Chapter 1

INTRODUCTION

1.1 Background

At the outset of the industrial development of nuclear energy for generating electricity, reliance on fast neutron reactors – offering better performance than thermal neutron reactors in terms of their ability to recycle and produce more fissile materials than they consume – was considered as a promising option. However, owing to several industrial, economic and policy factors, the attractiveness of fast neutron systems lowered significantly, their industrial development was slowed down and only a very few units of this type remain in operation today.

Today, the expectation of a revival of nuclear power programmes in a number of countries, that would increase the pressure on uranium resources and concerns regarding the disposal of high-level waste (HLW) containing very-long-life isotopes are reviving the interest for fast neutron reactors in light of their actinide burning as well as breeding capabilities.

Considering the composition and age of the current fleet of commercial nuclear power plants in operation, the implementation of strategies aiming at the deployment of fast neutron systems and material recycling should take into account issues raised by the transition period. Nuclear systems including an evolving mix of reactor types offer opportunities for synergies but have constraints, e.g., on the management of material flows. Decision makers should be aware of the potential bottlenecks that could hamper development strategies and need to identify the key factors for a successful introduction of new (Generation IV) systems. It is important in this context to analyse the impact of alternative scenarios ranging from business as usual (all thermal reactors operated once through) to transition (from thermal to fast neutron systems with full recycling) policies. Understanding the long-term consequences of choices made today in terms of reactor and fuel cycle types and timing of deployment is essential to assess the advantages and drawbacks of different approaches.

Against this backdrop, the Committee for Technical and Economic Studies on Nuclear Development and the Fuel Cycle (NDC) decided to include in its 2007-2008 Programme of Work a project on transition scenarios focusing on policy aspects, to be undertaken in cooperation with the Nuclear Science Committee (NSC).

1.2 Objectives and scope of the study

The overall goal of the study is to provide a comprehensive overview of issues raised by the transition from thermal to fast neutron reactors and their associated fuel cycles with emphasis on topics of interest to policy makers. Its main objectives are to:

- identify opportunities and challenges associated with the implementation of transition scenarios in various contexts (e.g., growth or stagnation of installed nuclear capacity, small or large nuclear power plant fleet in operation, and different domestic uranium and fuel cycle industry situations);

- analyse policy and strategic aspects of transition scenarios; and
- draw findings and conclusions for policy makers.

The project focused on strategic and policy issues, taking advantage of previous work carried out by the NEA and other organisations on the scientific and technical aspects of transition scenarios. The analyses were based on illustrative examples of transition scenarios provided by experts from member countries. The scope of the study covers a range of possibilities relevant in OECD countries. Transition scenarios are considered in countries with large and expanding nuclear programmes and with small fleets of reactors as well as in countries phasing-out nuclear energy but which might nevertheless be interested in fast neutron systems for burning actinides.

The analyses of illustrative examples identify the main driving forces and key parameters playing a role in facilitating the transition phase and enhancing the effectiveness of various strategies.

1.3 Working method

The study relied on previous work carried out by the NEA, in particular the status report on transition scenarios prepared by the NSC and the NDC publication on *Management of Recyclable Fissile and Fertile Materials* (OECD, 2007). The outcomes of studies and publications from other international organisations – mainly the International Atomic Energy Agency (IAEA), the European Commission and national institutes – were used to complement information from NEA studies and enrich the analyses.

The study was carried out by an *ad hoc* group of experts nominated by the NDC and the NSC. The group in charge of the project met three times in 2007 and 2008 to:

- agree on the objectives and detailed scope of the study;
- develop a table of contents for its final report;
- collect information and data, including reports describing national case studies;
- review, ensure the completeness and check the consistency of the data and information collected;
- analyse the data, draw findings and conclusions; and
- draft a report.

The draft report was submitted to the NDC and the NSC for review and approval before its publication by the OECD.

