

# Transition from thermal to fast neutron nuclear systems

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**C**oncerns about global climate change and security of energy supply are triggering renewed interest in nuclear energy. Although uranium resources for nuclear fuel are sufficiently abundant to support significant growth of nuclear electricity generation based on current reactor types for decades (NEA/IAEA, 2010), nuclear systems using fissile materials more efficiently are considered a desirable option from a long-term sustainable perspective.

Today, nearly 150 000 tonnes of spent nuclear fuel from light water and other nuclear reactor types are stored for cooling before disposal or treatment. These fuels contain 1 300-1 500 tonnes of transuranic elements (TRUs), mainly plutonium, and a smaller amount of minor actinides (MAs), such as neptunium, americium and curium. Continued generation of nuclear electricity in an increasing number of countries will inevitably lead to increased volumes of spent fuel requiring storage.

Advanced nuclear fuel cycles with critical or sub-critical fast neutron systems, such as Generation IV reactors and accelerator-driven systems (ADSs), can optimise the use of uranium resources, minimise radioactive waste and increase proliferation resistance. These nuclear fuel cycles can include the partitioning and transmutation (P&T) of TRUs and/or MAs, an option which can reduce radiotoxicity and heat load of radioactive waste.

In this context, researchers have studied the feasibility of implementing scenarios for a transition from the current fleet of thermal neutron reactors operated with a once-through or a partially closed fuel cycle to advanced fast neutron systems capable of using recycled fissile materials. Simultaneously, analysts responding to concerns of policy makers about cost-effectiveness, industrial aspects and international issues are investigating the opportunities and challenges associated with the different transition scenarios.

The NEA Nuclear Science Committee (NSC) (NEA, 2009a and NEA, 2009b) and the NEA Committee for Technical and Economic Studies on Nuclear Development and the Fuel Cycle (NDC) (NEA, 2009c) have undertaken several studies on technical, strategic and policy aspects of different fuel cycle transition scenarios. Their main findings are described below.

## Main findings from technical analyses of transition scenarios

Under the auspices of the NSC, the technical issues raised by transition scenarios, as well as the potential role of P&T, were investigated both at a national level and at a regional level for Europe. Global scenarios are also currently being studied.

P&T is an important component in some transition scenarios because it is considered as an efficient means to reduce the burden and stewardship requirement of radioactive waste. Indeed, most long-term radiotoxicity and residual heat from the radioactive waste are generated by plutonium and minor actinides, which may be significantly reduced through P&T. The concept is to separate such nuclides from the irradiated fuel and to transmute them into short-lived or stable materials. Partitioning and transmutation can be implemented by using thermal or fast neutron systems. In general, the use of a fast neutron critical or a sub-critical system has advantages in terms of an improved transmutation rate for TRUs and/or MAs. Analyses show that in countries without advanced fuel cycle technologies, it would take about 20 years to implement TRU fuel multi-recycling in sodium-cooled fast reactors, while it would take some 30 years to implement more advanced systems, such as TRU fuel recycling in other types of fast reactors or ADSs.

From a technical viewpoint, the major issues raised by transition scenarios include the design and development of:

- fuels for recycling in light water reactors (from standard plutonium recycling to TRU recycling);
- fuels for recycling in high-temperature reactors (from uranium fuels to deep plutonium burners);
- fuels for recycling in a fast reactor recycle (fuels for homogeneous or targets for heterogeneous TRU recycle, and dedicated fuels, e.g. for minor actinide consumption);

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- separation technologies (both with aqueous and pyro-processes);
- reactor (critical or sub-critical) design and related technologies (such as specific coolant technology and materials).

Beyond technology development requirements, issues such as adequate and timely management of fissile materials and industrial-scale deployment of advanced processes have to be addressed. Technology preparedness is essential to ensure that performance will remain excellent along the entire process chain from reprocessing to fuel fabrication when shifting from laboratory to commercial production in large industrial-scale facilities.

