

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

1. INTRODUCTION

1.1 Nuclear energy development in the past and objectives for the future

Today's nuclear energy system is the result of a fifty-year development during which this technology has reached industrial maturity and became a reliable resource for our electricity needs. Most of this development has been concentrated on light water reactor (LWR) concepts (pressurised water reactors and boiling water reactors) and their fuel cycle. In the OECD, several other reactor concepts have also been studied (and some prototypes have been constructed and operated) but, with the exception of the CANDU reactor,¹ were not developed to internationally commercial systems.

The success of the LWR is based on the early recognition that natural fissile material were considered scarce and that nuclear energy could develop only if systems with low fissile inventories per unit power would be built in the start phase. LWRs, as initially developed for naval applications, fulfilled this criterion and used simple and relatively cheap technology that enabled a first generation of power stations to be constructed rapidly. The necessary uranium enrichment technology was available from the military development. The significant plutonium generation in LWR fuels was considered to be an asset because plutonium is an excellent fuel for fast reactors and the anticipated deployment of fast reactors around the turn of the century would have required large fissile inventories.² In the early days of nuclear energy, however, the back-end of the fuel cycle was not given the same attention as the reactors, and the concept of geologic disposal of radioactive waste was not yet questioned by the public.

Because the known uranium resources increased with prospecting and the growth of nuclear energy did not meet the early expectations, uranium became cheap and the envisaged rapid introduction of fast reactors did not come to pass. In many countries, a once-through fuel cycle developed where spent fuel is accumulating in spent fuel storage pools and intermediate storage facilities. Other countries embarked on a reprocessing fuel cycle, taking advantage of the PUREX technology,³ which was also available from the military application, to separate plutonium and uranium. Whereas some of the recovered plutonium is recycled in the form of uranium-plutonium mixed-oxide (MOX) fuel in LWRs, the remaining mix of minor actinides and fission products is conditioned for final waste disposal.⁴ Today, after some forty years of nuclear energy deployment, most countries with a nuclear energy programme have a growing stock of spent fuel, or separated plutonium and vitrified high-level waste (HLW), where the further management of this material is uncertain.

This situation is particularly uncomfortable since, in the meantime, the back-end of the fuel cycle has become the main focus of much of the criticism against nuclear energy, mostly oriented towards the final storage of spent fuel or HLW. There is a consensus within the OECD Member countries that

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1. CANDU: a heavy-water-moderated and -cooled reactor developed and widely used in Canada.
 2. Fast reactor: a nuclear reactor in which most of the fissions are caused by fast neutrons. It contains no moderator and is capable of generating more fissile material than it consumes.
 3. PUREX: generic name for solvent-extraction processes using TBP as the extractant.
 4. Minor actinides (MA): neptunium (Np), americium (Am), curium (Cm) and higher-Z actinides.

geologic disposal, in one or another form, is an appropriate solution to protect humans and their environment in the far-reaching future. However, difficulties encountered in siting, constructing and licensing repositories, not to mention public opposition against nuclear waste, have caused delays in the construction of these facilities.

On the other hand, the growing awareness that the contribution from nuclear energy to sustainable development cannot be ignored calls for a re-evaluation of nuclear development strategies for the coming decades. Environmental friendliness, cost-effectiveness and resource-efficiency will be essential axes in such evaluations, and nuclear holds development potential along all these axes. It is clear that nuclear energy could play an important role more easily if it responds also to the concerns of the society. Considering this situation, three objectives can be put forward for future nuclear energy systems:

- While the known uranium resources give us some hundred more years of supply with today's nuclear power park, we should not forget that LWRs use less than one per cent of the energy content of the mined uranium, the rest of the energy content being stored in spent fuel and depleted uranium from the enrichment process. The requirement of resource-efficiency will increase pressure to move to fuel cycles which can exploit a higher fraction of the energy content of the mined uranium. The growing stockpiles of spent fuel, reprocessed plutonium and uranium, and depleted uranium hold in that respect a large amount of energy for the next millennia, sufficient to meet most of mankind's energy needs.
- Emission of greenhouse gases as well as generation of waste in general has become a major public concern. Nuclear energy does not produce greenhouse gases, but the generated highly radiotoxic waste has animated the public debate during the past years. More environmentally friendly ways of producing nuclear energy by reducing the amount of waste, and especially HLW, would enhance the potential of nuclear energy for the future.
- While LWRs will continue to cover a large fraction of the nuclear energy demand, some advanced reactors utilising the remaining energy content of spent fuel and dealing with the actinide waste should be integrated into the system to assist nuclear energy fulfilling its long-term promises. Since the economic viability of advanced reactors has not yet been proven, the ratio of conventional to advanced reactors should remain high in the short- to medium-term in order to reduce the incremental cost per unit power produced.

1.2 Fuel cycle options and paths to the future

Bearing these objectives in mind, energy policy makers will have to decide on a path forward while taking fuel cycle constraints dictated by national policies into account. In principle, the following strategies can be envisaged:

- A first strategy is to remain with the once-through fuel cycle. This could be the choice, for instance, for countries with a modest nuclear energy programme and no recycling infrastructure. If the spent fuel cannot be sent to an international fuel cycle centre, a national plan for direct disposal of the fuel, including the demonstration of the long-term safety of the geologic repository, will have to be implemented.
- A second strategy, the plutonium burning strategy, is to close the fuel cycle for plutonium with the principal motivation to utilise the plutonium and not dispose it with the spent fuel. The plutonium can be recycled, first in LWRs and later in fast reactors. Minor actinides and

fission products are vitrified and disposed in geologic repositories. Since the uranium and the plutonium are separated, the volume of the HLW is reduced. However, in terms of the uranium requirement and the overall radiotoxicity of the HLW,⁵ the benefit of the plutonium burning strategy is small and the long-term safety of the repository will still have to be demonstrated.

- A third strategy, the transmutation strategy, is to close the fuel cycle of conventional, i.e. LWR-dominated, reactor parks also for the minor actinides by recycling all actinides homogeneously or heterogeneously in existing and innovative reactor types. If the fuel reprocessing losses are sufficiently small, complete closure of the fuel cycle would result in a considerable reduction of the actinide content, and hence the long-term radiotoxicity, of the HLW. Innovative reactor types and new recycle infrastructures, including the pyrochemical or “dry” reprocessing technique, would be necessary, especially for burning highly concentrated transuranics (TRU) and minor actinides.⁶ If some of the long-lived fission products could also be transmuted or separately conditioned, the radiotoxicity of the remaining HLW would decay within a few hundred years, meaning that repository designs for such HLW may meet licensing requirements more easily.
- Lastly, the fast reactor strategy, in contrast to the first three strategies, aims primarily at improving the uranium utilisation and, to this end, substitutes LWRs by fast reactors at a large scale.⁷ Conventional fast reactors have a fuel cycle which is closed for plutonium, but leaves the minor actinides in the HLW stream and hence still generates a non-negligible amount of actinide waste. However, this actinide waste can be much reduced, if all actinides are recycled as this is realised in the Integral Fast Reactor (IFR) concept [3]. The pyrochemical reprocessing method is inherently suited for such a fully closed fuel cycle because it combines the fission product extraction with the co-processing of the actinides.

The achievements of these strategies with regard to the two axes “radiological cleanliness” (one of the most important features of an environmentally friendly nuclear energy system), measured in terms of actinide radiotoxicity reduction, and “uranium utilisation” are visualised in Figure 1.1. In Chapter 2, it will be shown that an actinide toxicity reduction by a factor of 100 relative to the once-through fuel cycle is feasible for high burn-up fuels and a fuel cycle which is optimised for small reprocessing and fabrication losses. A resource utilisation of 100% means that the mined uranium (or thorium) is completely fissioned. In particular, the figure illustrates that a future advanced nuclear energy system could deliver hundred times more energy than today’s conventional nuclear energy system without any increase in the uranium consumption and the actinide waste production.

Figure 1.1 also shows paths to the future. In the early days of nuclear energy, when the uranium resource was assumed to be the limiting parameter for the nuclear development, a rapid introduction of fast reactors based on the MOX fuel and PUREX reprocessing technology (Path A in the figure) appeared imperative. However, the conventional fast reactor development came to a halt in the 80s in the wake of the discovery of additional cheap uranium resources, unexpected technical difficulties with the sodium technology, and considerable cost increases in the demonstration programmes (see Chapter 4). The transition from the conventional fast reactor strategy to a fast reactor strategy

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5. In the context of the present study, the term radiotoxicity is used to quantify the radiation dose to which a human would be subjected, if he would incorporate the radioactive material in drinking water. The quantity does not take any protective barriers between the material and the human into account.
 6. Transuranics: actinides with a higher Z than that of uranium.
 7. High-converter LWRs (HCLWR) were not part of this study but a reactor park consisting of a suitable mix of fast reactors and such HCLWRs could also achieve this goal.

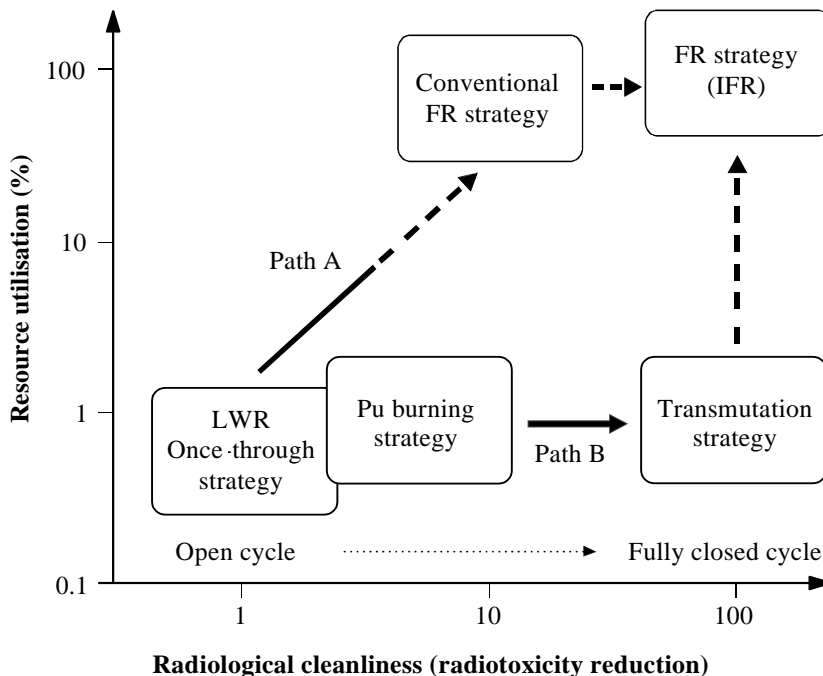
with a fully closed fuel cycle was envisaged already at that time, but not given much attention because the burning of minor actinides was judged to be of a lesser priority and economically unattractive.

Today, while cheap uranium is still available for the coming decades, the nuclear scene is preoccupied with the nuclear waste problem as a result of the world-wide difficulties with the implementation of HLW repositories. Under these boundary conditions, which can be expected to prevail for some decades, Path B in Figure 1.1 may become the favoured path to the future. Path B attempts to reach the long-term goal of the fast reactor strategy with fully closed fuel cycle via the transmutation strategy, with or without a preceding plutonium burning phase.

The clarification of the role and added value of the accelerator-driven system (ADS) with regard to Path B, to be called the *transmutation path*, is the principal purpose of the present study.⁸ The study examines and elucidates this role with the help of different transmutation “schemes”, with separation or co-processing of the actinides, and assesses the technology development status with emphasis on the sub-critical system, the target, the accelerator, new fuels, alternative reprocessing methods, safety, cost/benefit aspects, and R&D requirements. ADS applications with objectives other than transmutation, such as the development of “ultra-safe” fast reactors are not in the scope of this study.

While the potential of the ADS for breeding fissile material and transmuting nuclear waste was recognised already at the beginning of the development of nuclear energy, technological limits for a long time did not permit the application of this technology at a commercial scale. Recent progress, especially in accelerator technology, has led to a renewed interest in the concept and promoted increasing international collaboration in this field.

Figure 1.1. Nuclear energy strategies and paths to the future



8. In the context of the present study, the accelerator-driven system is a hybrid facility consisting of a high-current proton accelerator and a sub-critical reactor.