1.4 Previous studies and ongoing projects

In the context of the renewed interest of many countries in the nuclear option, many studies have been carried out or are ongoing to address issues that may be raised by a continued growth of installed nuclear capacity. Fast neutron systems, capable of using more effectively the energy content of fissile materials are attractive in this context and, therefore, many studies on transition scenarios from thermal to fast systems have been published or are ongoing. The following section provides a non-exhaustive overview on those studies.

Two recently-published studies undertaken within the NDC programme of work provide background materials on the rationale for implementing transition scenarios, their feasibility and preliminary insights on their potential impacts. The report on advanced fuel cycles and waste management (NEA, 2006) provides mass flows for a wide range of advanced fuel cycle schemes and gives insights on how they compare, at equilibrium state, in terms of natural uranium demand, volume and radiotoxicity of waste arising and economics. The report on management of recyclable fissile and fertile materials (NEA, 2007) investigates issues raised by storage, disposal and/or re-use of fissile and fertile materials and its findings identify key reasons transition from thermal to fast neutron systems.

Under the auspices of the NSC, an Expert Group on Fuel Cycle Transition Scenarios Studies was created in October 2004. This Expert Group is compiling and reviewing information on issues involved in transitioning from current fuel cycles to long-term sustainable fuel cycles or a phase-out of nuclear energy. The scope of the Expert Group covers existing and future technologies available for the transition period, including transmutation and storage of spent fuel, development and assessment of transition scenarios, and evaluation of the impact of the transition on reactors and fuel cycle facilities.

The Expert Group has completed a status report, to be published in 2009, which covers country specific scenarios for Belgium, Canada, France, Germany, Japan, the Republic of Korea, Spain, the United Kingdom and the United States, as well as a list of key technologies that were identified as crucial for the implementation of advanced fuel cycles. Also, it is investigating global and regional (European) transition scenarios to analyse the impacts of different strategies and policies and the role and characteristics of regional facilities. Finally, a benchmark study is underway to compare the results of scenario analysis codes developed by the member countries.

Studies on incentives, conditions and milestones of introduction of innovative nuclear systems (INS) into large-scale nuclear power are an integral part of the "International Project for Innovative Nuclear Reactors and Fuel Cycles" (INPRO) initiated in the year 2000 under the auspices of the IAEA. In particular, transition scenarios will be analysed in the context of the collaborative project on "Global Architecture of INS Based on Thermal and Fast Reactors Including a Closed Fuel Cycle" (GAINS). This study is being implemented jointly by Argentina, Belarus, Belgium, Canada, China, Czech Republic, France, India, Japan, Republic of Korea, Russian Federation, Slovakia, Ukraine, the United States and the European Commission plus Bulgaria, Italy and the NEA as observers. The objectives of the GAINS project are to:

- develop a framework (a common methodological platform, assumptions and boundary conditions) for the assessment of the transition from the current thermal reactors to a sustainable deployment of nuclear energy up to 2100;
- develop a reference base case for the architecture of a global system capable to meet in a sustainable manner requirements of energy supply, recognising regional differences in availability of material resources, energy growth rate and nuclear energy deployment options; and
- perform sensitivity studies to assess the impact of different key assumptions and to analyse the impact of different transition scenarios on sustainability metrics (as defined in the INPRO methodology).

GAINS is planned to be carried out over a period of three years proceeding in four main steps: selection of scenarios for nuclear growth; identifying fuel cycle options; simulation of nuclear deployment under different architecture; analysis of results.

