios will be used to illustrate the efficiency of the overall system and trade-offs between shorter duration, fewer facilities, and lower residual waste.

The key metrics for assessing a phase-out P&T scenario, as we model here for Germany, are the achievable reduction of the initial inventory and the time and costs required to reach that reduction. These metrics are intrinsically coupled: the lower the residual inventory targeted, the greater the required effort, because additional transmutation passes, longer operation, and better separation performance are needed. In scenarios with continued nuclear power generation, the assessment shifts from reducing a fixed legacy inventory to balancing ongoing waste generation against transmutation capacity. In long-term dynamic scenarios with evolving reactor and fuel-cycle technologies, the relevant quantities are the cumulative waste generated over the full implementation period and across the entire fuel cycle, together with the associated system costs. (Pistner et al. 2024)

The modelling is based on previous work to simulate hypothetical P&T scenarios for Germany (Frieß et al. 2021; Kirchner et al. 2015).

3 Scenario Parameters and Model Variables

In this section we describe the assumptions for the scenario comparison.

3.1 Input Parameters

In this section we describe the input parameters and their values as derived from (Houben et al. 2025). We compare them to literature values as well as to the choice of a standard scenario as used in (Kirchner et al. 2015; Pistner et al. 2024). This standard *Scenario S* was used for sensitivity studies in scenario (chapter 4.1) *and* is also used in this work for comparison to a thorium ADS fuel cycle *reference* Scenario *R (*also numbered as scenario 12*),* on which further variation-scenarios (scenario 12-28) are based for the sensitivity analysis. All parameters are explained in the following and summarized in Table 1.

Irradiation Time

Fuel is irradiated in the reactor for several years. During this period, a certain percentage of the initially loaded TRU inventory is consumed through fission. As a rule, the longer the fuel can remain in the reactor, the greater the fraction of the initial inventory that is fissioned. Usually, the irradiation time in the reactor core is limited by the fact that the fuel does not contain enough fissile material anymore.

Houben et al. (2025) assume an instantaneous transmutation (p. 57), which is a modelling assumption but not practical. They also give irradiation times of 4-7 years (p. 48) as a reference and claim that once the TRU stock is empty the reactor inventory can successively be reduced until no fissile content is in the reactor anymore (last core problem). This would increase irradiation time to achieve a certain transmutation efficiency, as neutron multiplication would be decreasingly available with diminishing fissile content and neutrons would increasingly come from the spallation reaction. Typical times for irradiation in a transmutation reactor core are 3 - 5 years (Frieß et al. 2021; Pistner et al. 2024; Renn 2014) based on achievable burnups.

We assume a reference of 3 years irradiation time. This is varied with a 5-year irradiation time.

Processing Time

After reactor operation, the spent fuel must be stored before reprocessing to allow its radioactivity and associated decay heat to decrease. Only after this interim cooling period is the fuel reprocessed, yielding separate TRU. As a rule, the longer the fuel was irradiated in the reactor, the longer the required cooling time. The separated TRU must then be fabricated into new fuel, and this fuel must be loaded for the next reactor cycle; the time needed for these steps constitutes the processing time. The cooling time depends on the composition of the spent fuel and on the reprocessing methods to be used. Accordingly, the range reported in the literature is broad, with typical values between 5 and 10 years (NEA/OECD 2002).

Houben et al. (2025) assume five years of cooling time (p.19).

We assume a reference of 3 years of cooling period and 2 years for fuel fabrication leading to a total processing time of 5 years. This is varied with processing times of 3, 7, and 10 years.

Transmutation Fraction per Cycle

The transmutation fraction describes how much TRU is destroyed during one fuel cycle. A higher transmutation fraction per step reduces the number of steps needed to achieve a targeted reduction of the initial inventory. Because each step requires one full cycle time to complete, the combination of per-step transmutation fraction and cycle time, together with the desired overall reduction, largely determines the total implementation period.

In the literature on accelerator-driven systems (ADS), per-cycle transmutation efficiencies are typically reported in the range of 10–20%, with about 5–10 cycles required depending on the targeted residual inventory (Renn 2014). These figures generally do not refer to thorium-based fuels. The literature on transmutation efficiency for thorium-based fuels is sparse. A recent publication reports per-cycle minor-actinide transmutation rates in thorium-based fuel of roughly 10–20% (Li 2024). It is, in any case, not meaningful to quote a single, averaged efficiency across all TRU, since individual isotopes behave differently—curium can even be built up rather than fissioned in TRU based fuel cycles (Pistner et al. 2024). Analyses of fast reactors with U–Th fuel show americium accumulation when americium is added to the fuel (Korobeinikov et al. 2022).

Houben et al. (2025) report on p. 63, that a TRU content of 26–29% (all percentages by weight unless otherwise noted) is reduced to approximately 20% at end of life (EOL). From this, transmutation efficiencies per reactor pass can be estimated to be between 0.23 and 0.31.

At the same time, the study states that "about 40% of the transuranic isotopes would be converted per reactor cycle" (p. 64). Without a different definition of "converted" or additional mass-balance information, this statement is not consistent with the above implied per-cycle efficiencies.

We assume a reference of 20% transmutation efficiency. This is varied with transmutation efficiency of 10, 30 and 40%.

Initial Inventory

The initial inventory is the total stock of TRU (mainly plutonium, neptunium, americium, curium) that will be available for treatment at the start of the scenario. It defines the baseline stock to be considered.

Houben et al. (2025) consider only the inventory at a single, unspecified site, where 14,058 kg of TRU are assumed to be contained in 1,426 spent fuel assemblies (p. 65). They further assume that even already vitrified waste canisters could be routed to transmutation (p. 9). However, the inventory data for these vitrified canisters is not reported, although they state that the retrieval of TRU from already vitrified waste is in principle feasible (p. 17).

We use the numbers for the total amount of spent fuel as of December 31, 2023 (BMUV 2023). Assuming that the TRU fraction stayed the same and using the spent fuel composition as presented in Schwenk-Ferrero (2013), this yields 148 t TRU as a baseline inventory. This total includes TRU in German LWR UOX and MOX spent fuel, VVER spent fuel and in vitrified waste.

In the following analysis, the isotope-specific composition of this transuranic quantity over time is not further examined. In a real transmutation system, however, the isotopic composition would change significantly over time—particularly, isotopes that are less readily fissionable in fast reactors would become enriched relative to more readily fissionable isotopes.

Target Reduction

The achievable target reduction is limited by the fact that, in every cycle, a fraction of the available TRU is diverted into the waste stream. In practice, a P&T scenario will also end with some TRU remaining in the fuel of the last reactor in operation. The residual inventory therefore consists of the cumulative TRU losses during reprocessing and the reactor inventory left at the end of the scenario. To achieve the same target reduction with a lower separation factor, the end-of-scenario reactor inventory must be reduced accordingly, which in turn increases the required implementation time.

Many scenario analysis assume very high target reduction, up to 99.0 - 99.9% (Renn 2013). These values are derived from the assumed losses during reprocessing that are multiplied by the number of cycles. They further assume an unlimited stock of TRU to be fueled into the system.

Houben et al. (2025) assume complete transmutation in their scenario (page 57). This assumption is based on the claim that once the TRU inventory is empty the reactor inventory of fuel elements will successively be reduced until no fissile content is in the reactor anymore. This will be achieved by replacing fuel elements in the outer core with dummy elements successively. This process would only end once almost no fissile material was present anymore. However, this would increase irradiation time, as successively neutron multiplication would be decreasingly available with diminishing fissile content and neutrons would increasingly come only from the spallation reaction.

One trade-off in scenario design therefore is between target reduction and number of irradiation cycles.

Separation factor

In each cycle, the spent fuel must be reprocessed. The separation factor achieved in the process determines what fraction of the remaining TRU inventory goes into the waste stream and is no longer available for another transmutation step. The higher the separation factor the lower the overall losses that ultimately must be sent to final disposal. For transmutation, separation factors of 99.9% are targeted. By contrast, if only a separation factor of 99.5% is achievable, the losses during reprocessing would increase by a factor of five.

Literature reports efficiencies in the range of 99,9% for several processes. Most of those values are either shown on lab scale or through modelling.

Houben et al. (2025) state a separation factor of “almost 100%” (p. 58).

Given the literature’s “~99.9%” baseline (with “almost 100%” aspirational), we use 99.9% as the reference and 99.95% and 99.99% as best available guesses of the stretch and upper-bound scenarios.

Reactor Lifetime

Once becoming operational, a reactor is available for a certain lifetime with a nameplate capacity. Current commercial nuclear power plants were generally designed for an operating lifetime of about 40 years. Many have since received license extensions to 50 and 60 years, and in some cases up to 80 years. There is, however, no operational experience with accelerator-driven systems (ADS) at industrial scale from which reliable lifetime expectations could be derived. After the defined operating lifetime, the reactor fleet would need to be replaced after this time.

