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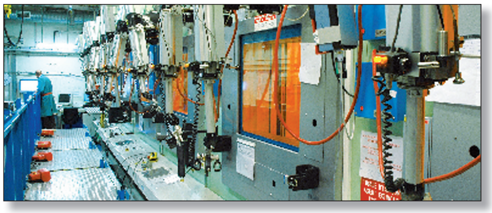
Strategic and Policy Issues Raised by the Transition from Thermal to Fast Nuclear Systems



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Nuclear Development

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

NEA No. 6352

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FOREWORD

Many studies have been published recently by national institutes and international organisations, including the OECD Nuclear Energy Agency (NEA), on scientific and technical aspects of transition from thermal to fast neutron nuclear systems. However, the implementation of transition scenarios raises a number of key strategic and policy issues which had not yet been investigated in depth. The main objective of the present study, undertaken under the auspices of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC), is to identify and to analyse those policy issues and to draw findings, conclusions and recommendations for policy makers.

The study, carried out by a group of experts, is based on a review of transition scenarios developed at the national, regional and international levels which provided the scientific and technical background materials for identifying the opportunities and challenges associated with those scenarios and the policy issues to be addressed by governments and the industry when considering the transition from thermal to fast nuclear systems.

The findings from the study highlight the need to evaluate the advantages and drawbacks of transition scenarios holistically, taking into consideration short-term and long-term aspects, and assessing environmental and social criteria as well as economics. Its conclusions show that the viability of transition scenarios and their successful implementation will require long-term commitments and comprehensive and consistent panning. The study also illustrates the potential role of international co-operation and multinational endeavours in facilitating the implementation of transition scenarios.

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This study on transitioning from thermal to fast neutron nuclear systems was carried out under the auspices of the Committee for Technical and Economic Studies on Nuclear Development and the Fuel Cycle (NDC). It benefitted from previous and ongoing activities on scientific and technical aspects of transition scenarios undertaken under the leadership of the Nuclear Science Committee. Its main objectives were to provide insights on strategic and policy issues raised by the transition, and to draw findings, conclusions and recommendations for consideration by decision makers on the opportunities and challenges associated with the introduction of fast neutron systems in a fleet of thermal neutron reactors.

The analyses presented in the report are based on a review of transition scenario studies developed by national institutes and international organisations under various background conditions and with different assumptions. Those studies cover a broad range of situations in terms of global context as well as nuclear energy programme. They illustrate the different goals of transitioning to fast neutron systems in various countries and regions. Approaches to transition described in the different studies provide insights on alternative strategies offered to decision makers and their respective achievements.

The results from various transition scenario studies show that the relevance of transitioning to fast neutron systems depends on the expected future role of nuclear energy and on the development of advanced nuclear technologies. According to most prospective studies on energy and electricity demand and supply in the coming decades, the contribution of nuclear energy will remain significant owing to its potential role in addressing global climate change and security of supply issues. The development and deployment of advanced nuclear technologies is expected as a result of ambitious R&D programmes undertaken within national and international frameworks.

Fast neutron systems have been considered an attractive option since the early development of nuclear electricity generation but have not reached the degree of industrial and commercial deployment achieved by thermal neutron reactors. However, several countries have accumulated significant feedback from experience on fast neutron reactors and technologies required for closing the fuel cycle, including reprocessing of spent fuel and recycling of plutonium.

In light of the age and performance of existing nuclear power plants, the role of nuclear energy is likely to be enhanced through extending the lifetime of existing plants as well as by developing and deploying advanced nuclear systems. Recognising that the lifetime of nuclear power plants in operation and being built is expected to exceed half a century, the transition to fast neutron systems will take several decades. Furthermore, the advanced fast neutron systems of 4th generation which are under development will not be available for commercial deployment before two decades or more. In this context, the implementation of transition scenarios will be pursued over long periods of time, likely up to the end of the century.

Fast neutron systems operated with closed fuel cycles offer capabilities to enhance security of energy supply through better use of the energy content of natural uranium and to facilitate waste management and disposal through reducing the volumes and radiotoxicity of ultimate radioactive waste. 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 radioactive waste requires stewardship.

However, the attractiveness of fast neutron systems and the relevance of transitioning from thermal to fast reactors vary from country to country. 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 policy 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 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 embark on transition scenarios and should be based upon reliable data and robust models.

Infrastructure adaption is another key challenge to ensure the successful implementation of transition from thermal to fast neutron systems. Building industrial capabilities adapted to 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 cooperation also could facilitate ensuring adequate supply of fuel cycle services at the global level while limiting the risk of proliferation.

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 strategy choices. Adaptation of legal and regulatory frameworks, R&D programmes, education and training, and stability of global energy policy are key aspects of government involvement and responsibilities.

The nuclear energy renaissance expected in the first decades of the 21st 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, however, will require sustained efforts and enhanced international cooperation to address challenges raised by the transition period. Scientists and analysts can provide policy makers with data and information in support to 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.

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.

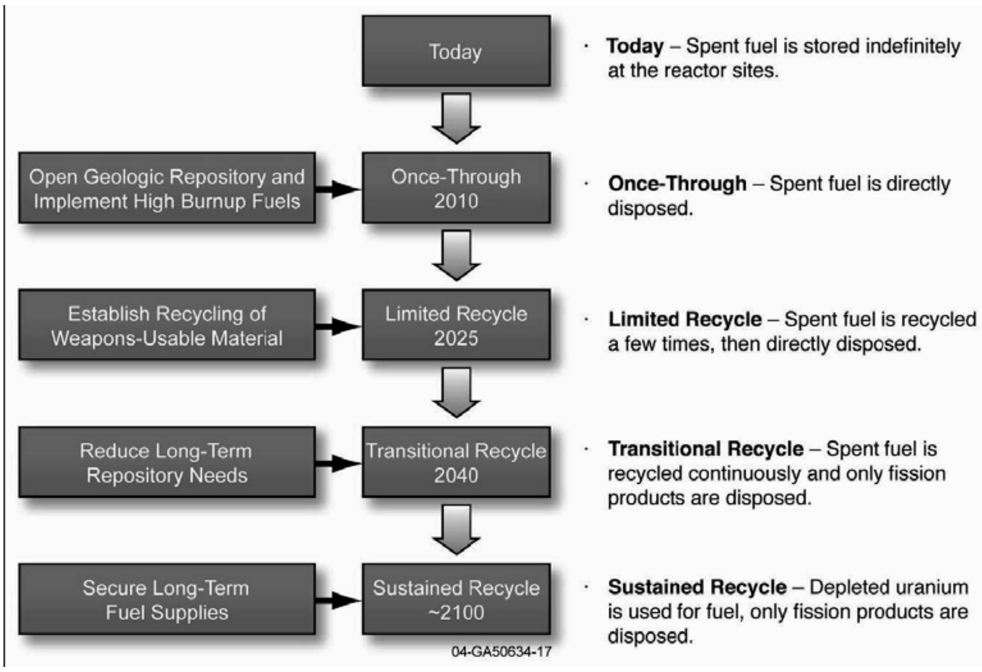
The European Commission has supported the Coordination Action PATEROS – Partitioning and Transmutation European Roadmap for Sustainable Nuclear Energy (EC, 2008a) – recognising that a closed fuel cycle based on Partitioning and Transmutation (P&T) is supporting a sustainable nuclear energy future by 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:

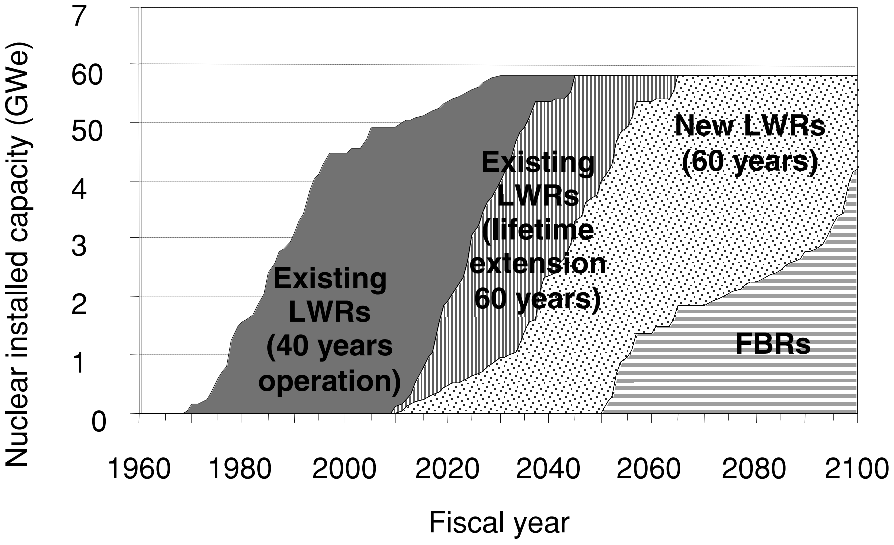
- improving the ultimate long lived waste form;
- adequate plutonium management to allow for the deployment of fast neutron reactors;
- optimising the use of existing reprocessing plants; and
- improving resistance to proliferation.

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

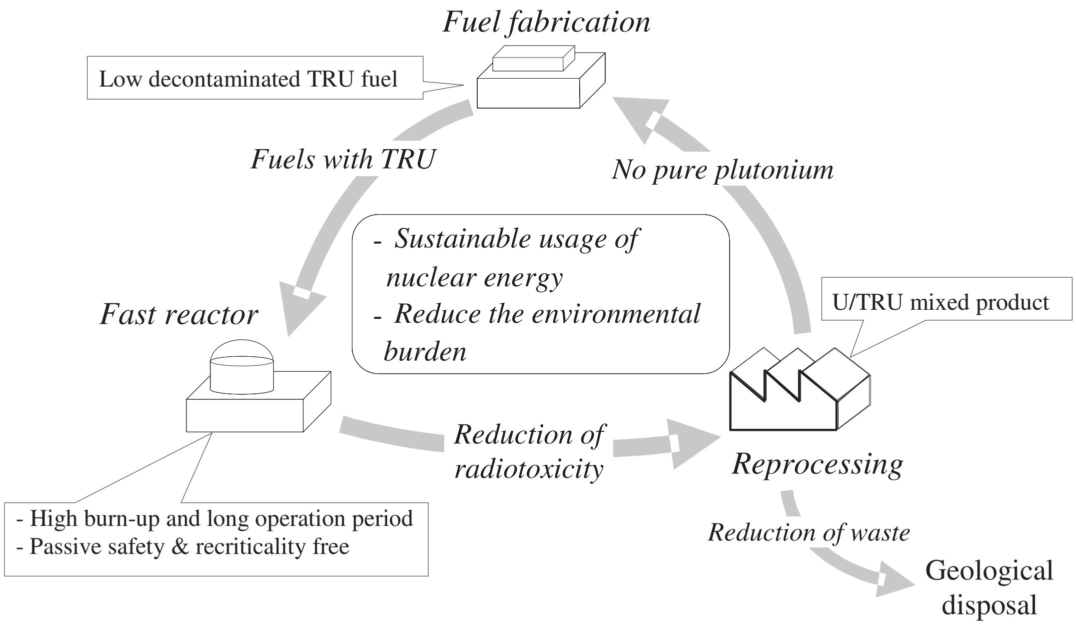


Source: METI, 2004.

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 22nd 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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Chapter 2

TRANSITION SCENARIOS IN PERSPECTIVE

This chapter provides background information on the overall context of transition scenario design and implementation. The first section gives illustrative scenarios to serve as a backdrop for assessing the relevance of transition scenarios in a global energy supply perspective. The second section is a short overview on nuclear reactor and fuel cycle technology developments expected in the coming decades, indicating the types of nuclear systems which could be implemented when transitioning from thermal to fast neutron reactors.

Nuclear energy development will be driven by the evolution of primary energy demand and electricity consumption and by the share of nuclear in the supply mix which will depend on the competitiveness of the nuclear option and on its acceptance by governments and the public. This evolution will not be uniform worldwide and may vary from country to country. Incentives to implement transition scenarios from thermal to fast neutron systems will vary according to the growth rates of nuclear electricity generation worldwide, and in each region or country.

The decision to implement transition scenarios aiming at replacing thermal reactors by fast neutron systems, and the strategy adopted for this purpose will be driven essentially by policy goals. However, technology preparedness will be a limiting factor as fast neutron systems, including reactors and fuel cycle facilities, are at an early stage of development as compared to thermal reactors.

The success of research and development programmes on fast neutron systems will determine how and when those systems, including reactors and fuel cycle facilities, will reach a level of technology preparedness and economic competitiveness that will allow them to replace thermal-neutron systems available on the market today and under development.

2.1 Evolution of energy demand and electricity generation

Energy is essential to economic and social development. With progress towards better quality of life worldwide, the demand for energy has increased steadily during the last decades. It is expected to continue growing globally, even if industrialised countries succeed in enhancing dramatically the energy efficiency of their industries and lifestyles. Electricity is a flexible energy supply vector, clean at the end-user point and which provides services, such as lighting, which cannot be substituted by any alternative. Furthermore, increased use of electricity in the transport sector is expected owing to environmental concerns and policy aiming at alleviating oil dependency. Therefore, it is projected that demand growth rates will remain higher for electricity than for total primary energy as also was the case in the past.

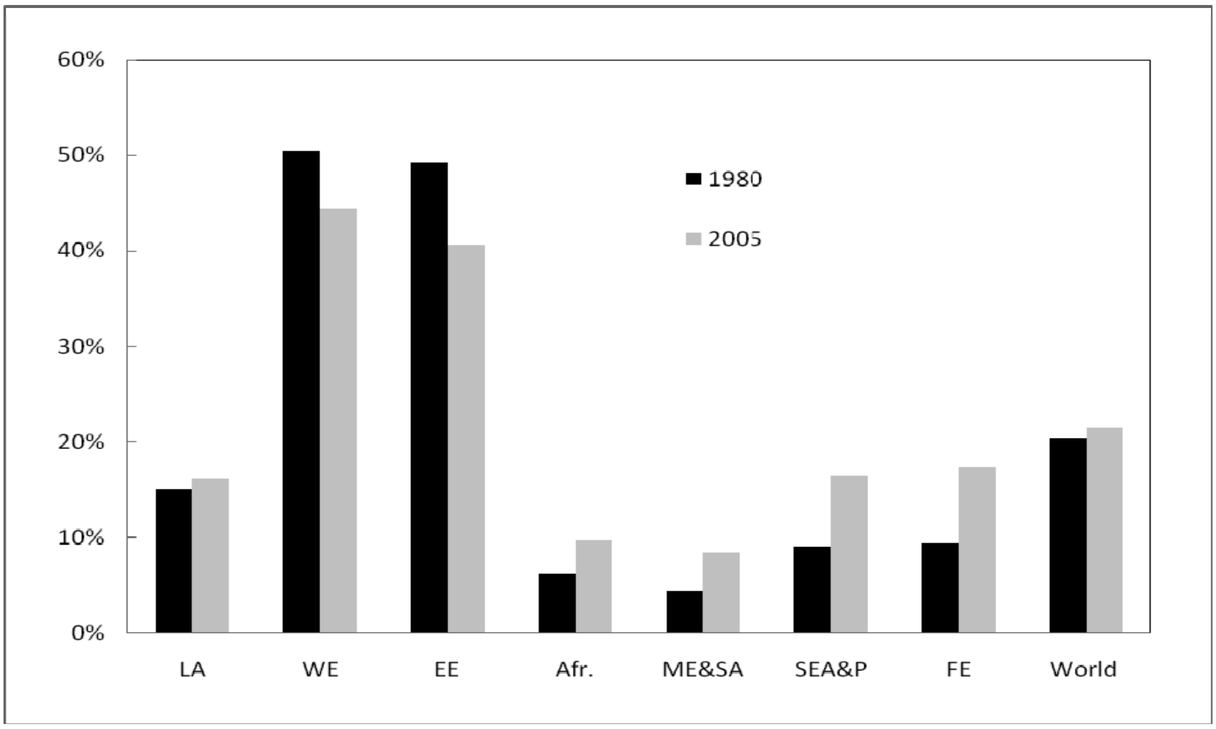
Although uncertainties are large on future energy demand and electricity consumption, especially in the long term, many authoritative studies provide indicative scenarios which can be used as a basis for analytical studies and in support of policy making. The main purpose of such scenarios is to highlight opportunities and challenges of alternative futures. They are designed primarily to help in identifying consequences of various policy choices, such as decisions to implement, or not, fast neutron systems within a national nuclear power programme.

The projections described below for the medium term, up to 2050, are drawn from work recently performed by NEA (NEA, 2008) which was based on energy and electricity demand and supply analyses published in the literature and expert judgment regarding nuclear energy market shares. For the long term, up to 2100, the scenarios of the Intergovernmental Panel on Climate Change (IPCC, 2000) provide a wide range of possible futures for total energy and nuclear share in supply. The projections summarised below are illustrative and intended to serve as a backdrop for assessing policy aspects of transition scenarios in contrasted contexts of demand. They should not be regarded as forecasts or predictions.

2.1.1 Past trends in energy and electricity demand growth

Although the world energy demand was 65% higher in 2005 than in 1980, its average growth rate (2% by year) during the period was only slightly above the population growth rate (1.6% by year). Therefore, the average per capita energy consumption was only some 10% higher in 2005 than in 1980. Furthermore, the regional disparities in energy use per capita were not significantly reduced over the period, as shown in Figure 2.1 which displays the ratios of per capita energy consumption in different regions, expressed as a percent of its value in North America for the years 1980 and 2005. Recognising that at the beginning of the 21st century a significant fraction of the world population has no or very little access to commercial energy supply, continued increase in energy demand is to be expected.

Figure 2.1 Energy consumption per capita in various regions
(% of its value in North America for the same year)



Note: LA = Latin America; WE = Western Europe; EE = Eastern Europe; Afr. = Africa; ME&SA = Middle East and South Asia; SEA&P = South East Asia and Pacific; FE = Far East.

Source: IAEA, 2005.

Although nuclear energy has increased its share in total supply significantly since the middle of the last century, its contribution remains modest compared to some other sources. Past trends show that fossil fuels, which were the most used sources of energy in 1980, remained the main component of supply up to 2005. With the exception of a slight decrease in the oil use around 1985, the consumption of oil has increased continuously, with an average growth rate of 1.1% by year, corresponding to about half of the growth rate of the total energy use. The use of solid fossil fuels reached a plateau around 1990-1995 and remained stable afterward but it remains the preferred fuel for emerging countries such as China and India. The use of biomass, other renewable sources and nuclear energy increased at average rates of 5.8, 6.3 and 3.8% per year, respectively.

World electricity consumption doubled between 1980 and 2005, growing at a higher rate than primary energy demand. While regional distribution of electricity generation changed significantly from 1980 to 2005, with much more rapid growth in developing countries than in the OECD, the gaps in electricity generation per capita remained very wide. In 2005, the electricity generation per capita in Africa was around 20 times lower than in North America. At the beginning of the 21st century, 85% of the world population remains significantly below the electricity threshold level of 4 000 kWh *per capita*, below which it has been observed that social indicators such as life expectancy and educational attainment are becoming significantly lower than in countries having access to more electricity supply.

Fossil-fuelled power plants remained the main electricity generation sources over the period 1980 to 2005 and, in spite of the "rush to gas" in OECD countries, coal kept its position as the primary fuel for electricity generation worldwide. Renewable sources progressed dramatically, multiplying their share in total electricity generation by four during the period, but their contribution remained below 1% in 2005. Nuclear power doubled its share to reach some 16% in 2005.

2.1.2 Future energy and electricity demand

The main drivers for increase in total primary energy demand during the 21st century will be the strong economic growth in many developing countries, leading to a more energy consuming lifestyle, and the projected expansion in world population. Trends to less energy intensive processes in industrialised countries might mitigate the growth rate of primary energy consumption but will not be sufficient to stabilise total demand. Electricity consumption is likely to grow faster than primary energy demand because it is a very flexible supply vector, user friendly in the domestic sector and has some industrial uses for which there is no substitute.

The scenarios developed by the International Energy Agency for their study on technology perspectives (IEA, 2008) indicate that world primary energy demand could nearly double between 2005 and 2050 in a business as usual case and would increase by some 50% assuming significant technology progress and efficient policy measures. In the longer term the IPCC scenarios provide a wide range of possible futures with a low scenario corresponding to practically zero growth between 2050 and 2100 and a high scenario leading to a world primary energy consumption five times higher in 2100 than in 2005.

The evolution of primary energy supply by source will depend on energy policies to be adopted in various countries in particular with regard to decarbonisation of world economies in order to address global climate change issues. However, in all scenarios the shares of fossil fuels remain significant until the end of the century and the shares of renewable energy sources, while increasing rapidly, especially when it is assumed that policy measures to reduce greenhouse gas emissions will be implemented, will become significant only after 2050.

With regard to electricity generation, all scenarios project significant increase in the coming decades because it is recognised that at least a doubling of present level would be needed for the poorest developing countries to reach an electricity consumption per capita compatible with the social goals of sustainable development.

By 2050, the IEA scenarios project electricity generation to range between twice and three times its present value, i.e., 35 000 TWh to 55 000 TWh. Over the period to 2030, the biggest growth in demand is expected to occur in China and India. Demand in the OECD countries is expected to grow at a slower pace although past trends are not showing drastic reduction in electricity demand growth rates in industrialised countries. As other countries reach higher levels of economic development, it is likely that their electricity demand will continue to increase.