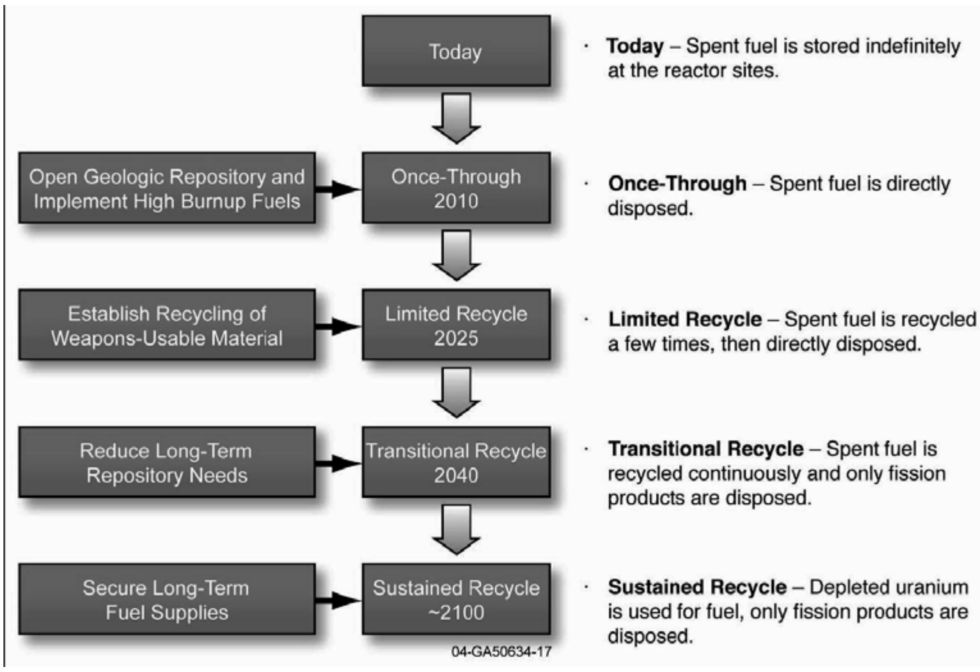
The European Commission has supported the Coordination Action PATEROS – Partitioning and Transmutation European Roadmap for Sustainable Nuclear Energy (EC, 2008a) – recognising that a closed fuel cycle based on Partitioning and Transmutation (P&T) is supporting a sustainable nuclear energy future by reducing the radiotoxicity and heat load of waste to be disposed of in geological repositories. The main objective of this project is to deliver a European vision for the deployment of the partitioning and transmutation technology, up to the scale level of pilot plants for all its components. This objective is of relevance both for countries committed to nuclear energy in the future and for countries not committed to a further deployment of nuclear energy.

The goal is to establish a global P&T roadmap up to the industrial scale deployment with indication of the critical milestones, preferred and back-up options, according to timescales and shared objectives at the European level. The number and the size of the needed installations – including fast spectrum systems, both critical and subcritical – will depend on the strategy and objectives of a specific policy of nuclear power development of a given European Union Member State. However, a common objective of all strategies using partitioning and transmutation is to reduce the burden on a long-term waste management, in terms of radiotoxicity, volume and heat load of high-level nuclear waste which has to be put into final repositories. Possible strategies range from global recycling of actinides in Generation IV fast neutron reactors to using dedicated fast spectrum transmutation reactors in a separate fuel cycle stratum. These strategies can be implemented to reduce drastically the amount of minor actinides (MA) sent to the repository in the context of stable or expanding nuclear energy scenarios as well as in a nuclear phase-out scenario.

The aim of the European Commission RED-IMPACT Project (EC, 2008b) was to study the impact of partitioning, transmutation and waste reduction technologies on the final waste disposal in granite, clay or salt repositories. The study covered analyses of toxicity and thermal load reduction due to material recycling and the associated reduction of repository gallery length required. Two types of scenarios – industrial and innovative – were considered and for each scenario type three cases were analysed for an equilibrium state. For the industrial scenarios once-through and direct disposal, mono-recycling of plutonium in pressurised water reactors (PWRs) and multi-recycling of plutonium in fast neutron reactors (FRs) were calculated. For the innovative scenarios, fast neutron Generation IV systems with homogeneous recycling of MA, simplified double strata – PWR and accelerator driven system (ADS) – and double strata scenario (PWR, FR and ADS) were calculated.