According to Houben et al. (2025), the minimum operating lifetime of a plant is 50 years (p. 3). We assume a facility lifetime of 50 years as a reference. This varies with reactor lifetimes of 40 and 60 years.

Reactor Power

The START facility’s power output is 604 MW (Houben et al, p. 15).

Fission Energy

The thermal output of the reactor determines how many radionuclides will be fissioned over the irradiation period. This value is defined by physical properties, namely the released energy per fission, that depend only slightly on the fissioned isotopes (U-235 ~ 202MeV, Pu-239 ~ 210 MeV, U-233 ~ 197 MeV). Typical values, depending on the fuel composition, are between 0.9-1.0 MWd/g. We chose an average value of 1MWd/gTRU for all calculations using UOX or MOX fuel.

When considering Thorium-based fuel, this value is of only limited value: for the simulation of a transmutation fuel cycle, it is of interest how many *transuranium* elements are fissioned, not how many fissile elements. The TRU consumption value reported by Houben et al. for START (30 kg TRU per 1 TWh of thermal energy) can be interpreted as an energy-normalized net TRU consumption. Assuming a standard fission energy release of 1 MWd/g, 1 TWh_{th} corresponds to a total fissioned mass of about 41.7 kg. If only 30 kg of this is net TRU consumption, then approximately 72% of the thermal energy is associated with TRU fission and the remaining ~28% must be provided by other fissile nuclides (in a thorium cycle, primarily U-233). This quantity should not be confused with the conversion ratio used in MOX-based fast-reactor scenarios (e.g. ASTRID scenario 8, where the conversion ratio describes net TRU breeding relative to TRU fission). In general, this lower value for thorium fuel leads to more reactors being needed to convert the same amount of TRU.

3.2 Calculated Parameters

In this section we describe the parameters that can be directly calculated from the input parameters (chapter 3.1).

The sum of irradiation time, interim storage (cooling) time, and processing time is the **cycle length**. It is the total time needed to irradiate the TRU in the reactor once, allow the fuel to cool, separate the remaining TRU from the spent fuel, and fabricate new reactor fuel from it. From the irradiation time of 7 years and a processing time of 5 years the cycle length for a full transmutation cycle for one batch of TRU is 12 years in Houben et al. (2025).

To reduce cost and necessity for reactors that would be operating only very briefly it is assumed, that the **In-core inventory (% of current TRU stock)** is not 100% at the begin of the transmutation campaign. Otherwise, there would be no stock of fresh fuel to reload the reactors after the first irradiation and the reactors would not be operating during the processing time. The In-core inventory therefore is only a fraction of the fuel determined by the ratio of irradiation to processing time, the rest is in storage (**Stored TRU**) (t=0). This also determines then the **initial thermal power** and the **initial number of reactors.**

The **target inventory** is simply calculated with the **target reduction** and the **initial inventory. Stored TRU (initial)** is the amount of TRU that cannot be loaded into the constant reactors at the beginning of the P&T campaign. **Separation Losses** are based on the separation factor.

3.3 Model Variables

In this section we describe the output variables of the models that are used for the presentation of scenario results later. Parameter variations used for the ADS thorium scenarios in section 4.3 are listed in Table 3.

A key performance metric for a phase-out P&T scenario is the **implementation period**, defined as the period from the start of the campaign until the specified **target reduction** is reached. The implementation time is largely governed by the cycle time, the per-cycle transmuted fraction, and the chosen target reduction**.** Some of the scenarios do not reach the target reduction as separation losses are bigger than the target reduction. For those scenarios we put an end when less than 100 kg TRU is available to fuel the last reactor.

If a constant per-cycle transmutation fraction is assumed, the remaining TRU inventory decreases approximately exponentially over successive cycles. As a result, the annual TRU fission rate and the required thermal power decline as well. The required number of reactors therefore decreases over time, roughly in proportion to the TRU stock. The cumulative number of reactors increases over the implementation period. The **total number of reactors** is necessary to transmute the TRU stock. For this reason, a fleet size derived from the time-averaged energy requirement can underestimate the peak capacity needed at the beginning of the program. A larger number of reactors is required initially to avoid extending the overall implementation time, with the required fleet shrinking as the inventory is depleted.

If a uranium-free fuel is used, the transmuted fraction of an initial TRU inventory corresponds directly to the amount of TRU eliminated predominantly by fission. The fissioned TRU mass is proportional to the fission energy released and therefore to the **thermal energy produced** by the transmutation reactors. In phase-out scenarios, this energy is generated within each cycle; consequently, the required reactor thermal power is set by the annual TRU throughput implied by the chosen transmutation and cycle time. In thorium fueled reactors, U-233 also contributes to fission in the reactor. This is integrated into the calculation by reducing the amount of fissioned TRU per cycle by 28% for phase-wise fixed-fleet scenarios, or by increasing the number of reactors in optimized scenarios.

In the following calculations, we adopt an optimistic assumption that partitioning and transmutation technologies exist for all TRU isotopes, although this is not currently the case and would require decades of R&D. For simplicity, we further assume identical separation efficiencies and transmutation fractions across isotopes. The results can therefore be seen as an lower boundary with more realistic scenario modelling leading to even longer implementation periods and higher number of reactors.

While most of the TRU inventory would be converted to fission products by fission, even with comprehensive separation and transmutation for Pu, Np, Am, and Cm, residual amounts of TRU would remain in the waste streams.

- After transmutation has finished, residual amounts of transuranic elements remain in spent transmutation fuel elements (**TRU in spent fuel**)
- For all separation processes, the achievable separation factor or separation efficiency is crucial to prevent residual amounts of the element being separated from remaining in the waste stream. The cumulative amount of separation losses are the **total separation losses.** The higher the separation factor, the lower the total losses that ultimately must be disposed of in a deep geological repository.
- In some scenarios not all TRU can be used, and some TRU stays in storage (**Rest of TRU in storage**).

Finally, the target reduction achieved in the scenario is noted (**Resulting Target transmutation**).

All model parameters are summarized in Table 1.

Table 1: Scenarios Parameters for the standard scenario of an ADS with inert-matrix fuel (IMF) and the START facility.

Parameter	Standard scenario ADS + IMF	SPRIN-D
Inputs		
Irradiation Time (y)	3	4-7
Processing Time (y)	3	-
Transmuted fraction per cycle (%)	10	40
Initial TRU Inventory (t)	140	14.1
Target reduction (%)	10	0
Separation factor (%)	99.9	100
Reactor lifetime (y)	40	min. 50
Fission Energy		
Reactor power (MW)	400	600
Calculated Variables		
Cycle length (y)	6	~12
In-core inventory (% of initial TRU stock)	50	-
Thermal power at t=0 (GW)	6.4	0.604
Number of reactors at t=0	16	1
Target inventory (t)	14	0
Model Variables - Results		
Implementation period (y)	148	98
Total separation losses (t)	1.2	0?
Total number of reactors	33	10?

Source: First column own calculations. Second column Houben et al. (2025).

4 Scenarios

This section presents the results of some simulations for using ADS in phase-out scenarios. As a reference, we report some previous results in Section 4.1 before we discuss our model assumptions in Section 4.2 and then show the results for phase-wise fixed-fleet scenarios based on a Thorium-fuelled ADS in Section 4.3.

4.1 Previous results – optimized P&T scenarios with minimum implementation time

The following section is slightly adapted from Pistner et al. (2024) and describes previous analysis of ADS in phase-out scenarios. We reproduce it here as a background for the reader and as context for the scenario analysis.

In the scenarios (1-11) listed in Table 2 a standard scenario (S) is varied. The assumption is made that the number of reactors is not optimized for cost, but rather for transmutation. E.g. the amount of material to be transmuted in each year is fixed by the transmutation fraction and the amount of TRU in that year. The number of reactors is then derived by calculating the necessary reactor power which gives the number of reactors needed. This scenario is optimized to achieve the maximal possible transmutation per year for the fixed transmutation fraction and therefore optimizes the implementation time. However, this approach can shorten reactor lifetime to only several years for some reactors, especially during the start of P&T implementation.

The calculation is based on information in Renn (2014) and varies parameters of the P&T scenario in order to make corresponding sensitivities visible. The starting point is a phase-out scenario with an initial inventory of 140 t TRU in the European Facility for Industrial Transmutation of Minor Actinides (EFIT). This accelerator-driven system represents an initial conceptual design study for an industrial plant with a thermal capacity of 400 MW cooled with a lead-bismuth alloy (Artioli et al. 2008). The subcriticality of the reactor is characterized by a criticality factor of keff = 0.97. This choice was based on previous studies on the XADS and XT-ADS designs (IAEA 2015). The spallation neutron source for EFIT is to be operated with a current of 20 mA and a proton energy of 800 MeV at an output of 16 MW (Biarotte and Müller 2011; Biarrotte et al. 2015).