1.3 Transmutation and role of ADS

1.3.1 Principle and benefit of transmutation

Transmutation aims at reducing the radiological impact of actinides and fission products in the HLW by nuclear transformation of troublesome long-lived nuclides in strong radiation fields.⁹ Assuming that the HLW can be safely enclosed in waste containers for about a millennium, the period of concern begins about 1 000 years after the irradiation of the fuel, i.e. at a time when the majority of the fission products have decayed and the radiotoxicity of the HLW is strongly dominated by actinides. However, long-lived fission products must also be considered since they are more mobile than the actinides and, therefore, dominate the long-term risk of geologic repositories.¹⁰

Regarding suitable radiation sources for transmutation, the requirement for high intensity and energy efficiency means that, in the medium term, only nuclear fission reactors and spallation sources can be utilised. These sources deliver neutrons which induce transmutation reactions in the energy range from thermal up to about 20 MeV. It should be noticed that, in realistic accelerator-driven systems, high-energy spallation neutrons do not significantly contribute to the transmutation reactions, but can influence the activation of components.

The primary benefit of transmutation is a reduction in the minor actinide and long-lived fission product content of the HLW. The first and most effective step to reduce the total mass of the HLW is the transition from an LWR once-through strategy with direct disposal of the fuel elements to a plutonium burning strategy with HLW vitrification. Compared with the latter, transmutation strategies have only a modest mass reduction potential. Since the radiotoxic nuclides in the HLW can only partially be eliminated, transmutation does not make geologic disposal concepts superfluous, but must be considered as a complementary waste management method which may ease the design and licensing requirements for geologic repositories because the geosphere barrier would no longer have an important safety function.

With regard to alternative advanced waste management methods, the partitioning of individual actinides and fission products in combination with their immobilisation in special matrices, i.e. their conditioning and confinement in matrices which are more stable than glass, is worth mentioning. An advantage of such methods is their applicability to short-lived fission products which cannot be transmuted (see Chapters 2 and 8). Partitioning/immobilisation could be employed, for example, to reduce the heat load of HLW which is also an important issue for geologic repositories. However, it should be emphasised that, whereas partitioning/immobilisation is a possible alternative for reducing the long-term risk of a repository, the method is not suited for mitigating the hazard in the case of human intrusion scenarios because the total inventory of the radiotoxic nuclides remains unchanged.

1.3.2 Actinide transmutation

For the transmutation of actinides, the key reaction is the *fission reaction* which transforms long-lived, highly radiotoxic actinides into mostly short-lived, less toxic fission products. Other reactions

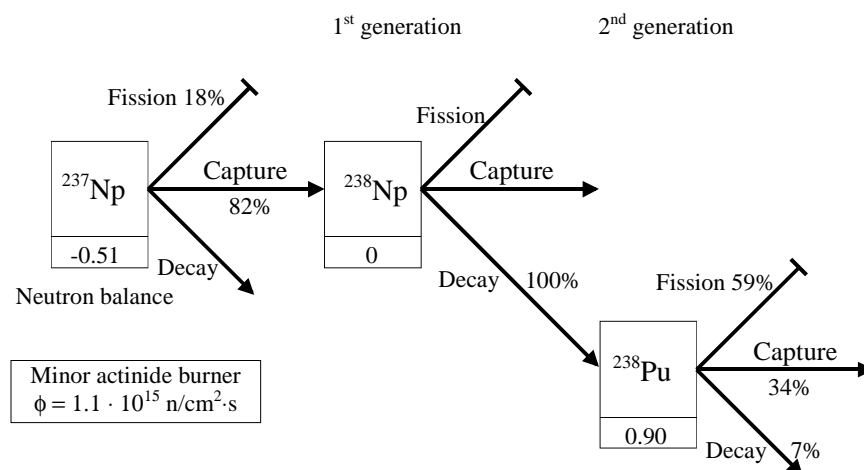
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9. It should be noted that transmutation addresses only one aspect of the impact of the fuel cycle on the environment and that, in a general risk assessment study, the environmental effects arising from the fuel cycle front-end activities, secondary wastes, etc., would also have to be considered.
 10. The long-term risk of a geologic repository is usually evaluated in terms of an annual individual dose for the concerned population (Sievert per year) taking the mitigation of the radiotoxic releases by the multiple barriers (waste container, engineered repository near-field, host rock) and the biosphere behaviour of the nuclides into account (see Chapter 2).

such as capture and (n,2n) reactions just transform actinide species into other actinide species without a significant effect on long-term radiotoxicity. However, these reactions are useful insofar as they transform fertile actinides with a low fission probability into fissile actinides with a high fission probability.¹¹ The release of additional fission energy is a small “extra gain” from the transmutation of minor actinides.

The transmutation of an actinide is completed, when the transformation chain, which involves “generations” of neutron reactions and radioactive decays, terminates with a fission. Figure 1.2 illustrates the first three steps of the transmutation process for ²³⁷Np. The first transformation step consumes on average 0.51 neutrons because it is dominated by capture reactions, the second step is a simple decay, and the third step produces on average 0.90 neutrons because it is dominated by fission reactions. Up to the second generation, the neutron balance (excess) is +0.39, and 66% of the original ²³⁷Np atoms are transmuted.¹² The “overall neutron balance”, i.e. the neutron balance over all generations until all original atoms are fissioned, is an important basic parameter which depends on the type of transmutation system. Interesting general observations regarding this parameter are that:

- Fast systems feature a significantly better overall neutron balance for the transmutation of actinides than thermal systems and provide many excess neutrons which could be utilised for other applications, e.g. the transmutation of fission products.
- The overall neutron balance of thermal systems does not constrain the transmutation of typical LWR discharged transuranic mixtures.
- A deficit in the overall neutron balance of thermal systems does not allow a complete transmutation of pure minor actinides.

Figure 1.2. Transformation chain for the transmutation of Neptunium-237



Points 2 and 3 mean that, from a neutron balance viewpoint, TRU burners can be designed as critical or sub-critical systems with any type of neutron spectrum, but dedicated minor actinide burners must be designed as critical or sub-critical fast reactors. It will be shown in Chapter 2 that critical and sub-critical fast reactors feature similar overall neutron balances, and that the advantages of the sub-

11. The fertile actinides have a fission threshold which makes the fission probability strongly dependent on the neutron spectrum.
 12. The numerical example applies to the accelerator-driven minor actinide burner described in Chapter 3.

criticality are primarily a gain in core design and operation flexibility due to the removal of the criticality constraint and its potential to compensate degraded safety characteristics of actinide burners with a fast neutron spectrum.¹³

The equivalence between the actinide transmutation and the fission process implies that the transmutation rate in an actinide burner is limited by the thermal power. Moreover, the fuel fraction which can be transmuted in a single pass of the fuel through the burner cannot exceed the fuel burn-up. Since the burn-up for solid fast reactor fuel is limited to about 25%,¹⁴ it is clear that an effective actinide burner cannot operate in a once-through mode, but requires a fuel cycle which allows the fuel to be recycled many times. For the maximum burn-up of 25% and recycle intervals of 6 years,¹⁵ it takes 96 years to achieve a hundredfold waste mass reduction. This means that the feasibility of transmutation depends not only on the establishment of a suitable fuel cycle, but also on the assumption that the technology can be sustained during a period of at least hundred years. High development costs and long lead times speak also for a minimum utilisation period of this length.

Important conclusions from this discussion are that:

- An effective transmutation system calls for a fully closed fuel cycle in which all actinides are recovered with a nearly 100% efficiency and recycled.
- To realise the potential of this system, it must be operated for an extended period of at least hundred years.

Under the present market forces, thermal, and especially fast, advanced systems with closed fuel cycles are not competitive with LWRs. Therefore, there exists a strong incentive to operate actinide burners in symbioses with LWRs and to optimise the burner efficiency for a high LWR-to-burner support ratio. Proposals for implementing such LWR-burner symbioses follow two basically different approaches:

- An evolutionary approach, where the plutonium and the minor actinides in LWR-discharged fuel are separated and recycled individually in different conventional and advanced reactor types using predominantly basically proven aqueous reprocessing technology.
- An *innovative approach*, where the transuranics in LWR-discharged fuel are recovered together and transferred to a closed TRU burner fuel cycle using pyrochemical reprocessing technology which is well suited for handling the high activity of multi-recycled fuels in closed fuel cycles.

The evolutionary approach has the advantage that it can be implemented in successive steps. In particular, the first step could be the establishment of a plutonium burning strategy, and this could later be upgraded to a transmutation strategy by complementing the reactor park with dedicated minor actinide burners whose fuel cycle is optimised for this task. An early introduction of a plutonium burning strategy could be motivated by the need to reduce the stocks of separated plutonium which have accumulated in some countries due to the delay in the commercialisation of fast reactors.

Since plutonium burning represents only a small first step towards a transmutation strategy (see Figure 1.1), it is not in the focus of the present study. It may, nevertheless, be recalled that plutonium

13. The increased design flexibility allows, for instance, improving the “burner effectiveness” (see Chapter 2).

14. 25% is the highest fuel burn-up considered by the expert group (see comparative assessment in Chapter 3).

15. The 6 years comprise 3 years of in-pile and 3 years of out-of-pile time and are typical for an accelerator-driven TRU burner (see Chapter 3).

can be managed effectively with LWRs and fast reactors; innovative reactor and reprocessing technologies are not required, and respective development issues have been dealt with extensively in the framework of working parties and workshops of OECD/NEA [4,5] as well as in many international conferences. The recycling of plutonium in the form of MOX in LWRs has already reached industrial maturity. It should, however, be noticed that LWRs alone cannot burn plutonium in the longer term because the buildup of the even, non-fissile plutonium isotopes in a thermal neutron spectrum constrains the number of recycles to two or three at most; the remaining degraded plutonium has to be disposed or transferred to a fast reactor fuel cycle. From the viewpoint of transmutation, the build-up of minor actinides, especially the highly radioactive curium, is also a drawback of a “thermal” recycling strategy.

As indicated before, fast-spectrum systems are required to handle the minor actinides. Conventional fast reactors can burn self-generated minor actinides in a closed cycle, but they are not suited for burning pure minor actinides. Compared with conventional MOX-fuelled fast reactor cores, dedicated minor actinide burner cores have significant safety disadvantages due to an increased coolant void reactivity effect in liquid-metal cooled systems, a generally smaller fuel Doppler reactivity coefficient and a considerably reduced fraction of delayed neutrons, β_{eff} .¹⁶ The coolant void reactivity effect can be mitigated by reducing the size and optimising the geometry of the core, or eliminated completely by replacing the liquid-metal by a gas coolant. The application of the ADS concept to a minor actinide burner core is an interesting possibility to compensate the safety disadvantages arising from the small Doppler coefficient and the small β_{eff} value which cannot be otherwise compensated. To cope with the high activity of the fuel, dedicated minor actinide burners require a fuel cycle with pyrochemical reprocessing. Thanks to a very favourable support ratio, however, the investments into advanced reactor and reprocessing technology remain small.

The innovative approach to LWR-burner symbioses aims at co-processing plutonium and minor actinides to avoid the use of technologies with a potentially high proliferation risk. After initial separation of the uranium from the LWR spent fuel, the actinides are recycled in a TRU burner with a closed fuel cycle using pyrochemical reprocessing without further actinide separation. The core characteristics of TRU burners are less degraded than those of minor actinide burners and allow the burner to be operated in a critical state. The ADS concept, however, offers additional design flexibility which can be utilised to increase the LWR-to-burner support ratio. Compared with the evolutionary approach, the innovative approach requires a larger investment in dedicated actinide burners.

In Chapter 3, the essential features of the different actinide transmutation approaches will be discussed and compared with the help of six *principal fuel cycle schemes*, including three transmutation schemes, an LWR once-through reference case, a plutonium burning scheme in which the fuel cycle is closed for plutonium only, and a pure fast reactor scheme. It will be shown in Chapter 2 that, for closed fuel cycles, the transmutation performance in terms of actinide waste mass and radiotoxicity reduction depends primarily on two parameters, the fuel burn-up and the fuel losses in the reprocessing which have to be maximised and minimised, respectively. Goals for waste mass and radiotoxicity reduction will be derived; and it will be shown that these goals can be met with both evolutionary and innovative transmutation approaches, but that the consequences on the fuel cycle can vary considerably between the different approaches.