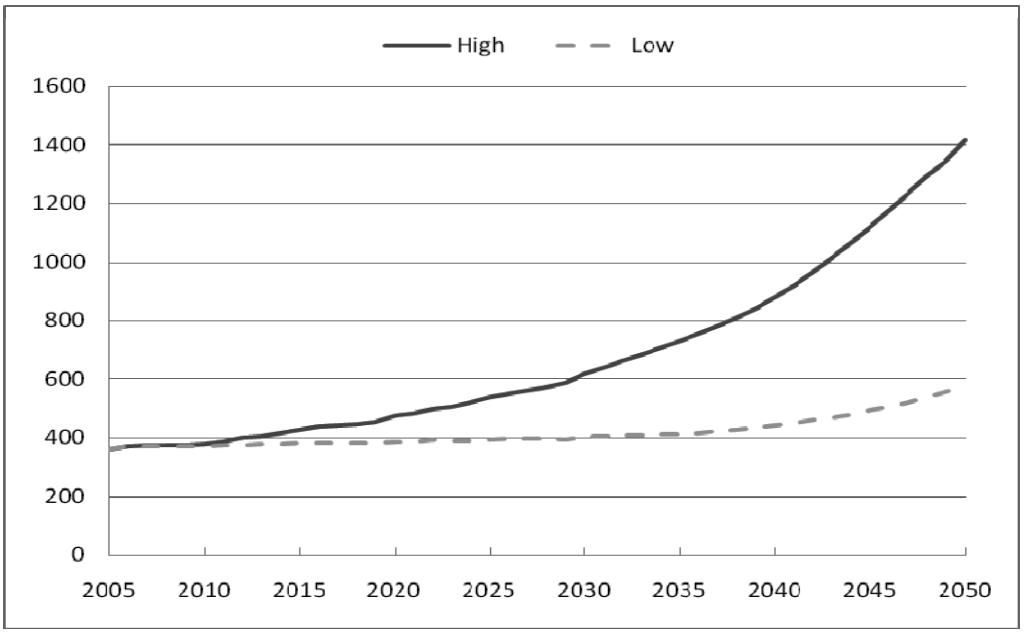
Beyond 2050, various scenarios display a broad range of possibilities depending on the assumptions adopted regarding energy/electricity efficiency of the economies, life styles and technology progress. At the end of the 21st century, according to IPCC scenarios, electricity generation in the world could range between four and sixteen times its present value.

2.1.3 Nuclear capacity projections

The development of nuclear electricity generation will be driven by energy and electricity demand growth, and by the relative competitiveness of nuclear energy versus relevant alternatives. The role to be played by nuclear energy in supplying electricity and eventually non-electricity products will be influenced also by nuclear technology progress and national policies.

The nuclear option offers advantages in terms of security of energy supply, cost stability and, maybe more importantly in many countries and regions, to reduce the risk of global climate change. With regard to cost stability, the price of uranium represents a very low fraction (around 5%) of total generation cost and this provides a guarantee of long term cost and price stability. With regard to global climate change, policy makers have recognised that the greenhouse gas emission reduction targets of the Kyoto Protocol and beyond are unlikely to be met with business as usual policies and are recognising the need to take voluntary measures aiming at de-carbonisation of our economies.

Figure 2.2 World nuclear capacity projections to 2050 (GWe)



Source: NEA, 2008.

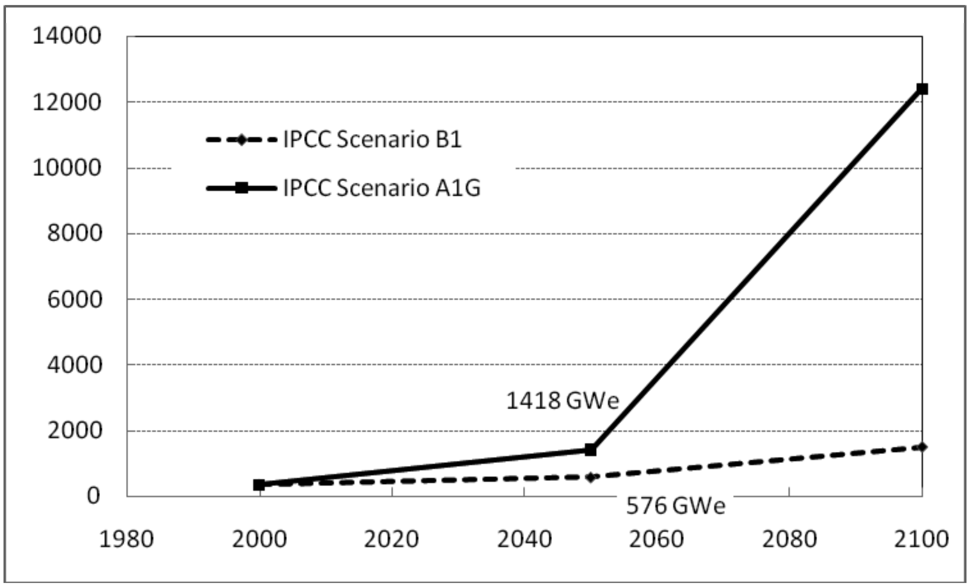
The NEA has developed two scenarios for nuclear capacity evolution to 2050, which are shown in Figure 2.2, based upon a thorough analysis of policies and technical capabilities in various countries (NEA, 2008). With an installed nuclear capacity ranging between 580 and 1 400 GWe by 2050 as compared to around 370 GWe in 2007, nuclear energy would provide some 5 to 13% of the world primary energy demand in 2050.

Although the projected growth of nuclear capacity during the coming decades may seem modest, higher growth rates, which are technically feasible, seem unlikely taking into account the lead times associated with decision making in the nuclear energy field and with licensing of nuclear power plants.

On the other hand, the evolution of installed nuclear capacity beyond 2030 could vary widely depending on many factors related to the overall policy-making landscape and to the nuclear technology progress. On the one hand, countries wishing to phase-out nuclear energy will have more technically mature alternatives at their disposal and an increasing number of their existing nuclear units will have reached the end of the economic lifetimes. On the other hand, countries wishing to increase their reliance on nuclear energy will have had the time to build adequate infrastructure and industrial capabilities to support large nuclear programmes.

For the period 2050 to 2100, the projections derived from the IPCC scenarios provide a very broad range. The scenario A1G is characterised by rapid economic growth with substantial reduction of regional differences in per capita income, with global population peaking in mid-century but declining thereafter, and by rapid introduction of new and more efficient technologies. It assumes that voluntary policies are not implemented or are not effective and that hydrocarbons, oil and gas, remain dominant in the supply mix. The B1 scenario is characterised by significantly lower economic growth than in the A scenarios but practically the same population pattern, rapid changes in economic structures towards a service and information economy with reductions in material intensity, and by forceful introduction of clean and resource-efficient technologies. Figure 2.3 shows the projected evolution of nuclear electricity generation to 2100 according to the IPCC scenarios B1 and A1G.

Figure 2.3 Projected nuclear capacity (GWe) for 2 IPCC scenarios



Source: IPCC, 2000.

2.2 Nuclear technology evolution

During the first decades of nuclear energy development, fast neutron systems were considered a fairly attractive option in light of their overall effectiveness in utilising the energy content of fissile materials. However, for various reasons including low price of uranium and technical difficulties encountered in industrial deployment of fast neutron reactors, the interest for those systems declined.

As a result, nuclear energy systems in operation today are based on the industrial development over several decades of light and, to a lesser extent heavy, water moderated reactors using thermal neutrons. Furthermore, most nuclear power plants under construction or planned are thermal reactors. Except in a few countries, fast neutron systems are at the conceptual stage with, at best, plans for constructing prototypes or first-of-a-kind units within one or two decades.

The recent emphasis placed by policy makers on the goals of sustainable development, which are driving energy policies in many countries, is fostering a renewed interest in technologies providing enhanced resource management efficiency such as fast neutron nuclear systems with recycling. However, the transition to fast neutron systems contemplated by several countries will require many decades taking into account a currently expected lifetime of more than 50 years for most state-of-the-art nuclear units.

2.2.1 Specific characteristics of fast neutron reactors

While thermal reactors use a moderator to slow-down neutrons, fast neutron reactors have no moderator and make use of fast neutrons with higher kinetic energy. They create more neutrons per fission than thermal reactors and make better use of the energy content of uranium because the neutron-capture probability decreases when the speed of the neutrons increase. The excess neutrons can be use to convert fertile materials, e.g., ^{238}U or ^{232}Th into fissile materials through neutron capture.

Fast neutron systems can be designed to produce more fuel than they consume; the so-called “breeder” reactors improve the efficiency of natural uranium utilisation and contribute to the long-term sustainability of nuclear energy. Recycling of major actinides, uranium and plutonium, in fast neutron reactors reduces the amount and activity of fissile materials in waste. On the other hand, fast neutron systems may be designed to manage also minor actinides in order to reduce even further the inventory of fissile materials and the volumes and radiotoxicity of nuclear waste. Such systems are aiming at reducing the number and size of deep geological repositories required for the disposal of high-level radioactive waste through actinide burning.

The capability of fast neutron reactors to accommodate a large range of fuel compositions provides high flexibility and the possibility to burn or breed actinides depending on the policy objectives of the users. This characteristic allows adaptation over time, from breeding to burning or the other way around as the goal pursued evolves.

2.2.2 Development of nuclear technologies

The Generation IV Roadmap (NERAC/GIF, 2002) introduced a representation of the evolution of nuclear power in which the different reactor types were grouped into generations. Figure 2.4 illustrates the evolution of nuclear power technologies since the middle of the last century.

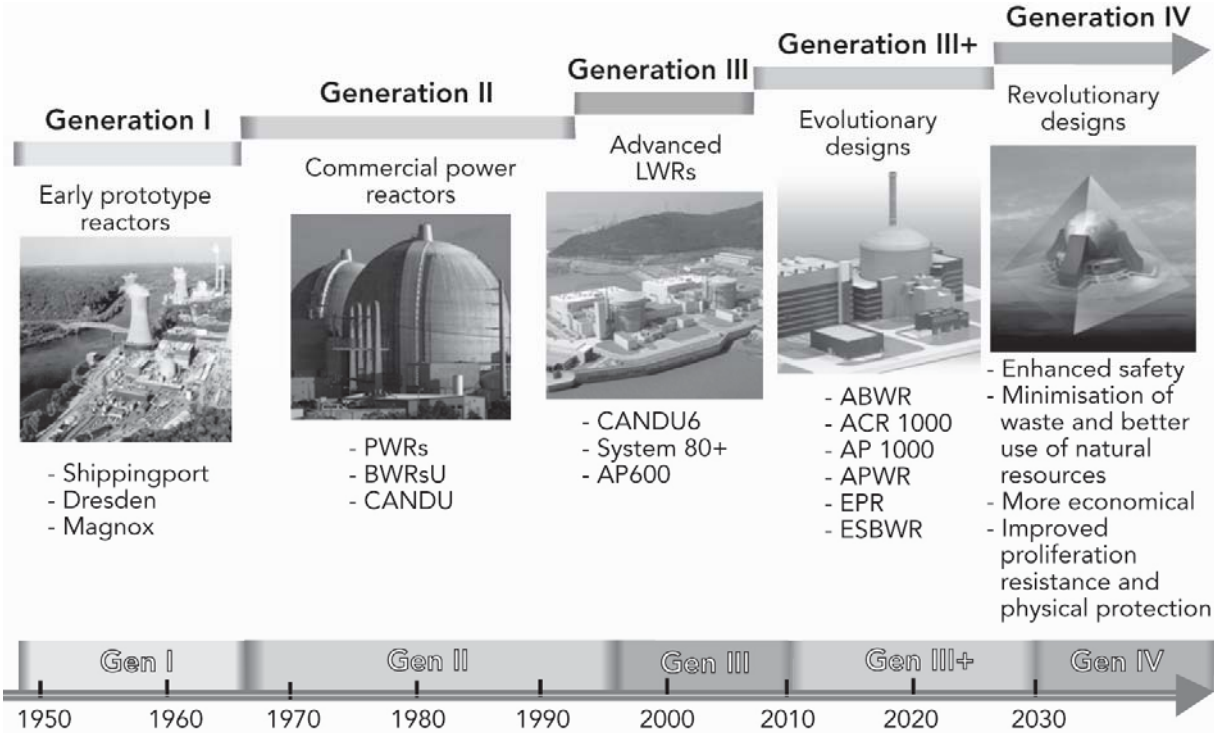
The first generation consists of the prototypes and early commercial plants developed in the 1950s and 1960s. It includes the first BWR Dresden 1 and the first PWR Shippingport in the United

States, the first fast neutron reactors and the first Magnox plants in Europe. Very few Generation I reactors are still in operation.

The first wave of commercial nuclear power plants – Generation II reactors – was built in the 1970s and 1980s. It includes mainly light water reactors (BWR and PWR, including Soviet-design PWR/VVER) and heavy water reactors (PHWR). The gas-cooled reactors in operation in the United Kingdom and the French sodium-cooled fast reactor Superphénix, pertain to this generation.

Generation III reactors, developed in the 1990s, are evolutionary designs with enhanced safety and economic performance. This generation includes a PHWR (CANDU6) and several LWRs (e.g., System 80+ and AP600). The more recent designs of generation III+ reactors offer more advanced features; they include LWRs and PHWRs but also high-temperature gas-cooled reactors (e.g., PBMR). There is no fast reactor design within Generations III/III+. Very few reactors of these generations have been built so far but the renewed interest in the nuclear option triggered several orders for those advanced systems in the recent years and more should be built in the coming decade.

Figure 2.4 Reactor generations



Source: Adapted from the NERAC/GIF Roadmap, 2002.

Generation IV reactors are innovative systems offering the prospect of further enhanced safety and economics, better utilisation of natural resources and improved proliferation resistance and physical protection. No vendor industry exists yet for these systems, which are at an early stage of conceptual design and will require at least some twenty years of R&D before being available for commercial deployment. Most Generation IV systems are based on fast neutron reactors and closed fuel cycle. Table 2.1 summarises the goals of Generation IV systems selected by the Generation IV International Forum.

Table 2.1 Goals for Generation IV nuclear energy systems

Sustainability	Provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilisation for worldwide energy production. Minimise and manage nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.
Economics	Have a clear life-cycle cost advantage over other energy sources. Have a level of financial risk comparable to other energy projects.
Safety & reliability	Excel in safety and reliability. Have a very low likelihood and degree of reactor core damage. Eliminate the need for offsite emergency response.
Proliferation resistance & physical protection	Increase the assurance of being very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

Source: NERAC/GIF, 2002.

The Accelerator Driven System which received renewed attention in the early 1990s did not reach the level of detailed design leading to an industrial system. It is a reactor with a subcritical core configuration coupled with a proton accelerator. The proton beam generates neutrons by a spallation process and the neutrons are used to transmute transuranic material inserted into the ADS core. Although suitable to transmute large amounts of transuranic elements and thereby help managing high-level waste from other reactors, the ADS is not among the Generation IV systems under active development and seems unlikely to reach industrial maturity and commercial deployment in the near- to medium-term.

2.2.3 Generation III/III+ reactor designs

All Generation III/III+ designs are thermal reactors. They can be divided into two groups: those available on the market; and those expected to be commercially available within a few years. In the first group, units are already built, under construction, ordered or have a design certification process on-going. For the second group, lead plants are in preparation as well, but at a less advanced stage. A non-exhaustive list (designs with at least one customer for a specific project with a selected site) is provided below with a very short description of their main features.

Most of the designs described below are large-size reactors (1 000 MWe or more). Various R&D organisations and vendors are developing smaller designs (IAEA, 2006), such as the IRIS design of Westinghouse and partners, but none have a customer yet except for the two high-temperature gas-cooled reactor under development in China and the Republic of South Africa (see below).

The description of the designs are very brief but more details may be found in the web sites and publications listed in the reference section at the end of the chapter and in particular in the IAEA technical document on status of advanced light-water reactor designs (IAEA, 2004).

Designs available on the market

ABWR (Advanced Boiling Water Reactor) is a 1 450 MWe BWR developed by a consortium of General Electric, Hitachi and Toshiba. It has been built already in Japan – Kashiwazaki-Kariwa units 6 and 7. This design has been assessed within the European Utilities Requirements (EUR) documentation and has a design certification from the United States Nuclear Regulatory Commission (USNRC).

AES92 (VVER-V392) is a 1 000 MWe pressurised water reactor of Russian design (VVER) commercialised by Atomstroyexport (Russia Federation). It has been pre-selected for the Belene plant in Bulgaria currently under consideration. The design has been assessed within the EUR documentation but has no design certification from the USNRC.

APWR (Advanced Pressurised Water Reactor) is a 1 538 MWe PWR design developed by the Japanese company Mitsubishi Heavy Industries. The construction of two *APWRs* is under consideration at Tsuruga (units 3 and 4). A US version of the design with a power level of 1 700 MWe is in preparation. The design was not assessed in the EUR documentation but has a design certification by the USNRC in review.

AP1000 is a two-loop PWR designed by Westinghouse Electric Company that will have a capacity of around 1 100 MWe. The option of using MOX fuel is possible. Four AP1000 units have been ordered in China at the Sanmen and Haiyang sites. The two units at Sanmen are under construction. The design was assessed within the EUR documentation and certified by the USNRC.

EPR (European Pressurised Reactor) is a 1 600 MWe PWR design of AREVA. MOX use is an option. The first *EPR* is under construction at Olkiluoto in Finland and a second unit is under construction at Flamanville in France. Two units are scheduled to be built in China. The design was assessed within the EUR documentation. A version for the US market is in preparation, with a power level of 1 700 MWe, and a design certification from the USNRC is in review for that design.

ESBWR (Economic Simplified Boiling Water Reactor) is a 1 450 MWe BWR design of the consortium General Electric/Hitashi. Several US utilities have submitted a Construction/Operating License application to the USNRC for a total of six units on five sites. The design was not assessed within the EUR documentation but an application for final design approval and standard design certification was submitted to USNRC in mid-2005.

Designs expected to be available in a few years

ACR-1000 is an evolution of the Canadian heavy water reactor design (CANDU) manufactured by Atomic Energy of Canada Ltd. It is 1 165 MWe reactor. The fuel elements are located horizontally in pressure tubes, avoiding the need of a large pressure vessel. Unlike previous CANDU designs, the coolant is light water, necessitating enriched-uranium fuel, but increasing the power density significantly. The moderator is heavy water.

APR-1400 is a 1 400 MWe PWR of Korean design, based on the System 80+ design of Combustion Engineering. The Korean utility Korean Hydro and Nuclear Power Company is leading its development and the equipment manufacturer Doosan is providing component design. In the long term, the design could use MOX fuel as an option. It is planned that Shin-Kori units 3 and 4 will be equipped with this design. A smaller version of this system – APR1000 – is currently under construction (Shin-Kori units 1 and 2).

HTR-PM has been developed in China by the Institute of Nuclear and New energy Technology, University of Tsinghua, on the basis of the German pebble bed high-temperature reactor technology (Zuoyi Zhang *et al.*, 2007). The reactor core consists of tennis-ball size graphite fuel pebbles, each containing about 10 000 coated UO_2 kernels, requiring uranium enriched at more than 6%. A demonstration unit was approved at the end of 2005 for building at Shidaowan in the Shandong Province of China. The unit will include two reactor modules each of 250 MWth driving a single steam turbine at about 40% thermal efficiency. Commissioning of the plant is scheduled for 2013.

PBMR (Pebble Bed Modular Reactor) is based on the German pebble bed high-temperature reactor technology, but it has been taken to a more advanced stage by introducing direct cycle gas-turbine technology and an annular core geometry. It has a power level of 165 MWe, and one plant is planned to exist from several reactor units (modules) that will share many services. The South African company PBMR (Pty) Ltd. was created for this development in the year 2000. Design certification by the USNRC is under preparation (pre-application review). A prototype is planned to be on line in 2014 at the Koeberg plant in South Africa for the national electric utility ESKOM.

2.2.4 Generation IV reactor designs

Six reactor systems were selected by the Generation IV International Forum (GIF) for further research and development (NERAC/GIF, 2002). Table 2.2 gives an overview of the main characteristics of the six systems (GIF, 2008) and they are described briefly below. The projected dates of commercial deployment for those systems indicated below are those provided by GIF participants (GIF, 2008) and assume successful achievement of GIF R&D objectives in the coming decade.

Table 2.2 Overview of Generation IV systems

System	Neutron spectrum	Coolant	Temperature (°C)	Fuel cycle	Size (MWe)
VHTR (very high-temperature reactor)	Thermal	Helium	900-1 000	Open/closed	250-300
SFR (sodium-cooled fast reactor)	Fast	Sodium	550	Closed	30-150; 300-1 500; 1 000-2 000
SCWR (super-critical water reactor)	Thermal (fast)	Water	510-625	Open/closed	300-700; 1 000-1 500
GFR (gas-cooled Fast Reactor)	Fast	Helium	850	Closed	1 200
LFR (lead-cooled fast reactor)	Fast	Lead	480-800	Closed	20-180; 300-1 200; 600-1 000
MSR (molten salt reactor)	Fast/thermal	Fluoride salts	700-800	Closed	1 000

Source: GIF, 2008.

The fast neutron reactors are well represented in the selected systems (see below) mainly in light of their expected performance in terms of sustainability through a closed fuel cycle with recycling of actinides reducing the volumes and radiotoxicity of ultimate radioactive waste. Three fast reactor designs are proposed in the Generation IV Roadmap: a gas-cooled fast reactor (GFR) with helium as a coolant, a sodium-cooled fast reactor (SFR) with liquid sodium as a coolant, and a lead-cooled fast reactor (LFR) with liquid lead as a coolant. Design variations of the molten salt reactor (MSR) and the supercritical water reactor (SCWR) have thermal or fast neutron spectra.

The main reason for development of the fast neutron reactors is clearly the sustainability goal of the Generation IV Roadmap: the possibility to breed fissile material and to transmute waste into shorter lived isotopes. The SFR development can use the experience base of the first generation fast neutron reactors that operated or are in operation in the participating countries. A reason for considering the relatively less developed roads of the GFR and LFR is the desire to work without the chemically reactive sodium. For all fast neutron reactors high-burnup fuels are foreseen, as well as actinide containing fuel versions.

Thermal neutron reactors

VHTR – The very-high-temperature reactor is a further step in the evolutionary development of high-temperature reactors. The VHTR is a helium-gas-cooled, graphite-moderated, thermal neutron spectrum reactor with a core outlet temperature higher than 900°C, and a goal of 1 000°C, sufficient to support high temperature processes such as production of hydrogen by thermo-chemical processes. The reference thermal power of the reactor is set at a level that allows passive decay heat removal, currently estimated to be about 600 MWth. The VHTR is useful for the cogeneration of electricity and hydrogen, as well as to other process heat applications. It is able to produce hydrogen from water by using thermo-chemical, electro-chemical or hybrid processes with reduced emission of CO_2 gases. At first, a once-through LEU (<20% ^{235}U) fuel cycle will be adopted, but a closed fuel cycle will be assessed, as well as potential symbiotic fuel cycles with other types of reactors (especially light-water reactors) for waste reduction purposes. The system is expected to be available for commercial deployment by 2020.