EFIT is to be operated with fuel with an inert matrix. The ratio of minor actinides to plutonium in the fuel is to be selected in such a way that the plutonium balance is equalized over the duration of use in the reactor, i.e. plutonium is neither burned nor produced (“isobreeder”). This results in a plutonium content of approx. 45% with 55% minor actinides (Biarrotte et al. 2015). This ratio causes a relatively low loss of reactivity during burnup. This makes it largely unnecessary to use the spallation neutron source to compensate for reactivity losses during burnup, which requires a lower maximum power of the accelerator. As a result, the costs for the spallation neutron source can be reduced.

The industrial plant should achieve a transmutation rate of 35 kg of minor actinides per TWh and, at a capacity of 80-85%, thereby burn around 100 kg of minor actinides per year (Aït Abderrahim et al. 2021).

(Renn 2014) also contains a comparison with the now-aborted French sodium-cooled fast breeder project ASTRID, in which homogeneous MOX fuels with a maximum burn-up of 137 MWd/kg$_{HM}$ were to be used. In reactors with uranium in the MOX fuel, TRU is bred and the transmutation fraction is lower; this is considered by a **conversion factor** ≠ 0. This means that with the same transmutation fraction and the same cycle length, the required installed thermal output is greater. Therefore, either a larger number of reactors is required, or the individual reactor must have a higher thermal output. In scenarios with inert matrix fuels or thorium fuels the conversion factor is set to zero as no new TRU is bred (in thorium fuel however reactor power also increases to transmute a fixed amount of TRU due to fission of U-233). According to Gabrielli et al. (2015), in a fast reactor such as the ASTRID design, plutonium transmutation could be -13.2 kg/TWh in a configuration designed for Pu burning, with a homogeneous fraction of 25% plutonium in the fuel. In this concept, a small fraction of minor actinides would also be used (MA/Pu ratio 1/20). The reactor can also be optimized for MA transmutation.

Several scenarios of ADS deployment are compared in the study Kirchner et al. (2015). Column S in Table 2 details a scenario (standard scenario S) that would result from the use of accelerator-driven systems of the EFIT type with a thermal output of 400 MW and the use of uranium-free fuel (IMF) with a conversion factor of 0. Depending on the fuel matrix used and the composition of the transuranium content, an EFIT plant with a thermal output of 400 MW contains a transuranium inventory of around 4.5 t, which remains in the reactor for around 3 years. Alternatively, an SFR such as the ASTRID reactor concept can be used with 1200 MW thermal output (variant 8, Table 2) 5 years of irradiation time and 5 t TRU in the reactor. According to (Renn 2014), the transmutation rates for EFIT are 45 kg/TWh$_{th}$ and for ASTRID 13 kg/TWh$_{th}$ with a corresponding reduction of the TRU share of -11% and -13% per cycle. For ASTRID, the conversion factor is 0.7 because the fuel contains uranium, so the installed reactor power must be increased by a factor of 3.33 compared to the use of uranium-free fuel. When converting 126 t of transuranic elements (14 t of residual inventory), a total of about 345 GWy of thermal energy is generated, if the fission of 1 g of transuranic elements results in about 1 MWd of energy.

Since the fission of transuranic elements produces a roughly equal mass of fission products, the use of EFIT reactors produces 126 t of fission products from the fission of 90% of the initial transuranic inventory, or 135 t if the remaining transuranic inventory were reduced to 5 t. When using ASTRID reactors, the assumed conversion factor of 0.7 results in a power output that is 3.33 times higher and thus a correspondingly higher fission product output of 420 t or 450 t.

If a target reduction of waste to 10% of the initial inventory (target reduction) is assumed when using EFIT reactors (remaining inventory 14 t, column S in Table 2) approximately 25 cycles (6 years cycle time) with a transmutation fraction of 10% is necessary to reach the target reduction. The number of cycles required increases if the target reduction is 5 t (variation 1 in Table 2) and the total implementation time of P&T treatment also increases to 242 years, as does the loss of TRU during partitioning. If a separation factor of 99.9% is assumed for all transuranic elements, this results in a residual amount of 0.84% of the initial transuranic element inventory in the waste stream, at the end of the entire P&T treatment, due to the frequent recycling (Kirchner et al. 2015). If the cycle time increases from 6 years to 8 years or 10 years, the implementation time also increases from 148 years to 199 or 249 years (variations 4-6 in Table 2).

In particular, the interim storage time required before reprocessing can also assume significantly higher values. Even if the required interim storage time is increased to 8 years and the resulting cycle time is 13 years, the implementation time increases to 325 years (Variation 7). This shows that the cycle length is a critical factor for the feasibility of a P&T scenario. If the sum of the interim storage and processing times are equal to the irradiation time, 50% of the inventory could be in the reactors at any given time (variations S and 5). If, however, the sum of the interim storage and processing times is only half as long as the irradiation time, two thirds of the inventory currently in the reactor could be in the reactor and vice versa (variations 4 and 5).

If the transmutation fraction can be increased from 10% according to column S to 15% or 20% (variations 2 and 3 in Table 2), the required implementation time is reduced from 148 years to 97 or 72 years respectively. Conversely, a lower achievable transmutation fraction would lead to correspondingly longer implementation times.

Separation factors of 99.9% are aimed for during partitioning. If, on the other hand, only a separation factor of 99.5% can be achieved, the losses during reprocessing would increase by a factor of 5 (variation 9 in Table 2). Since the losses from reprocessing would already be greater than 5 t with this separation factor, a target reduction to 5 t would no longer be possible. Only with very high separation factors are high target reductions at all conceivable.

Table 2: Optimal Scenario (shortest implementation period) – EFIT (V1-V7, V9-V11) and ASTRID (V8)

		S	1	2	3	4	5	6	7	8	9	10	11
Input													
Irradiation time	y	3				5	3	5	5	5			
Cooling time	y	0											
Processing time	y	3				3	5	5	8	5			
Transmuted Fraction per Cycle	%	10		15	20								
Initial TRU inventory	t	140											
Target reduction	%	10	3,6										
Separation factor	%	99,9									99,5		
Reactor lifetime	y	40										30	60
Conversion ratio TRU(new)/TRU(fis)	-	0								0,7			
Reactor power	MW	400								1200			
Calculated Results													
Cycle length	y	6				8	8	10	13	10			
In-core inventory	%	50				63	37	50	38	50			
Thermal power (initial)	GW$_{th}$	6,4		9,6	12,8	4,8	4,8	3,8	3,0	12,8			
Number of reactors (initial)	#	16		24	32	12	12	10	8	11			
Target inventory	t	14	5										
Model Results													
Implementation period	y	142	216	94	70	190	190	239	360	239	164		
Total Separation losses	t	1,2	1,3	0,8	0,6						6,1		
Total number of reactors	#	33	36	37	41	30	30	29	29	33		39	25
Total energy produced	TWh	3.000								10.100			

Source: Numbers based on (Pistner et al. 2024) but slightly corrected modelling. S is the so-called standard scenario of an ADS system with uranium free fuel. Numbers are only shown if the values differ from the standard scenario for better readability.

The achievable target reduction is limited by the fact that in each cycle step a proportion of the existing TRU is transferred to the waste stream. In practice, at the end of a P&T scenario, a proportion of TRU will remain in the fuel of the last reactor in operation. To achieve the same target reduction with a lower separation factor, the reactor inventory remaining at the end of the scenario must therefore be reduced accordingly. This also increases the required implementation time (also variation 9).

If different reactor operating times of 30 or 60 years are assumed, this would result in a correspondingly larger or smaller number of reactors to be built in total (variations 10 and 11). The operation of the individual plants required for P&T results in operational waste, most of which would probably be classified as non-heat-generating.

4.2 Model assumptions

Houben et al. (2025) only consider the initial inventory of 14 t of TRU to be transmuted with a single reactor. Consequently, to scale this approach to the complete German inventory of currently 148 t, one would need to operate 10 reactors.

In the simulation presented in the previous section, the number of reactors was chosen in a way to get the minimal implementation time. This means that reactors were not necessarily operating their whole planned lifetime (Scenarios 1-11 in Table 2).

For the following simulations we assumed a reactor utilization not optimized for transmutation but for economic usage of the reactors (phase-wise fixed-fleet scenarios). This means that reactors must operate at 100% of their design power for the full reactor lifetime. We also assume that all reactors start operating at the same time. After one full reactor lifetime (one phase), the number of reactors is re-evaluated to determine the number for the next phase. The **number of reactors** for each phase is calculated by keeping 100% reactor power without running out of fresh TRU in the stockpile at the end of the reactor lifetime in each phase. See Figure 1 for a comparison of both modelling approaches.