With regard to consequences for the fuel cycle, it is important to note that the multi-recycling of fuels, especially in minor actinide and TRU burners, results in very high activities, decay heats and

16. A sufficiently negative fuel Doppler coefficient restricts the energy release in an accidental prompt-critical power excursion and β_{eff} determines the reactivity margin within which the chain reaction can be controlled. By substituting minor actinide fuel for normal MOX fuel, β_{eff} is about halved.

neutron source strengths of the fuels which complicate the reprocessing, handling, and shielding of the fuels. To reduce these problems, it has been proposed to restrict the multi-recycling to neptunium and to recycle americium and curium in separate targets which are disposed of after a single irradiation in a fast reactor. Advantages of such “heterogeneous” recycling concepts are that the fuel cycle – a normal MOX fast reactor fuel cycle with standard aqueous reprocessing – is much less contaminated with minor actinides, the mass flows of the latter are generally reduced, and the safety of the burner is not significantly impeded. Disadvantages of the heterogeneous concepts are the limited number of target assemblies which can be accommodated in the reactor and the limited burn-up of the targets which allows only modest waste mass reductions to be achieved.

1.3.3 Fission product transmutation

For the long-lived fission products, the goal is to transform them into shorter-lived or stable species by means of *neutron capture reactions*. Other nuclear reactions have also been considered, but, presently, do not fulfil the criteria for a practical application. The fission product transmutation involves different problems than the actinide transmutation: the fission products have to be separated individually from HLW with a high decontamination factor and processed to stable targets for irradiation, the necessity of isotopic separations and small reaction cross sections constrain the practical implementation of the processes and, not least, the lack of producing net amounts of energy jeopardises the economic viability of the processes.

The traditional fission product transmutation method is the irradiation of targets in a strong flux of neutrons produced by a fission reactor or a spallation neutron source. Neutron economy considerations favour concepts where the fission product targets are irradiated in moderated sub-assemblies of fast reactors. More recently, it has been suggested to use lead or lead-bismuth as coolant for fast-spectrum systems because the small energy loss of neutrons in collisions with the lead atoms enhances the probability for the slowing down neutrons to be captured in the resonances of the nuclide to be transmuted. Based on this principle, an accelerator-driven fission product transmuter, in which nearly every source neutron induces a transmutation reaction, is theoretically feasible.

It appears that, in principle, the transmutation of long-lived fission products would be a useful method to mitigate the long-term risk of geologic repositories; however, the practical feasibility of the required processes is less obvious than in the case of the actinides and, so far, has been established only for ^{99}Tc . This means that, for most potentially troublesome long-lived fission products, including ^{135}Cs , ^{126}Sn , ^{79}Se and possibly also ^{129}I , partitioning followed by special conditioning and confinement in a very stable matrix may remain the only realistic method for reducing their radiological impact.

1.4 The ADS concept

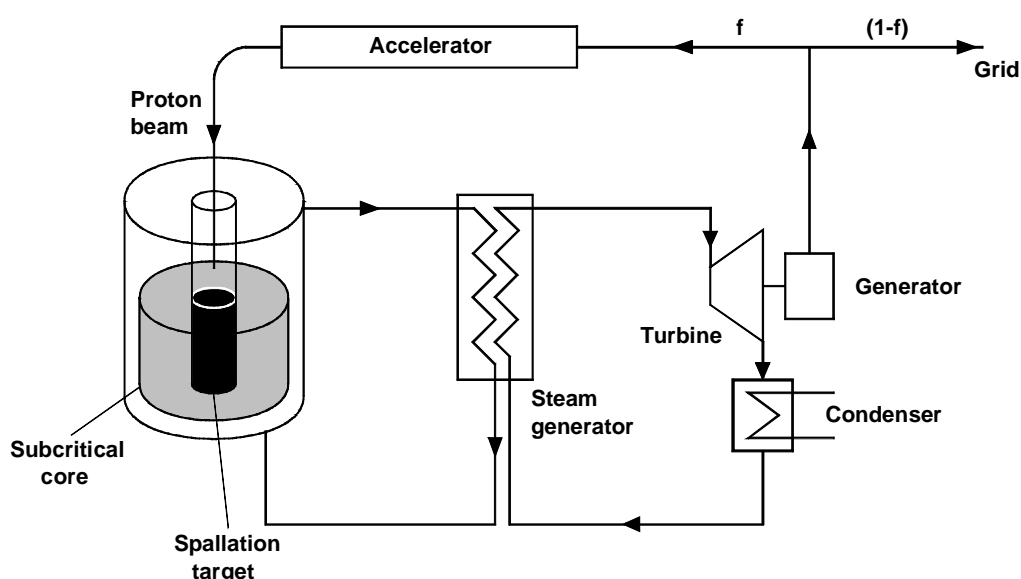
The concept of accelerator-driven systems (frequently called hybrid systems) combines a particle accelerator with a sub-critical core (see Figure 1.3). Most proposals assume proton accelerators, delivering continuous-wave beams with an energy around 1 GeV. The accelerator is either a linear accelerator (linac) or a circular accelerator (cyclotron). High-power accelerators have been under continuous development, and the construction of machines with the required specifications, i.e. electrical efficiencies in the vicinity of 50% and beam powers up to 10 MW for cyclotrons and up to 100 MW for linacs, now appears to be feasible.

The protons are injected onto a spallation target to produce source neutrons for driving the sub-critical core. The target is made of heavy metal in solid or liquid state. Spallation reactions in the

target emit a few tens of neutrons per incident proton, which are introduced into the sub-critical core to induce further nuclear reactions. Except for the sub-critical state, the core is very similar to that of a critical reactor. It can be designed to operate either with a thermal or fast neutron spectrum.

The energy conversion part of an accelerator-driven nuclear power system is similar to that of a normal power plant. However, in the accelerator-driven system, the electrical energy which is recycled to the accelerator reduces the net electrical efficiency of the system. For an ADS with a neutron multiplication factor of 0.95, the reduction amounts to about 12%. This means that the accelerator-driven system produces about 14% more high-level waste and rejects about 20% more heat to the atmosphere than a normal power plant with the same net electrical output.

Figure 1.3. Concept of an accelerator-driven system



The principal advantages and disadvantages of accelerator-driven systems as compared with the corresponding critical reactor systems are summarised in Table 1.1. The comparison applies not only to transmutation applications on which the present study is focussed, but also to other applications such as the breeding of fissile material (electro-breeding), the development of the thorium-²³³U fuel cycle, and the development of ultra-safe energy producers. For instance, the potential for improving the neutron economy, which is related to the neutron abundance of the spallation process, is more relevant for breeding than for transmutation applications.

In the context of transmutation, the principal non safety-related advantage of the ADS is the increased core design and fuel management flexibility resulting from the removal of the criticality condition. However, this advantage has to be weighted against several technical and operational disadvantages. For example, the benefit from lengthening the reactor cycle has to be balanced against the investment in the more powerful accelerator required for coping with the lower end-of-cycle neutron multiplication factor.

Table 1.1. Comparison of accelerator-driven sub-critical and critical reactor systems

	Advantages of accelerator-driven systems	Disadvantages of accelerator-driven systems
Design and operation	<ul style="list-style-type: none"> ◆ The possibility to operate a reactor core at a <i>neutron multiplication factor below 1</i> opens opportunities for new reactor concepts, including concepts which are otherwise ruled out by an insufficient neutron economy ◆ In particular, this allows transmuters to be designed as <u>pure TRU or MA burners</u> and hence the fraction of specialised transmuters in the reactor park to be minimised ◆ The proportionality of the reactor power to the accelerator current simplifies the reactor control 	<ul style="list-style-type: none"> ◆ <i>Accelerator</i>: Very high reliability required to protect structures from thermal shocks ◆ <i>Beam window and target</i> subjected to unusual stress, corrosion and irradiation conditions ◆ <i>Sub-critical core</i>: Increased power peaking effects due to external neutron source ◆ Compromises between neutron multiplication factor and accelerator power required ◆ Increased overall complexity of the plant ◆ Reduction in net plant electrical efficiency due to power consumption of accelerator
Safety	<ul style="list-style-type: none"> ◆ The reactivity margin to prompt criticality can be increased by an extra margin which does <i>not depend on the delayed neutrons</i> ◆ This enables the <u>safe operation of cores with degraded characteristics</u> as they are typical e.g. for pure MA burners ◆ <i>Excess reactivity can be eliminated</i>, allowing the design of cores with a reduced potential for reactivity-induced accidents 	<ul style="list-style-type: none"> ◆ <u>New types of reactivity and source transients</u> have to be dealt with (external neutron source can vary rapidly and reactivity feedbacks in TRU- and MA-dominated cores are weak)

Note: Issues of particular relevance for the transmutation of TRU and minor actinides (MA) are underlined.

Important design and material problems arise from the installation of a target in the centre of a reactor: the interfacing of an accelerator with a reactor rises containment questions, and the target and surrounding structure materials are subjected to complex degradation phenomena due to combined thermo-mechanical loads, high-energy particle irradiation and, in contact with liquid heavy metals, corrosion effects which are much more severe than those encountered in normal reactors. This applies particularly to the beam window which may, therefore, require frequent replacement.

High-power accelerators will have to be improved with respect to the beam losses which cause radiation damage and activation in the accelerator components and the frequency of beam trips. In an ADS, beam trips cause similar temperature and mechanical stress transients as fast control rod insertions (scrams) in critical reactors. Current accelerators feature beam trip frequencies which lie orders of magnitude above the current criteria for such transients.

Regarding safety aspects, the prominent feature of the ADS is its reduced potential for reactivity-induced accidents. This is particularly relevant for actinide burners which suffer from a general degradation of the safety parameters of the core. From the viewpoint of transmutation, a general conclusion from Table 1.1 is that an ADS has interesting design and safety advantages, but that these must be weighted against non-trivial technical and operational disadvantages which will also have economic consequences.

The diverse technical aspects of the ADS have been studied in many OECD Member countries. However, there is still a need for assessing more thoroughly the added value the ADS in the context of complete fuel cycles.

1.5 Framework for the present study

A first series of comprehensive studies investigating the role and feasibility of partitioning and transmutation as an alternative waste management option was conducted in the 1970s predominantly in Europe. On the whole, these studies denied the existence of a cost, safety, or any other incentive for developing this technology. A renewed interest in P&T arose in the 1980s in response to an increasing public opposition against the geologic disposal of radioactive waste. More recently, the difficulties in the commercialisation of the large, sodium-cooled fast reactor and the progress in the development of high-power accelerators strengthened the interest in transmutation technologies in general and accelerator-based technologies in particular. A detailed history of this development is given in Annex C.

In response to the increased interest in P&T and ADS technologies, OECD Member countries launched several R&D programmes, such as the OMEGA programme in Japan [6] and the SPIN programme in France [7], and, more recently, developed “roadmaps” for the demonstration of these technologies as e.g. the US Roadmap for Developing Accelerator Transmutation of Waste Technology [8] and the European Roadmap for Developing Accelerator-driven Systems for Nuclear Waste Incineration [9]. The Nuclear Energy Agency of the OECD initiated a long-term programme on P&T in 1989. The respective projects address a wide range of issues ranging from basic nuclear data questions to systems studies. In parallel, an International Information Exchange Programme has been established to strengthen the international collaboration.

A first P&T systems study, conducted by OECD/NEA from 1996 to 1998 [2], focused on a review of the progress in the separation of long-lived actinides and fission products, the options for their transmutation, and the benefit for the waste management. Specific fuel cycle schemes were discussed, covering plutonium-recycling and the additional burning of minor actinides in dedicated systems. However, the study did not address the more performant transmutation strategies with fully closed fuel cycles, nor the technology of the ADS and the specific role of the latter in such closed fuel cycles.

The present, second P&T systems study is complementary to the first study. It aims at clarifying the roles and relative merits of critical and sub-critical fast-spectrum systems in closed fuel cycles with the help of a set of representative “fuel cycle schemes” and assesses the development status of the ADS with emphasis on reactor technology and safety, fuel cycle technology, cost/benefit issues, and general feasibility.

Chapter 2 of the report defines target values for the waste mass and radiotoxicity reduction to be achieved by an effective transmutation strategy, discusses the incentive for closed fuel cycles in general, including the role of fast-spectrum systems in these fuel cycles, and summarises the principal results of the comparative analysis of the fuel cycle schemes. The fuel cycle schemes, the results of the comparative analyses and the associated fuel fabrication and reprocessing issues are described in detail in Chapter 3.

