

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

10. CONCLUSIONS

10.1 Introduction

The principle of sustainable development requires the fuel cycle of future nuclear energy systems to be closed for plutonium as well as minor actinides to ensure the production of fission energy with limited amounts of natural resources (i.e. uranium) and long-lived radioactive waste. It also requires a safe and cost-effective nuclear energy production. The resource efficiency and waste reduction goals together can ultimately only be reached by the introduction of advanced reactor systems with a significant fraction of fast reactors. For well-known reasons, however, a massive substitution of existing LWR-based, by such advanced, reactor and fuel cycle technology is not a realistic near-term scenario.

Partitioning and transmutation (P&T), which could address the high-level radioactive waste issue now and prepare the ground for a more resource-efficient nuclear energy system in the future, may become an attractive and appropriate intermediate strategy on the way to the ultimate goal of the sustainable nuclear energy system. In this context, the accelerator-driven system (ADS) can play an interesting role as a minor actinide or transuranics (TRU) burner. The interest in such burners is, of course, coupled with the P&T system and will diminish with an increase in the fraction of fast reactors in the park because, in a FR-dominated reactor park, dedicated burners will no longer play an essential role.

The scope of the present study comprises the clarification of the roles and merits of the fast reactor and the fast-spectrum accelerator-driven system (fast ADS) with regard to their application as actinide and fission product burners as well as the assessment of the development status of the ADS with emphasis on reactor technology and safety, fuel cycle technology, trends in electricity cost, and general feasibility. By concentrating on transmutation strategies with fully closed fuel cycles, i.e. the particularly effective transmutation strategies, the study complements the P&T status and assessment study published in 1999. The essential differences between the variety of proposals for implementing such strategies are evaluated with the help of a set of representative “fuel cycle schemes”, which are analysed in a consistent manner using reactor and fuel cycle parameters agreed by the Expert Group.

Technical conclusions have already been given at the end of each technical chapter. In this chapter these conclusions are combined and rearranged in agreement with the objectives of the study as follows:

- Role of ADS in actinide transmutation strategies.
- Fuel cycle technology.
- ADS technology and safety.
- Cost of actinide transmutation.
- Fission product transmutation.
- R&D needs.

For the benefit of policy makers, the detailed technical conclusions are preceded by a set of “general conclusions”. These combine principal messages from the study with generally known facts which deserve to be re-emphasised on this occasion. However, the results and merits of the study can only be fully comprehended by consulting the following detailed technical conclusions.

10.2 General conclusions

Principal messages which could influence policy decisions are:

- While P&T will not replace the need for appropriate geological disposal of high-level waste, the study has confirmed that different transmutation strategies could significantly reduce, i.e. a hundred-fold, the long-term radiotoxicity of the waste and thus improve the environmental friendliness of the nuclear energy option. In that respect, P&T could contribute to a sustainable nuclear energy system.
- Very effective fuel cycle strategies, including both fast spectrum transmutation systems (FR and/or ADS) and multiple recycling with very low losses, would be required to achieve this objective.
- Multiple recycle technologies that manage Pu and MA either together or separately could achieve equivalent reduction factors in the radiotoxicity of wastes to be disposed. The study shows that pyrochemical reprocessing techniques are essential for those cycles employing ADS and FRs where very high MA-content fuels are used.
- In strategies where Pu and MA are managed separately, ADS can provide additional flexibility by enabling Pu-consumption in conventional reactors and minimising the fraction of dedicated fast reactors in the nuclear system.
- In strategies where Pu and MAs are managed together, the waste radiotoxicity reduction potential by use of FRs and ADS is similar and the system selection would need to be made based on economic, safety and other considerations.
- Further R&D on fuels, recycle, reactor and accelerator technologies would be needed to deploy P&T. The incorporation of transmutation systems would probably occur incrementally and differently according to national situations and policies.
- Fully closed fuel cycles may be achieved with a relatively limited increase in electricity cost of about 10 to 20%, compared with the LWR once-through fuel cycle.
- The deployment of these transmutation schemes need long lead-times for the development of the necessary technology as well as making these technologies more cost-effective.

10.3 Technical conclusions

The following sections list the detailed conclusions for the different technical areas.

10.3.1 Role of ADS in actinide transmutation strategies

- All transmutation strategies with closed fuel cycles could, in principle, achieve high reductions in the actinide inventory and the long-term radiotoxicity of the waste, and these are comparable with those of a pure fast reactor strategy. With respect to these reductions, the potentials of the FR and the ADS are very similar.