The number of reactors decreases over the phases (e.g. 11 reactors for the first phase of 50 years, then 3 reactors etc.) until only one reactor is sufficient for the rest of the P&T cycle.

As long as fresh TRU remains in stock, this single reactor operates at 100% reactor power. After that, the reactor operates with an exponentially decreasing power and fuel inventory.

This procedure is continued until one of the two cutoff criteria is met:

- The scenario has reached the target reduction of the initial inventory.
- The minimum amount of fuel in the reactor is reached. This criterion mirrors that the power level of a reactor cannot be scaled down indefinitely. To calculate this inventory, we follow Houben et al. (2025, figure 45) which states that the last core consists of 12 fuel assemblies. Following that the minimum amount of fuel in the core is roughly 100 kg. This can be estimated by assuming 240 fuel elements in a full core (p. 64), TRU consumption of 134 kg TRU/y (p. 64), a transmutation fraction of 40% of the inventory per cycle (p. 64), and a cycle length of 4-7 years (p. 48), resulting in roughly 6-10 kg TRU per fuel element.

The values reported in Houben et al. (2025) are not fully internally consistent. the statement of 30 kg TRU per 1 $\mathrm{TWh_{th}}$ and 4.475 TWh th/a implies about 134 kg TRU/y, whereas a reactor operated at 600 $\mathrm{MW_{th}}$ for 330 days per year would produce 4.752 $\mathrm{TWh_{th}}$/y and thus consume about 143 kg TRU/y. This suggests that the annual TRU consumption is effectively calculated with a lower annual capacity factor (≈85%) rather than with 330 full-power days. We assumed conservatively no downtimes and a full 365 days of operation and a consumption of 158 kg TRU/y for a 600 MWth reactor in all caclulations.

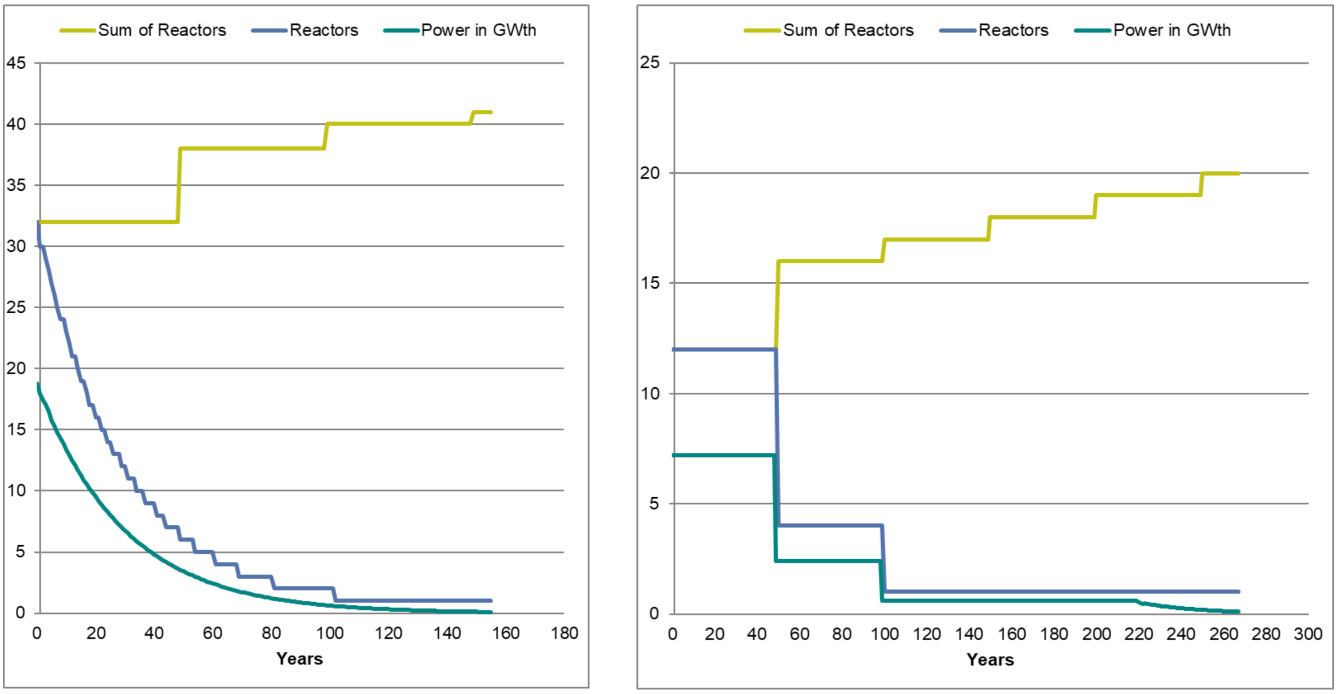

Figure 1: Reference Scenario R: optimal (as shortest implementation period) compared to optimum reactor utilization fleet (as reactors at full capacity for total lifetime) modelling. Plotted is the number of reactors operating at a certain point in time, the total number of reactors that need to be built and the operational power. For optimal transmutation the power decreases exponentially. This can be also seen as one reactor of the size needed is always available. For the modelling where reactors are expected to operational at full capacity during their whole lifetime, also the power shows a stepwise decline until last reactor in the phase-out scenario is reached. Here, the exponential decline is visible again.

4.3 Results for scenarios with optimum reactor utilization

Table 3 and Table 4 summarize thorium-ADS phase-out scenarios under the "optimum reactor utilization" modelling approach (as introduced in section 4.2) with a phase-wise fixed-fleet of reactors. In contrast to the "optimal fleet" cases reproduced in section 4.1 (Table 2), the reactor fleet is, with the exception of the last reactor, operated at full design power over the assumed plant lifetime, with stepwise fleet reductions across phases. This choice reduces the occurrence of very short-lived reactors, but it increases the implementation time because capacity cannot be perfectly matched to the exponentially declining TRU stock.

The optimum reactor utilization scenarios (S12 – S27) span implementation times of roughly 147– 535 years. "Deep" target reductions smaller than 1% residual TRU need several centuries. Separation losses remain generally below 0,7 ton for the assumed high separation efficiencies (typically ~0.6 t at 99.9%) for all elements but can exceed 1 ton in low performance scenarios (e.g. scenario 17: 1,36 t). The total number of reactors ranges from about 15 to 25 for the total German national inventory. Multiple fleet phases will be needed over long program durations.

Cycle length is one main driver for implementation time. With other parameters constant, increasing the cycle length from 6 years (Scenario 12) to 8 years (Scenario 13) increases the implementation period from 267 to 285 years. For a 10-year cycle length (Scenarios 14 and 15), the implementation time rises further to ~355 years, and for 13 years (Scenario 16) to ~439 years. This is similar to the results of earlier “optimal fleet” studies. Longer processing requirements directly stretch every transmutation cycle and therefore the overall implementation time of the campaign.

The assumed transmuted fraction per cycle (transmutation efficiency in the system model) is another dominant sensitivity. The baseline scenario assumes 20% (Scenario 12). Increasing the per-cycle fraction to 30% and 40% (Scenarios 18 and 19) reduces the implementation time substantially, down to 201 and 147 years, respectively. Conversely, reducing it to 10% (Scenario 17) increases the required duration (535 years). This is consistent with the basic stock-and-flow logic. Higher per-cycle depletion reduces the number of cycles needed to reach a given target and therefore shortens the implementation time for a P&T program. The impact of the transmutation fraction per cycle is illustrated in Figure 2 and in Figure 3. For both figures the graphical depiction ends when the shortest scenario reached the end of its implementation period after 147 years. The higher the transmutation fraction per cycle, the smaller number of reactors is needed in the second phase of the scenario. This allows for 15 reactors operating in the first phase of the scenario with the highest transmutation fraction. At the same time, the higher the transmutation fraction, the lower the total inventory of transuranium element: if less reprocessing and fuel fabrication cycles are needed, less material is lost – and consequently sent to final storage – during those steps.