The technological issues and differences between fast reactors and accelerator-driven fast reactors are covered in Chapter 4. ADS safety, with emphasis on uranium-free systems, is handled in Chapter 5; Chapter 6 is devoted to a preliminary cost analysis, and Chapter 7 overviews the perceived R&D needs. Chapter 8 focuses on the transmutation of long-lived fission products where Chapter 9 is introducing alternative actinide transmutation approaches.

2. TRANSMUTATION STRATEGIES

2.1 Introduction

The transmutation strategy as defined in Chapter 1 involves the recycling of both plutonium and minor actinides with the goal of converting all actinides to fission products. Immediate benefits of a reprocessing strategy, with or without minor actinide transmutation, are the elimination of plutonium from the HLW and a reduction in the total mass of the HLW in comparison with a (spent fuel) direct disposal strategy. The closure of the fuel cycle for plutonium reduces the natural uranium requirement by 30%, and the additional fissioning of the minor actinides reduces the natural uranium requirement by another 5%.¹⁷ The latter is an “extra gain” from transmutation which, alone, would not justify the development of new reactor and fuel cycle technology.

From a discussion of the contribution of actinides and fission products to the radiotoxicity and long-term risk of HLW, Chapter 2 first derives target values for the reduction of the actinide waste mass and the fuel reprocessing losses which have to be set for an effective actinide transmutation strategy. A second part of the chapter deals with the implications of a fully closed fuel cycle for the overall neutron economy and transmutation performance of an actinide burner, compares different actinide transmutation strategies, and summarises the results of a consistent analysis of “principal fuel cycle schemes”, carried out by the Expert Group. Finally, transient aspects in nuclear energy scenarios and the feasibility of transmuting long-lived fission products are briefly discussed.

2.2 Radiotoxicity and long-term risk of high-level waste

Figure 2.1 shows the radiotoxicity of uranium-oxide fuel with an average burn-up of 50 GWd/tHM as discharged from the reference LWR considered in the present study. In the figure, this radiotoxicity is compared with the radiotoxicity of the remaining HLW after separation of 99.9% of the uranium and plutonium, assuming a cooling time of 4 years between fuel discharge and reprocessing. A decomposition of the latter into nuclide contributions is also shown.

It can be seen that the radiotoxicity is dominated, first, by short-lived fission products, and later, by actinides. A few hundred-thousand years after the discharge, the radiotoxicity of the unprocessed fuel drops to the natural toxicity level for LWRs, i.e. the equilibrium radiotoxicity of the natural uranium required to fabricate the fuel.¹⁸ The separation (and intermediate storage) of uranium and plutonium would reduce the radiotoxicity of the remaining HLW in the time frame from 10^3 to 10^5 years by an order of magnitude, but it would still take some twenty-thousand years for the radiotoxicity of this waste to reach the LWR natural toxicity level. Moreover, when defining a HLW radiotoxicity reduction goal for a fuel cycle strategy involving reactors with increased resource

17. Evaluated for the plutonium burning and the “double strata” strategies discussed in Section 2.7.1.

18. The LWR natural toxicity level is calculated as the product of the natural uranium requirement for an LWR once-through strategy (20.5 t/TWhe for a burn-up of 50 GWd/tHM) and the radiotoxicity of natural uranium, including daughter products (20 Sv/kg).

efficiency, it should be borne in mind that the natural toxicity level decreases proportionally with the natural uranium requirement. The figure indicates that, for a pure fast reactor strategy, the natural toxicity level corresponds about to the radiotoxicity of the long-lived fission products.

Figure 2.1. Radiotoxicity of LWR spent fuel

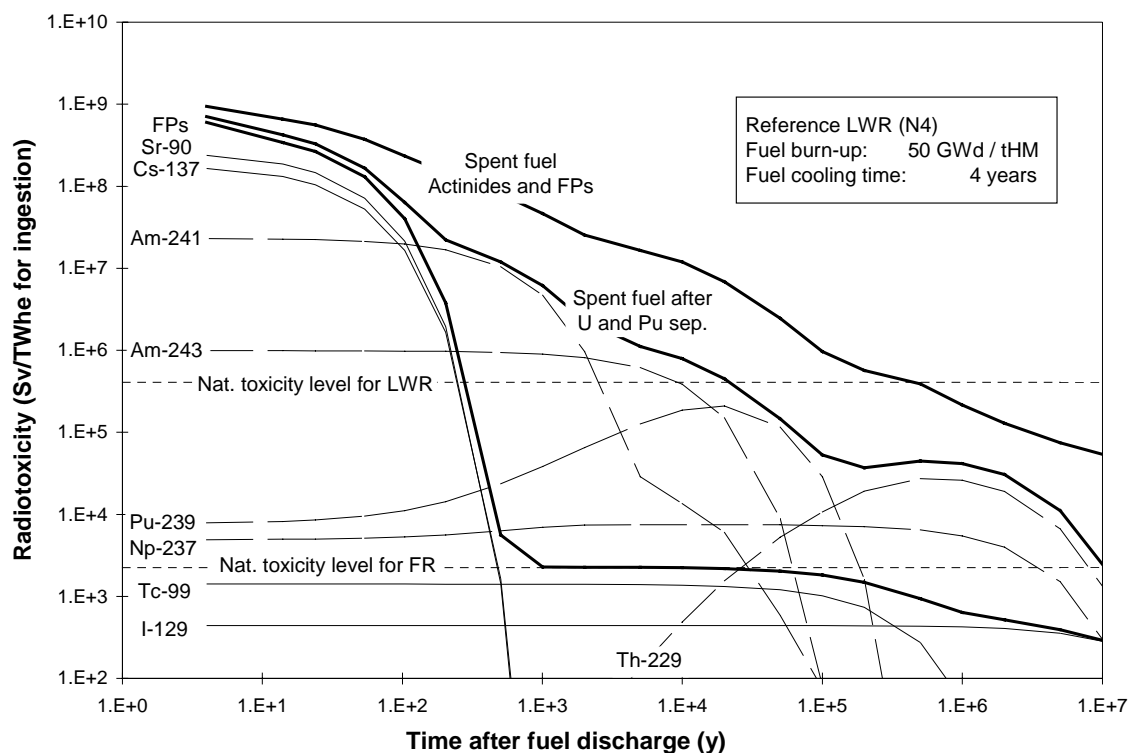


Figure 2.2 compares risks in terms of annual individual doses to the population for different concepts of geologic repositories, the four examples representing the direct storage of spent fuel in chemically reducing or oxidising environments [10,11], and the emplacement of vitrified HLW in crystalline host rock or clay [12,13]. It should be noted that the curves apply to nuclear energy scenarios with different energy production and different amounts of spent fuel. The figure shows that, with the exception of the Yucca Mountain repository, the doses to the population lie at least two orders of magnitude below the natural radiation exposure.

Conclusions of direct relevance for the present study are:

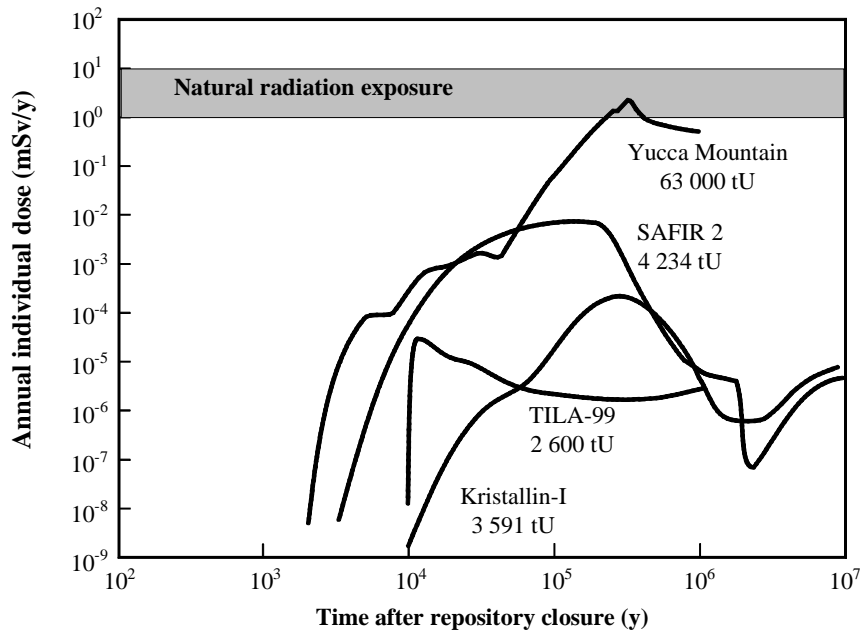
- From the viewpoint of the *radiotoxicity*, which plays a role mainly in accidental intrusion scenarios, P&T must first be concerned with the actinides, particularly the minor actinides americium and neptunium,¹⁹ the toxicity of the fission products lying at least two orders of magnitude below that of the actinides after a few hundred years.
- The *long-term risk* of a geologic repository is usually dominated by fission products which are generally more mobile than actinides. Dose contributions arise primarily from ¹²⁹I, ¹³⁵Cs,

19. Two other heavy nuclides appearing in Figure 2.1, ²³⁹Pu and ²²⁹Th, are decay products of ²⁴³Am and ²³⁷Np, respectively. In the time frame of interest to P&T, curium is not a dominant contributor to the waste radiotoxicity.

^{99}Tc , ^{126}Sn and ^{79}Se , their order of importance depending on the repository concept.²⁰ The fission product risk peaks in the time range 10^4 to 10^6 years after the closure of a repository, whereas the (smaller) actinide risk arises “only” after one million years).²¹

- Actinide transmutation strategies address primarily the radiotoxicity (hazard) of the HLW. To reduce the long-term risk (dose to the population), the long-lived fission products would also have to be transmuted or specially conditioned.

Figure 2.2. Annual individual dose for different repository concepts



Dominant nuclides:

TILA-99 spent UOX, reducing env.	^{129}I / ^{126}Sn / ^{129}I / ^{229}Th
Yucca Mountain spent UOX, oxidising env.	^{99}Tc / ^{237}Np (^{229}Th)
Kristallin-I vitrified HLW in granite	^{79}Se / ^{135}Cs / ^{99}Tc / ^{231}Pa
SAFIR 2, provisional vitrified HLW in clay	^{79}Se / ^{129}I / ^{229}Th

2.3 Goals for actinide mass reduction and fuel losses

2.3.1 Actinide mass reduction

As discussed in Section 2.2, the radiotoxicity of LWR-discharged fuel requires a few hundred-thousand years to decay to the LWR natural toxicity level. With a hundred-fold reduction in the

20. Vitrified HLW does not contain a significant amount of ^{129}I because iodine is released during reprocessing and (currently) discharged to the sea. Since sea disposal may no longer be practicable for advanced nuclear fuel cycles, ^{129}I is also a candidate for P&T in vitrification scenarios.

21. For the Yucca Mountain repository, the actinide risk becomes dominant after 50 000 years (see Figure 2.2).

actinide content of the HLW, this goal could be reached after about thousand years, i.e. within the time span during which the HLW container can be expected to fulfil its safety function. For transmutation strategies involving fast reactors, an even higher actinide reduction factor would be desirable. For such strategies, a reduction in the actinide content of the HLW by a *factor of 100* must therefore be set as a minimum goal.

It is obvious that a hundred-fold reduction of the actinide mass cannot be achieved in a single pass of the fuel through a reactor. Hence, *multi-recycling* of the fuel will be essential.²² In fact, the ideal P&T system has a fuel cycle which is fully closed for the actinides, meaning that only fission products are separated from the spent fuel and all actinides are returned to the reactor, together with a “top-up” of new fuel replacing the fuel which was fissioned. It is also clear that such a system must be operated for many decades before the composition of the discharged fuel, which determines the specific waste radiotoxicity, reaches an equilibrium.