Thermal/fast neutron reactors

SCWR – Supercritical-water-cooled reactors are a class of high-temperature, high-pressure water-cooled reactors operating with a direct energy conversion cycle and above the thermodynamic critical point of water (374°C, 22.1 MPa). The higher thermodynamic efficiency and plant simplification opportunities afforded by a high-temperature, single-phase coolant translate into improved economics. A wide variety of options are currently considered: both thermal-neutron and fast-neutron spectra are envisaged and both pressure vessel and pressure tube configurations are considered. The operation of a 30 to 150 MWe technology demonstration reactor is targeted for around 2020.

MSR – The molten-salt reactor system embodies the very special feature of a liquid fuel. MSR concepts, which may be used as efficient burners of transuranic elements from spent light-water reactor (LWR) fuel, also have a breeding capability in any kind of neutron spectrum ranging from thermal (with a thorium fuel cycle) to fast (with a uranium-plutonium fuel cycle). Whether configured for burning or breeding, MSRs have considerable promise for the minimisation of radiotoxic nuclear waste.

Fast neutron reactors

SFR – The sodium-cooled fast reactor system uses liquid sodium as the reactor coolant, allowing high power density with low coolant volume fraction. It features closed fuel cycle for fuel breeding and/or actinide management. The reactor may be arranged in a pool layout or a compact loop layout. The size of reactors under consideration ranges from small (50 to 300 MWe modular units) to large (up to 1 500 MWe units). The two primary fuel recycle technology options are advanced aqueous and pyrometallurgical processing. A variety of fuel options are being considered for the SFR, with mixed oxide preferred for advanced aqueous recycle and mixed metal alloy preferred for pyrometallurgical processing. Owing to the significant past experience accumulated with sodium-cooled reactors in several countries, the deployment of SFR systems is targeted for 2020.

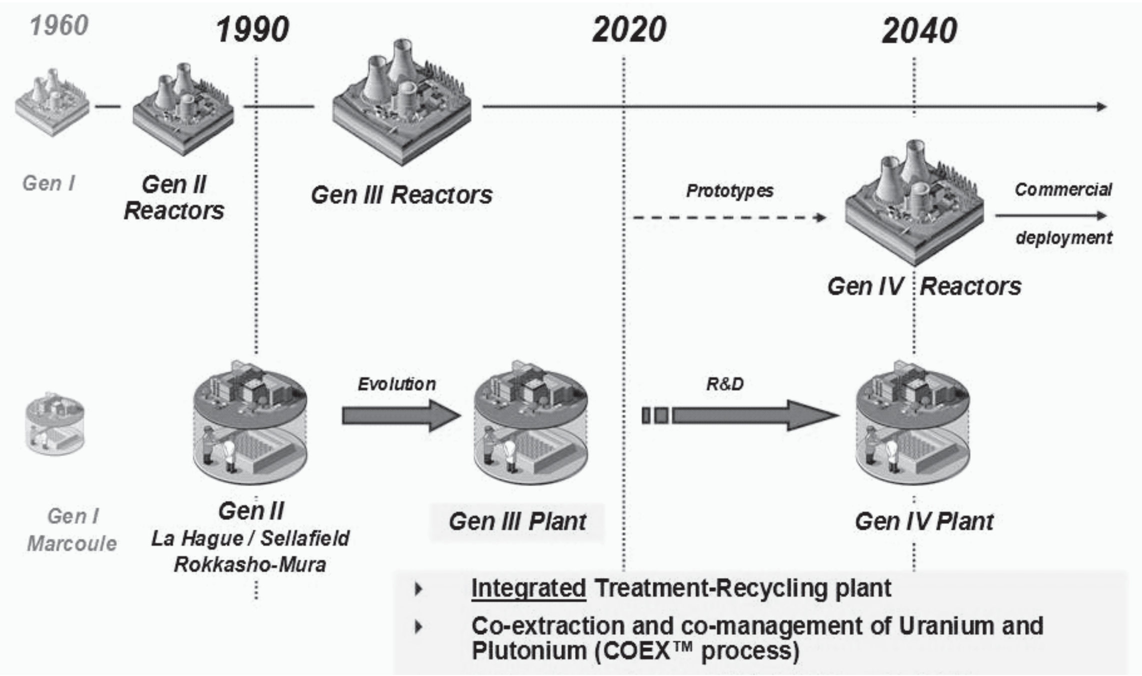
GFR – The gas-cooled fast reactor combines the advantages of a fast neutron core and helium coolant giving possible access to high temperatures. It requires the development of robust refractory fuel elements and appropriate safety architecture. The use of dense fuel as carbide or nitride provides good performance regarding plutonium breeding and minor actinide burning. A technology demonstration reactor needed for qualifying key technologies could be in operation by 2020.

LFR – The lead-cooled fast reactor system is characterised by a fast-neutron spectrum and a closed fuel cycle with full actinide recycling, possibly in central or regional fuel cycle facilities. The coolant may be either lead (preferred option), or lead/bismuth eutectic. The LFR may be operated as: a breeder; a burner of actinides from spent fuel, using inert matrix fuel; or a burner/breeder using thorium matrices. Two reactor size options are considered: a small 50-150 MWe transportable system with a very long core life; and a medium 300-600 MWe system. In the long term a large system of 1 200 MWe may be envisaged. The LFR system may be deployable by 2025.

2.2.5 Nuclear fuel cycle facilities

New system technology evolution is applied to the reactors and to the fuel cycle facilities together as shown in Figure 2.5. The evolution of a back-end scheme and associated technologies shall be consistent and synchronised with the evolution of reactor concepts and associated nuclear fuel cycles (Giroux, M., *et al.*, 2007).

Figure 2.5 Evolution of reactor systems and fuel reprocessing facilities



Source: AREVA.

The recycling of actinides can be performed in 3 ways:

- U and Pu recycling option and MA are disposed in the final disposal in a glass form;

- Minor actinides homogeneous recycling;
- MA heterogeneous recycling with high content of MA (typically 30% or more).

These 3 options need specific hydro or pyrometallurgical processes. The hydro processes are more mature and can treat spent fuels as UOX, MOX or MA fuels while the pyro processes which can treat ADS inert matrix spent fuels are less mature.

For U and Pu recycling the main industrial process used today is the PUREX process. For the future, an integrated treatment/recycling facility is planned with no pure plutonium isolated, higher throughput, high MOX performances both for LWRs and fast neutron reactors as COEX™ or UREX+.

For MA separation (heterogeneous recycling) of long lived radio-nuclides, the processes are based on the optimisation of DIAMEX-SANEX processes for their recycling in heterogeneous mode in Generation IV systems. This option can be implemented in combination with COEX^{TM}. Scientific feasibility of DIAMEX and SANEX has been performed at laboratory scale in 2005 in the French ATALANTE facility.

The GANEX process is one option for group extraction of actinides (homogeneous recycling) as an alternative fuel cycle strategy to allow for the homogeneous recycling of actinides in Generation IV fast systems. It is an adaptation of the DIAMEX-SANEX flow sheet and will be tested on genuine solution in 2008. Pyrochemical partitioning is also an option.

For the long term, the goal is to have a technology validated for industrial scale deployment of Generation IV fast neutron reactors by 2040.

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Chapter 3

OPPORTUNITIES AND CHALLENGES OF TRANSITION SCENARIOS

According to the scenarios introduced in Chapter 2, nuclear power is likely to contribute significantly to energy supply in the world during the 21st century. Rising energy demand in developing countries, security of supply concerns in OECD countries, and, last but not least, increasing awareness of the need to alleviate the risk of global climate change will provide strong incentive to policy makers for considering the nuclear option.

Any potential nuclear renaissance will undoubtedly have at its core the goal of sustainability, addressing issues such as environmentally sound waste management, diversity of energy supply, non-proliferation of nuclear weapons, economic competitiveness and social acceptance. In this context, a key objective for transitioning from thermal to fast neutron systems will be to enhance the performance of nuclear energy systems in a global long-term perspective.

From a policy-making viewpoint, it is important to recognise the opportunities offered by fast neutron systems and to be aware of the challenges raised by transition scenarios. Nuclear systems using reactors with fast neutron spectra and closed fuel cycles are a means to achieve energy policy goals. Therefore, the type of systems to be selected and the timing of their implementation within transition scenarios should be driven by, and adapted to, policy objectives.

The incentives to implement transition scenarios and the barriers to their implementation will vary from country to country. In each country or region, the objectives and relevance of implementing nuclear systems based on fast neutron reactors and closed fuel cycles will evolve as nuclear energy programmes are developed and/or phased-out. In some cases, nuclear systems based on thermal neutron reactors will remain the preferred option while in others early development of fast neutron systems will be the best choice.

Multi-criteria analyses will be needed to assess in each case the advantages and drawbacks of alternative approaches to transition scenarios. For each problem, there will be multiple solutions and their ranking will depend on the priorities of the policy maker as well as on the context of the country in terms of natural resources, infrastructure and technology.

3.1 Background

In the early days of nuclear power technology, plutonium produced from uranium in the core of reactors appeared to be a solution for mankind’s energy needs. It was thought that recycling plutonium in a fleet of “breeding” fast neutron reactors would reduce drastically the need for uranium mining and enrichment, and would contribute significantly to alleviating the dependence on fossil fuels.

These expectations fostered two distinct but related R&D programmes which were undertaken through the 50s and 60s: separation of the plutonium created in thermal reactor fuel through reprocessing of spent fuel; and design and development of fast neutron reactor systems.

While both technologies proved to be feasible at commercial scale, their industrial development did not follow parallel routes. As a result, today reprocessing of light water reactor spent fuel is carried out in industrial plants in several countries and plutonium has been produced in significant quantities while very few fast reactors were built and operated. It is generally considered that the main reasons for this lack of fast reactor development have been low prices of natural uranium, challenging their competitiveness because they generally have higher capital costs than thermal neutron reactors, and technical or political problems encountered with sodium-cooled fast neutron reactors.

Other factors affected the development of fast neutron systems which was anticipated in the 1980s including a lower than expected energy demand growth and the impact on nuclear energy deployment of the Chernobyl accident. While the construction of fast neutron reactors was planned in Western Europe (EFR) and Russia (BN-800), the projects were not implemented owing to lack of demand for electricity.

In this context, some countries decided not to reprocess spent fuel but rather to store it with the intention to eventually dispose of it together with other high-level radioactive waste in deep geological repositories. Those countries have developed strategies and concepts to manage spent fuel until its final disposal in ways which ensure its isolation from the biosphere over extensive periods of time and adequate protection of human health and the environment.

Most of these concepts include encapsulating the fuel elements in metallic canisters, manufactured in materials that are highly resistant to long-term degradation under certain assumed and given conditions. These canisters will then be placed in a central deep repository located in an area where the bedrock is considered to be adequate. In one concept, the individual canisters are additionally embedded in bentonite clay or similar material in order to avoid physical contact between the spent fuel and the viscous environment at the chosen site. For example, the Swedish research organisation has developed such a concept (SKB, 2003).

Among the countries which have chosen the direct disposal approach, most are relatively small countries with few nuclear power plants, such as Sweden and Finland, but also a country like the United States with more than 100 nuclear units had adopted solely this route until very recently (USDOE, 2008). The criteria upon which decisions have been taken in favour of the once through or the closed cycle cover a broad range of socio-political as well as technical and economic aspects.

The original goal of reprocessing was the recovery of fissionable elements, mainly ^{235}U and ^{239}Pu, present in thermal neutron reactor spent fuel to use them in a fleet of fast neutron breeder reactors. In view of the expected large-scale global use of nuclear energy, plans were developed for using mixtures of plutonium and (natural or depleted) uranium as fast neutron reactor fuel. Various fuel types have been investigated for these systems (oxides, metals, nitrides and carbides as pellets in a metallic cladding) and substantial research efforts have been made for all of them.

As almost all fast neutron reactors were shutdown prematurely, most countries which had embarked on reprocessing chose to recycle plutonium in thermal reactors systems. This option benefited from the fuel research undertaken for fast reactor technology, leading to the utilisation of mixed-oxide (MOX) fuel in light water reactors and to reducing by some 10% natural uranium consumption. In addition, a continuously-growing stockpile of separated civil plutonium has been accumulated and, in most of the countries, is stored in dedicated above-ground sites in reprocessing or fuel fabrication plants.

There are currently three industrial-scale MOX fuel fabrication facilities in Europe and MOX fuel is used in a limited number of light water reactors in a few countries. Only France, Germany and

Switzerland have industrial-scale experience in using MOX fuel for LWRs, all of which involve partial MOX core loading. Japan is currently making a transition from a programme involving utilisation of European-manufactured MOX to a domestic reprocessing and MOX fabrication programme.

Most of the reactors which today utilise MOX fuel operate with 70% of the core loaded with standard UO_2 fuel and 30% of the core loaded with MOX. The reason for limiting the MOX core loading fraction is due to the neutronic properties associated with the higher plutonium content inside the core and the resultant changes in overall core behaviour, as compared with full UO_2 loading (for which all LWRs currently operating were originally designed).

From the standpoint of sustainability, efficient use of resources and actinide management, the present-day fuel cycles involving partial MOX loading are unsatisfactory, as they do not allow for a continuous multi-recycling policy in LWRs. Moreover, since the MOX loading of operating LWRs is in practice limited to about one-third of the reactor core, the plutonium feed/discharge balance in these cores is close to one, and no net consumption is achieved.

The use of MOX fuel in LWRs leads to increasing amounts of minor actinides, such as Np, Am and especially Cm, in spent fuel. Mono recycling of plutonium in LWRs as practiced today without further reprocessing of MOX fuel and recycling of actinides in fast neutron reactors inherently increases the minor actinide load in spent fuel disposed of in repositories.

This strategy is not currently optimised in terms of plutonium utilisation, and serves only to prevent any further build-up of the separated plutonium stocks, without offering a possibility to decrease these stocks. Therefore, a wide and varied research programme has evolved in the last decade or two in order to achieve more effective utilisation of plutonium stocks in LWR systems.

Other alternative mixed oxide options have been suggested in the last decade, ranging from the use of enriched uranium in the MOX, to the omission of uranium in the MOX. The latter could be achieved by the use of thorium (^{232}Th) oxide (fertile not fissile) or a so-called inert matrix such as zirconium oxide. Efforts have been made to study the feasibility of such options.

3.2 Opportunities offered by transition scenarios

Policy makers will assess opportunities offered by transition scenarios in a holistic approach, taking into account efficiency of natural resource use, security of fuel supply, waste management, and resistance to proliferation and physical protection, as well as economic and safety performance. The importance of each aspect, however, will vary from country to country and depend on the national/ regional context and specific energy policy goals.

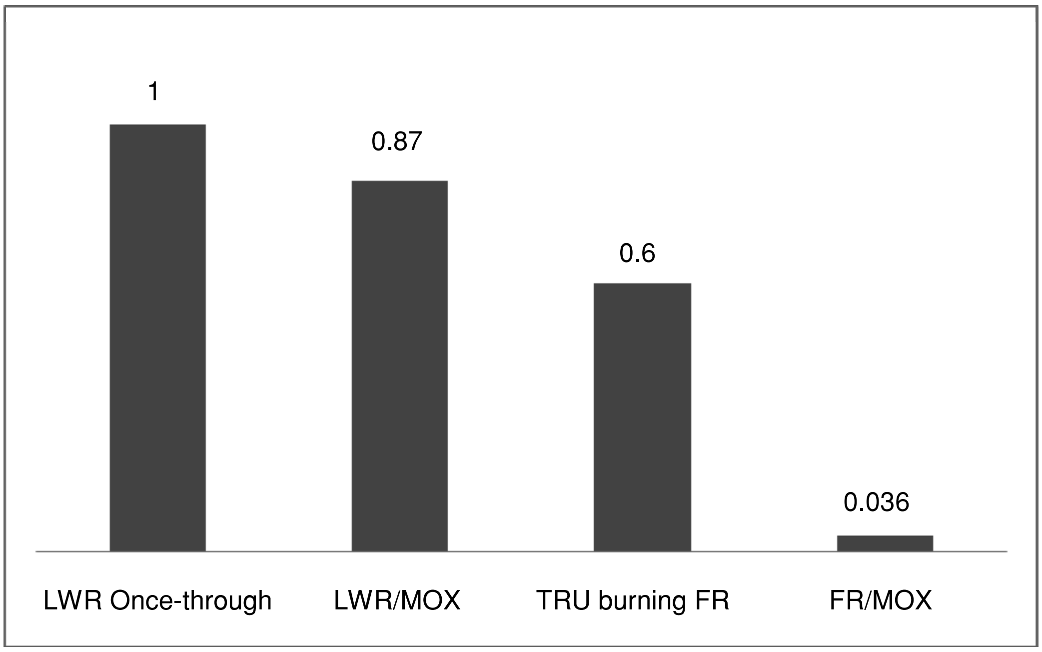
Efficiency of natural resource utilisation

In thermal neutron reactors of the current generation, i.e., water reactors, only a small fraction of the energy content of natural uranium is retrieved for electricity generation. Typically, with present thermal neutron systems, 99% of the energy content of natural uranium is not used. Spent fuel discharged from such water reactors contains uranium, plutonium and minor actinides which can be recycled in thermal or fast neutron reactors to produce additional energy.

Recycling uranium, plutonium and minor actinides offers opportunities to prolong the lifetime of natural uranium resources at reasonably low costs. Fast neutron systems operated in a breeder mode can multiply the energy retrieved from natural uranium by a factor of 50 or much more depending on their rate of introduction, their conversion ratio and the efficiency and losses of reprocessing and recycling processes used.

The study carried out by NEA on advanced fuel cycles (NEA, 2006) provides illustrative quantitative estimations of the reduction in uranium requirements obtained by the introduction of fast-neutron systems. The results summarised in Figure 3.1 correspond to uranium requirements at equilibrium and assume mature reprocessing and fuel fabrication technologies with very low losses. It should be stressed that such savings will be obtained after several decades of transition and provided that the performance of advanced fuel cycle processes and fast neutron reactors match present expectations.

Figure 3.1 Illustrative natural uranium requirements with different recycling schemes



Source: NEA, 2006.

Security of supply

A better utilisation of the energy content of uranium provides enhanced security of fuel supply for all users of nuclear energy by lowering the demand for freshly mined uranium. Furthermore, it reduces the environmental impacts of uranium mining and milling including the accumulation of mine tailings.

The nuclear systems based on fast neutron breeders were considered early on as a long-term option for boosting energy independence in countries such as France and Japan which have very limited resources of fossil fuels and uranium.

In a long-term perspective, nuclear systems based on fast neutron reactors with adequate breeding ratios behave as nearly-renewable because the quantities of ^{238}U that they need could be provided by inventories of depleted uranium and reprocessed uranium during many decades.

Radioactive waste management

The implementation of a robust approach to high level waste disposal ranks high on the agenda of policy makers as it is one of the major issues raised by civil society in connection with the use of nuclear energy. The transition to fast neutron systems offers opportunities to address back-end of the fuel cycle issues and in particular to facilitate the management of recyclable fissile and fertile materials including uranium, plutonium and minor actinides.

Several technical solutions already exist for the back end of the fuel cycle and the management of radioactive waste, and many more are the subject of ongoing large-scale research and development programmes, but their implementation at the industrial scale on a commercial basis is proving to be difficult in most countries owing to lack of public acceptance and very lengthy regulatory processes.

Therefore, although the volumes of high-level waste resulting from electricity generation are small as compared to the volumes of waste generated by most alternative generation sources, limiting the number and size of geological repositories needed for their disposal is a key objective of nuclear energy policies in most OECD countries. Methods to reduce the amount of radioactive waste and their radiotoxicity are needed to ensure the long-term sustainability of nuclear energy in countries aiming at phase-out as well as in countries considering a renaissance of nuclear programmes.

A large part of the waste arising from nuclear electricity generation and fuel cycle activities, including uranium mining, are managed on an industrial basis and disposed of safely in low- and medium-level waste repositories. Only a few percent of radioactive waste volumes, containing long-lived, highly-radioactive isotopes, require isolation from the biosphere for very long periods. A large part of those isotopes become high-level-waste with nuclear systems based on thermal reactors operated once-through while they are a source of energy in systems based on fast neutron reactors with reprocessing of spent fuel and recycling of fissile materials.

In a sustainable development perspective, reduction of the amount of actinides contained in high-level waste to be disposed of in geological repositories is highly beneficial. Through enhanced utilisation of the energy content of natural uranium, it reduces the requirements for fresh uranium and thereby the environmental impacts associated with uranium mining and milling. In addition, it shortens the time during which waste remain highly radioactive, limiting the stewardship period and the burden for future generations.

The direct disposal of spent fuel, which is the most technically mature and economically attractive option for most utilities at present, leads to discarding most of the energy content of uranium, as noted above, and generates large quantities of waste with high radiotoxicity. For example, at the rate spent fuel is discharged by the existing nuclear reactors in the United States, new repository capacity equal to the present statutory capacity for civilian reactor spent fuel (63 000 tonnes) of the designated US Geologic Repository (Yucca Mountain), would be needed every 20-30 years. Although recent studies indicate that Yucca Mountain could receive a much higher inventory of waste, the accumulation of spent fuel would become a concern eventually in the once through scenario.

3.3 Challenges raised by transition scenarios

Transition scenarios raise a number of issues which need to be addressed timely in order to ensure their successful implementation. The main challenge for policy makers will be to evaluate the multiple aspects of transition scenarios in a comprehensive manner taking into account the uncertainties on technical and economic performance of advanced systems as well as on the future energy supply and demand scenarios.

The role of analysts is essential in this regard. They have to provide decision makers with robust results from modelling and sensitivity studies showing the advantages and drawbacks of alternative scenarios in a multicriteria approach.

The present fleet of nuclear power plants in operation is constituted mostly by water reactors and the implementation of fast neutron systems will require a long transition period during which both types of reactors will be in operation simultaneously. The duration of the transition period and the evolution of reactor mixes in operation during that period will depend on the approach adopted.

The main challenges of transition scenarios are the duration of their implementation and the infrastructure required for their achievement. For policy makers and for civil society, it is difficult to assess the risks and benefits of programmes which require several decades to reach maturity and may take more than a century to be completed. This is why the implementation of some transition scenarios involving partitioning and transmutation of minor actinides, which would bring tangible results within a century or more, is likely to be difficult, if at all possible, owing to the lack of understanding and/or interest from various stakeholders in very long-term benefits.

