Nuclear Development

Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles

A Comparative Study

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

EXECUTIVE SUMMARY

Scope of study and principal messages

The long-term hazard of radioactive wastes arising from nuclear energy production is a matter of continued discussion and public concern in many countries. By the use of partitioning and transmutation (P&T)[1] of the actinides and some of the long-lived fission products, the radiotoxicity of the high-level waste (HLW) and, possibly, the safety requirements for its geologic disposal can be reduced compared with the current once-through fuel cycle. To make the technologically complex enterprise worthwhile, a reduction in the HLW radiotoxicity by a factor of at least one hundred is desirable. This requires very effective reactor and fuel cycle strategies, including fast reactors (FRs) and/or accelerator-driven, sub-critical systems. The accelerator-driven system (ADS) has recently been receiving increased attention due to its potential to improve the flexibility and safety characteristics of transmutation systems.

The present study compares FR- and ADS-based actinide transmutation systems with respect to reactor properties, fuel cycle requirements, economic aspects, and R&D needs. The essential differences between the various systems are evaluated with the help of a number of representative "fuel cycle schemes". The strategies investigated include an evolutionary transmutation strategy in which the ADS provides additional flexibility by enabling plutonium utilisation in conventional reactors and confining the minor actinides to a small part of the fuel cycle, and two innovative transuranics (TRU) burning strategies, with an FR or an ADS, in which plutonium and minor actinides are managed together to minimise the proliferation risk. A novelty in the present study is that the analyses are carried out in a consistent manner using reactor and fuel cycle parameters which have been agreed upon by international experts.

Principle messages from the study which could influence P&T policy development are:

- Fuel cycles with multiple recycling of the fuel and very low fuel losses are required to achieve the desired hundred-fold radiotoxicity reduction.
- All transmutation strategies with multiple recycling of the fuel can achieve similar radio-toxicity reductions, but the choice of the strategy strongly influences fuel cycle requirements.
- The ADS is particularly suited as a "dedicated" minor actinide burner in steady-state scenarios and provides flexibility in transient scenarios.
- The ADS-based evolutionary, and the FR-based innovative, approaches appear to be attractive transmutation strategies, from both technical and economic viewpoints.
- The full potential of a transmutation system can be exploited only if the system is utilised for a minimum time period of about a hundred years.
- A considerable amount of R&D on sub-critical reactors, advanced fuels, and materials would be needed before ADS-based transmutation technology could be deployed.

1. A list of acronyms is given in Annex B.

General context

The world-wide increasing energy demand in general, and electricity demand in particular, call for a re-evaluation of fission energy as a long-term energy source. In this context, a recent OECD/NEA publication has investigated the extent to which nuclear energy is compatible with the goals of sustainable development, and how it can best contribute to them [1]. Although present light water reactors (LWRs) are capable of covering the nuclear energy demand for many decades to come, there is a longer-term need for integrating advanced reactors, including fast reactors, into the nuclear energy system. Important development goals for such advanced systems are environmental friendliness, resource efficiency, and cost-effectiveness, while accounting for socio-political concerns such as proliferation.

In the early days of nuclear energy, electricity generation in LWRs as well as FRs was estimated to be economically competitive with other forms of electricity generation. At that time, uranium resources were assumed to be the limiting factor for nuclear deployment, while the limited amount of radioactive waste was seen as less of a concern than it is today. This early perspective called for a rapid introduction of conventional, uranium-plutonium mixed-oxide (MOX) fuelled fast reactors with a fuel cycle which is fully closed for plutonium, but not for the minor actinides neptunium, americium and curium, which are at least as radiotoxic as plutonium. A complete closure of the fuel cycle by recycling the minor actinides as well was already envisaged at that time, but not given much attention because the utilisation of the energy content of the minor actinides is not economically attractive.

Today, while uranium is still abundant but radioactive waste is giving increasing rise to public concern, an attempt to progress towards the ultimate goal of a fully closed, FR-based fuel cycle via the intermediate step of a transmutation system is appropriate. The partitioning and transmutation of actinides and fission products which are now put to waste would allow the “radiological cleanliness” of nuclear energy to be improved, and thus one of the most important requirements for an environmentally friendly nuclear energy system to be addressed. It is clear that not only the technical but also the economic feasibilities of such a system must be demonstrated.