In the United States, the USDOE Advanced Fuel Cycle Initiative has conducted a range of studies considering different scenarios of future nuclear energy demand and different spent nuclear fuel management strategies. These studies are currently ongoing and no final conclusions have been reached as to the final path-forward for an advanced fuel cycle. As illustration, a study conducted in response to a request from the US Congress (USDOE, 2005) recommended an approach that could prudently and flexibly address the environmental impacts, proliferation resistance and uranium resource sustainability issues associated with an advanced fuel cycle. The approach includes introduction of limited recycling with current reactors to begin destruction of plutonium and minor actinides in light water reactor (LWR) spent fuel, followed by a transitional recycling phase with a mix of current (thermal) and new (fast spectrum) reactors to fundamentally change the nature and reduce the environmental impact of nuclear waste, and ending in a sustained recycling infrastructure based on new reactors using recycled material as their primary fuel. This illustrative evolution and associated approximate time scales are depicted in Figure 1.1.

Figure 1.1 An illustrative nuclear fuel cycle evolution studied in the United States



Source: USDOE, 2005.

Two main studies on transition scenarios are ongoing in France. The first one focuses on waste management aiming at providing robust scientific and technical background for the policy decision to be taken before 2015 in the context of the French law on the "Sustainable management of nuclear materials and radioactive waste". The second focuses on long-term uranium consumption and fuel cycle costs in the context of introducing generation IV nuclear systems. Transition scenario analyses for the world were carried out using the models and computer tools developed for investigating the French case and presented in various international conferences (Masara *et al.*, 2007; Delpech *et al.*, 2007). Those studies illustrate key aspects of transition scenarios in terms of uranium requirements and waste management and disposal.

For the first French study, based on the results obtained in the context of the French law of 1991, different cases of transition scenarios were analysed assuming to a constant installed nuclear power capacity in France. Several transition scenarios were investigated through analyses of the systems at equilibrium state. The options studied were: MA recycling in PWRs (Np+Am+Cm or Am alone); MA recycling in FR (homogeneous or heterogeneous); and MA recycling in ADS. Based on the results of the transition scenarios, environmental and economical analyses were performed (CEA, 2005).

For the studies undertaken in the context of the new act voted in 2006, transition scenario evaluations are planned to be investigated by research organisations in cooperation with the industry. Robust transition scenarios from current LWRs to fast neutron reactors will be analysed based on their potential for:

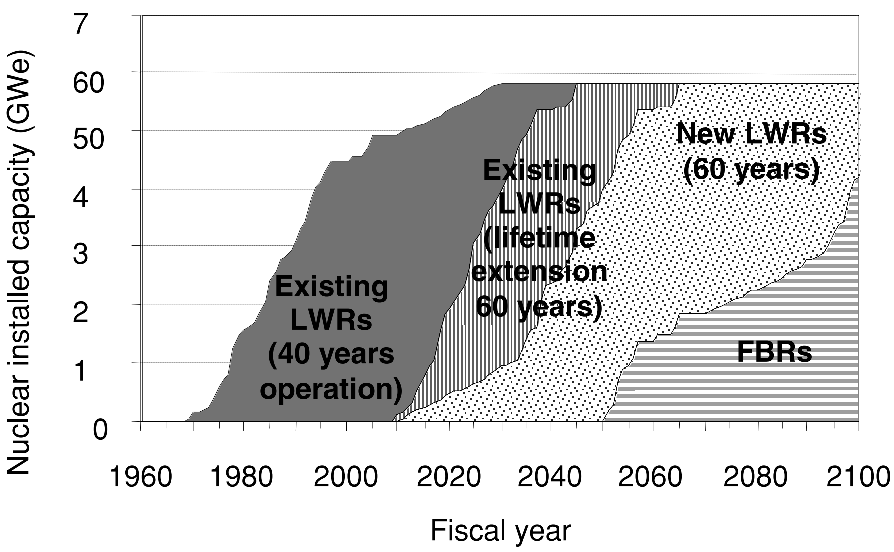
- improving the ultimate long lived waste form;
- adequate plutonium management to allow for the deployment of fast neutron reactors;
- optimising the use of existing reprocessing plants; and
- improving resistance to proliferation.

For these studies, quantitative data on material isotopic compositions, quantities and types of waste will be obtained using a reliable, validated computer code. The objectives are to review and assess the industrial feasibilities, costs, robustness of the different systems for partitioning and transmutation (P&T) and the impact of P&T on storage (e.g., capacities required, inventories and radioactivity of waste).