National scenarios were analysed in nine NEA member countries – Belgium, Canada, France, Germany, Japan, Korea, Spain, the United Kingdom and the United States – covering various nuclear energy development patterns. The analysis showed that:

- in countries which started using closed nuclear fuel cycles early and plan to continue using nuclear energy, stocks of TRUs and/or MAs can be stabilised by the end of the century;
- countries which want to diminish their dependence on nuclear energy can only partially reduce their inventories during this century, unless they act in a regional context;
- countries which will be implementing new nuclear fuel cycles, for example a fast reactor cycle, for plutonium and minor actinide recycle later in this century, e.g. around 2050, can still stabilise the minor actinide inventory over the entire nuclear fuel cycle during this century.

In addition, it is noted that the minor actinide inventory is related to the pace of fast reactor deployment and it will take a long time to replace all light water reactors by fast reactors as fast reactors will need plutonium from light water reactors as start-up fuel. To avoid growth in the minor actinide inventory, fast reactor fuel cycles should be deployed as early as possible. In this context, there can also be incentives, such as economic, resource availability, safety (use of best practices and internationally recognised technologies) and non-proliferation (strict international control over transport flows and a very limited number of jointly operated sites), to develop a “regional” approach.

Regional scenarios can in principle provide a framework for implementation of advanced nuclear fuel cycles, with efforts divided equitably among different countries and taking into account proliferation concerns and resource optimisation. Specific scenarios have been investigated as part of a wider effort underway in Europe to prepare a roadmap for the possible implementation of P&T technologies. Four potential groups of countries with different scenarios were suggested in the NEA study:

- Group A: stagnant or phase-out scenario for nuclear energy including management of the spent fuel;
- Group B: continued use of nuclear energy and optimisation of the plutonium resources for future deployment of fast reactors;
- Group C: subset of Group A, after stagnation, an envisaged “renaissance” of nuclear energy;
- Group D: initially with no nuclear energy but decides to add it to the energy mix.

Four different European scenarios using fast neutron systems, both ADS type (scenarios 1 and 2) or critical fast reactors (scenario 3), were investigated as follows:

- Scenarios 1 and 2 consider the deployment of a group of ADSs shared by Group A and B. The ADSs use the plutonium of Group A and transmute the minor actinides of the two groups. The plutonium of Group B is either mono-recycled in pressurised water reactors (PWR) and then stored for future deployment of fast reactors (scenario 1) or is continuously recycled in PWRs (scenario 2).
- Scenario 3 considers the deployment of fast reactors in Group B. These fast reactors use the plutonium of Groups A and B and recycle all the minor actinides.
- Scenario 4 corresponds to a “renaissance” of nuclear energy in selected countries. Starting from Scenario 3, Group B and some Group A countries will deploy fast reactors to manage their own transuranic elements.

The outcome of the studies indicates that P&T may benefit the whole region despite different nuclear energy policies in each country. A regional strategy may also favour a nuclear “renaissance” in some countries. If fast reactors with homogeneous recycling of non-separated TRUs are deployed, use of fast reactors and supporting infrastructure must take into consideration the relevant nuclear fuel cycle characteristics, e.g. conversion ratio, cooling time, etc., to meet the potentially different objectives of different countries within a regional area. If a “double strata” scenario, i.e. a scenario with both fast reactors and ADSs, is deployed, it should be noted that most of the ADSs will be used for minor actinide transmutation. The ADS is more apt to be used in a regional scenario where different countries with different objectives share resources, facilities and spent fuel inventories in order to minimise waste. The ADS would be less useful in the case of a single country with a stagnant or phase-out nuclear energy policy, which would deploy P&T in “isolation” for waste management.