- Under the assumptions used in the study, these strategies can achieve a more than hundred-fold reduction in the long-term waste radiotoxicity and even higher reductions in the heavy metal and TRU losses to repository, compared with the once-through fuel cycle.
- The reduction factors are primarily determined by the fuel burn-up and the reprocessing and fuel fabrication losses. An ambitious goal for the recovery of all actinides (99.9 %, as already achieved for uranium and plutonium) must be set, if the quoted reduction factors are to be realised.
- Multiple recycling of plutonium without minor actinide transmutation is useful for the management of plutonium, but cannot qualify as a transmutation strategy because it reduces the long-term waste radiotoxicity by only a factor of about five.
- With regard to actinide waste production and technological aspects, the TRU burning in FR and the double strata strategies are similarly attractive. The former can gradually evolve to a pure fast reactor strategy, but requires high initial investment in fast reactor and advanced fuel cycle technology. The latter confines the minor actinides to a small part of the fuel cycle, but calls for particularly innovative technology for this part of the fuel cycle.
- The sub-critical operation of an actinide burner with a fast neutron spectrum offers interesting additional parameters of freedom in the core design. In particular, the possibility of operating such a burner with a uranium-free (or thorium-free) fuel supply allows the fraction of specialised transmuters in the reactor park to be minimised.
- A further advantage of the sub-critical operation mode is the tolerance of the system against degradations in the safety characteristics of the core. Both of these advantages are of particular relevance for systems which burn pure minor actinides, e.g. minor actinide burners in a double strata strategy.
- Transmutation systems with partially closed fuel cycles, e.g. systems in which minor actinides are separated from the fuel and recycled in special “target” pins, are technologically less demanding and do not require an ADS, but cannot achieve the high transmutation effectiveness of systems with fully closed fuel cycles.
- Physical limitations associated with the production and destruction of in-pile and out-of-pile fuel inventories imply very long time constants for the start-up and final shut-down phase of new fission-based nuclear technologies. This implies that transmutation technology, with or without ADS, can fulfil its promises only, if it is introduced with the intention of using it for at least a century.
- 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 is burnt and not put to waste. Due to the low power-specific heavy metal inventory of the respective burner, the TRU burning in ADS strategy features a lower steady-state TRU inventory and, in the shut-down phase, can burn this inventory more quickly than the other investigated strategies.

10.3.2 Fuel cycle technology

- Actinide transmutation implies the handling of fuels with very high decay heats and neutron source strengths. A significant effort is required to investigate the manufacturability, burn-up behaviour and reprocessability of these fuels. This applies particularly to fuels with high minor actinide content, which can probably be reprocessed only with the help of pyrochemical methods. These methods have to be further developed to tolerate from ten to

more than twenty times higher decay heat levels than those encountered in the pyrochemical reprocessing of fast reactor fuels.

- The introduction of pyrochemical processing techniques at the industrial level will require the development of new process flowsheets and the use of potentially very corrosive reagents in hostile environments. These processes will generate chemical and radiological hazards which will have to be mitigated.
- The PUREX aqueous reprocessing can be considered as valid for the FR-MOX fuel in the plutonium-burning and double strata schemes. Reprocessing of this fuel within short cooling times and with the required high recovery yields, however, will require the plutonium dissolution yield to be improved and the PUREX flowsheet to be modified.
- Due to the high radioactivity of FR-MOX fuel, its handling will require measures to be taken to reduce the radiation doses in the fabrication plant and during the transportation of the fuel assemblies. The increased requirements for shielding, and preference for short transportation paths, of multiple recycled fuels also favour the pyrochemical reprocessing method.
- All transmutation strategies which include LWRs in the reactor mix produce large streams of depleted and irradiated uranium. If this uranium is not considered as a resource for future fast reactors, its long-term radiological impact has also to be taken into account.

10.3.3 ADS technology and safety

- For all ADS-based transmutation strategies, important technological challenges exist with regard to the accelerator, the target, the sub-critical reactor and new types of safety issues.
- On the whole, the development of accelerators is well-advanced, and beam powers of up to 10 MW for cyclotrons and 100 MW for linacs now appear to be feasible. However, further development is required with respect to the beam losses and especially the beam trips to avoid fast temperature and mechanical stress transients in the reactor.
- Various problems related to the accelerator-reactor coupling have still to be investigated. Thereby, special attention has to be given to the target and especially the beam-window, as these components are subjected to complex stress, corrosion and irradiation conditions which are not encountered in normal reactors.
- While the reactor physics of sub-critical systems is well-understood, the issues regarding the dynamic response to reactivity and source transients require further investigation because they are the area of greatest difference between critical and sub-critical systems.
- The presence of an external neutron source which can vary very rapidly, in combination with very weak reactivity feedbacks, especially from the Doppler effect, implies fast and (depending on the sub-criticality level) large responses to control actions which puts additional demands on the control actuators, the fuel behaviour, and the heat removal processes. In particular, the fuel should be capable of adiabatic heat storage to buffer any sharp changes.
- If hypothetical core disruptive accidents have to be taken into account in the safety analysis of an ADS, a prompt negative feedback mechanism for quenching such accidents has to be developed.