Management of fissile materials

The requirements for reprocessing and fissile material separation depend on the objectives of the transition scenarios considered and on the performance of the reactors and fuel cycle facilities available for implementing those scenarios. Recognising that the transition will take at least several decades, it is essential to estimate the dynamic evolution of mass flows in the system in order to ensure that supply of fissile materials will be adequate to fuel the fleet of reactors in operation.

The challenge in this regard is to balance short-term objectives with long-term goals. For example, recycling plutonium in water reactors is an attractive short- to medium-term option provided adequate plutonium inventory is set aside for fuelling fast neutron reactors when they will be commissioned.

Time needed to reduce the inventory of transuranic elements

The nuclear industry is characterised by long lead times with or without transition scenarios. It takes around a decade to put into service a nuclear unit, from decision to first delivery of electricity to the grid, and state-of-the-art nuclear power plants are expected to remain in operation for more than 50 years. However, the design and implementation of transition scenarios requires especially long-term planning.

Taking into account the number and age of nuclear units in service today, periods of transition during which symbiotic fleets of reactors will include thermal and fast systems will last for more than five decades in most circumstances. Such long lead times need to be integrated and reflected in the schedule to reach the ultimate goals, e.g., elimination of all actinides or established a self-sustaining fleet of fast neutron breeding reactors.

Infrastructure requirements

The complexity of nuclear systems in transition from thermal to fast reactors is likely to require a more sophisticated infrastructure than is the case for a homogeneous fleet of reactors and fuel cycle facilities. While the adaptation of the overall legal and regulatory structure will not be a challenge in countries where nuclear power plants and other facilities are already in operation, research and development, industrial capacities and human resources will deserve special attention while designing and implementing transition scenarios.

Industrial capabilities

Adapting industrial capabilities to demand in a period of transition is an issue because some of the required facilities, either power plants or fuel cycle facilities, might be sub-optimal in terms of size and lifetime when taking into account the dynamic evolution of the reactor fleet. In such conditions, it will be difficult to motive economic actors, investors and plant operators to design, develop and put into service all the facilities needed to support transition scenarios.

Furthermore, if the size and number of fuel cycle facilities and reactors of each type are too small the costs and thereby the prices of fuel cycle services and electricity generation might increase by lack of economy of scale. Such trends may jeopardise the economic feasibility of some transition scenarios. International cooperation could help reaching adequate demand size and alleviate economic risks associated with innovative systems to be amortised within a relatively short transition period. This would, however, require the establishment international markets with adequate safeguards to ensure that products and services are exchanged between countries while avoiding the risk of nuclear weapon proliferation.

Countries with a small number of reactors and fuel cycle facilities might have difficulties in building industrial capabilities to support transition scenarios relying on domestic supply of fuel cycle services. For such countries, the present technology of water reactors operated in the once through cycle could be a more realistic choice. For small nuclear power programmes, the cumulative amounts of spent fuel to be disposed of in a deep geological repository are not huge and finding adequate sites should not be too difficult while closing the fuel cycle would require building several small-size fuel cycle facilities with questionable economic viability. International cooperation, including for example the creation of regional facilities, could provide those countries with means for implementing transition to fast neutron system strategies. However, beyond industrial capacity building, such approached would require the development of adequate legal and regulatory frameworks.

Social perception, stakeholder involvement

Transition from thermal to fast neutron systems should not raise unique concerns in civil society beyond the usual reluctance to accept innovation and advanced systems which have not been proven. However, as noted above, the complexity of the systems to be constructed and operated and the time horizon to be considered for reaching the goals of transition scenarios might be difficult to explain.

Regarding proliferation resistance and physical protection, there is no evidence that systems based on fast neutron reactors would present more or less risks than systems based on thermal systems. The international safeguards regime has proven to be effective and its adaptation to closed fuel cycles is already in place as some countries are operating reprocessing and MOX fuel fabrication facilities.

Government policies

The stability of the energy and in particular nuclear energy policy of a country will be essential for the achievement of an effective transition from thermal to fast systems. The adaptation of the industrial capabilities to build and operate the necessary reactors and fuel cycle facilities will require significant investments in capital and human resources and the benefits from those investments for economic actors and civil society will be obtained only over a long period of time.

Stable and predictable licensing processes and regulatory regimes, including tax policies applied to energy products and/or carbon emissions, are necessary to provide investors with the required incentives when embarking on long-term projects with high capital investments and long periods of return.

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Chapter 4

POLICY ASPECTS

When evaluating alternative routes for nuclear energy development in the long term, policy makers should take into account the requirements for human resources, raw materials and services, R&D support and industrial facilities associated with each option considered. The transition from thermal to fast neutron nuclear systems raises policy issues to be identified at the early stage of designing scenarios for its implementation. Those issues have to be assessed during all phases of the transition period and when the fleet of nuclear reactors and fuel cycle facilities has reached the status targeted by the policy. This chapter reviews key topics deserving attention and aims at drawing findings on the best approaches to support decisions to implement or not transition scenarios and to do it successfully. It includes a short overview on relevant international initiatives highlighting their potential impact on facilitating the implementation of transition scenarios.

4.1 Intergovernmental initiatives

International cooperation has proven to be essential for the development of peaceful uses of nuclear energy. It will be a prerequisite for the successful development of nuclear energy in the future and especially for transitioning to fast neutron systems with closed fuel cycles. Several recent international initiatives are covering some aspects of the transition from thermal to fast neutron systems from technical and/or policy viewpoints.

Proposals on international cooperation to manage the nuclear fuel in a way that would ensure security of supply, resistance to proliferation and economic effectiveness are highly relevant in the context of investigating policy issues related to transition scenarios. Five of them are reviewed in this section but others have been suggested by various countries and organisations (CRS, 2008).

An IAEA Expert Group suggested in its report published in 2005 (IAEA, 2005) the creation of a fuel bank, conversion of existing fuel cycle facilities into multinational facilities and creation of jointly-owned facilities co-managed by several countries. The goals of this proposal are to identify multilateral approaches for improving proliferation resistance without disrupting market mechanisms in the nuclear fuel sector. Multinational fuel cycle facilities would enhance the economic viability of advanced fuel cycle schemes and provide opportunities to benefit from economy of scale even for fuel cycle facilities which would operate only during transition periods.

The initiative announced in January 2006 by the Russian President aimed at establishing international commercially operated fuel cycle service centres in Russia to provide enrichment services, education and training and spent fuel management services. One of the outcomes from such a scheme would be to limit the number of countries needing to undertake the establishment of industrial infrastructure required to support transition scenarios, even in the case of broad deployment of nuclear power worldwide. Today, the first step of this initiative – creation of an International Uranium Enrichment Centre at Angarsk as pilot project – is under realisation. The creation of an international fuel reprocessing centre is being considered in the framework of developing closed fuel cycle approaches.

In 2006, the US Department of Energy introduced the Global Nuclear Energy Partnership (GNEP) motivated by the realisation that future deployment of nuclear energy would likely be worldwide and would further increase concerns about the fate of spent nuclear fuel and the proliferation of technologies for making special nuclear materials (USDOE, 2006). The overall objective of GNEP is to provide countries wishing to use nuclear energy but not eager to implement fuel cycle facilities for all required services at the front-end and back-end of the fuel cycle.

The cooperation to be undertaken as part of GNEP includes the following objectives, excerpted from the GNEP Statement of Principles, relevant in connection with transition scenarios:

- "Expand nuclear power to help meet growing energy demand in a sustainable manner and in a way that provides for safe operations of nuclear power plants and management of waste[s].
- In cooperation with the IAEA, continue to develop enhanced nuclear safeguards to effectively and efficiently monitor nuclear materials and facilities, to ensure that nuclear energy systems are used only for peaceful purposes.
- Establish international supply frameworks […] providing options for […] fostering development while reducing the risk of nuclear proliferation by creating a viable alternative to acquisition of sensitive fuel cycle technologies.
- Develop, demonstrate and in due course deploy advanced fast reactors that consume transuranic elements from recycled spent fuel.
- Develop and demonstrate, *inter alia*, advanced technologies for recycling spent nuclear fuel […] with the long-term goal of ceasing separation of plutonium and eventually eliminating stocks of separated civilian plutonium. […]"

Two other international endeavours relate to transition scenarios although they have a broader scope: the International Project on Innovative Nuclear Reactors and Fuel Cycles; and the Generation IV International Forum.

INPRO was initiated by the IAEA in 2001 based on a resolution of its General Conference in 2000. Some thirty IAEA Member States participate in this project. Its main objective is to support the safe, sustainable, economic and proliferation-resistant use of nuclear technology to meet the global energy needs of the 21st century. The project aims at bringing together technology holders and users so that they can contribute jointly the international and national actions required for achieving desired innovations in nuclear reactors and fuel cycles.

INPRO has a broad range of missions including analysing the sustainable development of nuclear energy, facilitating international cooperation for the deployment of new nuclear systems, and responding to the needs of developing countries interested in new nuclear systems, and developing methodologies for assessing new nuclear systems. Within INPRO some collaborative projects such as GAINS (see Chapter 1) are investigating transition scenarios and aiming at identifying international synergies in support of the implementation of such scenarios.

GIF is a joint endeavour by 11 countries and Euratom to promote R&D on advanced nuclear systems. Most of the nuclear systems selected by GIF for further R&D are based on fast neutron reactors and closed fuel cycle (see Chapter 2). The scope of GIF activities does not cover dynamic scenario analysis but the R&D carried out within the GIF framework should enhance the technology preparedness of fast neutron and other advanced systems.

4.2 Technology preparedness and industrial considerations

The use of recycled fissile materials, in particular in breeding fast neutron systems, eventually will enhance security of nuclear fuel supply and more broadly of energy supply. However, during the transition period, adequate and timely supplies of fissile materials and fuel cycle services need to be ensured through timely commissioning of the necessary industrial capabilities. This requires long-term planning taking into account the evolution of reactor mixes over time, the characteristics of the nuclear systems deployed in succession and the demands at each step of the fuel cycles from the mines to the waste repositories.

Replacing thermal reactors by fast neutron systems with closed fuel cycles requires R&D to design and develop those systems, and eventually industrial infrastructure to deploy them. Building or adapting industrial capacity will be needed in all countries wishing to build and operate fast neutron reactors. New fuel cycle facilities for reprocessing spent fuel, and for recycling plutonium, uranium and minor actinides, will be required as well as repositories for final disposal of HLW.

For example, the estimates of global recycling capacity needed to introduce fast neutron reactors with closed fuel cycle in 2040 range between 10 000 and 25 000 tonnes per year of UOX spent fuels in order to introduce 5 to 15 GWe per year of fast neutron reactors. While this might not be a challenge at the world level, countries with a limited nuclear infrastructure and/or relying on nuclear energy for a small part of their supply may not wish to embark on building national capacity for reprocessing and recycling.

4.2.1 Front-end of the fuel cycle

Uranium supply

Security of uranium supply is not a key issue at present and should not become a concern in the medium term (NEA, 2008a). However, cumulated uranium consumption could become quite large by 2050 if advanced nuclear systems were not introduced progressively. Furthermore, in a long-term holistic perspective of sustainable development, efficient management of natural resources will require recycling.

World uranium production was around 43 thousand tonnes U in 2007, significantly lower than reactor-related requirements which were estimated at 69 thousand tonnes U, but supply was adequate owing to secondary sources such as ex-military materials and accumulated inventories. The production capability which was around 55 thousand tonnes U in 2007 is expected to range between 80 and 118 thousand tonnes U per year in 2030 (see Table 4.1). The main producers include Australia, Canada, Kazakhstan, Namibia, Niger and Russia, a geopolitical diversity which reinforces security of supply.

Table 4.1 World uranium production capability to 2030 (10^3 tU/year)

Year	I*	II*
2010	80.7	86.7
2020	88.5	122.6
2030	83.1	117.9

* I = Production capability of existing and committed centres supported by identified resources recoverable at <USD 80/kgU.

* II = Production capability of existing, committed, planned and prospective centres supported by identified resources recoverable at <USD 80/kgU.

Source: NEA, 2008a.

However, projected production capabilities barely cover the estimated annual requirements in 2030 shown in Table 4.2. These estimated uranium requirements were calculated based on the nuclear power capacity scenarios presented in Chapter 2 and the average performance of reactors in operation today. In 2050, the annual uranium requirements per year would range between 100 and 265 thousand tonnes U. Those estimates correspond to cumulated uranium requirements up to 2050 of some 5.4 million tonnes of uranium in the high scenario, roughly equal to the total identified uranium resources which were estimated at some 5.5 million tonnes at the beginning of 2007.

Table 4.2 Estimated reactor-related uranium requirements in the world

	Nuclear capacity (GWe)		**Uranium requirement (10^3 tU/y)**	
	Low	**High**	**Low**	**High**
2010	373	379	69.5	70.7
2020	388	474	72.3	88.4
2030	404	619	75.4	115.5
2040	442	879	82.3	163.8
2050	576	1 418	107.4	264.4

Source: Secretariat estimates.

The committed uranium requirements (i.e., the cumulated amount of uranium needed to fuel the reactors in service in 2050 up to the end of their lifetime) would reach 8.8 million tonnes U in the low case and 13.3 million tonnes U in the high case.

Recent trends have shown that uranium price increase triggered a revival of exploration efforts and the discovery of new resources as well as re-evaluation of existing resources, shifting previously uneconomic resources into the economically recoverable categories. Therefore overall security of uranium supply at the global is unlikely to become a major concern in the foreseeable future.

The negative impact on the mining industry of the expected eventual decline of uranium demand might be an issue in the framework of transition scenarios. This may lead to reduced exploration and development investments and even to premature closure of production centres which could entail imbalance between supply and demand during the transition period. However, the introduction of advanced reactors and fuel cycles is likely to be very progressive and to allow for a timely adaptation of the uranium mining industry.

Conversion

The present capacity of conversion plants processing yellow cake into UF_6 is slightly above 55 000 tU/year, sufficient to meet demand. Conversion capacity is expected to increase in the coming decade to reach around 75 000 tU/year by 2015 (NEA, 2008b). The major capacities are located in the United States, Canada, France and Russia.

The creation of specific facilities capable of converting reprocessed uranium will be needed to support the implementation of transition scenarios. The challenge for adapting industrial capabilities to evolving demand in this sector is not technical but economic. In the context of transition scenarios, the industry will be confronted with uncertainties on future demand which increases the financial risks associated with building plants dedicated to, for example, conversion of uranium arising from LWR spent fuel reprocessing. The economic viability of such facilities could be improved by international cooperation to broaden markets beyond a domestic supply.

Enrichment

The existing enrichment capacities are adequate to meet expected demand and new plants are planned in several countries to replace ageing facilities at the end of their lifetime and increase the total capacity available worldwide (see Table 4.3). The new plants under construction or planned will use the gaseous centrifuge technology which is less energy intensive than the gaseous diffusion technology used in plants already shut down or to be decommissioned soon.

Table 4.3 Major world enrichment capacities (10^3 SWU/year)

Country/consortium	2007	2015 (projected)
China	1 000	3 500
France	10 000	10 000
Japan	1 000	1 500
Russia	14 500 (+8 000**)	20 500
United States	11 000 (+4 500**)	10 500
Urenco*	8 500	17 500
Total	46 000 (+12 500**)	63 500

* Germany/Netherlands/United Kingdom.

** Capacity for processing ex-military HEU.

Source: NEA, 2008b.

Like for conversion, the recycling of reprocessed uranium raises technical issues for enrichment. Although centrifuge plants are more readily adaptable to re-enrichment of reprocessed uranium, the industry will have to adjust to evolving demand in the framework of transition scenarios. Furthermore, if and when fast neutron reactors will have replaced thermal reactors, the demand for enrichment will be eliminated. Although this will occur in the very long term, the industry should be prepared to amortise investments in new facilities before the expected end of the transition period.

Fuel fabrication

Fuel fabrication facilities are not very capital intensive and can be built reasonably rapidly to adapt to demand for new types of fuels, as demonstrated by the evolution of this sector of the nuclear industry over the period of development of commercial nuclear power plants. Like for other sectors of the fuel cycle, transition scenarios could raise the issue of economy of scale at the country level. However, international markets would likely alleviate this problem as fuel fabrication plants for each type of fuel required within transition scenarios could produce fuel for several countries, as is the case today for most light water reactor fuels.

4.2.2 Reactor construction and operation

The existing nuclear power plants represent a capacity of some 370 GWe with a large majority of thermal, water-cooled reactors (see Table 4.4). In addition, some 30 GWe are under construction in a dozen countries.

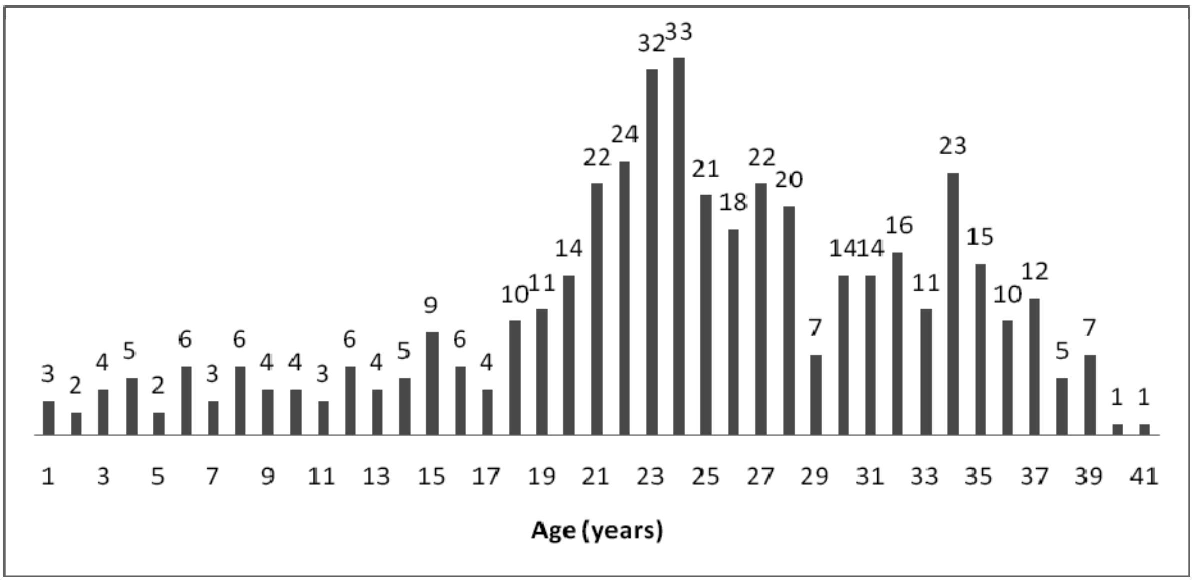
Table 4.4 Installed nuclear capacity by reactor type

Reactor type	Capacity (GWe)	% of total capacity
PWR	243.4	65
BWR	85.3	23
PHWR	22.4	6
Others	21.1	6
(of which FR	*0.7*	*0.2)*
Total	372.2	100

Source: IAEA, PRIS database.

Most of the reactors in operation today were connected to the grid in the 1970s or 1980s and have been in service for 30 years or more (see Figure 4.1). While the initial expected lifetime of nuclear units was 30 to 40 years, lifetime extensions up to some 60 years are underway for a majority of the reactors and, accordingly, their replacement will occur in the period 2020 to 2050.

Figure 4.1 Number of reactors in operation by age in 2008



Source: IAEA, PRIS database

The current age and expected ultimate lifetime of the existing reactors is a key parameter in the schedule that will be adopted for replacing them by fast neutron reactors. It would not be realistic to consider the implementation of transition scenarios leading to premature shut down of thermal reactors in operation as long as their safety and technical performance remain excellent and while they provide reliable electricity supply at very attractive costs.

4.2.3 Back-end of the fuel cycle

At the back end of the fuel cycle, the accumulation of spent fuel could become a concern when the once through option is adopted, if adequate disposal repositories would not be available timely. However, it has been demonstrated that safe interim storage of spent fuel can be prolonged over several decades.

On the other hand, the transition to closed fuel cycle, which requires building reprocessing and recycling capacities, does not eliminate completely the need for waste repositories although it reduces significantly the size/number of repositories to be built and operated.

Spent fuel inventories

It was estimated in 2007 (NEA, 2007) that around 200 thousand tonnes of spent fuel had been accumulated in the world (see Table 4.5). These spent fuel inventories, which contain in average close to 1% of plutonium, could be used for fuelling a fleet of fast neutron reactors in the context of implementing transition scenarios, provided that adequate reprocessing and fuel fabrication capacities would be developed timely.

Table 4.5 Spent fuel inventories at the end of 2005 (10^3 tHM)

Region	LWR UOX	LWR MOX	FBR	Others
OECD America	54.2		0.06	35.6
OECD Europe	30.8	1	–	6.4
OECD Pacific	19.5			
Non-OECD	53.0			
Total	157.5	1	0.06	42.0

Source: NEA, 2007.

In the context of the nuclear capacity growth described in Chapter 2, the discharge of spent fuel would range between 15 and 38 thousand tonnes per year in 2050 (see Table 4.6). The disposal of all spent fuel arising worldwide would require opening by 2050 some 10 sites of the size of the planned repository at Yucca Mountain in the United States.

Table 4.6 Annual spent fuel arising

	Nuclear capacity (GWe)		Spent fuel discharged (10^3 tHM/y)	
	Low	High	Low	High
2010	373	379	10.3	10.9
2020	388	474	12.4	14.4
2030	404	619	13.7	17.8
2040	442	879	13.8	23.6
2050	576	1 418	15.4	38.0

Spent fuel treatment

Reprocessing capacities reflect the fuel cycle choices made so far by various countries and only very few plants are in operation at present (see Table 4.7).

Table 4.7 Major reprocessing capacities in the world (tHM/year)

Country	Nominal capacity in 2007	Cumulative production to 2007
China	–	–
France	1 700	22 700
India	–	–
Japan	800	0
Russia	400	4 000
United Kingdom	900	4 000
United States	–	–
Total	3 800	30 700

Source: NEA, 2008b.

The existing capacity is sufficient to meet demand in the coming years but, obviously, significant increase will be needed in order to support the implementation of transition scenarios worldwide. According to the projects and plans announced by the industry, reprocessing capacity could reach 7 000 tonnes of heavy metal per year by 2030 if the market demand would justify it (NEA, 2008b).

4.2.4 Strategic considerations for the transition

Assuming that new nuclear technologies under development will be ready for industrial and commercial deployment within three decades, transition from thermal to fast neutron reactor systems can be foreseen to be initiated in the 2040 to 2050 time frame (see French and Japanese scenarios in Chapter 5).