Analyses of global transition scenarios currently underway at the NEA cover the infrastructure development needed to support global growth of nuclear energy, as well as how that infrastructure might be deployed in various regions. Nuclear fuel cycles such as once-through, limited recycling and continuous recycling are all options over the next several

Figure 1: Schematic diagram of scenarios 1 and 2

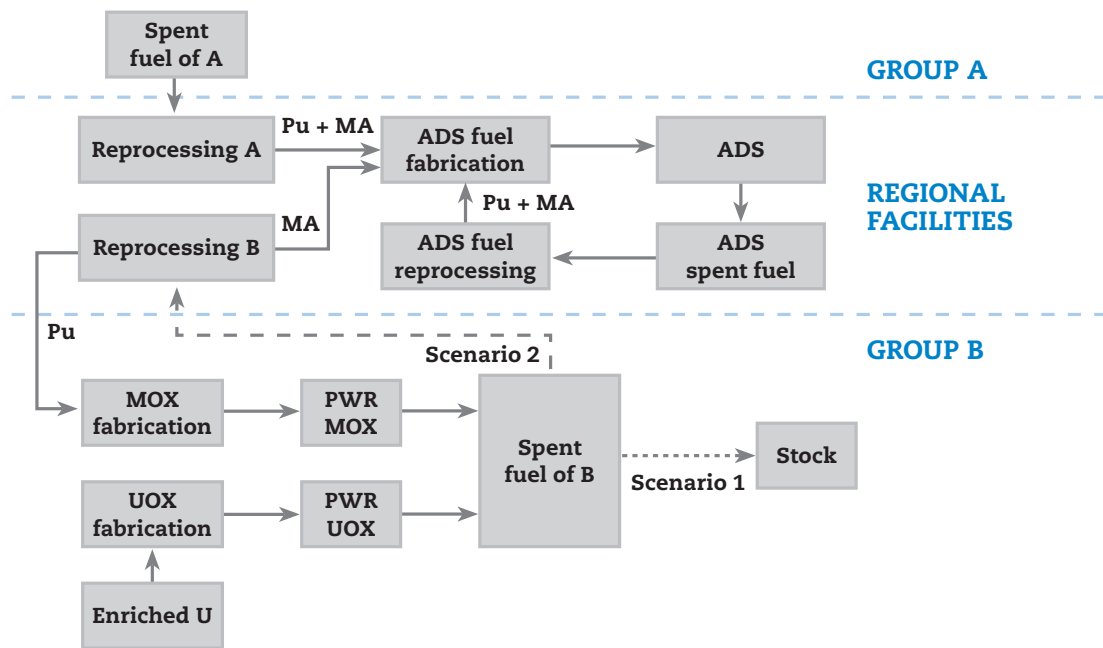


Figure 2: Schematic diagram of scenario 3

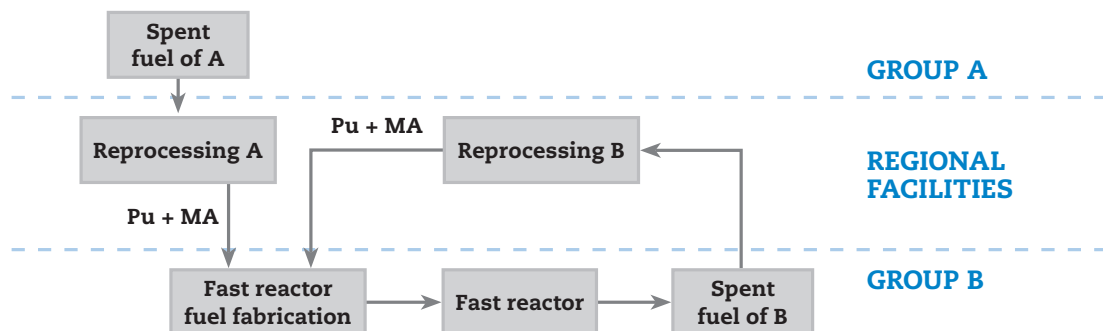
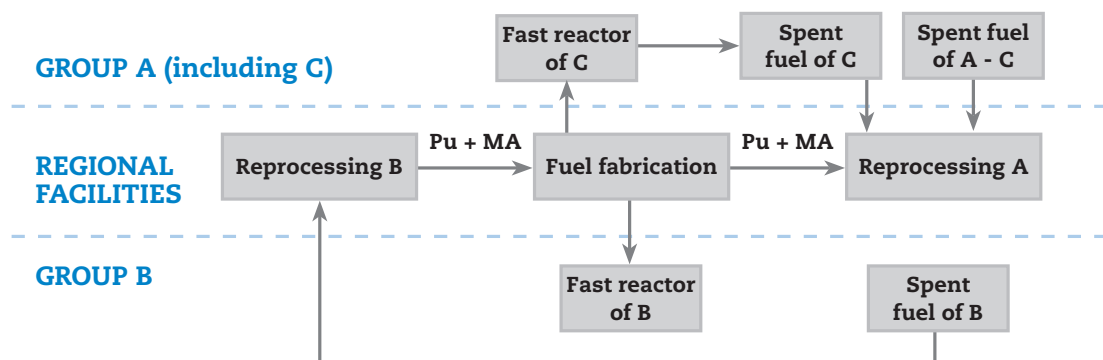