2.3.2 Fuel losses in the reprocessing

In practice, the actinides cannot be recovered completely from the spent fuel, and the remainder will go to waste. For the fully closed system illustrated in Figure 2.3, the mass of actinides going to waste is:

$$M^W = \delta L M^F,$$

where M^F is the total mass of actinides fissioned, L is the actinide loss fraction during reprocessing and fuel fabrication, and the burn-up factor, δ , can be evaluated from the fraction of heavy metal fissioned, B , as $(1 - B)/B$. For equilibrium conditions and small actinide losses, M^F equals the top-up fuel mass, M^T , which, in general, can be divided into the mass, M^B , of transuranic or minor actinides to be burnt, and a diluent, usually consisting of uranium (see Figure 2.3, TRU/MA and diluent supply). The diluent allows to optimise the core characteristics of the actinide burner (see Section 2.3.4).

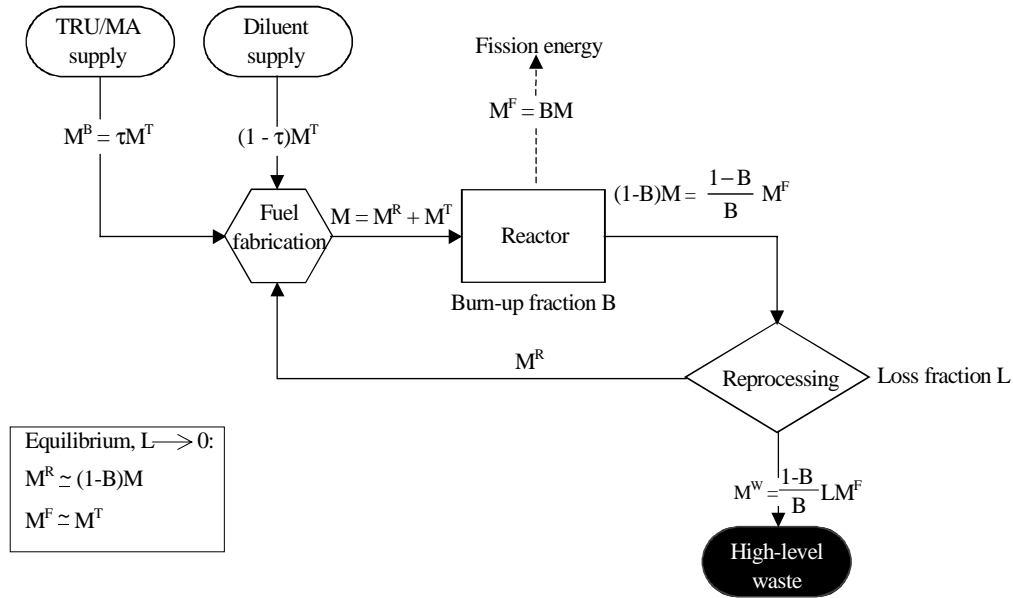
Denoting the transuranic or minor actinide fraction of the top-up fuel, M^B/M^T , by τ and the “waste mass reduction factor”, M^B/M^W , by R^M , one obtains the simple expression

$$L = \tau/(\delta R^M),$$

which gives the allowable losses as a function of the waste mass reduction factor. For the desired reduction factor of 100, an achievable average fuel burn-up of 15%,²³ and a top-up fuel without a diluent ($\tau = 1$), the expression yields $L = 0.18\%$. Since average burn-ups beyond 15% have not yet been proven with known fuel technologies, a *target value of 99.9%* for the actinide recovery yield must consequently be set for an effective actinide transmutation system.

-
22. The highest average fuel burn-up for systems with solid fuels considered by the Expert Group is 25% (ATW project goal). The burn-up can be higher, if the actinides are recycled heterogeneously in separate target pins (see Chapter 3, Section 3.3.2) or if alternative fuels, consisting e.g. of coated particles, are introduced (see Chapter 9), but would still be far from the goal of 99%.
23. In agreement with the reference burn-up of 140 GWd/tHM for TRU and MA burners (see Table 2.3).

Figure 2.3. Actinide mass flow in fully closed fuel cycle in equilibrium



2.4 Reactor requirements in fully closed fuel cycles

2.4.1 Neutron balance of equilibrium core

For neutronic reasons, not all reactors can operate with a fully closed fuel cycle. To assess the suitability of an equilibrium core in terms of neutron multiplication,²⁴ the production-to-absorption ratio of the actinides in the equilibrium core, η_{ec} , is a useful parameter. Alternatively, the overall neutron balance for the complete fissioning of an actinide or an actinide mixture can be measured in terms of the neutron excess parameter $-D$ (see Chapter 1, Section 1.3.2, and [14]). An η_{ec} value smaller than 1 means that the equilibrium core cannot maintain a chain reaction; a negative $-D$ value indicates that an actinide or an actinide mixture cannot be completely transmuted. The parameters are mainly influenced by the top-up fuel composition, the neutron spectrum, and the flux level. It can be shown that both approaches lead to the same conclusions.

The η_{ec} and $-D$ values in Table 2.1 refer to different ADS concepts which are designed to burn pure transuranics or minor actinides as well as an ALMR-type fast reactor which is fed with pure uranium. The fast-spectrum systems are those described in Table 2.3, the thermal ADS is the graphite-moderated molten-salt system proposed in [15]. Different top-up fuels are considered: the plutonium and transuranic mixtures correspond to PWR spent fuel with a burn-up of 50 GWd/tHM; the MA mixture is that produced by the first stratum of the “double strata strategy” described in Section 2.7.1.

It can be seen that minor actinides cannot be completely transmuted in thermal systems and that fast systems offer more excess neutrons than thermal systems. Interestingly, the accelerator-driven fast systems have smaller neutron excesses than the critical fast reactor. This is due to the moderation effect of the high zirconium content of the uranium-free fuels on the neutron spectrum of the fast

24. The equilibrium core is the core which is established asymptotically by recycling the discharged fuel indefinitely in the same reactor as illustrated in Figure 2.3. Its neutronic parameters can differ considerably from those of a start-up core.

burners. Large neutron excesses are advantageous, if the systems are also utilised as fission product transmuters (see Chapter 8, Section 8.2).

Table 2.1. Overall neutron balance parameters of different equilibrium cores

Top-up fuel	Thermal TRU burner (ADS)		Fast TRU burner (ADS)		MA burner (ADS)		Critical fast reactor	
	η_{ec}	-D	η_{ec}	-D	η_{ec}	-D	η_{ec}	-D
Uranium-238	0.92	-0.24	1.28	0.64	1.28	0.64	<u>1.41</u>	<u>0.85</u>
Plutonium	1.15	0.40	1.80	1.34	1.74	1.28	2.03	1.53
Minor actinides	0.89	-0.37	1.37	0.86	<u>1.33</u>	<u>0.79</u>	1.52	1.10
Transuranics	<u>1.11</u>	<u>0.30</u>	<u>1.75</u>	<u>1.29</u>	1.69	1.23	1.96	1.48

Notes:

1. Underlined values indicate that the concept has been optimised for the indicated top-up fuel.
2. A PWR loaded with 30% MOX has a similar neutron economy as the thermal ADS.

2.4.2 Core design constraints

In practice, the design of a TRU or MA burner core, like that of any reactor core, is also constrained by performance and safety parameters, such as the reactivity swing during burn-up, the coolant void reactivity effect, the fuel Doppler coefficient, and the effective delayed-neutron fraction. Unfortunately, for a sodium-cooled fast reactor, the substitution of normal MOX fuel by TRU- or MA-dominated fuel has an unfavourable influence on several of these parameters. This shortcoming of the conventional fast reactor has led to a renewed interest not only in the ADS, but also in various alternative fast and thermal reactor concepts which had been studied in the past, but have not been developed to commercial systems.²⁵

To ensure that a critical burner core performs satisfactorily and has acceptable safety parameters, it is usually necessary to blend the TRU or minor actinides with the fertile materials uranium or thorium. However, blending reduces the transmutation effectiveness of the system. Accelerator-driven systems do not require blending and offer the possibility to increase the safety margin to prompt criticality. The latter feature is particularly important for MA burners, which are difficult to control as critical systems because the effective delayed-neutron fraction is only about half of that of a normal fast reactor.

In response to the new core design issues raised by actinide burners and the increased interest in advanced reactor technology in general, government and industry funded design teams in many countries with nuclear programmes are currently spending a considerable effort on the optimisation of a broad range of advanced reactor designs featuring both critical and accelerator-driven cores.

25. For example, the (positive) coolant void effect in sodium-cooled fast reactors could be mitigated by substituting the sodium by lead, or even eliminated by substituting the liquid metal by a gas coolant.

2.5 Transmutation performance in fully closed fuel cycles

2.5.1 Transmutation effectiveness

Various definitions for the transmutation effectiveness of actinide burner cores, usually based on the minor actinide balance of the core, are given in the literature [2]. However, since these definitions do not account for the recycling of the fuel, they do not give meaningful results for an equilibrium core. For measuring the overall transmutation effectiveness of a system with a fully closed fuel cycle, the most appropriate parameter is the “burner effectiveness”, defined as the relative content of the top-up fuel in transuranic and minor actinides, M^B/M^T , i.e. the already discussed parameter τ . This parameter is directly related to the supplier-to-burner support ratio which indicates how many supplier reactors (usually LWRs) can be supported by a burner reactor.

It is important to note that the thus defined burner effectiveness does not depend directly on the choice of the neutron spectrum, the fuel type and the coolant, but is governed by the above-mentioned performance and safety constraints of the core. For a critical TRU burner based on liquid metal technology, τ is smaller than about 0.5, and in the case of homogeneous MA recycling in a EFR-type fast reactor τ is less than 0.1. The possibility to operate sub-critical MA and TRU burner cores with a uranium-free top-up fuel and hence 100% burner effectiveness, i.e. $\tau = 1$, is probably the *most important advantage of accelerator-driven systems*; it allows to maximise the supplier-to-burner support ratio and the waste mass reduction factor.²⁶

2.5.2 Radiotoxicity reduction

The actinide waste radiotoxicity reduction, i.e. the radiotoxicity of the top-up fuel divided by the radiotoxicity of the actinide losses in the fuel cycle, can be separated into a constant mass reduction factor and a time-dependent neutronic transmutation factor, $R^N(t)$, sometimes called “neutronic toxicity reduction” [16]. The latter depends on the characteristics of the core and the composition of the top-up fuel. Using the same notation as before, the radiotoxicity reduction relative to the top-up fuel, $R^T(t)$, is:

$$R^T(t) = R^N(t) M^T/M^W$$

or, in terms of the fuel burn-up and the fuel loss,

$$R^T(t) = R^N(t)/(\delta L)$$

For the TRU and MA burners studied by the Expert Group, the factor $R^N(t)$ assumes values between 0.7 and 2.4, meaning that the neutronic contribution to the radiotoxicity reduction is small compared with the goal for the total toxicity reduction by a factor of 100. The analysis in [17] shows that the addition of uranium to a fertile-free top-up fuel has a small positive effect on $R^N(t)$, i.e. increases $R^N(t)$ by a factor of about two. This applies to both critical and sub-critical cores.

Important conclusions to be drawn from the discussion in Section 2.5 are that:

- Regarding the neutronic transmutation factor, no single actinide burner design has a significant advantage over other designs and this factor is close to 1.

26. Since the waste mass reduction is proportional to τ/L , an actinide burner with a higher burner effectiveness allows the same waste mass reduction goal to be achieved with higher fuel losses (see Section 2.3.2).

- The ADS has the advantage that it can burn pure transuranics and minor actinides and thus support a large number of supplier reactors.
- Radiotoxicity reduction has to be achieved primarily by an *actinide mass reduction* which implies the maximisation of the fuel burn-up and the minimisation of the reprocessing and fuel fabrication losses.

The importance of advanced reprocessing and fuel technologies for P&T is thus confirmed.

2.6 Actinide transmutation strategies

From the neutron economy considerations in Section 2.4.1 it follows that the complete closure of the fuel cycle of a fission-based nuclear energy system is eased by integrating (critical or sub-critical) fast reactors into the system. From the viewpoint of both the resource utilisation and the actinide waste production, the ideal system is a single component system based only on fast reactors with a fully closed fuel cycle. It is well known that such a system has the potential of fissioning the natural uranium and thorium resources with a close to 100% efficiency while producing only a very small amount of actinide waste.²⁷

In practice, the rapid substitution of the existing LWRs by fast reactors would require considerable technical and economic investments which are currently not justified because the long-term future of nuclear energy is still unclear and the operation of the current LWRs is not constrained by a uranium shortage. This has led to the development of various multi-component approaches to actinide transmutation which take account of different regional boundary conditions as well as political factors. A common feature of the currently discussed approaches is the incorporation of a relatively high fraction of conventional LWRs. Table 2.2 provides an overview of the principal approaches and indicates respective driving forces. In view of the historic development, the table distinguishes between evolutionary and innovative approaches.