Previous studies and adopted approach

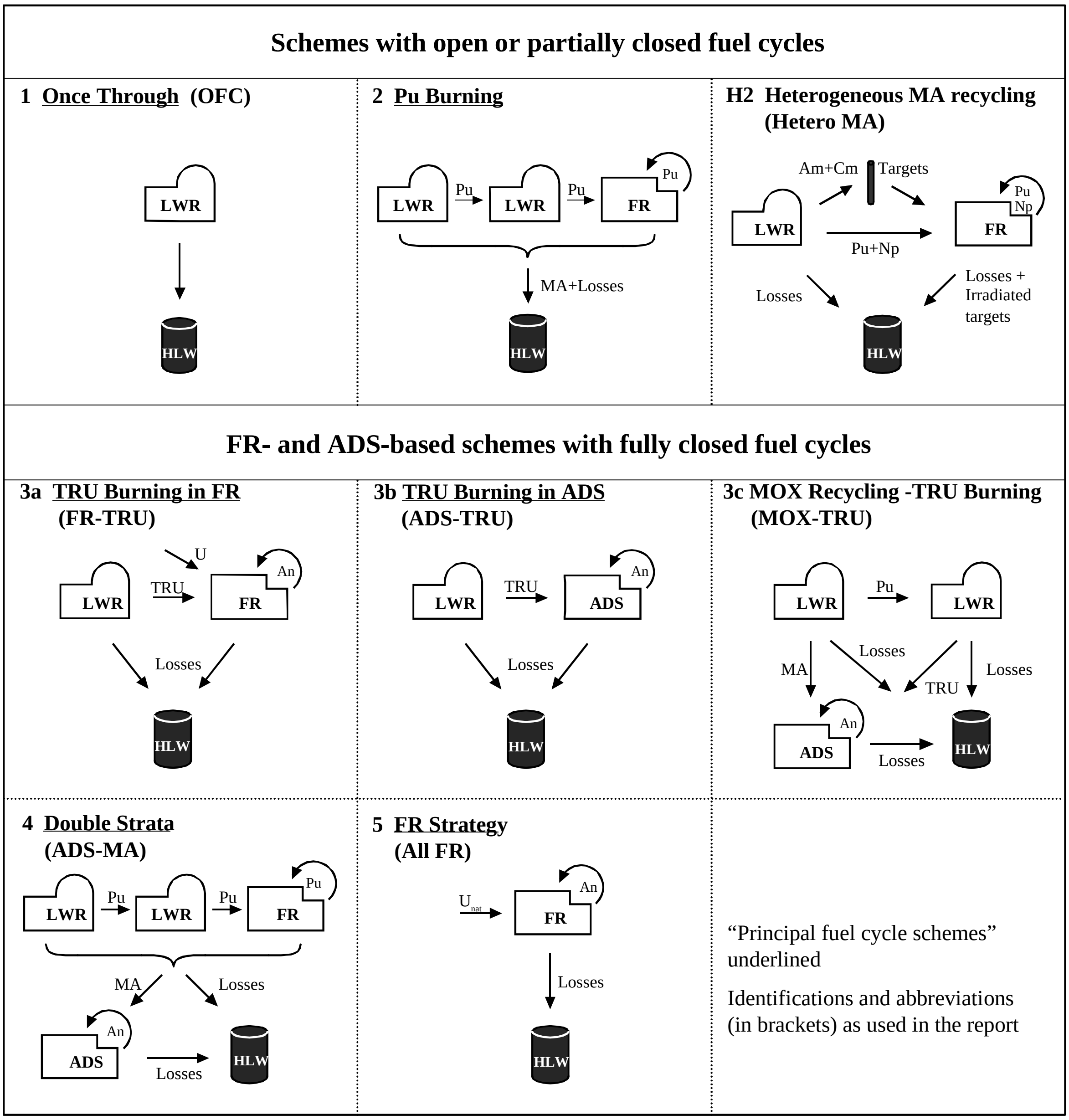
In response to the interest of Member countries, and recognising the activities pursued, the Nuclear Energy Agency initiated a long-term programme on P&T in 1989, addressing a wide range of technical and scientific issues.[2] An International Exchange Programme was established to strengthen international collaboration, and a first P&T systems study was carried out from 1996 to 1998 [2]. This systems study focused on a review of the progress in P&T and the possible benefits for waste management. Specific fuel cycle strategies were discussed, covering plutonium recycling and the additional burning of minor actinides in dedicated reactor systems; however, the more effective transmutation strategies with fully closed fuel cycles and the specific role of the ADS in these fuel cycles were not addressed. The present, second P&T systems study tries to close this gap and thereby complements the first study. Specific aims of this second study are the clarification of the roles and relative merits of the FR and the fast-spectrum ADS in closed fuel cycles by means of comparative analysis, as well as the assessment of the development status of the ADS with emphasis on reactor and fuel cycle technology, safety, economics, and general feasibility.