Figure 3: Schematic diagram of scenario 4



decades. The transition from current fuel cycles to advanced fuel cycles obviously will be dependent on the maturity and availability of specific technologies, as well as non-technical factors such as economics and various country-specific policies.

## Main findings on strategic and policy issues

In light of the age and performance of existing nuclear power plants, the role of nuclear energy is likely to grow in the coming decades through the lifetime extension of existing plants and the construction of new reactors, followed by the development and deployment of advanced nuclear systems beyond 2050. The lifetime of nuclear power plants in operation or currently being built is expected to exceed half a century. Advanced fast neutron systems of the fourth generation, which are under development, will not be available for commercial deployment before two decades or more. Therefore, transition to fast neutron systems will be pursued over long periods of time, likely up to the end of this century.

Fast neutron systems operated with closed fuel cycles offer possibilities for enhancing security of energy supply through better use of the energy content of natural uranium, and for facilitating waste management by reducing the volumes and radio-toxicity of radioactive waste ultimately requiring disposal. Recycling uranium, plutonium and minor actinides in fast neutron reactors can multiply by 50 or more the energy extracted from each unit of natural uranium mined. Furthermore, it shortens the time during which most radioactive waste requires stewardship.

However, the attractiveness of fast neutron systems and the relevance of transitioning from thermal to fast reactors vary from one country to another. Key parameters affecting the cost/benefit analysis of transitioning include the size and age of the nuclear reactor fleet, the expected future reliance on nuclear energy, access to uranium resources, domestic nuclear infrastructure and technology development, and radioactive waste management policies in place.

Transitioning from the current fleet of thermal reactors to systems based on fast neutron reactors and closed fuel cycles is a challenging endeavour. The management of fissile materials during the transition period requires careful long-term planning to evaluate the dynamic evolution of mass flows in evolving systems and to ensure continuing security of supply at all steps of the fuel cycle. In-depth analyses of requirements for materials and services are a prerequisite to embarking on transition scenarios and should be based upon reliable data and robust models.

Infrastructure adaptation is another key challenge to ensuring the successful transition from

thermal to fast neutron systems. Building industrial capabilities for the transition period might be difficult at the national level. Multinational facilities could provide opportunities for economies of scale and economic optimisation, which would be impossible at national level. International co-operation could also help ensure adequate supply of fuel cycle services at the global level while limiting the risk of proliferation.

The transition from thermal to fast neutron systems is a means to achieve national energy policy goals, and governments, which are responsible for designing energy policies, have a major role to play in facilitating the implementation of fast neutron reactors and closed fuel cycles when they are integrated within their strategic choices. Adaptation of legal and regulatory frameworks, R&D programmes, education and training, and stability of energy policy are key aspects of government involvement and responsibilities.

The nuclear energy renaissance expected in the first decades of the 21<sup>st</sup> century is likely to reinforce the attractiveness of fast neutron systems. Ambitious R&D programmes have been undertaken at the national level in many countries and in the framework of several international projects; they should lead to the design and development of advanced reactors and fuel cycle facilities responding to the sustainable development goals of governments and society.

The implementation of fast neutron systems will, however, require sustained efforts and enhanced international co-operation to address the challenges raised by the transition period. Scientists and analysts can provide policy makers with data and information in support of robust decision-making in this regard. Ultimately, decision makers should take adequate measures in order to ensure that the infrastructure is adapted to the requirements of evolving systems, and that the overall context of national energy policy is coherent and consistent with its goals.

## References

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