The *evolutionary approach*, adopted mainly in Europe and Japan, aims at closing the fuel cycle in successive steps, starting with the recycling of plutonium in LWRs and later in fast reactors using conventional reprocessing and MOX fuel technology, and finally eliminating the minor actinides partially or completely by either burning them in a dedicated fast-spectrum burner with a fully closed fuel cycle operating in the second stratum of a double strata fuel cycle [18], or recycling them heterogeneously as targets in conventional reactors.²⁸ The evolutionary approach has the advantage that it can respond flexibly to changes in the priorities for plutonium and minor actinide management, and that new technologies have to be developed only for a comparatively small number of minor actinide burners which support a large park of conventional LWRs and fast reactors.

The *innovative approach*, first suggested in the USA, aims at co-processing plutonium and minor actinides to avoid the use of technologies with a potentially high proliferation risk. After initial separation of the uranium from the LWR spent fuel, the actinides are recycled in a transuranic burner with a closed fuel cycle using pyrochemical reprocessing without further actinide separation. For a TRU burning strategy, the number of burners is four to six times larger than the number of minor actinide burners in an equivalent double strata strategy, but the burners are not subjected to a (fast) neutron-spectrum condition. Nevertheless, most of the currently evaluated critical and sub-critical

27. The actinide waste mass is equal to the uranium or thorium mass that was not fissioned.

28. For the heterogeneous recycling of minor actinides, which is technologically more conventional but less effective in reducing the radiotoxicity, see Chapter 3, Section 3.3.2.

transuranic burners feature a fast neutron spectrum. Notable exceptions are, for instance, the AMSTER [19] and the thermal ATW concepts [15].

Table 2.2. **Principal actinide transmutation strategies**

<p style="text-align: center;">Innovative: co-processing of Pu and MA</p>	<p style="text-align: center;">Evolutionary: Pu and MA handled separately</p>
<p style="text-align: center;">Principal driving force: non-proliferation</p> <p><i>TRU burnt in fully closed fuel cycle:</i></p> <ul style="list-style-type: none"> • New fuel technology required (metal fuel, molten salts, etc.) • Dry reprocessing particularly suited for closed fuel cycles and very active fuels • Technology for uranium-free fuels not yet demonstrated <p><i>Different TRU burner options:</i></p> <ul style="list-style-type: none"> • <u>TRU burning in FR</u> Requires fuel with a fertile component, limiting the LWR-to-FR support ratio to about 2 (transition to pure IFR strategy possible) • <u>TRU burning in fast-spectrum ADS</u> Possibility to utilise uranium-free fuel and hence increase the LWR-to-ADS support ratio to about 3 (transition to pure ADS, i.e. Energy Amplifier, strategy possible) • TRU burning in thermal reactor Requires fuel with a fertile component (e.g. AMSTER molten-salt reactor) • TRU burning in thermal-spectrum ADS Possibility to utilise uranium-free fuel and hence achieve a very low HM inventory (e.g. thermal ATW concept) 	<p style="text-align: center;">Principal driving forces: Plutonium utilisation and waste management</p> <p><i>Plutonium burnt in semi-closed fuel cycle:</i></p> <ul style="list-style-type: none"> • After two to three “thermal” recycles, plutonium must be transferred to a fast reactor fuel cycle • MOX fast reactor requires fuel with a fertile component, limiting the LWR-to-FR support ratio to about 4 • Plutonium burning does not require an ADS • Transition to pure FR-MOX system possible • Existing MOX fuel technology and PUREX-type reprocessing appropriate <p><i>MAAs burnt in dedicated fully closed fuel cycle:</i></p> <ul style="list-style-type: none"> • <u>Double strata strategy</u>, requires new reactor type with a fast neutron spectrum • ADS can utilise pure MA fuel and hence support about 15 conventional reactors • ADS has safety advantages • New fuel technology and dry reprocessing for very active fuels has to be developed <p><i>Alternative MA handling options:</i></p> <ul style="list-style-type: none"> • Heterogeneous recycling of Am and Cm in targets (Np can be burnt together with Pu) • MA immobilisation in a very stable matrix

Notes:

1. Transmutation strategies involving critical and sub-critical fast-spectrum systems, on which the present study is focussed, are underlined.
2. Some alternative or “mixed” transmutation strategies which cannot be assigned to a single category of the table are described in Chapter 9, Section 9.3.

2.7 Comparison of nuclear fuel cycle schemes

2.7.1 Characteristics of the schemes

Six “principal fuel cycle schemes”, which are representative for and encompass most of the currently proposed schemes, have been selected by the Expert Group and compared with respect to different sustainability parameters.

The schemes represent:

- 1) The *LWR once-through fuel cycle* with direct disposal of the spent fuel (reference case).
- 2) *Plutonium burning in LWRs and fast reactors*, where the fast reactor is optimised for a high plutonium consumption to minimise the number of fast reactors in the reactor park.
- 3a) *TRU burning in ALMR-type critical fast reactors* optimised for a low conversion ratio (CR = 0.5).
- 3b) *TRU burning in ATW-type sub-critical fast reactors* (Same strategy as 3a, but substituting the FR by an ADS to increase the fraction of LWRs in the reactor park).
- 4) The *double strata strategy* with LWRs and fast reactors in the first stratum as in scheme 2 and accelerator-driven dedicated MA burners in the second (P&T) stratum.
- 5) The *pure fast reactor strategy* based on the IFR concept where the fuel cycle is closed for all actinides, representing the long-term goal for the nuclear development.

The schemes are illustrated in Figure 2.4, and information on the assumed reactor and fuel cycle characteristics is given in Table 2.3. The plutonium burning scheme, scheme 2, is not a transmutation scheme. It is included in the analyses because, in combination with the double strata scheme, it allows to assess the “extra gains” from burning the minor actinides. LWR-MOX reactors are incorporated in this scheme, because it is representative for the evolutionary path and MOX recycling in LWRs is already a standard practice. The TRU burning schemes, 3a and 3b, implement a pure co-processing strategy. For the fast-spectrum systems in schemes 3a, 3b and 5, IFR-type fuel cycles [3] are appropriate. A lead-bismuth cooled ADS with nitride fuel as proposed by Japan [20] is chosen for the MA burner in scheme 4. European alternatives for accelerator-driven MA burners described in [21] can be expected to have a similar transmutation performance.

To ensure direct comparability of the results, the six principal fuel cycle schemes were analysed using a single nuclear data library, a single reactor code system, and consistent input data for reactor and fuel cycle parameters based on recommendations of the Expert Group. Two additional schemes were analysed independently, but using compatible reactor and fuel cycle assumptions. The additional schemes represent:

- 3c) *TRU burning in ADS with preceding MOX recycling* (MOX-TRU burning) to maximise the fraction of LWRs in the reactor park.
- H2) *Heterogeneous recycling of americium and curium* in special “target” pins which are disposed of after irradiation in special fast reactor subassemblies (This is a technologically more conventional, but less effective transmutation method which does not depend on an ADS and is being explored as a near term option).

Figure 2.5 shows the percentage contributions of the reactor components to the total electricity production (usually called electrical support ratio) as derived from the calculated mass flows for the different schemes. It is interesting to note that, among the transmutation schemes, the MOX-TRU burning scheme and the double strata scheme feature maximum electricity productions in LWRs, and in conventional reactors (LWR and FR-MOX), respectively. The heterogeneous recycling scheme is unique in that it produces less electricity in LWRs than any of the other schemes.

Since nuclear energy scenarios for the medium- and long-term future differ considerably between countries and in many countries are uncertain, the analyses were performed for steady-state conditions, i.e. for the operation of a reactor park at a constant power level over many reactor generations. However, this approach is quite adequate for discussing the principal differences between the strategies. Some general remarks concerning the start-up and shut-down phases of nuclear energy scenarios are made in Section 2.8.

Figure 2.4. Overview of principal fuel cycle schemes

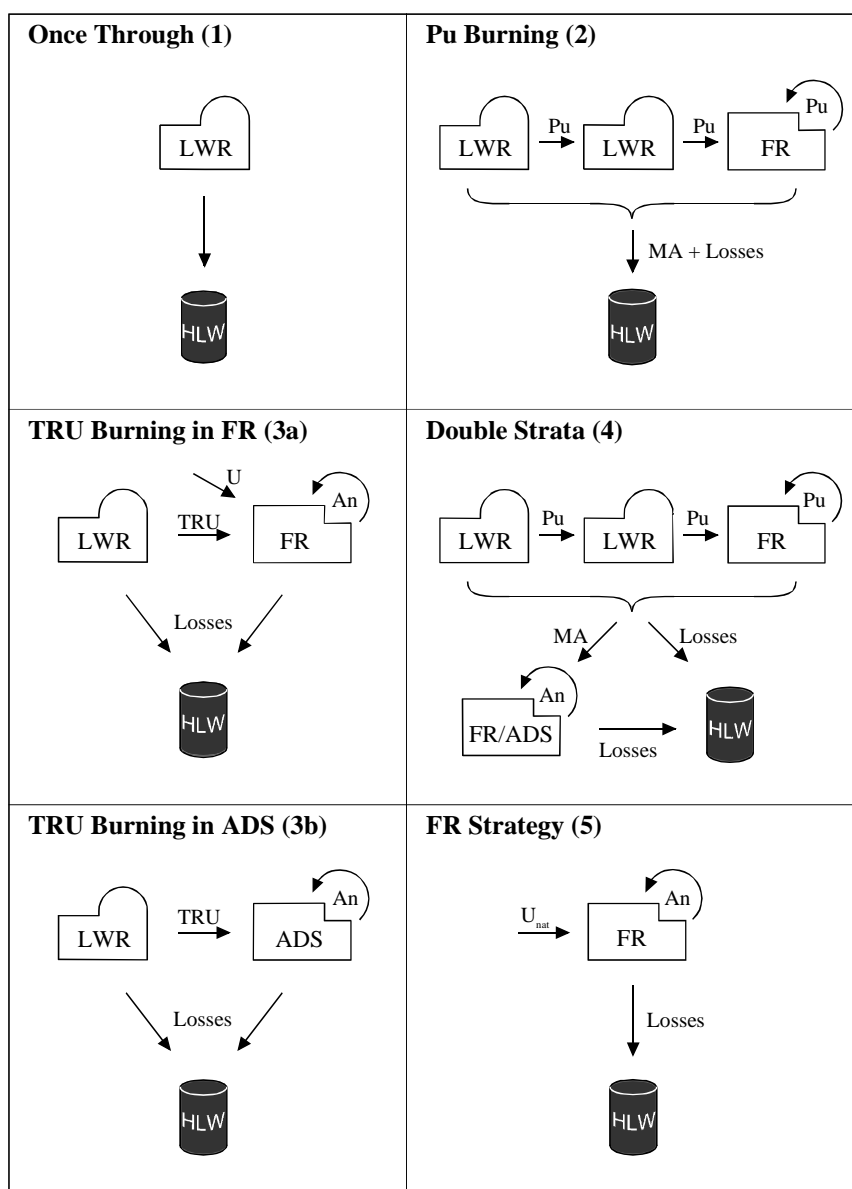
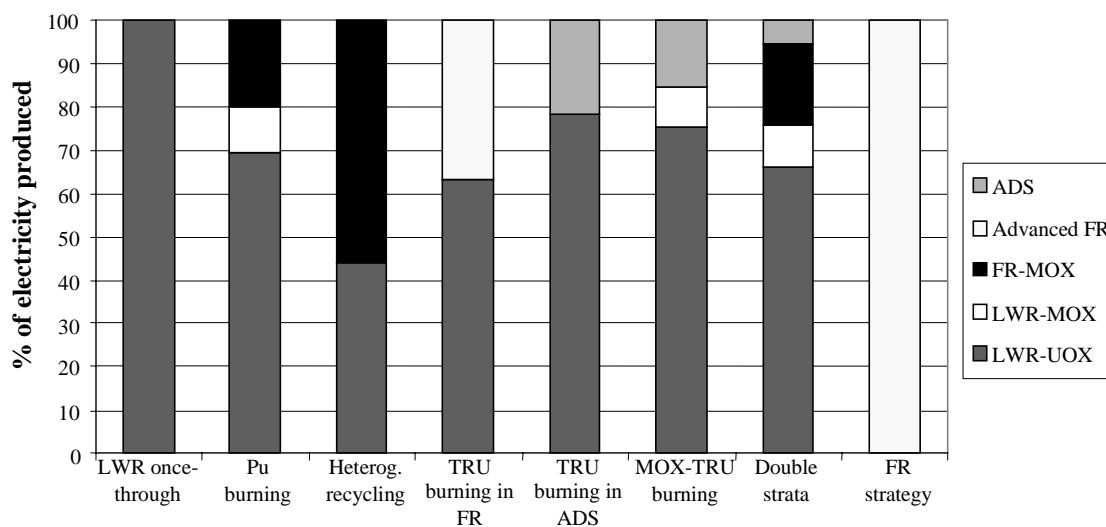