As noted in previous chapter, the objectives of introducing fast neutron systems in a reactor fleet vary from country to country but generally one of the two following main goals is pursued and the fast systems implemented will be selected accordingly:

- If the primary objective is to reduce radioactive waste arising, usually with emphasis on reducing the amount of plutonium sent to waste, and to lower the thermal load in the repository aiming at extending its capacity by a factor 3 or more, systems with low conversion factors (close to 0.5 to 0.6) will be selected.
- If the main objective is to reduce the constraint on uranium supply and decreasing the amount of waste is a lower priority, systems with high conversion factors close to 1.0 to 1.2 will be adopted. In this connection, it should be noted that, theoretically, one LWR loaded with UOX fuel produces enough plutonium during its lifetime (60 years) to start a fast breeder reactor having the same capacity, and this breeder capacity can be self sustaining for many centuries.

During the transition, in the context of a global increase of installed nuclear capacity, the following assumptions can be made regarding the fuel cycle facilities:

- The front-end capacities will be adjusted to the needs, typically the LWR UOX reactor capacities, knowing that each unit of 1 GWe will require around 160 tonnes of natural uranium and 100 000 SWU per year.
- The back-end capacities will depend on the introduction rate of fast neutron reactors and on the spent fuel availability. For example, some 8 to 15 tPu – depending on the characteristics of reactors and fuel cycle options – are needed to fuel a sodium fast reactor of 1 GWe operating in recycling mode. This mass inventory can be provided by reprocessing 1 500 tonnes of LWR UOX spent fuel or 300 tonnes of LWR MOX spent fuel. Reprocessed uranium will be recycled together with plutonium to avoid any need of natural uranium for a long time.

4.3 Economic aspects

The transition from the existing thermal reactors to fast neutron systems will last for several decades during which the cost of generating nuclear electricity will evolve, as well as all economic aspects of the nuclear systems in operation. There are methodologies and models to evaluate the costs of advanced fast neutron systems which can provide reliable estimates when unit costs are known with reasonable uncertainty margins, i.e., when the concepts have reached the level of advanced design development. The methodology and computer tool developed by the Economic Modeling Group (EMWG) of GIF (GIF, 2007 and 2008), for example, can be used to evaluate the costs of advanced fast neutron systems. However, the full economic assessment of transition scenarios requires not only generation cost estimates but also a complex dynamic analysis covering total investment costs and evolution of generation costs over time.

When evaluating the costs associated with transition scenarios, it is essential to take into account all the steps leading eventually to a fleet of fast neutron systems. In particular research, development and demonstration (RD&D) costs have to be integrated in the economic assessment. Those costs may be a major challenge at the national level when considering advanced systems for which not only the reactor but several fuel cycle facilities require RD&D.

The classic economic indicators including investment costs and total electricity generation costs are relevant in the context of transition scenarios but need to be evaluated with a dynamic model because the fleet of reactor and fuel cycle facilities is evolving in time as the transition takes place. Furthermore, in a broad holistic economic assessment, externalities such as security of supply, generation cost stability, long-term sustainability, and non-internalised health and environmental impacts have to be taken into consideration.

4.3.1 Research, development and demonstration costs

The thermal reactors in operation today, or to be built in the coming years, have reached the stage of industrial and commercial maturity. Therefore, their construction and operation will require only marginal R&D efforts, funded mainly by the industry and integrated in the costs and prices of generated electricity. On the other hand, fast neutron reactors will require extensive RD&D efforts although some of the concepts under consideration such as the sodium fast reactors have been demonstrated already. Even the SFR will require the construction of a prototype or demonstration plant. More advanced concepts such as the GFR or LFR are likely to require longer and more costly research including material and fuel testing and the construction of reactor and fuel cycle facility prototypes.

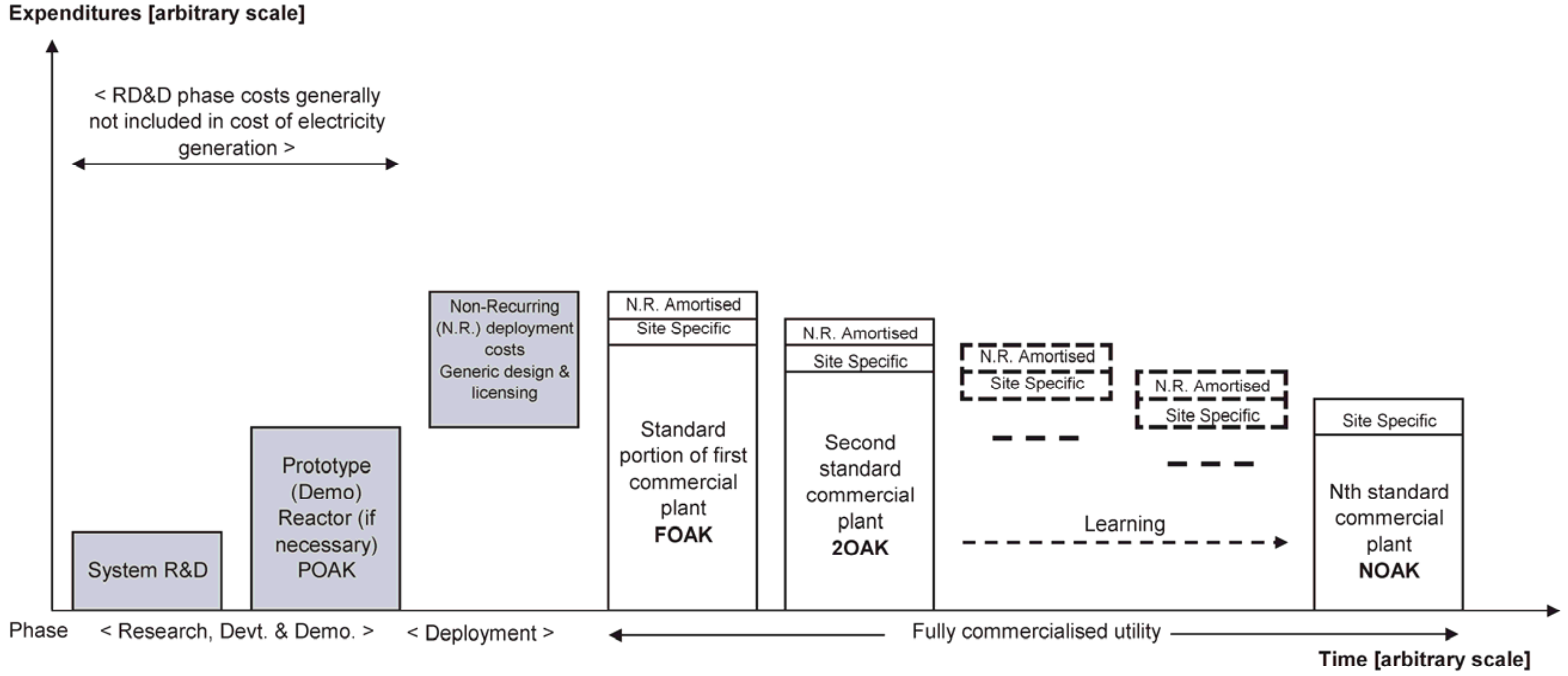
Figure 4.2, drawn from the GIF economic guidelines (GIF, 2007) shows the time distribution of the cost categories from research and development to Nth-Of-A-Kind (NOAK) plant. The Figure indicates which parts of those costs are included in the price of electricity (or any other product issued from the nuclear plant) and which parts (grey areas) usually are not internalised. The graphic representation is illustrative only and the horizontal and vertical scales are not based on real cost estimates for any specific concept.

Recognising that a significant part of the research and development costs will not be financed fully by the industry, governments will have a key role to play in supporting the development of advanced systems which will eventually be deployed within transition scenarios. Governments and decision makers from the industry need an early understanding of the costs of the RD&D programmes required to support the implementation of fast neutron systems and of the lead times involved, during which economic competitiveness is unlikely to be reached.

Strengthening international cooperation for the development of advanced nuclear systems should facilitate the funding of the required R&D and enhance the cost-effectiveness of investments owing to synergies between various countries and research institutes. International endeavours, such as GIF, should facilitate the implementation of joint research and the eventual development of high-performance innovative systems.

Nevertheless, in each country, thorough economic analyses will be helpful to assess the costs and benefits of transition scenarios before embarking on costly long-term programmes. The benefits of transition scenarios depends on the size of the electricity (and if applicable other products) market accessible (domestic and potential exportation) but also on the value given in the national policy to security of supply and actinide management.

Figure 4.2 Illustrative distribution of RD&D and standard NOAK plant costs



Note: Grey areas correspond to costs usually not internalised electricity prices.

Source: GIF, 2007.

4.3.2 Assessing economics during transition periods

As noted in previous chapters, the transition periods will be very long, several decades at least, and might exceed a century until equilibrium is reached. If recycling of plutonium in water reactors is considered as the first stage of a transition scenario (which is the case in some countries), some transition scenarios have started a few years ago. The introduction of advanced fast neutron reactors, planned for 2040 to 2050 will be the beginning of the second stage during which water reactors will continue to be operated until the end of their design lifetime (in most cases 60 years). The end of the transition period will occur when the entire fleet of reactors will be constituted of fast neutron systems at equilibrium.

From an economic viewpoint, the transition period *per se* (from 2040/2050 to beyond 2100) should be assessed in comparison with the present equilibrium period with a fleet of thermal water reactors, and taking into account the target future with a fleet of fast neutron systems. Recognising the uncertainties on external parameters such as electricity market demand and fossil fuel prices, those economic studies can only be indicative and carried out through sensitivity analyses in a parametric approach. However, they can support decision making within multi-criteria frameworks covering the other dimensions of sustainable development, i.e., social and environmental aspects.

The economic analysis of the first period is straightforward using the classic approach for estimating total investment costs, fuel cycle costs and levelised electricity generation costs. Unit costs are well established with limited margins of contingency and uncertainties for thermal reactors and fuel cycle services as fuel cycle facilities are already in operation.

The transition period *per se* during which thermal and fast neutron systems coexist requires a dynamic approach to economic assessment. The installed fleet is a variable mix of water reactors and fast neutron reactors. Fuel cycle facilities have to be adapted to both fuels and their capacities have to be adapted to small and variable flows of demand. During this period, the economic optimisation of fuel cycle facilities will have to be tailored to variable demand and sub-optimal capacities (see Chapter 5).

The additional costs incurred during the transition period should be carefully assessed and balanced against the expected benefits of the end point, i.e., a fleet of fast neutron systems operating at equilibrium. During the transition period, multinational, regional or international fuel cycle facilities may be considered as a means to achieve a better economic optimisation. However, multinational facilities may raise other economic issues (e.g., costs of transports and safeguards controls) which should not be overlooked.

During the transition period, the main economic indicators remain investment costs, fuel cycle costs and total generation costs but the methods to estimate those parameters needs to be dynamic and beyond absolute values at a given point in time, the average during the period and the amplitude of variation are important aspects to be considered.

The last period is characterised by a more homogeneous fleet with only one or more types of fast neutron systems. Fuel cycle facilities can be adapted to an expected stable demand evolving only with the total installed nuclear capacity. Production costs indicators can be assessed with equilibrium cost models. Uncertainties on unit costs remain a challenge for economic assessment of that period. Recognising that reactors and fuel cycle facilities are at an early stage of design development today, uncertainty margins and contingencies on their costs are very large and may, in some case, prevent robust cost-benefit assessment of transition scenarios.

4.3.3 System investment costs

The investment cost evaluation in the context of transition scenarios should cover reactors and also fuel cycle facilities. In particular, it is essential to evaluate the total investment cost of fuel cycle facilities which will be required during the transition period and will become obsolete when a system entirely based on fast neutron reactors will be in place. The investment cost of those facilities should be balanced against the expected benefit of the fast neutron system at equilibrium.

The major indicators to be evaluated for analysing investment costs are direct construction cost and total investment cost including interest during construction. Contingencies and uncertainty margins are an important part of the assessment because the reactors and fuel cycle facilities considered within transition scenarios are based on advanced technologies for which cost estimations are prospective as for any innovative systems and technologies.

Two approaches to construction cost estimation can be adopted for advanced systems:

- a top-down method based on scaling and detailed information from similar reactor systems;
- conventional bottom-up (cost engineering) estimating techniques, that can be used for conventional projects close to deployment or sections of project scope that are adequately detailed to account for all construction commodities, plant equipment, and labour hours.

Recent trends to rapidly increasing prices of raw materials and commodities have shown that economic evaluations are volatile. Costs of building power plants, nuclear or fossil fuelled, and of generating electricity evaluated a few years ago are obsolete today. Therefore, it is important to review periodically the economic assessments carried out in support of decisions to implement or not transition scenarios in order to ensure that they remain valid in spite of the evolution of the overall economic context. Furthermore, the economic analysis should include sensitivity studies to assess the robustness of the results to variations of unit costs an prices.

4.3.4 Total fuel cycle cost

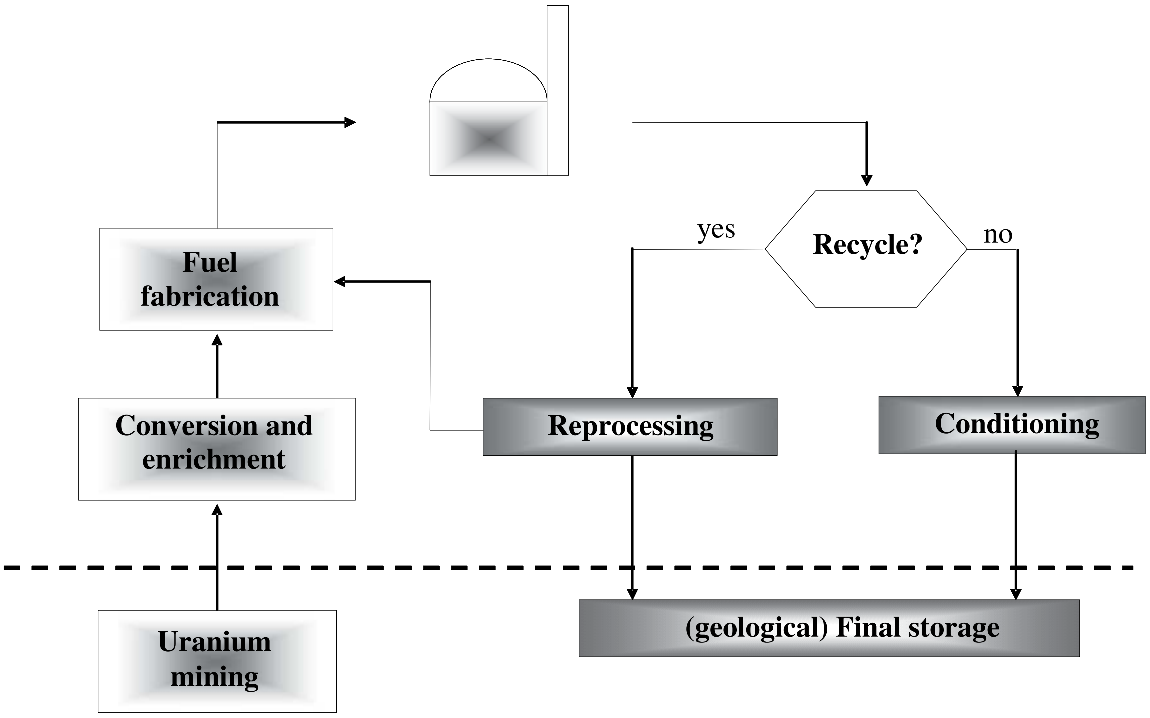
Figure 4.3 illustrate the steps to be taken into account when calculating nuclear fuel cycle costs.

Except for the acquisition of uranium, all steps correspond to services delivered by suppliers and indicators for economic assessment are provided by market prices. For existing fuel cycles, such as the thermal water reactor fuel cycle including partly closed cycle with MOX fuel in LWRs, the industry is providing services is mature and prices are driven by market mechanisms. Fuel cycle costs can be estimated based on those unit prices.

For advanced fuel cycles, on the other hand, there are no industrial scale facilities in operation and, therefore, no market prices. This is the case for innovative pyrometallurgical and pyrochemical facilities for fuel fabrication, reprocessing, and re-fabrication. For such systems, price data for fuel cycle services generally are not available. In that case, a unit cost of a fuel cycle service, such as $/kgHM for fuel fabrication, should be calculated using a methodology similar to those used for electricity generation cost calculation. The cost of a service is estimated based on the investment cost of the facility, its running costs (operation, maintenance and consumables) and its total production during its economic lifetime, taking into account its capacity and expected availability factor.

During the transition, the average fuel cycle cost for the evolving mixed fleet of reactors should be estimated taking into account both types of facilities (mature and advanced) and the demands for each types. When multinational facilities are considered, fuel cycle costs should be evaluated taking into account international transport costs.

Figure 4.3 Schematic of the steps in the nuclear fuel cycle



4.3.5 Electricity generation cost

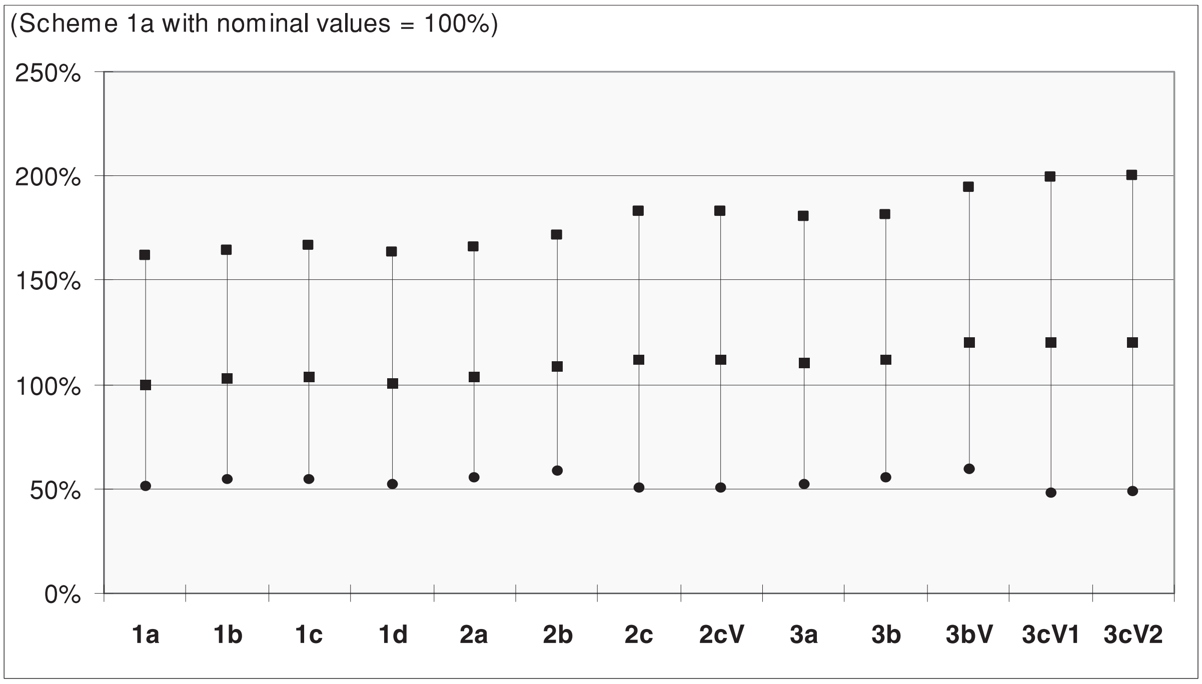
The levelised unit of electricity cost is a key indicator for the economic assessment of electricity generation systems, although it is not by far the only relevant figure of merit. This cost includes four main components: capital cost (direct construction costs and interest during construction); operation and maintenance cost; fuel cycle cost; and decommissioning and dismantling cost.

An in depth analysis of generation costs for various advanced fast neutron systems at equilibrium as compared with generation costs for once-through thermal reactors is provided in report published by NEA in 2006. The main finding from this analysis is that economics is not a discriminating factor between thermal reactors operating once through and fast neutron systems with closed cycle. As illustrated in Figure 4.4, taking into account the uncertainties on unit costs, it is not possible to identify “the cheapest” option.

During the transition, several reactors and fuel cycles are in operation simultaneously and the evaluation of the generation costs should be made year by year, taking into account the evolution of the technology mix in the fleet. Such evaluations are scenario specific and it is difficult to draw generic conclusions from those estimates which reflect the particular national or regional context assumed.

Although cost is not the sole indicator to be taken into account and, in many cases is not even a driving parameter in the choice of alternative options for the management of fissile materials, improving the economics of transition from thermal to fast neutron systems is a relevant objective. Technology progress and careful planning of the transition period are efficient means to monitor the costs associated with the transition. In addition, international cooperation and multinational facilities could be very effective in optimising the service costs of various fuel cycle facilities and thereby reducing their specific costs.

Figure 4.4 Relative levelised generation costs for various nuclear systems



Source: NEA, 2006.

Note: 1a Once-through fuel cycle (reference); 1b = Conventional reprocessing (mono recycling of Pu in MOX for LWRs); 1c = Variant of 1b recycling of Np together with Pu; 1d = DUPIC cycle, spent LWR fuel used in CANDU reactors; 2a = Plutonium burning in LWR (MOX fuel with enriched uranium); 2b = Plutonium and americium burning in LWRs; 2c = Heterogeneous americium recycling; 2cV = variant of 2c americium and curium sent to storage facility; 3a = TRU burning in FRs; 3b = Double strata, including ADS, burning Pu in LWRs and FRs; 3bV = Variant of 3b with direct transfer of Pu from LWR MOX to ADS; 3cV1 = All-FR strategy with Generation IV gas-cooled fast reactors; 3cV2 = Variant of 3cV1 with UREX+. See (NEA, 2006) for more details on the schemes.

4.4 Role of governments

This section focuses on key topics deserving government attention in the process of designing and implementing transition scenarios. Governments have a major role to play in all aspects and phases of nuclear energy policy design and implementation. However, governments tend to be more closely involved when national decisions have to be taken in a long-term perspective, as is the case for choosing or not to launch transitions, and cannot be driven by market mechanisms only owing to the lack of short-term incentives for private economic actors.