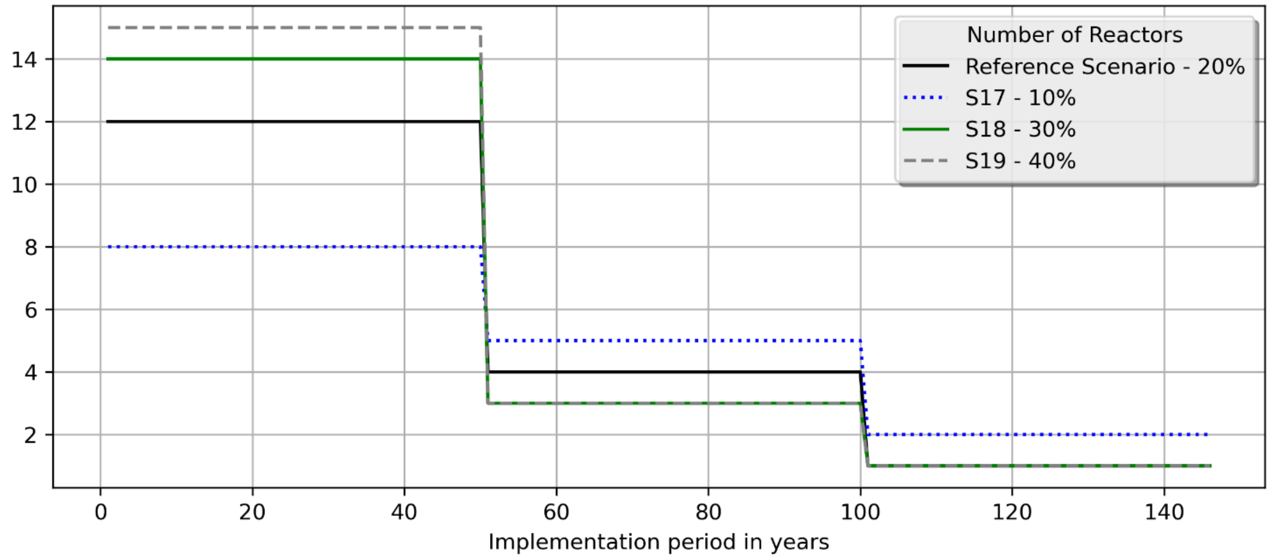

Figure 2: Number of Reactors per phase for scenarios with different transmutation fractions per cycle. The figure ends after 147 years of implementation time, when the first scenario reaches its target reduction. With higher transmutation fractions, one can start with more reactors, but the number drops faster during the different phases.

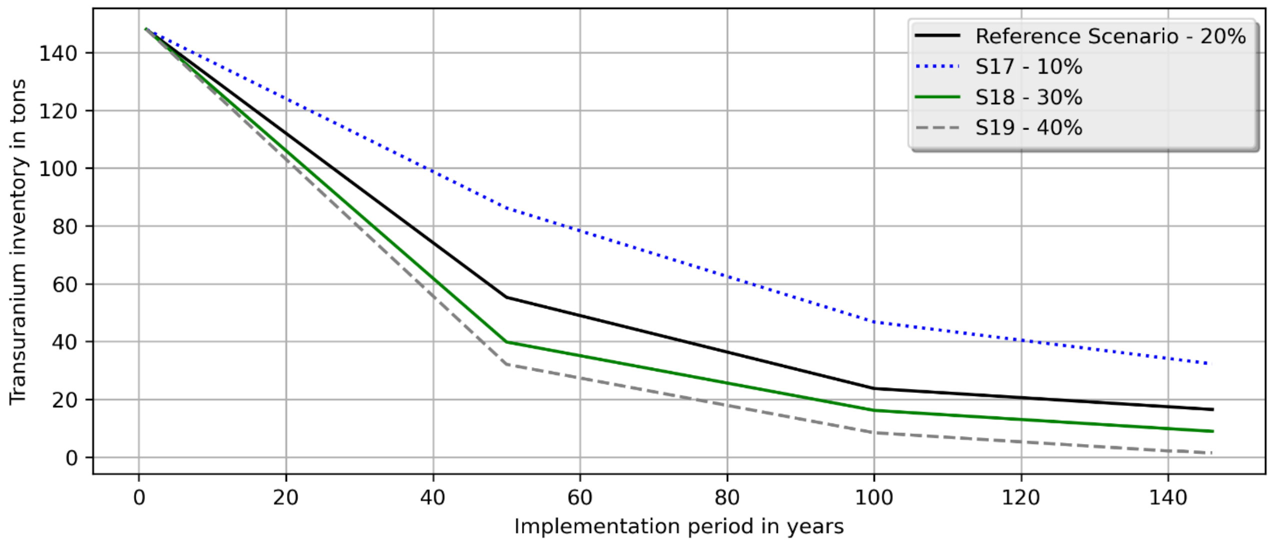

Figure 3: Transuranium inventory in tons. The figure includes transuranium mass lost during separation and fuel fabrication processes. The figure ends after 147 years of implementation time, when the first scenario reaches its target reduction.

The target reduction also is important for the implementation time duration. Scenarios with a relatively moderate target (e.g., 10% residual; Scenario 20) reach the target much faster (157 years), but they do so by definition with a much larger remaining TRU mass (~14.6 t residual). "Deep"-reduction targets (≤1% or ≤0.1%) lead to several centuries of operation, because they require many additional cycles. Furthermore, they become increasingly sensitive to irreducible losses (separation losses and end-of-program core inventories). This is also the reason why several scenarios stop due to the "cut-off" criteria. The model terminates when the last core can no longer be fueled above the cut-off threshold and different target settings yield identical outcomes in target reduction at the time once that threshold is reached (Scenarios 21 and 22).

The scenarios assume a narrow range of very high separation efficiencies (99.9% to 99.95%, and 99.99%). The separation losses are strongly affected. For example, raising the separation factor from 99.9% to 99.99% reduces the cumulative separation losses from the ~0.6 t level to values closer to ~0.06 t. At 99,999% the losses approach 0 t in the model, which is also assumed in the SPRIN-D case. This illustrates that separation performance is decisive for the achievable end-state (how low the residual TRU mass can be made without being dominated by losses). The campaign duration is primarily set by cycle length and transmuted fraction per cycle.

A recurring feature of the optimum reactor utilization approach is that the fleet must be sized for the early program phase, when the TRU stock is largest. As the inventory declines approximately exponentially, the required thermal power and reactor count drop. Successively other fleet phases need fewer reactors. This implies that time-averaged sizing can understate the initial capacity needed if the objective is to minimize implementation time. The stepwise fleet design used here makes this trade-off explicit. Initial overcapacity of the reactor fleet with "stranded" short-lived reactors like in the optimal scenario in Table 2 is avoided but leads to longer total implementation time.

The SPRIN-D case in Table 3 and Table 4 is not scaled to the full national inventory. It has only a single site with an inventory order of ~14 t TRU and one START unit. The model outcome highlights the core scaling issue. A single unit can only sustain full-power operation while sufficient “fresh” TRU exists in the stockpile. Thereafter, power must decline as the inventory is depleted. In the SPRIN-D case the model stops at an implementation time of 147 y at the cut-off of 100 kg TRU. In Houben et al. (2025, p. 65) it is stated that it will take 98 years to treat the whole inventory at the reactor site.

The example of a single reactor does not really represent a national implementation scenario. Treating the full national inventory requires a fleet at multiple sites plus the complete associated fuel-cycle infrastructure.

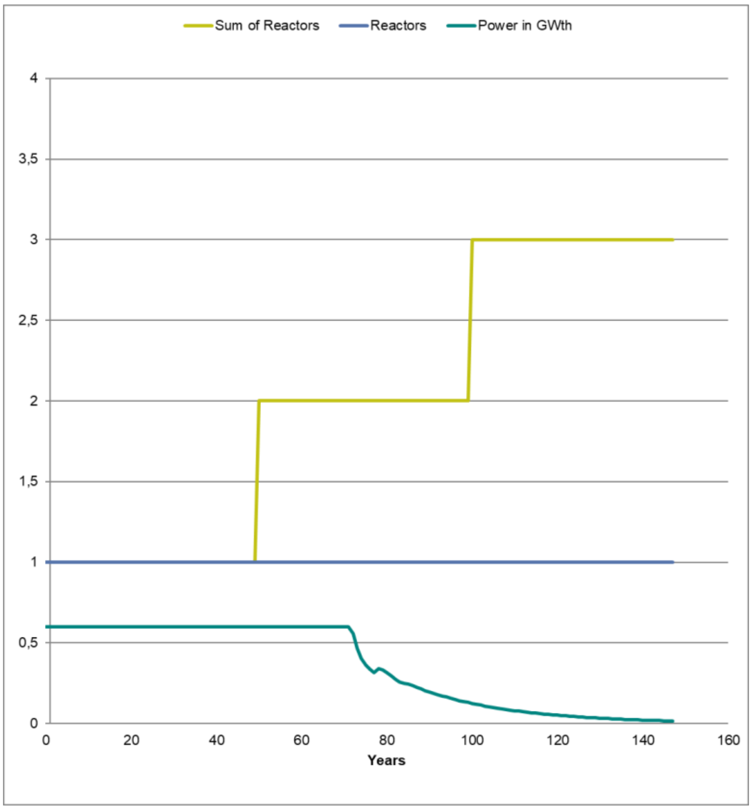

Figure 4: Scenario 28 – the SPRIN-D case. This modelling does not cover the total German inventory as the other scenarios do, but only one single site inventory of about 14 tons.