Japan is considering the introduction of fast neutron reactors as a key element in its nuclear energy strategies for sustainability and security of supply reasons. Many studies on transition scenarios have been carried out and provide mass flow analyses as well insights on strategic and policy issues addressed by the transition to fast neutron reactors (e.g., Ohtaki and Ono, 2005).

In October 2005, the Atomic Energy Commission of Japan (AEC) published the "Framework for Nuclear Energy Policy" and the Cabinet Council decided on 14 October 2005 that government should respect it as a fundamental principle for research, development and utilisation of nuclear science and engineering. In this Framework, AEC stated that the FR cycle is a promising future option for the Japanese nuclear fuel cycle.

Figure 1.2 Typical Japanese nuclear power scenario

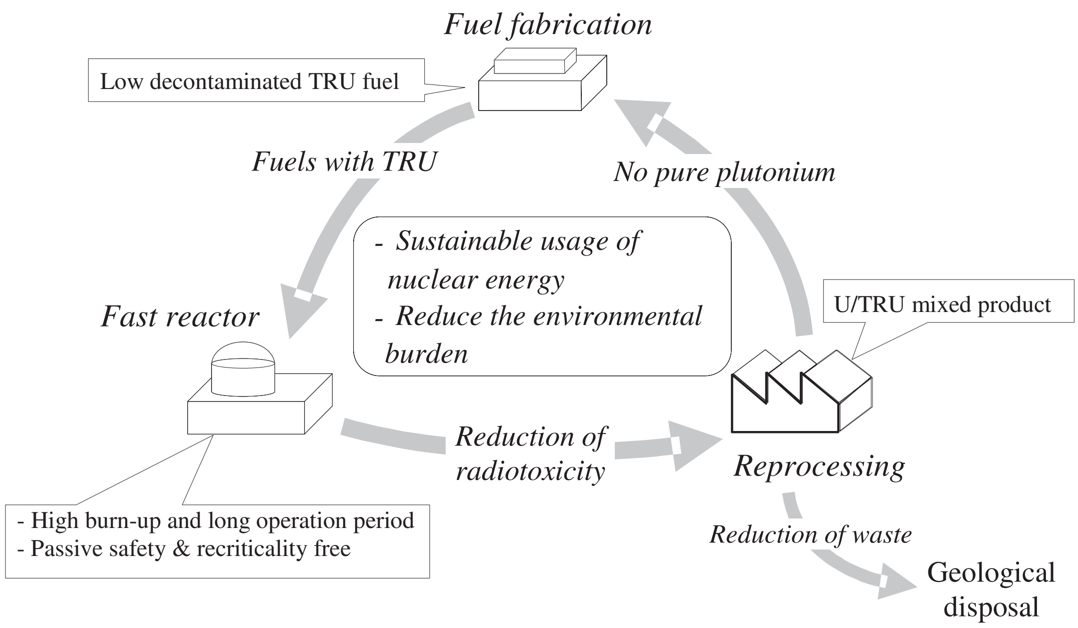


Source: METI, 2004.

Japan has developed nuclear power for the last fifty years and, as a national policy, has promoted the development of nuclear fuel cycle to enhance the efficient use of uranium resources and to reduce high-level radioactive waste. The Rokkasho reprocessing plant with annual throughput of 800 tHM will start to operate commercially in 2009. The construction of a mixed-oxide (MOX) fuel fabrication plant is also in progress at the Rokkasho site. Plutonium extracted from the reprocessing of spent fuel will be recycled into LWRs as MOX fuel until the deployment of FRs. In 2030, the nuclear power generation capacity is expected to increase to 58 GWe from present 50 GWe to help reducing the Japanese CO_2 emissions to their 1990s level. The nuclear power generation capacity evolution is based on the reference case of the interim report *Long-Term Outlook for Energy Supply and Demand*, prepared in October 2004 by the Energy Supply and Demand Subcommittee in the Advisory Committee for Natural Resources and Energy of the Ministry of Economy, Trade and Industry. The nuclear power generation capacity is assumed to remain constant at 58 GWe after 2030. Figure 1.2, which illustrates a typical scenario considered in Japan, shows that LWR will be decommissioned after 40 or 60 years of operation and advanced LWR will be introduced after 2030. The recycling of plutonium in LWRs will end at around 2045. After 2050, LWRs will be replaced by FRs at a rate of 1 GWe per year leading to a fleet composed only of FRs at the beginning of the 22^{nd} century.