Many aspects of transition scenarios, ranging from research and education to legal infrastructure building and policy measures, are fully or partly under the responsibility of governments. For example, governments may, if it is in line with national energy policy goals, support options which will benefit society in the long term although they might not be economically viable from a narrow competitive market perspective.

4.4.1 R&D, education and training, infrastructure

The development of advanced nuclear systems requires basic and long-term R&D programmes which have to be supported at least partly by governments because the expected outcomes are not of direct benefit to the industry. Recognising that the main drivers for the implementation of transition scenarios are "social" benefits – security of energy supply and reduction of waste volumes and long-term toxicity – associated with closure of the fuel cycle, it is considered relevant that governments support the infrastructure building, R&D and education and training required to develop fast neutron systems.

It is important that countries which embark on transition scenarios adapt the objectives and scope of their national R&D programmes, their education and training and their infrastructure to the needs of those scenarios. Consequently, small countries or countries with limited existing nuclear energy infrastructure might choose to develop only thermal reactors with direct disposal of spent fuel in order to avoid building capabilities for supporting fast neutron systems. Alternatively, those countries might choose recycling through buying services on the international market or, eventually if they are implemented through international facilities and centres.

Different countries make a different evaluation of the cost and risk of nuclear energy versus its benefits. Some countries have a clear policy to maintain or increase the presently installed nuclear power, some are planning to reduce or phase out the electricity generation from nuclear fission and others are considering to start or to restart their nuclear industry in the coming years. These national policies might change (and indeed have changed in the past) as the economic, social and political context of a country evolves and as the overall global policy-making landscape is changing worldwide (e.g., enhanced importance given by policy makers to global climate change and sustainability issues).

Irrespective of the political decision of continuation or phase out nuclear energy, all countries using nuclear energy to generate electricity have to manage, and eventually dispose of, their spent nuclear fuel and other high-level radioactive waste. Many countries have defined their present policy for waste management as the eventual direct disposal of spent fuel, after some interim storage near surface for 40 to 150 years. However, the use of fast neutron systems is considered in most of the R&D programmes undertaken in various countries and in multinational or international frameworks for addressing radioactive waste management issues.

The disposal in stable deep geological formations, which has been demonstrated to be a technically viable solution to handle the already produced and future HLW, has not been implemented yet. Finland and the United States have approved construction of a geological disposal facility and, in each country, a site has been identified to build it. Other countries like Sweden and France are also close to identifying an emplacement, but most countries have still not selected a site. However, two factors are driving large interest in viable alternatives to direct geological disposal: ensuring long-term sustainability of nuclear energy and reducing the long-term stewardship of HLW.

As a consequence of the potential benefits of fast neutron systems, large R&D initiatives on transitioning from present LWR fleets in an open fuel cycle to future fully closed fuel cycles using fast spectrum reactors have been launched worldwide. Examples of such programmes include: the Omega project in Japan; the Accelerator Transmutation of Waste, Advanced Accelerator Applications, and Advanced Fuel Cycle Initiative programmes in the United States; and a large partitioning and transmutation programme in the European Union. Similar initiatives have been undertaken in Russia and the Republic of Korea, and many national programmes are coordinated in several NEA working groups and IAEA projects (see Section 1.4). In parallel, the GIF, GNEP and other initiatives for the preparation of the medium-long term future of nuclear energy have incorporated these concepts in their strategies in order to define a roadmap or strategic vision for R&D and industrial deployment.

The development of advanced fuel cycles up to the full industrial deployment needs a large R&D effort, including the realisation of a number of demonstration facilities and testing installations at pilot scale. With the stagnation of nuclear power programmes in many countries, R&D suffered drastic cut backs. Over the last decades a continued trend to reduce nuclear R&D activities, cut down governmental funding in the field and decrease the number of research facilities was observed in most OECD countries. As a result, the research facilities in service today are not adequate in number and capabilities to support transition to fast neutron systems. For example, in the context of GIF, several system research plans have identified gaps in the infrastructure required for material testing and fuel irradiation.

In order to implement the research facilities required to carry out the various testing required for the development of innovative reactors and advanced fuel cycles, many research institutes and industries have coordinated their efforts at the regional or international levels. This allows sharing the development costs and the implementation plans, within a larger geo-political area. This seems particularly beneficial for countries which are not already committed to spent-fuel reprocessing.

This has also led to considering and analysing so-called regional approaches which foresee the possibility to share expensive fuel cycle facilities and a concerted use of materials, in order to optimise the use of resources and investments in an enhanced proliferation resistant environment at a regional level. However, the challenges raised by national regulatory body requirements – of the host country of a facility designed for multinational uses as well as of the user countries – should not be overlooked when considering such projects.

The diversity of systems in operation during the transition period entails need for multiple specific qualifications within the staff designing, building and operating reactors and fuel cycle facilities. Human resources are scarce already in the nuclear energy sector owing to ageing of the workforce and lower interest in this field from young professionals, resulting from the stagnation of nuclear power programmes during the last decades.

The expected renaissance of nuclear energy programmes requires the creation of new education and training programmes and/or the adaptation of existing ones, in order to face demand for highly qualified manpower in all sectors of the industry as well as in regulatory bodies. Anticipating the specific requirements associated with transition scenarios is necessary in order to initiate the adaptation of the national or regional education and training capabilities accordingly.

4.4.2 Regulatory frameworks, safety, physical protection and non-proliferation

In all countries where nuclear power plants and fuel cycle facilities are in service, regulatory frameworks are in place for their licensing, for ensuring health and environmental protection, for monitoring international trade associated with their operation, physical protection and avoiding proliferation of nuclear weapons. The introduction of advanced fast neutron systems in the context of transition scenarios will require some adaptation but will not need drastic changes or new developments in the legal and regulatory frameworks in place.

At the international level, the Multinational Design Evaluation Program (MDEP) is expected to facilitate the licensing of new reactor designs in different countries through sharing the resources and knowledge of national regulatory authorities assessing those designs. The outcomes from this endeavour could facilitate the implementation of transition scenarios in various countries. Currently, ten countries participate in MDEP: Canada, Finland, France, Japan, the People's Republic of China, the Republic of Korea, the Republic of South Africa, the Russian Federation, the United Kingdom and the United States.

MDEP is proceeding in three stages. In the first stage, which started in 2005, nuclear regulators are using technical data gathered during the certification of a reactor design in one country for its certification in another, thereby avoiding duplication of work. In particular, the nuclear regulatory authorities of France and Finland are working with their US counterpart on the review and evaluation of the European Pressurised Water Reactor.

The second MDEP stage, which was initiated mid-2006, focuses on identifying common regulatory practices and regulations that enhance the safety of new reactor designs. Ultimately, this phase is expected to lead to a convergence of codes, standards and safety goals in the participating countries. During the third stage, which is a much longer-term endeavour, the lessons learnt during the earlier stages will be used to facilitate the licensing of Generation IV reactor designs.

In some countries, national initiatives have been launched to assess regulatory issues raised by transition to fast neutron systems and identify ways and means to address them. In the United States, for example, modifications are required to the US Code of Federal Regulations to include fuel cycle production facilities for reprocessing and recycling, to establish a one-step licensing process, and to address security and safeguards requirements. The regulatory framework has to be modernised to make it more efficient (reduce time for licensing). This would entail more resources for the USNRC to support licensing facilities for a closed fuel cycle.

Another example is the legislative and regulatory changes that will be necessary in the United States to permit transuranic elements arising from commercial recycling to be disposed in a waste repository. Additionally, in light of the recent proposal for the creation of a government or quasi-government entity for the management of waste, the Nuclear Waste Policy Act (NWPA) of 1982 would have to be modified to create the entity and to provide funding for its operations.

In the context of GNEP, the USNRC SECY-07-0081 (May 2007) outlines a regulatory framework for licensing the proposed GNEP facilities. It recommends developing technical-basis documentation to support 10 CFR Part 70 rulemaking and a gap analysis on Part 50 to address the reprocessing facility and advanced burner reactors. Modifications to Part 52 may also be required to support sodium fast reactor technology. The staff of the commission was thereafter directed to (USNRC SECY-07-0198, November 2007): perform a gap analysis for all NRC regulations, to identify changes in regulatory requirements that would be necessary for licensing a reprocessing facility and an advanced recycling reactor; and prepare a technical-basis document to support rulemaking for 10 CFR Part 70, with revisions to 10 CFR Part 50, as appropriate.

Although fast neutron systems to be introduced in the framework of transition scenarios raise specific issues from a proliferation resistance and physical protection viewpoint, they do not create more concerns than thermal neutron systems. Provided adequate intrinsic and extrinsic measures are taken to ensure physical protection and resistance to proliferation, all nuclear energy systems can be operated with satisfactory assurances that materials and technologies will not be misused for non-civil purposes.

One goal of the methodology work undertaken in the framework of GIF is to facilitate proliferation resistance and physical protection "by design", i.e., to reflect proliferation resistance and physical protection requirements in the design of a system at a very early stage. The methodology established in this context and tested on some "hypothetical" sodium fast systems provides a robust approach for assessing proliferation resistance and physical protection aspects of advanced systems.

4.4.3 Waste management policy

In all OECD countries the owners/operators of nuclear facilities are responsible for the management and disposal of radioactive waste and for ensuring that adequate funding is available for these purposes. The role of governments in this field is to establish a legal framework and specific regulations applicable to each category of radioactive waste. When considering transition scenarios, governments should adapt the regulatory context to reflect the evolution of waste types and volumes resulting from the development of fast neutron systems.

Furthermore, governments are responsible for defining long-term strategies covering various aspects of radioactive waste treatment and ultimate disposal including, for example, the recognition that reducing the volumes and radiotoxicity of radioactive waste and ensuring the reversibility of disposal approaches provide social benefits.

In France, for example, the Waste Management Act of 1991 defined the legal framework for managing high-level waste. It covers R&D requirements and defines the three axes of research to be pursued:

- separation and transmutation;
- disposal in deep geological layers; and
- long-term (sub)-surface storage.

A status report assessing the most promising R&D routes was submitted to the French authorities in 2005. As a result, the legal framework for waste management in France was updated with two important laws, both enacted in 2006.

The Law on nuclear transparency and security established a new independent safety authority ASN (*Autorité de Sûreté Nucléaire*). It ensures the control of nuclear safety and radiation protection to protect workers, patients, the public and the environment from risks related to the use of nuclear technology.

The Programme Act on the sustainable management of radioactive materials and waste covers all types of radioactive waste (not only long-lived high-level waste). It defines three main principles concerning radioactive waste and substances: reduction of quantity and toxicity, interim storage of radioactive substances and ultimate deep geological disposal of waste. The law defines financial arrangements for research, nuclear plant decommissioning charges, and additional taxes on nuclear facilities to finance research programmes. It provides clear definitions of radioactive materials and waste and specifies that treatment is the way to reduce the volume and radiotoxicity of nuclear waste. A central point is the creation of a national management plan defining the solutions, the goals and the research actions to be launched to reach these goals. This plan is updated every three years and published according to the law on nuclear transparency and security.

In the United States, the disposal of spent nuclear fuel is currently the responsible of the federal government, with the nuclear utilities contributing annually into a Nuclear Waste Fund (1 mill/kWh). It is generally acknowledged that under all strategies and scenarios for the future of nuclear power, the United States will need a permanent geologic repository to dispose of spent nuclear fuel or high-level waste. Consequently, the current planning for the Yucca Mountain geologic repository is continuing, assuming that the legislated capacity limit of 70 000 tonnes heavy metal stipulated for the site, under the Nuclear Waste Policy Act (NWPA), would be used. Under this premise, any spent nuclear fuel or high-level waste exceeding the legislated capacity of the first repository could be ultimately disposed in a geologic repository. Such future repository capacity could be an expansion of the Yucca Mountain repository (if the NWPA is amended to remove the statutory limit on waste emplacement at the first repository) or a separate geologic repository at a site yet to be determined. If a closed fuel cycle is practiced in the future, the amount of transuranic elements in the HLW would greatly decrease and the effective loading of the repository could be greatly increased.

While not debated at the current time, it is not inconceivable to imagine the possibility of private ownership of a nuclear waste repository. This could alleviate the public allocation of funds for the effort (though government support and incentives would be required at least initially), but would not remove the difficulties that have been associated with the setting of a repository in the United States (local opposition being a key item). In any event, the long-term security of the repository might still need to be a federal government function or at a minimum require federal regulatory oversight.

Some industry teams have proposed to the United States Government the establishment or a new government entity (USDOE, 2008a and 2008b) or quasi-government entity (USDOE, 2008c) for the management of nuclear fuel and waste as a business enterprise. This organisation could be modelled after the Tennessee Valley Authority (a federal corporation which is the largest public power company in the United States.) This entity would be financed by contributions made by the nuclear utilities to the United States Nuclear Waste Fund; typically suggesting foregoing existing funds, but with the possibility to increase the amount contributed by utilities. The primary source of income by the entity would be the waste fees and revenues generated by recycling recovered material in new fuel. The entity could be responsible for waste repository construction and operation, contracting with industry for the construction and operation of recycle facilities, and for transport of used nuclear material from reactors to the recycle facility. The teams indicated that support exists today in the United States nuclear utility community to establish such an entity. The utilities would be major members on the board of the entity and would provide the necessary commercial oversight to ensure efficient use of funds.

4.4.4 Policy measures

The main goals of transition scenarios are to enhance the effectiveness of nuclear systems through better use of natural resources and reduction of long-term burdens associated with long-lived radioactive waste disposal. Those objectives respond to social concerns that governments may wish to address by taking policy measures in support of nuclear systems based on fast neutron reactors.

The challenge for governments, however, is to design policy measures in support of advanced technologies, such as fast neutron systems or renewable energy sources, without interfering with market mechanisms. Although it might be difficult, there are many examples of well-designed and effective government measures in support of non-competitive energy options aiming at enhancing security of energy supply and/or at alleviating the risk of global climate change.

In the case of fast neutron systems, a broad range of government policy measures could be adopted to facilitate their deployment, if and where it is identified as a beneficial option for society. The measures to be adopted will depend on many factors and criteria and will vary according to the main policy goal(s) of the country.

When the main objective of the country is to reduce radioactive waste volumes and radiotoxicity, the social value of burning actinide could be recognised through a mechanism similar to the carbon emission permits and/or taxes adopted in some countries. Such an approach would increase the cost of electricity generated by thermal reactors operated once through and make fast neutron systems burning actinide more attractive.

In many cases, the critical barrier to investment in fast neutron reactors will not be their fuel cycle costs but the risk associated with investing in a new nuclear technology, generally more capital intensive than state-of-the-art thermal water reactors. Governments could provide support through guaranteed loan and insurance in case of delays in the licensing process, in the same way as is done currently in the United States in the framework of the 2005 Energy Policy Act.

Many other mechanisms could be put in place to facilitate the penetration on the market of fast neutron systems at an early stage when they will not be fully competitive on liberalised electricity markets. Such measures should, however, be compatible with market mechanisms and eventually benefit to consumers and society as a whole.

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Chapter 5

ILLUSTRATIVE SCENARIOS: OVERVIEW AND KEY FINDINGS

This chapter provides the key findings from 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 policy issues.

5.1 Background

At the beginning of 2008, the nuclear capacity in operation worldwide was around 370 GWe and some 20 GWe were under construction. Most of the commercial power reactors in operation today were connected to the grid in the 1970s or 1980s, with an initial expected lifetime of 30 to 40 years. However, lifetime extensions are underway for a majority of these reactors and, consequently, their replacement is expected to occur between 2020 and 2050. During the same period, the total installed nuclear capacity is expected to increase. For example, the NEA scenarios (NEA, 2008) project that nuclear capacity could range between 400 and 620 GWe in 2030, and between 580 and 1 400 GWe in 2050. Other scenarios project even higher growth of installed nuclear capacity

With current thermal reactor technologies, the increasing nuclear capacity in operation would lead to a proportional increase in uranium demand and, by around the middle of the century, the cumulated consumption would reach the level of currently known uranium resources recoverable at economically viable costs and acceptable environmental impacts. Increasing demand likely would lead to higher market prices and thereby to a broadening of the resource base but exploiting lower grade resources could increase not only recovery costs (and prices) but also environmental impacts of mining and milling activities.

At the back end of the fuel cycle, the inventory of spent fuel is estimated to have reached around 200 000 tonnes and is increasing by about 7 000 tonnes each year. This spent fuel requires interim storage, and eventually disposal if it is not reprocessed. Building spent fuel repositories does not raise technical problems but their licensing processes have proven to be challenging and local public acceptance remains an issue for most on-going projects. Furthermore, spent fuel contains valuable fissile materials such as plutonium and uranium which could be used in fast neutron reactors.

Addressing one or both of these two key issues – uranium resources and/or spent-fuel management – is driving the decisions to implement transition scenarios leading to closed fuel cycles allowing for enhanced effectiveness in managing fissile and fertile materials. Depending on which of the two is given priority, the design of the scenarios will vary and their evaluation will be based on different sets of criteria. The two typical contrasted contexts for implementing and assessing transition scenarios are:

- Need to manage spent fuel (focus on waste management issues), no significant constraint on uranium resource availability; or

- Need to alleviate constraints on uranium supply (focus on enhanced use of fissile content of natural resources) resulting from shortage of accessible resources and/or production capabilities.

In all cases, the approach selected and the fuel cycle options adopted must be compatible with sustainable development goals, including enhanced safety, resistance to the proliferation of nuclear weapons and physical protection. The options for future fuel cycles include:

- No recycling and direct storage of spent fuels assemblies, close to business as usual in most countries.
- Transition with a limited introduction of fast reactor systems (critical or sub-critical) for recycling transuranic elements (TRU) to reduce the mass, thermal load and radiotoxicity of waste arisings.
- Transition to fast neutron reactors for a large multi-recycling of TRU, plutonium (Pu) alone, plutonium plus americium (Pu+Am) or plutonium plus minor actinides (Pu+MA), aiming at reducing the mass, thermal load and radiotoxicity of waste, and uranium requirements.

5.2 Approaches adopted in transition scenario studies

Transition scenario studies generally evaluate and analyse the impact over time of introducing advanced reactors and fuel cycle technologies on fissile material balances, uranium and fuel cycle service requirements, radioactivity releases and doses taking into account the evolution of total nuclear capacity and electricity generation. Characteristics such as reactor conversion ratio (breeding or burning core) and fissile inventory requirements are system performance parameters that can be optimised in the framework of transition scenario design variations.

The transition schedules depend on the technical and commercial availability of the reactors and fuel cycle facilities required for achieving the goals of the scenarios considered. If Generation IV systems are planned to be included in the fleet their penetration at industrial scale on the market cannot be scheduled before 2040, especially for the fast neutron systems requiring advanced fuel cycle facilities. Thus, the transition from the existing reactor fleet to TRU recycling systems needs to be scheduled over a period of several decades and will not be fully effective before the second half of the century. The introduction of new fuel cycle facilities should be scheduled timely to ensure that the processing capacities required at all steps of the fuel cycle (e.g., fuel fabrication and reprocessing) are in place when needed.

Generally, transition scenario studies assume the introduction of new systems with fully closed fuel cycle after 2040. A previous step with partial recycling of plutonium and uranium is assumed in some cases but not always and, accordingly, spent fuel treatment capacities are introduced or not in the period previous to the introduction of fast neutron systems.

Typically, studies on transition scenarios are carried out in two steps:

- Establishment of a reference scenario considering initial inventories of materials, fuel cycle facilities and reactors; and
- Evaluation of alternatives (design variation scenarios) with different hypotheses and parameters for the future: renewing existing reactors and introducing new systems (fuel cycle facilities and reactors).

The criteria for comparing the different options include: maturity and deployment dates of the systems considered; technical and industrial feasibility; uranium (and other natural resource) consumption; impact on waste management (number and size of needed repositories); economics; and non-proliferation.

The assessment of a transition scenario is based on the availability of the fissile material and on the availability and capacities of repository sites for the wastes. The system performances in terms of breeding-burning factor and fissile inventory requirements are parameters that can be optimised depending of the scenarios.

The following review of transition scenario studies covers two aspects:

- initial inventories of material, fuel cycle facilities and reactors; and
- description of the hypothesis and parameters for the future, including timetable for renewing existing reactors and introducing new systems (fuel cycle and reactor).

5.3 Overview of some illustrative scenarios

For the purpose of the present study, a number of scenarios carried out previously for different countries and regions were reviewed and analysed in order to assess their key findings from a policy viewpoint. The scenarios considered were selected because they illustrate various goals and contexts. Key features, findings and lessons learnt from the studies reviewed are summarised in the following sections.

5.3.1 Regional scenario[1]

International transition scenarios could offer more promising perspectives than transition scenarios designed for a single country, as the wider geographic context provides more flexibility in terms of timing, access to resources and facilities and potential for economy of scale.

International/regional transition scenarios would necessitate the development of regional nuclear fuel cycle facilities/centres that would be shared by neighbouring countries. Such facilities already exist in some regions but would have to be expanded, while in other regions they would have to be developed and built in one of the participating countries. Potentially, advanced fast neutron reactors and closed fuel cycles would exist only in countries with large and dynamic nuclear programmes.

This approach opens up different possibilities:

- Certain countries might want to phase out nuclear reactors or keep constant production level and might want their spent nuclear fuels managed by the regional centres which will be located in countries with large nuclear programmes.
- The dynamic nuclear countries might agree to burn plutonium and minor actinides from the spent fuel of the countries in which nuclear is being phased out. Additionally, those countries might perform the same mission for countries that do not want to deploy a closed nuclear fuel cycle and intend to operate thermal reactors only.

Nuclear stagnant or phase-out countries might see better prospects in nuclear power (based on economic, security, or environmental reasons) and start deploying advanced reactors and fuel cycle facilities in the future. These countries could share some of the roles initially supported only by the countries with dynamic nuclear programmes.

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[1] This section is based on a note, prepared for the Expert Group, on the PATEROS programme undertaken in the framework of the European Commission (Monti, 2008) and on Salvatores, 2008.

Countries with no nuclear power might want to develop nuclear power facilities for economic, security, or environmental reasons. Initially, they might need the support of the regional nuclear centres and subsequently could decide to host regional centres, thus, playing varying roles with time.

Various scenarios can be defined utilising a mix of these countries. In general, the scenarios based on regional groups might provide a better approach for managing spent nuclear fuel and increasing nuclear material security. Obviously, this would require that all participating countries adhere to international laws and regulations designed to ensure safe and secured transfer of large volumes of nuclear materials.