Table 2.3. Reactor and fuel cycle characteristics

Schemes	Reactor/ADS	Fuel	Av. Burn-up ¹ (GWd/tHM)	Storage/ Cooling ² (y)	Reprocessing method ³
1 to 4	LWR ⁴	UOX	50	2/4	wet
2, 4	LWR ⁴	MOX	50	2/7	wet
2, 4	Pu burner (FR) ⁵	MOX	185	2/7	wet
3a	TRU burner (FR) ⁶	Ac-Zr	140 (139)	1/2	dry
3b	TRU burner (ADS) ⁷	Ac-Zr	140 (250)	1/2	dry
4	MA burner (ADS) ⁸	AcN-ZrN	140 (149)	1/2	dry
5	Fast reactor	Ac-Zr	140 (127)	1/2	dry

1. The burn-up for the reactors with dry reprocessing is a reference burn-up for the radiotoxicity reduction comparison. The reactor core analysis is performed for the project-specific burn-up given in brackets.
2. Fuel storage time after fabrication / fuel cooling time before reprocessing.
3. A nuclide-independent recovery yield of 99.9% is assumed.
4. PWR (French N4 reactor).
5. CAPRA design with high-burn-up core.
6. ALMR burner core with a conversion ratio of 0.5.
7. ATW, lead-bismuth cooled core as proposed by ANL.
8. Design according to [20] except for core radius (92 cm instead of 120 cm).

Figure 2.5. Electricity contributions of reactor components for different schemes



2.7.2 Resource efficiency and environmental friendliness

As mentioned in Chapter 1, resource efficiency and environmental friendliness are principal axes along the path towards a more sustainable nuclear energy system, together with cost effectiveness and proliferation resistance. The resource efficiency is usually measured in terms of the natural uranium requirement of a fuel cycle strategy; it is currently not a limiting factor, since uranium resources are still plentiful. Important parameters along the environmental friendliness axis are the actinide waste production with emphasis on the transuranic elements, the waste radiotoxicity, the repository requirements and, last but not least, the production of depleted and irradiated uranium.

Figures 2.6 and 2.7 compare the performance of the fuel cycle schemes, relative to the once-through fuel cycle, with regard to natural uranium requirement, TRU and heavy metal losses to repository, and actinide waste radiotoxicity. Important observations are:

- All strategies including LWRs in the reactor park require similar uranium resources. Compared with the once-through strategy, the reductions in the natural uranium requirement are in the range 20 to 37%. Regarding this parameter, only the pure fast reactor strategy achieves a break-through (180-fold reduction when the fuel cycle is fully closed).
- All transmutation strategies with closed fuel cycles have similar TRU-, HM- and radiotoxicity-reduction potentials and these are comparable with those of the pure fast reactor strategy. Under the assumptions made in the analysis (e.g. recovery of 99.9% of all actinides), the mass reduction factors exceed 170 for the transuranics and 1 100 for the heavy metal, and the goal of a hundred-fold radiotoxicity reduction is comfortably met. In particular, this means that the FR and the ADS have similar reduction potentials with respect to these parameters.
- Multiple recycling of plutonium without minor actinide transmutation is useful for the management of plutonium. It effectively reduces the heavy metal losses to the repository and reduces the natural uranium requirement by 30%. However, plutonium burning alone cannot qualify as a transmutation strategy because it reduces the radiotoxicity of the HLW by only a factor of about five.

With regard to the repository requirements for vitrified HLW, it should be noted that the total mass and the initial heat production of the vitrified waste are dominated by the fission products and, hence, mainly depend on the total thermal energy produced.²⁹ Moreover, due to the non-linear relationship between the actinide content of the waste matrix and the repository release rates, actinide mass reductions achieved by transmutation do not necessarily translate into proportional actinide risk reductions.

To illustrate the non-linear behaviour of the actinide releases, maximum repository near-field release rates for the plutonium burning and the double strata schemes, i.e. the schemes with HLW vitrification, were compared with those of a conventional (LWR) fuel cycle strategy with uranium and plutonium recovery and HLW vitrification (see Chapter 3, Section 3.2.5). It was found that, relative to the latter strategy, plutonium burning generally increases the maximum actinide release rates from the repository near-field, and the additional minor actinide burning reduces the maximum near-field release rates for the more important, but not for all potentially troublesome nuclides. For example, the release of ²³⁷Np from the waste matrix is nearly constant because it is solubility limited, whereas the release of the daughter nuclide ²²⁹Th, which is about four times more radiotoxic, reduces nearly proportionally when the ²³⁷Np content of the glass is reduced.

In the conventional LWR fuel cycle, the radiological hazard of the depleted uranium arising from the enrichment process and the recovered irradiated uranium (irradiated enriched uranium from LWR-UOX fuel and irradiated depleted uranium from LWR-MOX fuel) is only of secondary concern. However, in P&T scenarios with fully closed fuel cycles, the long-term radiotoxicity of this residual uranium becomes comparable with the HLW radiotoxicity.

29. A typical canister with HLW from the reprocessing of LWR-UOX fuel contains 320 kg of glass, 48 kg of fission products, 3.5 kg of actinides and 4.5 kg of activation products [22].

Figure 2.6. Resource efficiency and HLW production relative to open fuel cycle

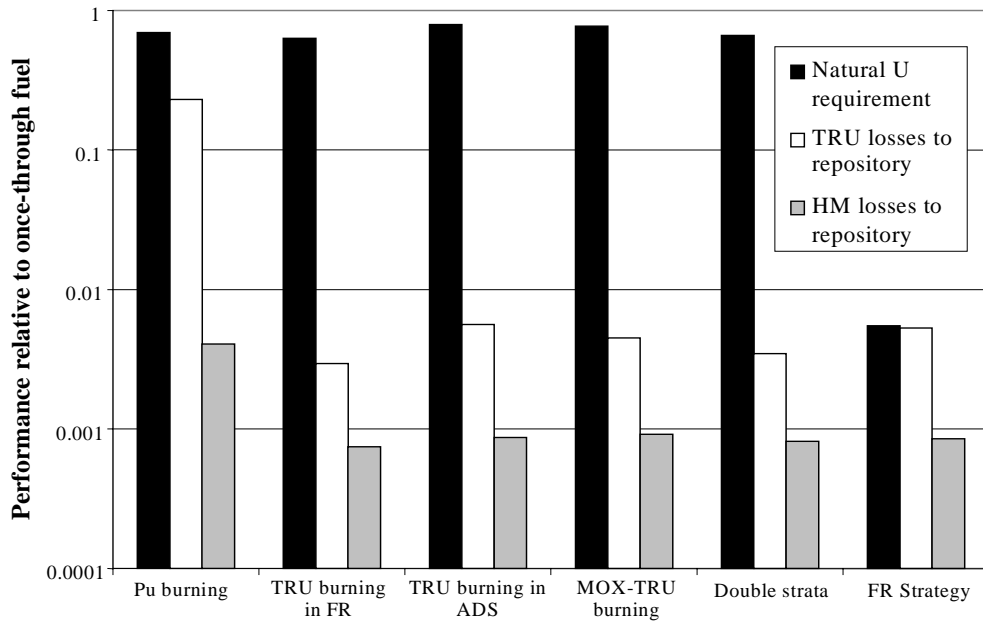


Figure 2.7. Actinide waste radiotoxicity reduction relative to open fuel cycle

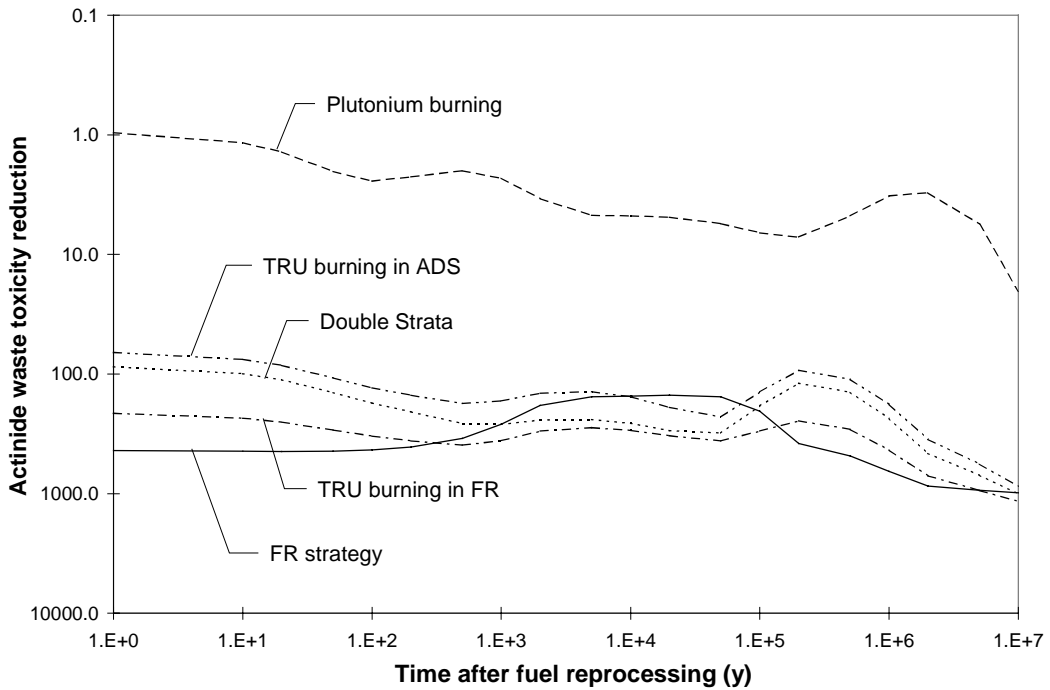
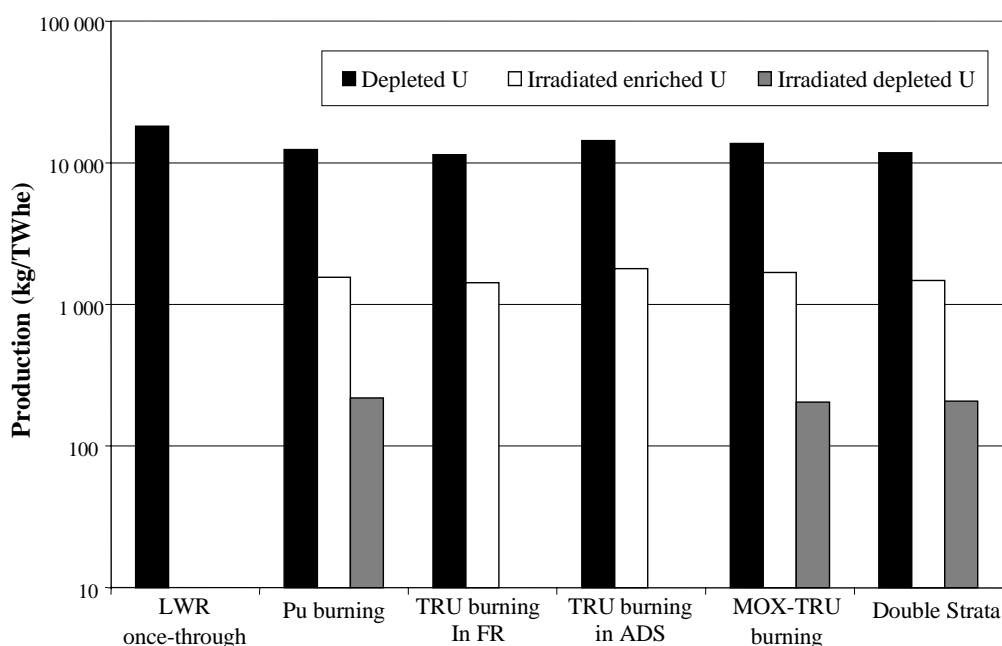


Figure 2.8 shows that all strategies including LWRs in the reactor park produce similar quantities of depleted and irradiated uranium. In the most favourable case (TRU burning in FR), the depleted uranium production relative to the once-through reference case reduces only by 28%. Compared with

the plutonium burning and the other transmutation strategies, the pure TRU burning strategies have the advantage of avoiding the production of additional irradiated depleted uranium streams.³⁰ The fast reactor strategy is unique in that it does not produce any residual uranium at all.