Table 3: Thorium ADS Scenario – Input Variation

Input Parameters		**R (12)**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**SPRIN-D**
Irradiation time	y	3	5	7														7
Cooling time	y	3		3	7	10												5
Transmuted fraction	%	20,00					10,00	30,00	40,00									40,00
Initial TRU inventory	t	148																14
Target reduction	%	1						2		10	0,1	0,01						0,01
Separation factor	%	99,900											99,950	99,990				99,999
Reactor lifetime	y	50													40	60		
Nr. of Reactors Phase 1	#	12	10	9	10	9	8	14	15						14	10	8	1
Nr. of Reactors Phase 2	#	4	5	5			5	3	3						5	3	3	1
Nr. of Reactors Phase 3	#	1	2	2	2	2	2								2			
Fraction of fission energy from TRU	%	1															0,7	
Calculated Parameters																		
Cycle length	y	6	8	10	10	13												9
In-core inventory	%	50	63	70	30	23												44
Thermal power (initial)	GW_{th}	4,2	6	5	6	5	5	8	9						8	6	5	1
Target inventory	t	1,48								14,8	0,15	0,015						0,0014
Stored TRU (initial)	t	74,0	55,5	44,4	103,6	113,8												7,8
Losses	t	0,1											0,05	0,01				0,001

Source: Own calculation. Only changes are shown for better readability. Empty entries assume the same input and output as the (R) scenario (scenario 12).

Table 4: Thorium ADS Scenario – Results of the simulations.

Parameter Variation		R (12)	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	SPRIN-D
Irradiation time	y	3	5	7														7
Cooling time	y	3		3	7	10												5
Transmuted fraction per cycle	%	20,00					10,00	30,00	40,00									40,00
Initial TRU inventory	t	148																14
Target reduction	%	1								10	0,1	0,01						0,01
Separation factor	%	99,90											99,95	99,99				99,999
Reactor lifetime	y	50													40	60		
In-core inventory	%	50	63	70	30	23												58
Thermal power (initial)	GW_{th}	4,2		3,6	3,6	6,0	6,0	4,8	4,8	4,8	4,8		6,0			0,6		
Number of reactors (initial)	#	12	10	9	10	9	8	14	15						14	10	8	1
Simulation Results																		
Implementation period	y	267	285	355	355	439	535	201	147	157	330	330	261	256	250	305	261	147
Total number of reactors	#	20		21	21	21	23		19	18	21	21			25	17	15	3
Total energy produced	TWh	4886								4452							3518	464
Total residual TRU	t	1,45					1,48	1,40	1,36	14,60	0,72	0,72	1,40	1,43	1,43			0,09
Total Separation losses	t	0,61	0,63	0,64			1,36	0,36	0,24	0,56			0,31	0,06				0,00
TRU in fuel	t	0,84	0,81	0,82		0,85	0,12	1,04	1,12	4,26	0,10	0,10	1,10	1,37	0,81			0,09
TRU storage	t	0,00								9,79								
Transmutation to	%	0,98					1,00	0,95	0,92	9,87	0,48	0,48	0,95	0,97	0,96			0,67

Source: Own calculation. Only changes are shown for better readability. Empty entries assume the same input and output as the (R = reference) scenario 12.

5 Safety Aspects

5.1 Reactor Safety

The reactor safety risks associated with sub-critical fast systems have been discussed extensively in the literature (Englert and Mohr 2023; Frieß et al. 2021; IAEA 2015, 1998; NEA/OECD 2011, 2002; OECD/NEA 2006). However, there is comparatively little published work on the safety characteristics of sub-critical systems fueled with thorium, as even critical thorium-fueled systems remain at the development stage (Guilbaud et al. 2024).

Compared to other reactors, an essential feature of accelerator-driven systems is that they are operated in a subcritical condition. This feature makes an accelerator-driven system more robust than critical fast reactors related to variations in important safety parameters (reactivity coefficients, delayed neutrons), even when minor actinides are used in the fuel.

The decisive advantage of ADS is that the safety margin can be selected by way of the subcriticality. A highly subcritical design of the reactor core increases the safety margin against reactivity accidents, but it simultaneously reduces the energy amplification of the system. This can be compensated for by increasing the power of the spallation neutron source, though this entails correspondingly high costs and requires correspondingly higher accelerator power.

Besides reactivity and loss of coolant accidents, for ADS new accident sequences and boundary conditions are possible. One example is power excursions based on sudden power changes in the particle beam due to the interaction between the required high-power particle accelerator and the subcritical reactor core. Moreover, the subcritical core configuration produces a steep radial power-density gradient that originates at the spallation neutron source and decreases toward the core periphery. The accelerator beam current must be fed from outside the reactor into the core, traversing the principal containment barriers — the primary coolant boundary and the reactor building — used to confine the radioactive inventory.

In terms of safety, accelerator-driven reactors could offer significant advantages over LWR, although scenarios for potential serious accidents cannot currently be ruled out for ADS either and depend very much on the specific design.

The START facility is a subcritical, lead-cooled reactor. Lead-cooled reactors operate with a fast neutron spectrum, which enables higher transmutation rates than thermal spectra. A general drawback of critical fast systems is their less favorable inherent safety characteristics during operation (Lamarsh and Baratta 2001; Lewis 2008). This disadvantage is amplified when fuels contain high fractions of transuranic elements, yet such compositions are essential for the incineration of radioactive waste as envisaged in partitioning-and-transmutation concepts (Fanghänel et al. 2010). START is intended to operate at a neutron multiplication factor of at most $k_{\text{eff}} = 0.98$, which is consistent with typical undercritical operation (see, e.g., MYRRHA documentation (Abderrahim et al. 2001; Sarotto et al. 2013)). The available study does not make clear at what point in the irradiation history this value is reached. In describing the methodology, Houben et al. (2025) mention only deterministic codes; it remains unclear how time-dependent fuel compositions are determined with sufficient accuracy using these tools alone.

During irradiation, the composition of nuclear fuel evolves. This affects not only k_{eff} but also the reactivity coefficients, which quantify the reactor's response to external perturbations, such as small variations in coolant temperature. Negative coefficients provide self-regulation, whereas positive coefficients can amplify perturbations. The SPRIN-D study does not report core neutronic parameters during operation. This gap concerns not only the assessment of transmutation efficiency but also core safety characteristics. Different transuranic isotopes exhibit distinct nuclear characteristics, for example, different fractions of delayed neutrons released upon fission and different average neutron yields per fission. Such properties are known to affect reactor behavior in ways that can be unfavorable from a safety perspective. To what extent a subcritical configuration mitigates these effects is not demonstrated in the available material.

The study itself notes that data is insufficient for a conclusive evaluation: It is stated that no factors have emerged that would render the project infeasible. However, substantial additional work is still required to fully meet regulatory requirements (own translation, Houben et al., 2025, p. 133).

5.2 Scenario Risks

All facilities required for the transmutation of high-level radioactive waste contain an inventory that poses a risk of release in accident scenarios.

The inventory of high-level waste either as spent LWR UOX- or MOX-fuel and the remains of already reprocessed waste contained in glass matrices would have to be reprocessed in dedicated and specialized facilities to extract all TRU. According to Houben et al. (2025), one reprocessing facility could supply four START reactors. Achieving high utilization of both the reprocessing plant(s) and the reactors would require transport of spent fuel between sites.

The TRU must be fabricated into new fuel for the ADS reactor in dedicated fuel fabrication facilities that can handle highly radioactive fuel types containing significant fractions of minor actinides.

After fabrication the fuel would be used in several ADS transmutation reactors. After irradiation, the spent fuel elements contain fuel compositions scarcely used to date. They can be characterized by higher decay heat, neutron and gamma background compared to spent UOX- or MOX-fuel (Frieß and Liebert 2022). They must cool in an interim storage before reprocessing and subsequent reinsertion as fresh elements for renewed irradiation is possible.

While the irradiation process obviously increases the amount of fission products, the whole cycle of reprocessing, fuel fabrication and irradiation produces additional waste streams of low- and intermediate level waste.

Houben et al. (2025) estimate a program duration of roughly 100 years in a limited scenario with an very optimistic choice of parameters. We estimate longer times to complete the transmutation operation for the national TRU stock. Over this entire period, nuclear facilities at multiple sites would be in operation. The routine environmental releases from reprocessing facilities are generally higher than those from power reactors, and the overall accident risk increases simply because more facilities would be operating.

In addition, a highly sophisticated safety and regulatory framework would need to be maintained over an extended period. This entails the risk that, due to political or societal instability or cost overruns, the program could be abandoned, leaving large quantities of radioactive materials stranded. While such risks exist for all nuclear programs, they conflict with the objectives of nuclear phase-out strategies, which aim to minimize nuclear hazards.