5.3.2 Market share scenarios for advanced reactors in Europe

A study conducted by the EC research centre of Petten (Roelofs, 2008) evaluated future nuclear reactor mixes in Europe for the 27 member states of the European Union. The systems considered in the scenarios include: sodium-cooled fast neutron reactors, either breeders or self-sustaining, i.e., breeding only their own fuel; Gen III LWR using mixed oxide fuel (LWR-MOX); and Gen IV reactors of the type being evaluated internationally. The analysis covers a 100-year period. The scenario takes into account the lifetime of nuclear power plants in operation at present and an assumed modest growth of nuclear electricity generation. Accordingly, it was assumed that the existing reactors would be retired mostly in the 2020 to 2025 time frame. The decision on the replacement reactors is driven primarily by intra-nuclear economic considerations and constraint on when the fast neutron reactors can be deployed (after 2030).

Scenarios with different fuel cycle front- and back-end costs were evaluated. The study found that:

- The new nuclear capacity installed up to 2030 can only be based on Gen III LWR, which may use MOX fuel.
- Both the self-sustaining and breeding fast reactors are attractive when increased fuel cycle costs are assumed. As breeders are more efficient in uranium ore consumption, they are more attractive when increased front-end fuel cycle costs are assumed.
- Although it is assumed generally that nuclear electricity generation costs are driven essentially by capital costs, some scenarios show that this assumption is not always valid. For some advanced systems, fuel cycle costs become high enough to be of equal to or even larger than capital costs.
- The share of fuel-cycle-related cost in total generation cost is almost constant for fast reactors in the scenarios considered, indicating the attractiveness of fast reactors in scenarios with increased front-end fuel cycle costs of thermal reactor systems.

5.3.3 Case of small country (Czech Republic)

The transition to a fast reactor fuel cycle in a small country has been evaluated for the Czech Republic (Vocka, 2008). There are currently six nuclear reactors operating in the Czech Republic: four VVER-440s and two VVER-1000s. Combined, these reactors produce about 25 TWh of electricity (31% of total electricity production in the country in 2006). The study focused primarily on material flows and balances. It was assumed that the nuclear power share in energy supply will double by 2040 and remain at that level until the end of the century. Additionally, the study assumed that new reactors built up to 2040 would be PWRs and that advanced fast breeder reactors would be deployed starting in 2040. The deployment of the fast neutron reactors depends on the availability of sufficient stock of plutonium derived from the thermal reactor (VVER and PWR) spent nuclear fuel.

The impact of the time interval between thermal reactor spent fuel discharge and plutonium fuel loading into the fast reactor was evaluated. The study found that the introduction of fast breeder reactors in a country with a small number of operating nuclear reactors and with limited plutonium reserves in spent nuclear fuel can be very difficult and that the rhythm of fast reactor introduction strongly depends on the schedule adopted for spent fuel reprocessing and recycling. If the time interval between down load of spent fuel and loading of MOX fuel in fast reactors is 15 years, only one fast breeder reactor can be deployed in the Czech Republic by 2050, and full-scale transition to the fast reactor technology would be infeasible during the 21st century. On the other hand, if the time interval is seven years, the transition to fast reactors is possible by the end of the century. In both variants the transition to fast reactor fuel cycle would require reprocessing of a significant amount of accumulated spent fuel (unlimited reprocessing capacity was assumed in the study).

5.3.4 Canadian studies on the potential role of heavy water reactors

The Canadian nuclear power program is based on CANDU® technology, which provides flexibility for the use of different fuel cycles. Its inherent high neutron economy, fuel channel design, on-power refuelling capability and simple fuel bundle design allow for the optimisation of an assortment of different nuclear fuel cycles.

Atomic Energy of Canada Limited (AECL) is actively examining CANDU fuel cycles that exploit synergies between heavy water moderated CANDU reactors and light-water reactors, as well as fast neutron reactors. Optimisation of thermal- to fast-reactor transition scenarios involves the exploitation of these synergies.

Canadian research has shown that because of their specific characteristics heavy water reactors can provide valuable contributions, complementing those of light-water reactors in thermal- to fast-neutron reactor transition scenarios. Heavy water reactors could be used to match the size of the reactor fleet to electricity demands, make efficient use of fissile resources and potentially to manage the minor-actinide inventory in the fuel cycle.

In a transition scenario where there is a limited supply of available fissile material, and where the fast neutron reactors have low breeding ratios, it could be difficult to increase the size of the fast reactor fleet to match increasing demand for electricity. In these scenarios, a small fleet of HWRs would be the most efficient way to convert uranium resources to fissile plutonium for use in the initial core load for next-generation fast reactors. In scenarios where this supply of plutonium comes from reprocessing spent LWR fuel, the addition of a small number of HWRs would allow the reprocessed uranium, from the LWR spent fuel, to be converted to both fissile plutonium and depleted uranium for use in the fast reactors, while generating valuable electricity.

The high neutron economy of HWRs allows them to produce a large amount of energy from a small amount of fissile material. In fuel cycle scenarios involving fast neutron reactors with high breeding ratios, net plutonium production would exceed the demand for increases in the size of the fast reactor fleet. Here, a HWR could efficiently convert the excess plutonium production to electricity with minimal impact on uranium resource utilisation through either a plutonium-uranium MOX fuel cycle, or a plutonium-thorium fuel cycle. In these fuel cycles, HWRs would make more efficient use of both plutonium and uranium resources than LWRs.

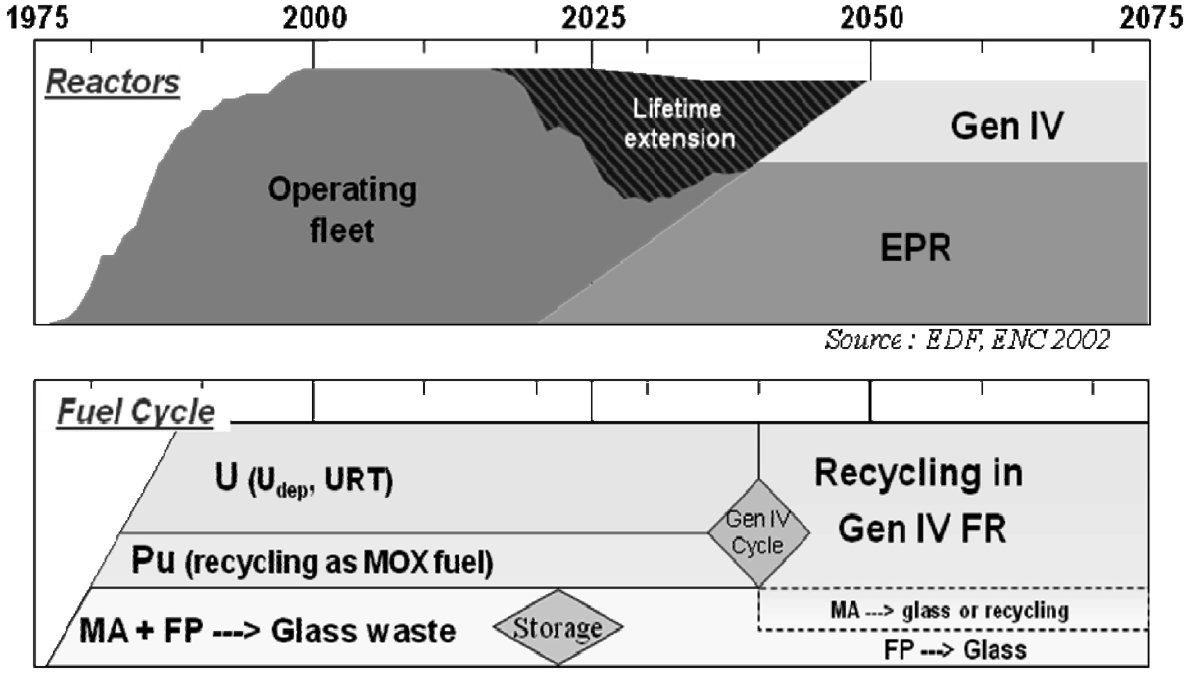
There may also be instances where the transition to a nuclear fleet containing fast reactors is driven by a desire to reduce the requirements for spent nuclear fuel disposal requirements. Reducing the requirements for spent nuclear fuel disposal involves the reduction in decay heat from the spent fuel, and in particular, the reduction of the minor actinide content of the spent fuel.

5.3.5 French transition scenario

National scenario studies applied to nuclear material management are performed in the framework of the French national Act on “the sustainable management of radioactive materials and wastes”. These ongoing studies should be completed by 2012 and their results will contribute to support decision making for the future of nuclear energy in France.

The strategy adopted in France takes advantage of the existing fuel cycle facilities and of the industrial experience already acquired in the country. A total of 22 700 tHM of spent fuel have been reprocessed and some 1 100 tHM of MOX fuel have been fabricated and loaded in the 20 PWRs licensed for using this fuel type; this recycling of plutonium in PWRs has reduced the volume of spent fuel in interim storage by a factor 7 and lowered natural uranium consumption by some 10%.

Figure 5.1 French reactor deployment and transition scenario



Source : EDF, ENC 2002

Source: Delpech *et al.*, 2007.

The transition considered, illustrated in Figure 5.1, is a renewal of the existing nuclear reactor fleet, composed of light water reactors, starting in 2020. Generation III evolutionary pressurised water reactors (EPRs) are built first and then, starting in 2040, Generation IV fast reactors are introduced progressively. It assumes the introduction of a new generation of reactors and fuel cycle facilities, including an integrated recycling-fabrication facility.

The studies assume a constant installed nuclear capacity of 60 GWe and the following hypotheses:

- plant life time extension (to 50 years in average);
- renewal of the existing reactor fleet with EPRs from 2020 up to 2040 (2 GWe/year, 40 GWe total); and
- introduction of sodium-cooled fast reactors (SFR) after 2040 (20 GWe).

The Generation IV gas-cooled fast reactor concept is investigated as an alternative to the sodium fast concept. The goal of the studies is to compare the different options for nuclear material management using detailed analyses during the transition period covering the fuels and reactors, recycling processes and waste repository requirements.

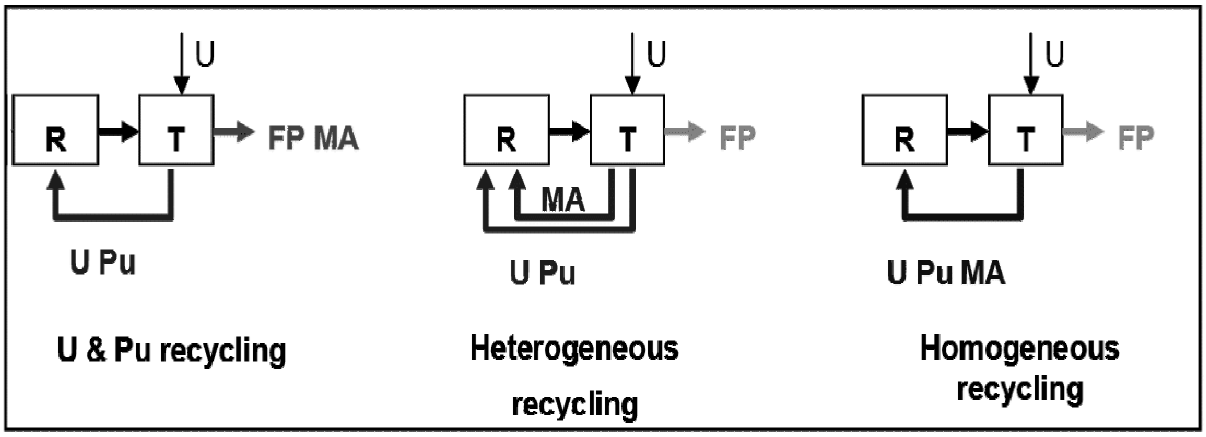
The different options for nuclear material management after 2040 are summarised in Figure 5.2. Three main fuel cycle strategies are investigated for the long term in order to identify technically feasible and economically acceptable solutions that will facilitate the decision-making process when appropriate:

- Optimisation of uranium and plutonium recycling strategy using existing PWRs and future EPRs as a first step, followed in a second step by co-management of uranium, plutonium and possibly neptunium in SFR (COEX^{TM} process).

- Minor actinide heterogeneous recycling with a higher content of MA (typically 10%-15% in mass) in blanket assemblies of SFRs or as target in accelerator driven systems (MA content of 40 to 50%).

- Minor actinides homogeneous recycling in driver fuels of SFRs (with a low content of MA, typically 2.5%).

Figure 5.2 Options for future nuclear material management



Note: R = reactor; T = separation/fabrication facility.

Source: Delpech *et al.*, 2007.

Preliminary results show that all the replacement of all PWRs by FRs could be completed before the end of the century. The available plutonium inventory would allow the implementation of a FR capacity reaching 60 GWe by 2090. Another key result is that it is possible to keep spent fuel processing capacities constant during the transition, close to 1 100 tonnes/year between 2040 and 2100. The reprocessing plant would process MOX and UOX spent fuels from LWRs during the two first decades of the transition and MOX from FRs with UOX spent fuels afterwards.

5.3.6 Japanese scenarios

Japan imports most of the energy that it consumes, making its energy supply structure fragile. To enhance its security of supply, the country has developed nuclear power for the last 50 years.

Currently, there are 55 nuclear power plants (28 BWRs, 4 ABWRs, and 23 PWRs) in commercial operation in Japan with a total installed capacity of about 50 GWe. One ABWR and one PWR are under construction and eleven nuclear power plants are under planning. Nuclear power plants provide 16% of primary energy supply and one-third of electricity supply, reducing the dependence of the country on energy import. Furthermore, nuclear power contributes to reaching the climate change policy goals of the country through reducing greenhouse gas emissions from the energy sector. According to the Japanese *Long-Term Outlook for Energy Supply and Demand* (ACNRE/METI, 2005), the nuclear power generation capacity in 2030 is expected to increase to 58 GWe from present 50 GWe and is assumed to remain constant at 58 GWe after 2030.

The country has fuel cycle facilities for uranium enrichment (capacity 1 050 tSWU/year), low-level radioactive waste disposal, and spent fuel reprocessing (capacity 800 tHM/year at Rokkasho). The construction of a mixed-oxide (MOX) fuel fabrication plant is in progress at the Rokkasho site. As a national policy, Japan has promoted the development of a closed nuclear fuel cycle to enhance the efficient use of uranium resources and to reduce high-level radioactive waste. In a first phase, the plutonium issued from the reprocessing of LWR spent fuel will be recycled into LWRs as MOX fuel. The legal framework for the disposal of HLW was promulgated in 2000. Potential sites are now being surveyed in accordance with the law, and construction and operation of facilities are planned to commence by the late 2030s (Maeda, 2005).

As part of its closed fuel cycle strategy, Japan plans to burn TRU in SFRs using MOX fuel produced through advanced aqueous reprocessing and simplified pelletising fuel fabrication. In the scenario studies, the SFRs are assumed to be deployed steadily for commercial use after 2050. The recycling of plutonium in LWR will be stopped before the introduction of fast neutron reactors; Pu and MA recovered in the LWR reprocessing plant around 2050 will be reused in SFRs. MOX spent fuels discharged from LWRs and from fast neutron reactors will be treated together in the same reprocessing plants. Pu and MA recovered from LWR MOX spent fuels will also be reused in the MOX-fuelled fast neutron reactors. The breeding ratios of the fast neutron reactors will be 1.10 (breeding core) and 1.03 (break-even core) and there will be transition from breeding to break-even core according to the plutonium balance.

The fast reactor deployment scenario is shown in Figure 5.3. The switchover from LWRs to SFRs will be completed around 2110. With the SFR cycle, it will take about 60 years to complete the switchover from LWRs to SFRs, a period of the same length as LWR plant lifetime. This strategy will lead to independence from uranium resources early in the 22nd century.

Figure 5.4 shows cumulative natural uranium demands. In 2200, the cumulative demands reach approximately 2.3 million tU and 1.9 million tU, in the LWR once-through and Pu multi-recycling in LWR scenarios respectively, compared to total conventional resources amounting to some 16 million tU (NEA, 2008). In the FR deployment scenario, the cumulative uranium demand decreases to around 0.7 million tU (about 4% of the total conventional resources). The current Japanese uranium demand accounts for 10 to 15% of the whole world demand and it will decrease to approximately 5% during the second half of this century because of the increase in nuclear electricity generation in other countries especially in Asia.

Figure 5.3 Japanese transition scenarios

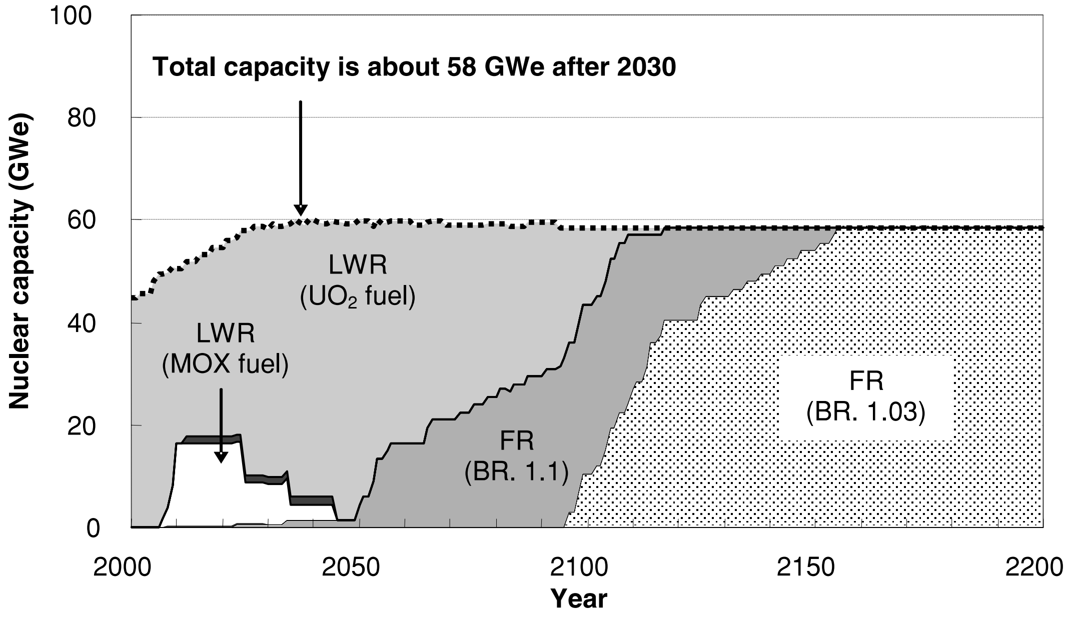
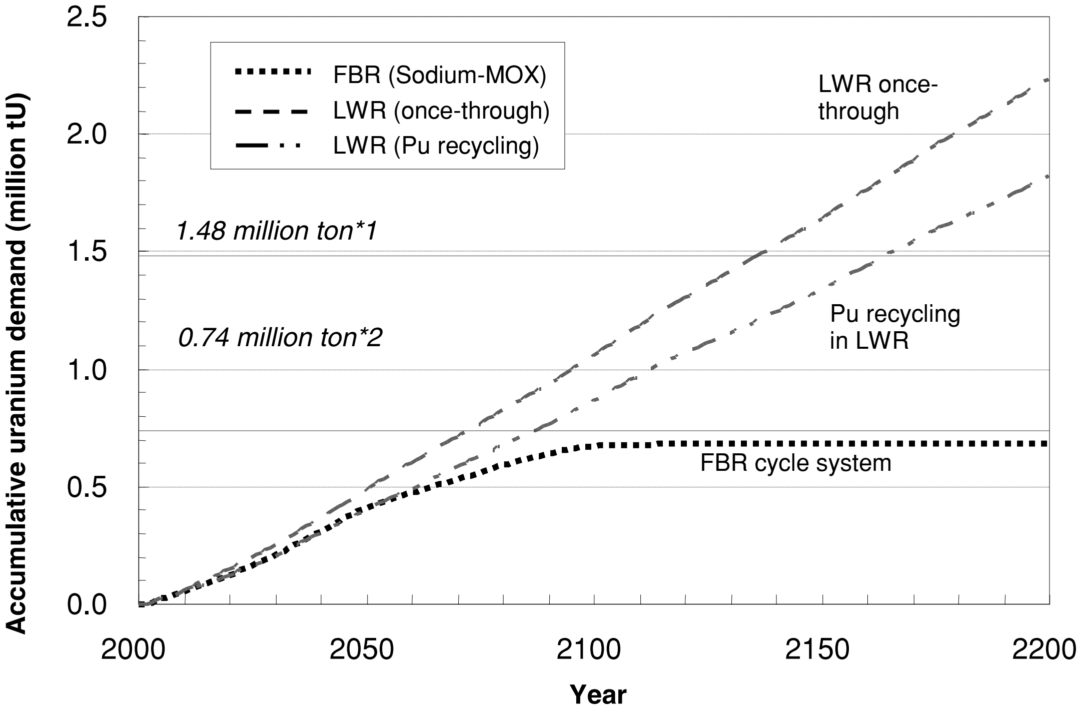


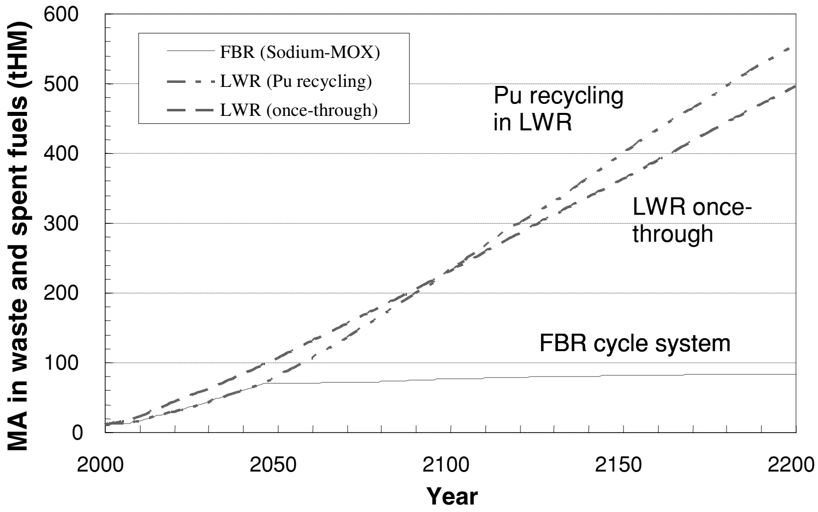
Figure 5.4 Cumulated natural uranium demand (Japanese scenarios)



*1: 10% of total conventional uranium resources.