To quantitatively assess the advantages and drawbacks of different plutonium and minor actinide (MA) burning strategies, seven “fuel cycle schemes”, shown in Figure 1, have been selected and

2. A historic overview of P&T activities in NEA Member countries and international organisations is given in Annex C.

compared with the current once-through fuel cycle (OFC). The schemes are generic and stand for groups of strategies with scope for variation according to national preferences. All reactors are assumed to be electricity producers.

Figure 1. **Overview of analysed fuel cycle schemes**



Note:
The "principal" fuel cycle schemes represent cornerstone strategies. Combinations of these are possible. For example, the MOX-TRU scheme combines elements of the ADS-TRU and plutonium burning schemes. The principal schemes were analysed using a single nuclear data library and a single reactor code system.

Schemes 3a, 3b, 3c and 4 allow the essential differences between FR- and ADS-based transmutation strategies with fully closed fuel cycles to be demonstrated. In addition, two schemes with partially closed fuel cycles are considered: scheme 2 is of interest because plutonium burning itself is an important issue and transmutation always involves plutonium burning as a preceding or simultaneous process. The heterogeneous recycling scheme H2 represents a possible alternative to the closed fuel cycle which, however, has an inferior transmutation potential. Finally, the all-FR strategy represents the long-term goal for nuclear development. Only "burner" reactors with solid fuels are considered, and these are optimised for a high burning efficiency so that they can support a large fraction of LWRs in the reactor park. The comparison is unique with regard to the use of consistent calculation methods, and reactor and fuel cycle parameters which have been evaluated specifically for this study.

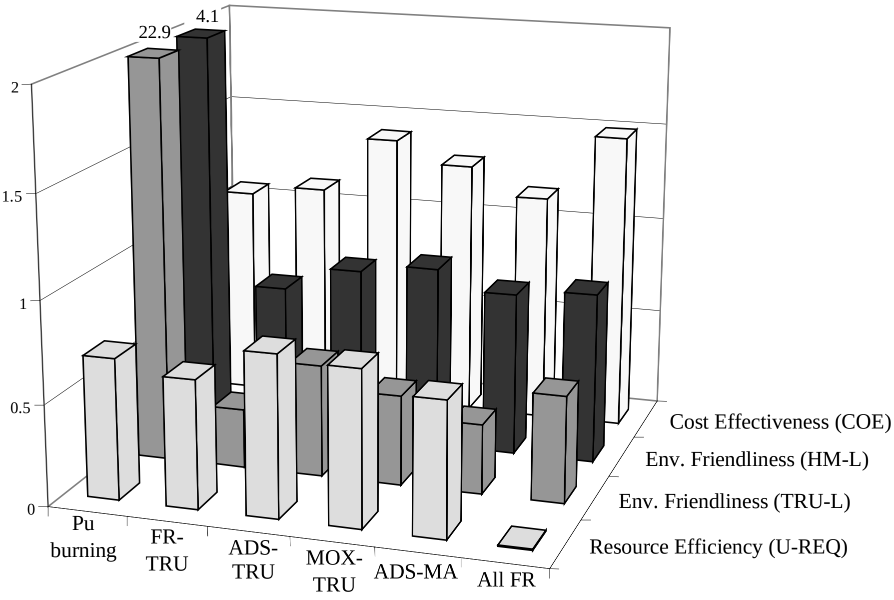
Sustainability comparison

The comparison considers three axes of sustainability, namely resource efficiency, environmental friendliness, and cost-effectiveness. Key criteria along the second axis are the heavy metal and TRU losses, and the radiotoxicity of the losses, to repository. The principal results are illustrated in Figure 2 and can be summarised as follows:

- All transmutation strategies with fully closed fuel cycles can, in principle, achieve similar reductions in the actinide inventory and the long-term radiotoxicity of the high-level waste, and these are comparable with those of a pure fast reactor strategy. This implies that there are no distinct differences between the respective potentials of the FR and the ADS.
- With the assumed reactor and fuel cycle parameters, these strategies can achieve a more than hundred-fold reduction in the long-term waste radiotoxicity and even higher reductions in the heavy metal and TRU losses to repository, compared with the once-through fuel cycle. This applies for multiple recycling of the fuels, high fuel burn-ups, and very low reprocessing and fuel fabrication losses. For the latter, a value of 0.1% for all actinides is assumed, as already achieved for uranium and plutonium, though an ambitious target for the other actinides.
- Regarding actinide waste production and technological aspects, the FR-TRU and the ADS-MA scheme are similarly attractive. The first can gradually evolve to a pure fast reactor strategy, but requires higher initial investment in fast reactor and advanced fuel cycle technologies. The second confines the minor actinides to a small side-stream of the fuel cycle where, however, very innovative technology is needed. Here, the ADS has the advantage that it can burn pure minor actinides while avoiding a deterioration of the core safety characteristics.
- The economic analysis indicates that ADS-based transmutation technology can be made more competitive by burning as much plutonium as possible in conventional reactors, i.e. MOX-fuelled LWRs and FRs. This favours the ADS-MA scheme, which, together with the FR-TRU scheme, also features the lowest electricity costs of all transmutation schemes. In these cases, P&T is estimated to add a relatively modest 10-20% to the electricity costs of the once-through fuel cycle. Although such cost increases would be unacceptable to the market at present, they are limited and might be affordable in the future if price increases rendered fossil fuels less competitive or society placed a premium on reducing waste radiotoxicity.

The study also shows that plutonium burning alone is useful for the management of plutonium, but cannot qualify as a transmutation strategy because it reduces the long-term waste radiotoxicity by only a factor of about five. Recycling americium and curium heterogeneously in special "target" pins which are disposed of after irradiation, as shown in the hetero MA scheme H2, is technically less demanding than a closed fuel cycle strategy, but is also about a factor of two less effective in reducing the radiotoxicity; this strategy is being explored as a near-term transmutation option.

Figure 2. **Sustainability comparison**



U-REQ: Natural uranium requirement relative to OFC.
TRU-L: Transuranics losses to repository (% of OFC).
HM-L: Heavy metal losses to repository (tenths of % of OFC).
COE: Cost of electricity relative to OFC (nominal case).

Note: For the Pu-burning scheme, TRU-L and HM-L are off-scale.

Regarding the utilisation period of transmutation systems, the study confirms that physical limitations associated with the production and destruction of in-pile and out-of-pile fuel inventories imply very long time constants for the introduction and final phase-out of such systems, and that P&T technology can, therefore, achieve its goal only if it is introduced with the intention of using it for at least a century. In particular, the full radiotoxicity reduction benefit can be realised only if the TRU inventory of the system is ultimately burnt and not put to waste.

Finally, it should be noted that all transmutation strategies including LWRs in the reactor mix require similar uranium resources and produce similarly large streams of residual uranium as the LWR once-through strategy. If the residual uranium is not considered as a resource for future fast reactors, its long-term radiological impact must also be assessed.

ADS technology and safety

Though the FR and the ADS perform similarly with respect to environmental friendliness criteria, they differ considerably from technology, operation, and safety viewpoints.

In this context, two advantages of the ADS are of particular interest:

- The sub-critical, ADS concept enables the design of reactor cores which would otherwise not have acceptable operating characteristics. In particular, the possibility of operating a sub-critical actinide burner with a uranium-free (or thorium-free) fuel supply allows burner effectiveness to be maximised and hence the fraction of specialised transmuters in the reactor park to be minimised.
- Moreover, the concept allows the adjustment, i.e. increase, of the reactivity margin to prompt criticality, thereby reducing the potential of the core for a power excursion. This is useful primarily for minor actinide burners, for which this margin is only about half of that of a normal fast reactor if the core is operated in a critical mode. TRU burner cores are less degraded in this respect.