Lastly, there remains a risk of nuclear proliferation. Large quantities of weapons-usable fissile material would be processed. While access to fissile material in spent fuel is impeded by the strong radiation of fission products (the “radiation barrier”), transmutation schemes require separation of these fission products from the fissile and fertile materials, thereby increasing proliferation risk. Houben et al. (2025, p. 62) argue that the proposed system is proliferation-resistant, emphasizing the fuel’s isotopic composition. Consistent with publications by the U.S. Department of Energy, the National Academies, and MIT, plutonium is, in principle, usable for the construction of nuclear explosive devices regardless of its isotopic composition; isotopic variations primarily affect handling complexity and weapon performance, not fundamental usability (Bathke et al. 2012; Buongiorno et al. 2018; Kankeleit et al. 1989; Staff 1995; The United States Department and of Energy 1997). Houben et al. (2025) provide only general statements about plutonium isotope fractions. It is unclear whether more detailed, burnup-based isotopic data were produced. They further assert that individual transuranic elements cannot be separated in the envisaged process. However, the technology could be easily adapted to separate out specific elements such as plutonium, once a state decides to break out of its nonproliferation commitments.

6 Conclusion

This working paper provides a system-dimensioning analysis for a hypothetical national P&T program in Germany. The ADS/thorium “START”-type reactor concept as described in Houben et al. (2025) was taken as a reference point. Thorium fuel cycles have the advantage that, compared to the use of uranium in the fuel, very few new TRU is bred. The analysis is intentionally limited to technical and system-scale aspects and explicitly assumes hypothetical technical feasibility. Today almost none of the technologies necessary have left laboratory scale experimenting or are still completely hypothetical. A consistent set of input parameters was derived from the SPRIN-D study to the extent possible. Obviously unrealistic assumptions such as instantaneous transmutation and 100% efficiency were replaced by choices from literature or previous work of the authors and varied in sensitivity cases.

The missing or even contradictory data in the SPRIN-D data is one of the obvious limitations of our modelling. We further treat TRU as a lumped inventory and assume uniform separation efficiencies and transmutation fractions across isotopes. The model does not resolve isotopic vector evolution, time-dependent burnup constraints, or reactor-physics feedback (e.g. reactivity coefficients) that can further restrict feasible fuel compositions or extend cycle times. The results should therefore be interpreted as optimistic lower-bound estimates, rather than realistic projections.

Nevertheless, the following findings can be derived from the simulations:

First, the implementation time in phase-out scenarios is heavily influenced by a small set of parameters: the cycle length (irradiation, cooling, partitioning, refabrication) and the per-cycle transmuted fraction, and the target reduction. For a full national program to treat the

German HLW waste inventories, the model results show that even very optimistic parameter combinations imply program durations extending well beyond a century for deep target reductions. Even the scenario with the highest transmutation fraction per cycle lasts almost 150 years and needs 19 reactors in total during that period. Longer cycle times or lower achievable per-cycle transmutation fractions shift the results into multi-century P&T campaigns.

Second, target reduction and residual inventory of TRU are intrinsically limited by cumulative losses and end-of-implementation-period reactor inventory. Even with very high separation efficiencies the need to repeat the recycling step produces non-zero partitioning losses which accumulate over many cycles. In addition, some TRU remains in the final reactor at program termination. Consequently, “complete transmutation” is not a meaningful system-level assumption. In every scenario, a residual TRU mass remains that needs to go to a final repository.

Third, the framing in Houben et al. (2025) does not constitute a national system description. A Germany-wide implementation necessarily requires a fleet of irradiation facilities and the associated fuel-cycle infrastructure: interim storage for high-decay-heat fuels, dedicated reprocessing and fuel-fabrication plants capable of handling minor-actinide-bearing fuels, and transports between sites to maintain utilization. System sizing therefore scales with the national inventory and with cycle constraints. A study that is based on the analysis of a single reactor and the inventory at one site is not transparent with regards to the scale of the necessary complete infrastructure. This invites public misperceptions that a single reactor or just a few reactors could solve the conundrum of highly radioactive waste without addressing the long-term operational and regulatory commitment as well as safety risks from such an infrastructure. Another example for this kind of misleading information would be the accelerator-driven ADES (Accelerator-Driven Energy Source) promoted by Emerald horizon[1] which also planned to use thorium fuel for transmutation. It claims, without further details, to have “*NO nuclear waste problem*” (Mueller 1/24/2017).

Besides those results derived directly from the simulations we would like to stress that safety risks by a P&T program of the scale implied here are not characterized by a single reactor, but by the long-term operation of multiple high-hazard facilities, including reprocessing and minor-actinide-bearing fuel fabrication. Those facilities generally have higher routine releases and add accident risks beyond those of reactors alone. In addition, sustaining regulatory institutions, qualified staffing, maintenance, and emergency preparedness over several centuries constitutes a systemic risk. It increases the probability that interruptions or premature termination leave significant radioactive inventories stranded in intermediate stages of the fuel cycle which contradicts some of the reasoning to phase-out of nuclear fission technologies namely to reduce intergenerational burdens.

Overall, the results indicate that the optimistic assumptions in Houben et al. (2025) do not provide a transparent, reproducible nationwide mass-balance model and results change drastically if parameter ranges are applied as reported in the scientific literature. Even under optimistic modelling assumptions, P&T does not remove the need for a geological repository. Rather, the burden of nuclear waste is shifted into a long-lived multi-site nuclear industrial system with additional facilities, operational waste streams, and prolonged institutional requirements.

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[1] https://emerald-horizon.com/en/ades/

7 Abbreviations

ADS	Accelerator-driven System
EFIT	European Facility for Industrial-sized Transmutation
IMF	Inert Matrix Fuel
LWR	Light-water Reactor
MA	Minor Actinides
MOX	Mixed Oxide Fuel
P&T	Partitioning and Transmutation
SNF	Spent Nuclear Fuel
TRU	Transuranium Elements
UOX	Uranium Oxide Fuel

8 Publication bibliography

Abderrahim, H. A.; Kupschus, P.; Malambu, E.; Benoit, P.; van Tichelen, K.; Arien, B. et al. (2001): MYRRHA: A multipurpose accelerator driven system for research & development. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* (463), pp. 487–494.

Aït Abderrahim, Hamid; Bruyn, Didier de; van den Eynde, Gert; Fernandez, Rafaël (2021): Accelerator Driven Subcritical Systems. In: Encyclopedia of Nuclear Energy: Elsevier, pp. 191–202.

Artioli, C.; Chen, X.; Gabrielli, F.; Glinatsis, G.; Liu, P.; Maschek, W. et al. (2008): Minor Actinide Transmutation in ADS: The EFIT Core Design. Proceedings of PHYSOR'08, 14. - 18. September 2008 Interlaken, Schweiz.

Bathke, Charles G.; Ebbinghaus, Bartley B.; Collins, Brian A.; Sleaford, Brad W.; Hase, Kevin R.; Robel, Martin et al. (2012): The Attractiveness of Materials in Advanced Nuclear Fuel Cycles for Various Proliferation and Theft Scenarios. In: *Nuclear Technology* 179 (1), pp. 5–30. DOI: https://doi.org/10.13182/NT10-203.

Biarotte, J. L.; Müller, A. C. (2011): Accelerator reference design for the European ADS demonstrator. In: Technology and Components of Accelerator-driven Systems. First International Workshop Proceedings. Karlsruhe, 15-17 March 2010. OECD Nuclear Energy Agency (NEA) (NEA No. 6897), pp. 197–207.

Biarrotte, Jean-Luc; Uriot, Didier; Medeiros Romao, Luis; Vandeplassche, Dirk (2015): Beam operation aspects for the MYRRHA linear accelerator. In: Technology and Components of Accelerator-driven Systems. Second International Workshop Proceedings. Nantes, 21-23 May 2013. Nuclear Energy Agency (NEA Proc.) (NEA/NSC/DOC(2015)7).

BMUV (2023): Verzeichnis radioaktiver Abfälle. Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz. Berlin. Available online at https://www.bundesumweltministerium.de/fileadmin/Daten_BMU/Download_PDF/Nukleare_Sicherheit/verzeichnis_radioaktive_abfaelle_2023_bf.pdf.

Bundesamt für die Sicherheit der nuklearen Entsorgung (BASE) (2025): Fachstellungnahme zur „Umsetzungsstudie über eine beschleunigergetriebene Neutronenquelle am Standort eines ehemaligen Kernkraftwerks“ der Bundesagentur für Sprunginnovationen (SPRIN-D) (F 4 - BASE - BASE60210#0001). Available online at https://www.base.bund.de/shareddocs/downloads/de/fachinfo/fa/fachstellungnahme-umsetzungsstudie-sprin-d.pdf?__blob=publicationFile&v=4, checked on 1/13/2026.