10.3.4 Cost of actinide transmutation

- Fully closed fuel cycles may be achieved with a relatively limited increase in electricity cost of about 10 to 20%, compared with the LWR once-through fuel cycle. In case of partially closed fuel cycles, e.g. only closed for plutonium, the cost increase is about 7%.
- Among the fully closed fuel cycle strategies investigated in the present study, TRU burning in FR and the double strata strategy feature the lowest increases in system-wide electricity cost relative to the LWR once-through fuel cycle.
- Fuel cycle strategies which involve the use of ADS-technology show an overall economic benefit by burning as much plutonium as possible in less-expensive, more-conventional systems, i.e. MOX-LWRs and MOX-FRs.
- Especially the TRU burning in ADS strategy is sensitive to accelerator beam costs. Reducing the accelerator cost by a factor three would halve the electricity cost increase for this strategy.
- The economic incentive to increase the burn-up fraction in the minor actinide and TRU burners beyond a value of 15% becomes marginal. Further reductions in fuel losses to repository at an acceptable system-wide energy costs, therefore, are to be obtained preferentially by increasing the fuel recovery rate.
- For the closed fuel cycle strategies, the advanced technology contribution to the system-wide electricity cost is in the range of 10 to 50%. If all non-LWR technology is considered as advanced, the advanced technology cost contribution for the closed fuel cycle strategies lies in the range of 30 to 50%.
- The cost analysis confirms the long-term potential of P&T for reducing the transuranic inventory and the radiotoxicity of the waste with a rather limited increase in the electricity generation cost, despite that this cost increase may not be acceptable in today's market environment. It also means that transmutation may become affordable with only a limited cost increase, if a reduction in the actinide waste radiotoxicity becomes important for the society.

10.3.5 Fission product transmutation

- Excess neutrons produced by critical and sub-critical burners can, in principle, be utilised to transmute fission products. With the neutron fluxes available in these systems, it is theoretically possible to transmute the long-lived fission products; the transmutation of the more abundant short-lived fission products, however, is impracticable due to insufficient transmutation rates. This means that transmutation, in principle, allows the mitigation of the long-term risk from fission products in a geologic repository, but cannot significantly reduce the heat generation and mass of the disposed fission products.
- Maximising the supplier-to-burner reactor support ratio can result in an insufficient neutronic potential for transmuting the long-lived fission products of the entire reactor park. If the transmutation would be limited to ^{129}I and ^{99}Tc , all TRU burning strategies could, theoretically, accomplish the task.
- In practice, the necessity of isotopic separations and difficulties in the preparation of targets present difficult obstacles for the fission product transmutation, which currently reduce the number of candidate nuclides to only one or two, i.e. ^{99}Tc and, possibly, ^{129}I . So far, the feasibility has been established only for ^{99}Tc . This means that, for the remaining long-lived

fission products, partitioning followed by immobilisation in a specially stable matrix may remain the only realistic method for reducing their radiological impact.

10.3.6 R&D needs

- *Basic R&D* is needed for the new FR and ADS in the fields of nuclear data and neutronic calculations, fuel technologies, structural materials, liquid metals, reprocessing technologies, target materials and high power accelerators (the last two only for ADS).
- *Experimentation on fuels is a priority.* No concept can be considered seriously, if the appropriate fuels are not defined and proven, i.e. characterised, fabricated, irradiated and reprocessed.
 - Since fuels play a central role in all scenarios of waste minimisation and nuclear power development, an international share of efforts around nitrides, oxides and metals should be organised in order to ensure an optimum use of resources in the few existing laboratories which can handle very active fuels.
 - In this context, *the availability of irradiation facilities, in particular fast neutron facilities which can produce high damage rates in the specimens, is a key issue and major concern.* Again, an international initiative could be envisaged to harmonise programmes and to allow the best use of existing resources to be made. Identification of the experimental irradiation needs in such a shared international fast-spectrum facility would be a worthwhile undertaking.
- *Demonstration at appropriate scale of the performance of pyrochemical processes* (level of losses, secondary waste, etc.) is needed in order to assess in more detail the technico-economic viability of certain fuel cycle options.
- In the field of basic R&D supporting FRs as well as ADS, the discussion around the *coolants for fast-spectrum systems* would benefit from a better international agreement on pro and cons of the different options.
- *Improved modelling tools to simulate the materials behaviour* under (mixed) irradiation conditions (and possibly high temperatures) may prove to be a very valuable approach and a sharing of expertise and benchmarking within an international context may be advocated.
- *Safety analysis of ADS* should identify the possible paths to exclude hypothetical core disruptive accidents (HCDA) in ADS. If such a HCDA has to be taken into account in the safety analysis of an ADS, a prompt negative feedback mechanism for quenching such an accident has to be developed.
- In addition to this R&D, countries embarking on an ADS-based fuel cycle strategy should envisage a *demonstration experiment* which allows the ADS concept to be validated from operation and safety viewpoints.
- And last but not least, *Performance assessment studies for a geological disposal site using a P&T source term* are necessary in order to seek clarification of the cost/benefit analysis of such advanced fuel cycles, including geological disposal.