If the residual uranium is not considered as a resource for future fast reactors, its long-term radiological impact in a P&T scenario must also be assessed. In the nuclear waste discussion, not much attention has yet been given to this issue, since the management and future use of the residual uranium is a political issue.

Figure 2.8. **Residual uranium production**



Notes:

1. In the LWR once-through strategy, the irradiated uranium goes to the repository with the spent fuel.
2. The fast reactor strategy is not included in the figure; it produces no residual uranium.

2.7.3 Consequences for the fuel cycle

Whereas all transmutation strategies with fully closed fuel cycles perform similarly with respect to the resource efficiency and environmental friendliness parameters, different requirements and consequences arise for the establishment of the fuel cycle. In this context, important parameters are the TRU inventory of the fuel cycle and the decay heat and neutron source strength of the fuel.

The analyses show that, among the different transmutation strategies, TRU burning in ADS is associated with the lowest TRU inventory and hence the lowest α activity inventory. This means that this strategy can respond flexibly to unexpected changes in the nuclear energy scenario and has safety advantages.

Table 2.4 shows that the recycling of plutonium and minor actinides in equilibrium scenarios implies the handling of fuels with very high decay heat and neutron source strength levels which are

30. Irradiated depleted uranium is more radioactive than depleted uranium and unattractive for re-utilisation.

beyond the capability of currently operating fuel cycle facilities. Experience with pilot plants in the UK and France shows that the PUREX-type aqueous reprocessing (“wet” reprocessing) can be considered as valid for MOX fuels with high plutonium content such as the plutonium burner fuel arising in schemes 2 and 4. Aqueous reprocessing of this fuel within short cooling times and with the required high recovery yield of 99.9%, however, will require measures to improve the plutonium dissolution yield and modifications of the PUREX flowsheet.

Table 2.4. **Decay heat and neutron source strength**

Reactor/ADS	Fuel at fabrication time		Fuel after cooling time ¹	
	Decay heat (W/kgHM)	Neutron source (10 ⁶ n/s·kgHM)	Decay heat (W/kgHM)	Neutron source (10 ⁶ n/s·kgHM)
LWR-UOX	1.1·10 ⁻⁵	2.1·10 ⁻⁵	3.48	0.97
LWR-MOX	1.94	0.10	6.31	10.9
Pu burner (FR)	9.64	0.66	21.8	39.3
TRU burner (FR)	33.8	92.1	46.0	86.1
TRU burner (ADS)	168	670	193	649
MA burner (ADS)	489	1 992	455	1 812
Fast reactor	5.79	9.76	18.6	9.76

1. Fuel burn-up and cooling time see Table 2.3.

On the other hand, the decay heat of the ADS fuels arising in schemes 3b and 4 is well beyond the limit for which the radiation stability of the organic extractant in the aqueous process can be guaranteed. For these and all other systems with fully closed fuel cycles, the less developed pyrochemical reprocessing (“dry” reprocessing) is the appropriate reprocessing method because it circumvents unnecessary separation processes (only fission products are extracted) and can handle highly active product streams without major radiation degradation.

Due to the strong source of spontaneous neutrons, the fuel fabrication will have to adapt its handling technology to reduce the radiation doses to the workers in the plant and during the transport of the fuel assemblies. This also speaks for the pyrochemical reprocessing method which is applicable in small facilities in the immediate vicinity of the reactors, whereas the aqueous process favours large facilities which operate on continental or even world scale, requiring the shipment of fuel over long distances.

2.8 Transient phases in nuclear energy scenarios

2.8.1 Time constants in transient scenarios

Nuclear energy scenarios can be divided into a start-up, an equilibrium, and a shut-down phase. The discussion of the fuel cycle schemes in the preceding section was restricted to the equilibrium phase with the tacit assumption that the latter lasts much longer than the other phases.

In this context, an important aspect of nuclear fission energy are the long time constants for the penetration and phase-out of new reactor and fuel cycle technology. The long time constants reflect fundamental physical limitations in the production and destruction of in-pile and out-of-pile fuel inventories and are of the order of 50 years. This implies that transmutation technology can fulfil its promises only, if it is introduced with the intention to utilise it for at least a century. In view of the required expensive R&D, including the construction and operation of demonstration facilities,

economic reasons call for a similar time horizon. More generally speaking: the long time constants inherent in advanced fuel cycle strategies and the necessity of avoiding an interruption of the chosen strategy require a continuous political, economical and strategic support for the nuclear option to be assured over a period of *at least hundred years*.

It is likely that transmutation technology will penetrate the market only, if the nuclear contribution to the world energy demand has to be stepped up considerably for ecologic reasons. Under this assumption, the start-up phase will also be a growth phase. As was shown by many studies in the past, fast breeder reactors with an appropriately designed core can reach a doubling time in the order of 50 years which allows to support an annual growth rate of 1.4%. If necessary, an ADS could reach a *shorter doubling time* than a normal fast breeder reactor due to the lower fissile inventory and the richness of the spallation process in neutrons. Moreover, the ADS has the unique potential to start a nuclear energy system without an initial inventory of fissile material, i.e. it could be used to launch a new nuclear era at a time when all ^{235}U or plutonium stocks are exhausted. Such applications, however, are not in the scope of the present study.

2.8.2 Role of ADS in the shut-down phase

For a nuclear energy scenario with a finite time horizon, the full benefit from transmutation can be realised only if, in the shut-down phase, the TRU inventory of the system is burnt and not put to waste. Core analyses confirm that sub-critical as well as critical fast-spectrum burners can operate in a multi-recycling mode without any fuel top-up. The inventory burning process will, of course, stop when the remaining fuel mass becomes smaller than a single reactor inventory.

The most rapid nuclear phase-out is achieved, if all LWRs (or other TRU supplier reactors) are taken out of service at the same instant. In this case, the total heavy metal inventory of the burner system decreases exponentially with a half-life of

$$T_{1/2}^{\text{Inv}} = \ln 2 S / (\gamma r f),$$

where the parameters S , r and f are the power-specific heavy metal inventory of the burner, the in-pile time fraction of the fuel and the load factor of the burner, respectively. The constant γ , the mass-energy conversion factor, has a value of $\simeq 1.0 \text{ kg/GWdth}$.³¹

Table 2.5 gives a numerical example for each of the four TRU burner options referred to in Table 2.2. It is evident that, in the shut-down phase of a nuclear energy scenario, a thermal neutron spectrum has a theoretical advantage. In more moderate and probably more realistic shut-down scenarios, however, the supplier reactors will remain in service until they have reached their useful lifetime; the shut-down phase will consequently be longer and not depend so strongly on the burner type.

2.9 Fission product transmutation

As mentioned before, the primary concern of geologic repositories are possible releases of the relatively mobile fission products. Since the fission product yields are not very sensitive to the fuel composition and the neutron spectrum of the reactor,³² the fission product risk depends primarily on the number of fissions, i.e. the energy, produced in the fuel. This means that the fission product risk

31. In the derivation of this equation it was assumed that the specific burner inventory, S , remains constant during the shut-down phase. Realistic phase-out simulations show that this is a questionable assumption.
 32. The neutron spectrum of the reactor can, however, influence the in-situ transmutation of a fission product.

cannot be much influenced by the actinide transmutation strategy and can only be mitigated by separating troublesome fission products from the waste.

Table 2.5. **TRU burner characteristics in nuclear phase-out scenario**

TRU burner option	HM inventory (kg/MWth)	In-pile time fraction	Load factor	$T_{1/2}^{Inv}$ (y)
Fast, critical ¹	11.14	0.62	0.85	40.1
Fast, ADS ¹	3.48	0.50	0.80	16.5
Thermal, critical ²	2.2 ⁴	0.63	1.0 ⁵	6.6
Thermal, ADS ³	1.34	0.5	1.0 ⁵	5.1

1. Same as TRU burners in Table 2.3.
2. AMSTER molten-salt TRU incinerator with uranium top-up [19,23].
3. ATW molten-salt incinerator pure TRU fuel [15,16].
4. TRU inventory only.
5. On-line reprocessing of the fuel.

The neutron capture process is currently the only promising nuclear reaction for transmuting fission products. Other processes which have been proposed in the past rely on technologies which are still at a very early stage of development (e.g. fusion neutron sources) and generally suffer from a poor energy balance. The capture process consumes neutrons, but fast reactors could deliver enough excess neutrons to allow the potentially troublesome long-lived fission products to be completely transmuted to shorter-lived or stable species.³³

The transmutation of a fission product makes sense only if the reaction rate (microscopic cross-section times neutron flux) is higher than the natural decay rate of the nuclide. With the practically achievable neutron fluxes, this condition cannot be met for the most abundant fission products ¹³⁷Cs and ⁹⁰Sr with half-lives of only about 30 years, i.e. these fission products are “non-transmutable”. However, since their radioactive life is limited to less than 300 years, they can be safely enclosed using engineered barriers only. In many cases, the necessity of an isotopic separation and difficulties in the target preparation present other important obstacles for the fission product transmutation.

Long-lived fission products which dominate the long-term risk of HLW repositories are, in order of decreasing half-life, ¹²⁹I, ¹³⁵Cs, ⁹⁹Tc, ¹²⁶Sn and ⁷⁹Se. Activation products such as ¹⁴C and ³⁶Cl can also contribute to the dose. The relative radiological importance of these nuclides varies depending on the repository concept and the type of host rock (see Section 2.2, Figure 2.2). From the characteristics in Table 2.6, it follows that, in practice, only ¹²⁹I and ⁹⁹Tc can be transmuted and the radiological impact of the other long-lived fission products can be reduced only by special conditioning and confinement. More detailed information on the transmutability of long-lived fission products is given in Chapter 8, Section 8.2.

33. Table 2.1 shows that an ADS does not necessarily deliver more excess neutrons than a normal fast reactor. The reason is that the particular ADS core has been optimised for actinide burning. It follows that a burner core cannot be optimised simultaneously for best actinide and best fission product transmutation.

Table 2.6. **Transmutability of long-lived fission products**

Fission product	$T_{1/2}^{\text{Decay}}$ (y)	$T_{1/2}^{\text{Trans}}$ (y) ¹	Isotopic separation	Transmutable (yes/no)
¹²⁹ I	$1.6 \cdot 10^7$	51	no	yes ²
¹³⁵ Cs	$2.3 \cdot 10^6$	170	yes	no
⁹⁹ Tc	$2.1 \cdot 10^5$	51	no	yes
¹²⁶ Sn	$1.0 \cdot 10^5$	$4.4 \cdot 10^3$	yes	no
⁷⁹ Se ³	$6.5 \cdot 10^4$	$2.2 \cdot 10^3$	yes	no

1. Thermal flux: 10^{14} n/cm²·s.
2. R&D necessary to improve the iodine separation yield and the stability of the target material.
3. Half-lives for ⁷⁹Se around $6.5 \cdot 10^4$ years have been used widely in waste inventory and repository performance assessments. Recent nuclear data studies, however, indicate a much longer half-live for this nuclide (see <http://nucleardata.nuclear.lu.se/nucleardata/>).

Finally, it should be noted that the transmutable fission products represent only a small fraction of all fission products and that the vitrified waste mass, which is primarily determined by the fission products, therefore, *cannot be much reduced* by P&T operations. A combined transmutation-conditioning strategy for the long-lived fission products, however, would allow easing the licensing requirements for vitrified waste repositories because the geosphere barrier would no longer have an important safety function.