Buongiorno, J.; Corradini, M.; Parson, J.; Petti, D. (Eds.) (2018): The Future of Nuclear Energy in a Carbon-Constrained World. An interdisciplinary MIT study. MIT Energy Initiative.

Englert, Matthias; Mohr, Simone (2023): Verfolgung und Aufbereitung des Standes von Wissenschaft und Technik bei alternativen Entsorgungsoptionen für hochradioaktive Abfälle (altEr).

Fanghänel, Thomas; Glatz, Jean-Paul; Konings, Rudy J. M.; Rondinella, Vincenzo V.; Somers, Joe (Eds.) (2010): Transuranium Elements in the Nuclear Fuel Cycle. Boston, MA: Springer US (Handbook of Nuclear Engineering).

Frieß, Friederike; Arnold, Nikolaus; Liebert, Wolfgang; Müllner, Nikolaus (2021): Sicherheitstechnische Analyse und Risikobewertung von Konzepten zu P&T. Wissenschaftliches Gutachten im Auftrag des Bundesamtes für die Sicherheit der nuklearen Entsorgung (BASE). Institut für Sicherheits- und Risikowissenschaften, Universität für Bodenkultur (BOKU) Wien. Berlin (BASE-002/21). Available online at https://www.base.bund.de/SharedDocs/Downloads/BASE/DE/berichte/kt/gutachten-partitionierung-und-transmutation.html.

Frieß, Friederike; Liebert, Wolfgang (2018): Entschärfung der Atommüllproblematik durch Partitionierung und Transmutation? Beiträge zur Einschätzung des Potentials. In: Michael Decker, Ralf Lindner, Stephan Lingner, Constanze Scherz, Mashid Sotoudeh (Eds.): Grand Challenges" meistern: Der Beitrag der Technikfolgenabschätzung. Baden-Baden: Nomos (Gesellschaft Technik Umwelt), p. 420.

Frieß, Friederike; Liebert, Wolfgang (2022): Inert-Matrix Fuel for Transmutation: Selected Mid- and Long-Term Effects on Reprocessing, Fuel Fabrication and Inventory Sent to Final Disposal. In: *Progress in Nuclear Energy* 145. DOI: https://doi.org/10.1016/j.pnucene.2021.104106.

Gabrielli, Fabrizio; Rineiski, Andrei; Vezzoni, Barbara; Maschek, Werner; Fazio, Concetta; Salvatores, Massimo (2015): ASTRID-like Fast Reactor Cores for Burning Plutonium and Minor Actinides. In: *Energy Procedia* 71, pp. 130–139. DOI: https://doi.org/10.1016/j.egypro.2014.11.863.

Guilbaud, Thomas; Fiorina, Carlo; Pautz, Andreas; Carminati, Federico (2024): Preliminary safety analysis of the TRANSMUTEX sub-critical reactor using the GeN-Foam multi-physics solver. In: *Progress in Nuclear Energy* 168, p. 104980. DOI: https://doi.org/10.1016/j.pnucene.2023.104980.

Houben, Guido; Esen, Sevda; Groska, Judit; Stromer, Franz; Andernat, Martin (2025): Umsetzungsstudie über eine beschleunigergetriebene Neutronenquelle am Standort eines ehemaligen Kernkraftwerks zwecks Produktion von Krebsmedikamenten, Fernwärme und geothermischer Energie sowie zur Entsorgung hochradioaktiver Abfälle. Bundesagentur für Sprunginnovation.

IAEA (1998): Accelerator Driven Systems: Energy Generation and Transmutation of Nuclear Waste. International Atomic Energy Agency. Vienna.

IAEA (2015): Status of Accelerator Driven Systems Research and Technology Development. Vienna: IAEA (IAEA TECDOC Series No. 1766, v.1766).

Kankeleit, E.; Küppers, C.; Imkeller, U. (1989): Bericht zur Waffentauglichkeit von Reaktorplutonium (IANUS 1/1989).

Kirchner, Gerald; Englert, Matthias; Pistner, Christoph; Kallenbach-Herbert, Beate; Neles, Julia (2015): Gutachten "Transmutation. Öko-Institut e.V., Zentrum für Naturwissenschaft und Friedensforschung Universität Hamburg. Darmstadt/Hamburg.

Korobeinikov, Valery V.; Kolesov, Valery V.; Mikhalev, Aleksandr V. (2022): Comparison of the minor actinide transmutation efficiency in models of a fast neutron uranium-thorium fueled reactor. In: *Nuclear Energy and Technology* 8 (1), pp. 49–53. DOI: https://doi.org/10.3897/nucet.8.82757.

Lamarsh, John R.; Baratta, Anthony John (2001): Introduction to nuclear engineering. 3rd ed. Upper Saddle River N.J.: Prentice Hall (Addison-Wesley series in nuclear science and engineering).

Lewis, E. E. (2008): Fundamentals of nuclear reactor physics. Amsterdam/Boston: Academic Press.

Li, Dongguo (2024): TRU utilization and MA transmutation in thorium-based fluorinated molten salt fast reactor. In: *Progress in Nuclear Energy* 168, p. 105015. DOI: https://doi.org/10.1016/j.pnucene.2023.105015.

Mueller, M. (2017): Emerald Horizon: The Future of carbon-free energy supply. Energiewende: Neue Ansätze in der Kernkraft-Technologie. Österreichische Nationalbank, 1/24/2017. Available online at https://www.oenb.at/Termine/2024/2024-01-17-energiewende.html.

NEA/OECD (2002): Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles: A Comparative Study.

NEA/OECD (2011): Potential Benefits and Impacts of Advanced Nuclear Fuel Cycles with Actinide Partitioning and Transmutation. OECD Publishing. Available online at https://www.oecd-nea.org/jcms/pl_14572/potential-benefits-and-impacts-of-advanced-nuclear-fuel-cycles-with-actinide-partitioning-and-transmutation?details=true.

OECD/NEA (2006): Advanced Nuclear Fuel Cycles and Radioactive Waste Management: Nuclear Energy Agency, Organisation for Economic Co-operation and Development (Nuclear Development).

Pistner, Christoph; Englert, Matthias; Hirschhausen, Christian von; Böse, Fanny; Steigerwald, Björn; Gast, Lukas; Donderer, Richard (2024): Analyse und Bewertung des Entwicklungsstands, der Sicherheit und des regulatorischen Rahmens für sogenannte neuartige Reaktorkonzepte. Edited by Bundesamt für die Sicherheit der nuklearen Entsorgung. Öko-Institut e.V. and TU-Berlin, Fachgebiet Wirtschafts- und Infrastrukturpolitik and Physikerbüro Bremen. Berlin. Available online at https://www.oeko.de/publikation/analyse-und-bewertung-des-entwicklungsstands-der-sicherheit-und-des-regulatorischen-rahmens-fuer-sogenannte-neuartige-reaktorkonzepte/, checked on 4/14/2026.

Renn, Ortwin (2013): Auf dem Weg zu einer sozialökologischen Fundierung der Technikfolgenabschätzung. In: Georg Simonis (Ed.): Konzepte und Verfahren der Technikfolgenabschätzung. Wiesbaden: Springer Fachmedien Wiesbaden, pp. 21–34.

Renn, Ortwin (Ed.) (2014): Partitionierung und Transmutation, Forschung – Entwicklung – Gesellschaftliche Implikationen. acatech STUDIE. Deutsche Akademie der Technikwissenschaften. München: Herbert Utz Verlag GmbH.

Sarotto, Massimo; Castelliti, Diego; Fernandez, Rafael; Lamberts, Damien; Malambu, Edouard; Stankovskiy, Alexey et al. (2013): The MYRRHA-FASTEF cores design for critical and sub-critical operational modes (EU FP7 Central Design Team project). In: *Nuclear Engineering and Design* 265, pp. 184–200. DOI: https://doi.org/10.1016/j.nucengdes.2013.08.055.

Schwenk-Ferrero, A. (2013): German Spent Nuclear Fuel Legacy: Characteristics and High-Level Waste Management Issues. In: *Science and Technology of Nuclear Installations* 2013, pp. 1–11. DOI: https://doi.org/10/gbcj4q.

Staff, National Research Council (1995): Management and Disposition of Excess Weapons Plutonium. Reactor-Related Options. With assistance of Panel on Reactor-Related Options for Disposition, Policy and Global Affairs, National Research Council, National Academy of Sciences. Washington: National Academies Press. Available online at https://www.nationalacademies.org/read/4754/chapter/1.

The United States Department and of Energy (1997): Nonproliferation and arms control assessment of weapons-usable fissile material storage and excess plutonium disposition alternatives. In: *DOE-NN-0007*.