The above-mentioned advantages of the ADS have to be balanced against the technological challenges arising from the coupling of a reactor and an accelerator, and the necessity to accommodate new types of operational and accidental transients. Regarding the former, the following problems require attention:

- Although the development of accelerators is well-advanced, with beam powers up to 10 MW for cyclotrons and 100 MW for linacs appearing feasible, beam losses and, most importantly, beam trip frequency must be further reduced to satisfy activation, fast temperature fluctuation and mechanical stress criteria for sensitive structures.
- Various problems related to accelerator-reactor coupling have still to be investigated. Thereby, special attention has to be given to the target and especially the beam window, as these components are subjected to complex stress, corrosion and irradiation conditions which are not encountered in normal reactors.

In the area of control and dynamic response, the following issues must be investigated:

- Controlling an ADS with beam power rather than an absorber-based reactivity compensation system reduces the potential of the core for reactivity-induced transients. For a sub-critical TRU burner, however, this advantage has to be balanced against the economic penalty arising from the high burn-up reactivity loss, which implies a higher beam current to maintain power at the end of the reactor cycle. The comparison is complicated because it also involves the balancing of safety-grade requirements for the two control systems.
- In contrast to the static behaviour of sub-critical cores, their response to reactivity and source transients is not yet well studied. The presence of an external neutron source which can vary very rapidly, in combination with very weak reactivity feedback, implies fast and (depending on the sub-criticality level) large responses to accelerator trips and control actions, which put additional demands on the control actuators, the fuel behaviour, and the heat removal processes. In particular, the fuel should be capable of buffering the respective heat balance disturbances.
- If a hypothetical core disruptive accident cannot be excluded deterministically, a prompt negative feedback mechanism must be developed to quench it.

Fuel cycle requirements

Important technological challenges also arise for the fuel cycle of a transmutation system. These are a direct consequence of the goal of transmutation, which implies the contamination of the fuel cycle by high concentrations of minor actinides. A central issue is the reprocessing of the fuel, but fuel fabrication and handling also pose new problems. The respective conclusions can be summarised as follows:

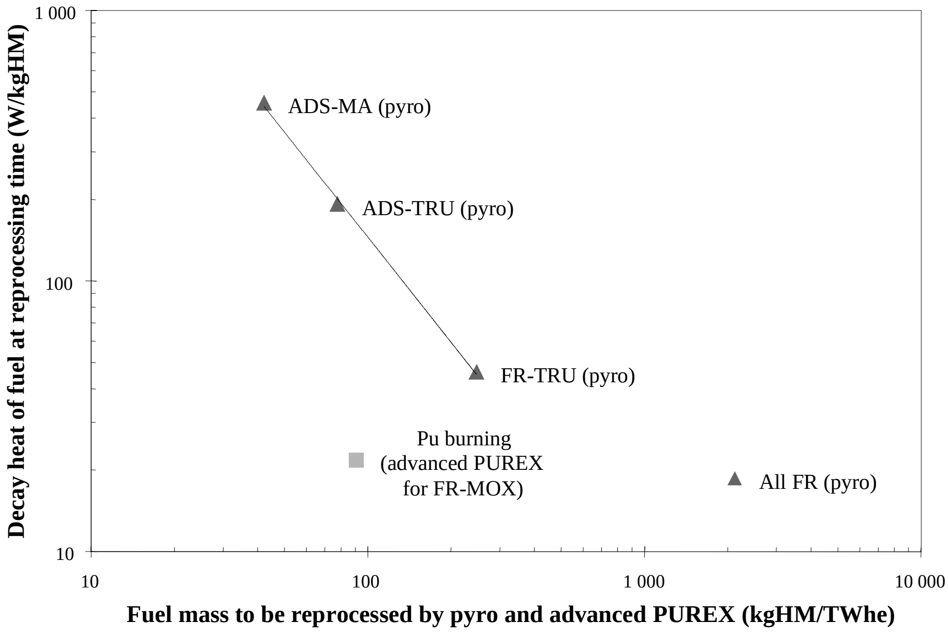
- Transmutation systems involve unusual fuels with high decay heat and neutron emission. A significant effort is required to demonstrate the manufacturability, burn-up behaviour, and reprocessability of these fuels. ADS fuels are particularly enriched in minor actinides and can probably be reprocessed only with the help of pyrochemical methods. These methods have to be further developed to tolerate from ten to more than twenty times higher decay heat levels than those encountered in the pyrochemical reprocessing of fast reactor fuels.
- The introduction of pyrochemical processing technologies at the industrial level will require the development of new process flowsheets and the use of potentially very corrosive reagents in hostile environments. These processes will generate chemical and radiological hazards which will have to be mitigated.
- PUREX aqueous reprocessing can be considered as valid for the FR-MOX fuel in the plutonium-burning and double strata schemes. Reprocessing of this fuel within short cooling times and with the required high recovery yields, however, will require the plutonium dissolution yield to be improved and the PUREX process to be modified.
- Due to the high radioactivity of FR-MOX fuel, its handling will require measures to be taken to reduce the radiation doses in the fabrication plant and during the transportation of the fuel assemblies. The increased requirements for shielding, and the preference for short transportation paths, of multiple recycled fuels also favour the pyrochemical reprocessing method at the reactor site.