The Japanese basic policy is that spent fuels are reprocessed and all high level wastes are vitrified and disposed in geological repository. The Japan Atomic Energy Agency and the Japan Atomic Power Company started a feasibility study on commercial FR systems in 1999 and are evaluating several promising FR cycle concepts in cooperation with the Central Research Institute of Electric Power Industry and the former Japan Atomic Energy Research Institute. During phase 2 of the feasibility study which started in 2001 the sodium-cooled FR cycle was selected as the main concept on the basis of comprehensive assessment of various aspects such as safety, economics, efficiency of resource utilisation, reduction of environmental burden, non-proliferation, technical feasibility, and social acceptability. Figure 1.3 shows the FR cycle system considered in the feasibility study.

Figure 1.3 Concept of FR cycle system



Source: Sato, 2007.

In the feasibility study, transuranic elements (TRU) are not considered as waste and most of them are assumed to be recovered from LWR and FR spent fuels to be recycled (burned) and transmuted in FR. Minor actinides from LWR spent fuels will be recovered in a second reprocessing plant (next to the first Rokkasho plant) and 99.9% of the minor actinides from FR spent fuels will be recycled in FRs in homogeneous mode. The basic strategy is to shift from plutonium recycling in LWRs to TRU recycling in FRs. The specification of the second reprocessing plant and the significance and mode of minor actinide recycling are being discussed in detail at present.

Another Japanese initiative, the "Options Making Extra Gains from Actinides and Fission Products" project (OMEGA Project) started at 1988 under AEC. Its objectives are to seek: further efficiency and rationalisation of final disposal; dramatic improvement of safety; and more efficient utilisation of resources. In the OMEGA project, the Japan Atomic Energy Agency and the Central

Research Institute of Electric Power Industry researched and developed the partitioning process and the transmutation system (accelerator-driven system) as a basic technology.

1.5 Overview of the report

The present report contains six chapters including the present Chapter 1 which provides the objectives, scope of the study, the working mode adopted and a brief summary of other relevant studies.

Chapter 2 gives an overview on the overall energy and electricity demand landscape which serves as a backdrop to investigate strategic issues associated with nuclear development scenarios including transition from thermal to fast neutron systems. It provides also background information on nuclear technologies and their evolution in the coming decades, highlighting the characteristics of various systems which can be integrated into transition scenarios.

Chapter 3 reviews the reasons why transition scenarios may be contemplated by different countries, such as enhancing security of energy supply and/or reducing the number and size of repositories for high level waste, and the implementation issues raised by those scenarios, such as research and development and infrastructure requirements.

Chapter 4 identifies and analyses policy issues and some technical issues associated with transition scenarios in the fields of technology, industrial considerations and economics, and highlights the role of government and international cooperation.

Chapter 5 provides key findings provided by illustrative scenarios developed and analysed in various studies, highlighting their respective goals, expected achievements and lessons learnt from the results in terms of strategic approaches and issues.

Chapter 6 draws findings and conclusions from the scenarios which are reviewed and analysed in the study. It offers some recommendations for consideration by policy makers in the process of implementing transition scenarios.

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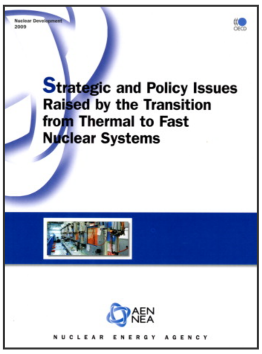
Strategic and Policy Issues Raised by the Transition from Thermal to Fast Nuclear Systems
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