During the past few years, many of these problems, especially in the separation area, have been addressed very successfully on a laboratory scale. The application of the processes on an industrial scale, however, still requires large extrapolations.

Figure 3 summarises the requirements of the different fuel cycle schemes for advanced aqueous reprocessing technology, as needed for the multiple recycled FR-MOX fuel, and for pyrochemical reprocessing technology. Regarding the pyrochemical reprocessing requirements of the transmutation schemes, there is some compensation for a high decay heat level by a low throughput, indicating that the reprocessing challenges are not very different (the trendline in the figure illustrates that the product of the two quantities is approximately constant).

A striking feature is that the pyroprocessing requirement of the all-FR scheme is much higher than that of the transmutation schemes. This is a consequence of accommodating the driver and the blanket fuel in the same fuel rod and blending the two components before processing. The blending has the advantage of reducing the decay heat of the fuel to be reprocessed and increasing the proliferation resistance of the system, but imposes high fuel throughput, and hence also economic, penalties on the scheme. These penalties could be reduced if the blanket were separated from the driver fuel and reprocessed using PUREX or UREX technology.

Figure 3. **Advanced reprocessing requirements**



Notes:
1. The ADS-MA scheme requires both pyro and advanced PUREX reprocessing. The requirements for the latter are very similar to those for the Pu-burning scheme.
2. Decay heats have to be compared with a "normal" decay heat of about 6 W/kgHM for LWR-MOX fuel.

Fission product transmutation

Fission product transmutation was already reviewed in the status and assessment report published in 1999 [2]. The present study indicates that, apart from its interesting potential as a powerful neutron source, the ADS does not open fundamentally new perspectives on this topic. Important general conclusions are:

- Excess neutrons produced by critical and sub-critical burners can, in principle, be utilised to transmute fission products. With the neutron fluxes available in these systems, it is theoretically possible to transmute the long-lived fission products; the transmutation of the more abundant short-lived fission products, however, is impracticable due to insufficient transmutation rates. This means that transmutation, in principle, allows the mitigation of the long-term risk from fission products in a geologic repository, but cannot significantly reduce the heat generation and mass of the disposed fission products.
- Minimising the fraction of specialised transmuters in the reactor park can result in an insufficient neutronic potential for transmuting the long-lived fission products of the entire park. If the transmutation would be limited to ^{129}I and ^{99}Tc, all TRU burning strategies could, theoretically, accomplish the task.
- In practice, the necessity of isotopic separation, as well as difficulties in the preparation of targets, present difficult obstacles for fission product transmutation, which currently reduces the number of candidate nuclides to only one or two, i.e. ^{99}Tc and, possibly, ^{129}I (so far, the feasibility has been established only for ^{99}Tc). This means that, for the remaining long-lived fission products, partitioning followed by immobilisation in a specially stable matrix may remain the only realistic method for reducing their radiological impact.