*2: 5% of total conventional uranium resources.

Figure 5.5 Cumulated amount of MA in HLW (Japanese scenarios)



Source: ACNRE/METI, 2005.

Figure 5.5 illustrates the MA accumulation in high-level radioactive waste, from the spent fuels for direct disposal and the vitrified glasses for Pu recycle scenarios. With direct disposal of LWR spent fuel (both UO_2 and MOX) the MA will continue to accumulate. The MA accumulation in the vitrified waste changes significantly whether LWR spent fuel is reprocessed and Pu recycled in LWRs or not (LWR-MOX or once-through). On the other hand, in the SFR deployment scenario, as MA recovered from LWR reprocessing plants is recycled in SFR fuels, the MA accumulation in waste is estimated to be kept under 100 tHM through the next century.

5.3.7 Russian scenario

Russia has recently seen an increase in energy demand associated with its high rate of economic growth over the last few years. It is planning to meet this growing demand mainly by increasing the use of nuclear power. The main goals for nuclear power development are as follows:

- increasing the nuclear electricity share in total electricity generation to the level of 25-30% by 2030 and 45-50% by 2050;
- closing the nuclear fuel cycle using fast breeder reactors;
- developing non-electricity uses of nuclear power after 2030, including production of synthetic motor fuel and hydrogen; and
- creating an industrial infrastructure for the management of radioactive waste providing reliable isolation from the biosphere, and for the decommissioning of nuclear power plants and fuel cycle facilities.

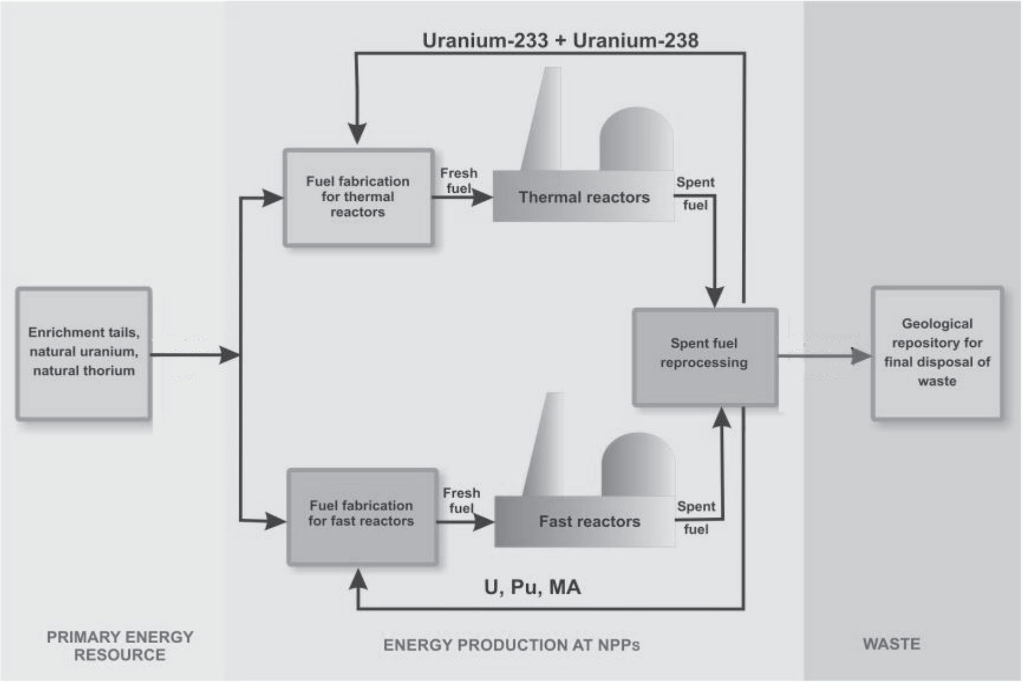
At present, "*The General Scheme for the Location of Electrical Energy Facilities being developed for the period to 2020*" has been approved. In the document, it was proposed to increase the nuclear electricity generation by a factor 1.7 to 2 as compared with its 2007 level. According to the scheme, the total nuclear power capacity would be increased to 33.4 GWe in the moderate option or 39.4 GWe in the maximum option by 2020. A new Russian strategy for nuclear power development up to 2050 is under development. The total nuclear power capacity considered is between 100 and 300 GWe by 2050.

The main tasks related to the development of new technological platform to be fulfilled by 2030 are the following:

- commissioning of the BN-800 (by 2012);
- development of a modified PUREX separation technology and commissioning of a commercial plant for radiochemical reprocessing of LWR spent nuclear fuel (SNF);
- creation of a commercial plant for fabrication of MOX fuel for first series of FBR;
- designing and construction of a few first generation commercial sodium cooled FBRs; and
- R&D work and demonstration of innovative reactors (with lead and lead-bismuth coolants) and recycling fuel technologies.

Figure 5.6 shows the possible structure of equilibrium innovative nuclear power in the second half of the 21st century in Russia. This nuclear power system would contain FBRs providing extended reproduction of fuel from ^{238}U and ^{232}Th and reprocessing facilities for multi-recycling of fuel and fuel fabrication facility for fast neutron reactors.

Figure 5.6 Principal scheme of equilibrium innovative nuclear power in Russia



In order to fulfil these goals, it will be necessary to develop new technological bases for commercial FBRs and closed nuclear fuel cycle. At present, a fast reactor, the BN-800, is under construction. The main mission of the BN-800 and its associated fuel cycle facilities is to master technologies for the sodium cooled fast reactor and closed nuclear fuel cycle, including MOX-fuel fabrication, reprocessing of spent nuclear fuel, fabrication of fuel with minor actinides for its further transmutation in fast neutron reactors. Commercial fast neutron reactors are planned to be deployed after 2030. In the meantime, the growth of nuclear power capacity will be fulfilled by construction of advanced VVER thermal reactors, the mainstream of nuclear power in Russia. Taking into account the 50-year lifetime of these reactors, it is expected that the transition to new technology bases and structure of nuclear power would occur during the second half of this century.

5.3.8 United States scenario studies

Scenario studies for transition from light water reactors to a fast reactor closed fuel cycle have been and continue to be evaluated under the USDOE advanced fuel cycle program. No definitive approach has been selected, and therefore, no specific set of results are presented here. The studies however provide insights into the parameters that are pertinent in evaluating the period of the transition and the potential benefits of transition to the fuel cycle and repository.

The following are some insights from the studies in the United States:

- As nuclear energy production level increases, the continuation of the current once-through fuel cycle practice could lead to unfavourable consequences such as substantial increase in the number of geologic repository sites (depends on site capacity), continued accumulation of reactor-grade plutonium in SNF, and inefficient use of uranium resources. These concerns can be addressed by employing an advanced fast reactor closed fuel cycle (Yacout, 2005).
- The most important assumptions in estimating the transition periods and benefits are the nuclear power growth rate, fuel separation capacity and deployment scheme (especially for the LWR SNF), time lag between LWR SNF discharge and utilisation of recovered reactor-grade plutonium in the fast neutron reactors, capacity of any fuel bank, and fast reactor deployment scheme and conversion ratio. Nuclear annual growth rates between 0% and 2.5% have been considered. Assumptions on spent nuclear fuels have included the use of the Yucca Mountain repository to store the first 63 000 MT of commercial spent nuclear fuels; other cases did not make this assumption. Fast neutron reactors have been typically assumed to be deployed in the 2030 and beyond time frame. For the most part, it has been assumed that demonstration or test facilities could be on-line by 2025.
- The plutonium inventory has significant impact on the deployment of the fast neutron reactors and hence their share of total reactors in the fuel cycle.
- The dynamic equilibrium and static equilibrium ratios of the fast-reactor to total-reactor in the nuclear park could be different and quite dependent on the time interval between LWR SNF discharge and plutonium loading into the fast reactors.
- Most of the analyses have shown that LWRs would be around for the balance of the 21st century. Higher fast reactor conversion ratios could allow an increased fraction of the fleet to be comprised of fast reactors with time, but with a decrease in quantity of transuranics destoyed. However, this penalty may not be as significant as one might initially imagine since an increased fraction of fast reactors in the fleet can help to avoid transuranic production otherwise likely occur in LWRs needed to generate the same amount of nuclear power.

5.4 Findings from illustrative transition scenario studies

A number of transition scenarios have been considered by various countries and regions. Some scenarios have included a complete transition from thermal to fast neutron systems leading at the end point to a fleet compose only of fast reactors with closed fuel cycle. In some cases, it has also been envisioned that intermediate thermal transmutation systems will be deployed prior to the ultimate utilisation of fast reactors.

The intermediate systems could be deployed with the final fast reactor fuel cycle in order to minimise the cost of the advanced transmutation reactor systems, especially when burner fast reactors are more expensive than thermal reactors. However, fast neutron systems are more efficient than thermal neutron systems to burn actinides and leave lower amounts of residual waste. In Europe (notably France) and Japan, the use of plutonium in MOX fuels for LWRs is ongoing or about to be initiated. This option has also been considered in the United States as a way to get the advanced fuel cycle started pending the finalisation of the technologies that utilise transuranic fuels in fast reactors.

5.4.1 Water-cooled reactors will remain a major component of the fleet for decades

Even in countries considering advanced recycling fast reactors, evaluations have shown that the commercial water-cooled reactors will be a major component of the national nuclear fuel cycle infrastructure for the balance of the 21st century, especially with extended life time up to 60 years or more. Since some new LWRs and HWRs are planned to be commissioned in the 2015-2040 time-frame they will be in operation for most of the 21st century.

5.4.2 Potential strategies for burning actinides or breeding fuel

The direct transition into a fast reactor fuel cycle is termed *single-tier* strategy. The inclusion of an intermediate thermal reactor tier results in the so-called *dual-tier* strategy. Some possible single- and dual-tier strategies are summarised in Table 5.1, for a national infrastructure initially containing commercial LWRs.

Table 5.1 Potential single- and dual-tier strategies starting with commercial LWRs

Type	Commercial sector	Intermediate tier	Final tier
1	LWR-UOX		Fast reactor (burner or breeder)
2	LWR-UOX	LWR MOX-Pu	Fast reactor (burner or breeder)
3	LWR-UOX		LWR MOX-TRU burner
4	LWR-UOX	VHTR-IMF-Pu/MA	Fast reactor (burner)
5	LWR → VHTR (UOX)		Fast reactor (burner or breeder)
6	LWR → VHTR (UOX)	VHTR-IMF-Pu/MA	Fast reactor (burner)
7	LWR-UOX	HWR MOX-Pu	Fast reactor (burner)
8	LWR-UOX	LWR UOX FR self-sustaining	ALWR {UOX/M(OX/^{233}U-^{238}U)OX} + Fast reactor (breeder)

Definitions: IMF – Inert matrix fuel; VHTR – Very High Temperature Reactor.

Similar transitions could be envisaged starting with commercial HWRs, e.g., the CANDUs used in Canada, or commercial gas-cooled reactors used in the United Kingdom. The transmutation in LWRs considered during the intermediate period may be achieved not only with MOX fuels but also with other types of fuels such as inert matrix fuels, minor-actinide targets, and thorium fuels.

5.4.3 Flexibility of the transition to fast reactors

In the United States, the recent emphasis has been on the deployment of fast reactors that could be used for burning transuranic elements. In this case, fast reactor designs with conversion ratios lower than 1.0 are being considered. Depending on future demands for electricity and for other nuclear applications, it is conceivable that as uranium resources become scarce these reactors could be altered to have higher conversion ratio.

Designs with high breeding ratio are also being pursued by some member countries, for example Japan, due to initial shortage in transuranics for making fast reactor fuel, consistent with the deployment plan. This is to ensure a successful transition to an advanced fuel cycle using fast reactors in a relatively shorter time period.

In other countries, such as in France, zero breeding gain design may be considered for a transition aiming at a renewal of the thermal reactor fleet, in order to stabilise and minimise all actinide mass flows and inventories.

5.5 Generic issues

Factors that affect the transition period include requirements on the advanced fast reactors and the time required for deployment of advanced technologies for the advanced fuel cycle, including reactors, separations plants and fuel fabrication facilities. Prototype and demonstration fast reactors have been built and operated with various degrees of success internationally. Experiences have been achieved in the EBR-II and FFTF systems in the United States, the Phenix Reactor in France, and the BN-600 system in the Russian Federation, to name a few. If these existing reactor technologies are to be used for the fast reactors for deployment, then the end of the transition period could be well defined.

However, additional requirements may be imposed on the advanced fast reactors depending on country specific requirements and objectives, including their applications for transuranics burning and lower plant costs. Evaluations have shown that this would result in different reactor plant designs, including using advanced core fuel and structural materials, advanced balance of plant concepts, and advanced safety philosophies. These considerations necessitate additional research and development. Consequently, the minimum time to start of transition would depend on the amount of development required for the new fast reactors, unless existing technologies are used initially. Similar considerations apply to the fuel separations and fabrication technologies. These considerations indicate the attraction of an initial LWR MOX fuel cycle in some member countries for starting the transmutation mission.

The following is a summary of the pertinent generic issues and attributes identified from the transition scenario studies that have been performed:

- As nuclear energy production level increases, the continuation of the current once-through fuel cycle practice could lead to substantial increase in the number of geologic repository sites (depends on site capacity), continued accumulation of reactor-grade plutonium in spent nuclear fuel, and inefficient use of uranium resources.

- Improved natural resource management, enhanced security of energy supply, and reduction of radioactive waste volumes and toxicity are key incentives for transitioning to fast neutron nuclear systems. This transition would require the development of advanced fuel cycle facilities that have not been fully deployed in OECD member countries, including fuel reprocessing and fabrication facilities and associated technologies. The transition to fast reactor fuel cycle would require reprocessing of a significant amount of accumulated spent fuel but will reduce the final waste inventories and activities.

- Many OECD countries are considering transitioning from thermal to fast reactors either on country or regional basis. Such evaluations suggest that transition scenarios will be implemented in many, but not all, countries. Transition to fast neutron reactors appears possible in OECD member countries but will occur fully in the latter part of this century or early next century primarily. Thermal reactors will continue to play a major role as their expected lifetime exceeds half a century, first step (up to 2040/2050) to renew the existing fleet and to increase capacities being done with LWR or HWR technology.

- The introduction of fast breeder reactors in a country with a small number of operating nuclear reactors and with limited plutonium reserves will be difficult.

- Alternatively to considering transition scenarios on a country basis, international or regional transition scenarios provide flexibility to transitioning in a given time period. It would however entail the adhering to international laws and regulations designed to ensure safe and secured transfer of large volumes of nuclear materials.

- Transitions to fast breeder reactors that produce fissile materials for use in advanced thermal reactors have been considered by a few of the countries. At the equilibrium state for this approach, enrichment services would not be required for the thermal and fast reactors, per example, the utilisation of thorium fuels in fast reactors for breeding fissile ^{233}U for the thermal reactors.

- Generally, most important parameters or hypothesis to study and to analyse the transition periods and benefits are the nuclear power growth rate, fuel separation capacity and deployment scheme (especially for the LWR spent fuel), time lag between LWR spent fuel discharge, time lag between recycling (out-of-pile period), fast reactor initial fissile inventory and fast reactor conversion ratio (depending of the design), the final waste production (mass, activity and radiotoxicity), the global natural uranium consumption and the non-proliferation issues.

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Chapter 6

FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

Nuclear power provides a significant share (around 15%) of the world electricity supply today and will remain an important energy source for decades, irrespective of individual country decisions to phase out nuclear programmes or to increase the role of nuclear energy in their national policies. The fleet of nuclear units in operation at present is reliable and globally has very good safety and economic performance. Most plants built in the 1980s and 1990s are expected to have lifetimes exceeding 50 years. Simultaneously, new, advanced nuclear reactors and fuel cycles – most of which are based on fast neutron reactors operated in closed fuel cycles – are being developed with the objective of enhancing the safety, economics, sustainability, and proliferation resistance and physical protection of future nuclear systems.

Against this backdrop, the implementation of transition scenarios from thermal to fast neutron systems is likely to be a major aspect of nuclear energy development in the coming decades, up to the end of the century and beyond with the aims to reduce constraints on the resources and to reduce impacts of the wastes. This transition will raise specific issues which need to be addressed timely in order to select the best scenario taking into account many factors, including national policy goals, industrial capabilities and technology preparedness. Analysing the opportunities and challenges raised by the transition period is a prerequisite for policy makers to support a robust decision-making process in this regard.

Fast neutron systems can be operated in breeding or burning modes. Fast breeders could multiply by 50 or more the amount of energy extracted from natural uranium, thereby extending the lifetime of presently known uranium resources to many centuries. Fast burners can eliminate progressively actinides, including plutonium if it is the goal of the strategy adopted. Consequently, they can reduce the period during which radioactive waste requires stewardship, and the number and size of high-level waste repositories needed to dispose of the waste.

While fast neutron systems are attractive at the global level for enhancing security of nuclear fuel supply and reducing the volumes and radiotoxicity of waste, their relevance and viability in a given country highly depends on each national and regional context. In particular, the size of the national nuclear fleet and its expected growth rate are key factors in assessing the interest of introducing fast neutron systems. The radioactive waste management policy of the country also determines the relevance of fast neutron systems as an option for facilitating waste management and disposal.

For countries with a small fleet of reactors in operation and with modest expected growth of nuclear electricity generation, building the infrastructure to support the transition from thermal to fast neutron reactor systems is unlikely to be cost effective but could be considered nevertheless in a broad sustainable development perspective. In such countries, multilateral agreements and international cooperation may be required to ensure the viability of reprocessing and recycling spent nuclear fuel in fast neutron reactors.

Countries with a well defined policy for the direct disposal of spent fuel, including an ongoing programme expected to lead to the opening of a repository for this purpose in the coming years, might have little interest in embarking on the implementation of a transition from thermal to fast neutron systems. On the other hand, for countries where the final disposal of current and future spent fuel and/or high-level radioactive waste remains an open question, fast neutron systems offer an attractive strategy for waste management and disposal.

Although some fast neutron reactors and associated fuel cycle facilities have been built and operated in several countries, nuclear systems based on fast neutrons have not reached the level of technology preparedness and industrial maturity as that achieved by thermal nuclear systems. Therefore, research and development efforts will be required to design and develop those systems at the industrial scale.

The challenges raised by fast neutron systems are not different from those to be addressed by nuclear technology in general. The objective is to design, build and operate reliable, safe and cost-effective reactors and fuel cycle facilities, including fuel fabrication and reprocessing plants, capable of delivering the expected fissile material management services.

In light of the broad range of scientific and technical issues to be tackled by R&D programmes, international endeavours might be necessary to promote collaborative efforts for reducing the financial burden of each participating country and creating synergies within multinational teams.

Long lead times are basic features of nuclear energy policies, and transition from thermal to fast neutron systems is no exception to this rule. It will take several decades to replace the fleet of thermal reactors in operation today by fast neutron reactors. Furthermore, the ultimate goals of transition scenarios, i.e., build and operate a self-sustaining fleet of fast breeders and/or implement full recycling of all actinides, will not be reached before roughly a century.

In this context, long-term planning and stable global energy policy are prerequisite for the successful implementation of transition scenarios. The stability of governmental energy policy is essential to ensure that the role of nuclear energy is defined in a long-term perspective and that the goals remain unchanged over decades.

There is a wide range of technical options for fast neutron reactors, fuels and fuel cycles. In order to optimise the utilisation of fast neutron spectra it is essential to analyse the capabilities of the systems considered taking into account the policy goals pursued. The selection of relevant technologies should rely on a thorough analysis of scientific and technical parameters from the viewpoint of their potential contribution to reaching the policy goals.

Economic aspects have to be analysed thoroughly taking into account short- and long-term considerations. Recognising that fast neutron reactors generally have higher construction costs than thermal neutron reactors, one of the key objectives of R&D on fast neutron systems should be capital cost reduction.

The technology choices concern not only the end point, i.e., the fleet of fast neutron systems at equilibrium with or without standard thermal reactors, but are very important for the selection of transition paths and mixes of fast and thermal systems during several decades. The most important parameters to consider for the transition period, besides the need to ensure adequate supply of fissile materials for each reactor type in operation, are the economics of various fuel cycle facilities and socio-political aspects such as public acceptance and proliferation resistance.

The introduction of advanced technologies often raises public concerns which need to be addressed timely though stakeholder involvement and dialogue between policy makers, industrial actors and civil society. Such interactions are especially relevant when undertaking the implementation of transition scenarios in the light of the long lead times involved.

Even in countries with a well developed nuclear energy infrastructure and industry, the transition to fast neutron systems will require significant efforts of adaptation and the commissioning of new facilities. The infrastructures to be reviewed and eventually adapted include legal and regulatory frameworks, laboratories and other research equipment and human resources.

Education and training programmes are important for the nuclear sector in general but the development of advanced fast neutron systems will require specific qualifications and skills which will need to be acquired through dedicated university and technical school programmes. Human resource management will be a key element for the success of strategies put in place for renaissance and transitioning from thermal to fast neutron systems.

Lessons learnt from the industrial experience with fast neutron reactors and reprocessing/recycling of fissile materials in some countries could help future developments and international collaborations. In this connection, knowledge management should not be overlooked to avoid losing the competencies of ageing workforce and preserving the key outcomes and findings from previous experience.

Proliferation resistance issues are important for all nuclear energy systems and should be assessed carefully taking into account intrinsic and extrinsic measures in order to select the best options during and after the transition period. The effectiveness of international safeguards system could be enhanced by innovative approaches to fuel cycle service supply relying on multinational facilities. At the national level, co-location of reactors and fuel cycle facilities is among the measures which can strengthen proliferation resistance and physical protection effectiveness.

International co-operation is a very efficient means to share knowledge, know-how and infrastructure, reducing R&D costs supported by each country and enhancing the overall effectiveness of development efforts. At the stage of industrial deployment, multinational endeavours might be a key element for the economic viability of transition scenarios.

Further efforts to realise transition from thermal to fast neutron reactors and their associated fuel cycles are important in view of preservation of the environment and effective utilisation of natural resources, and all of the recommendations in this report should be considered according to each country's situation.

The findings, conclusions and recommendations included in this report are of generic nature and do not necessarily apply to all countries. Country specific circumstances are major drivers in the assessment of alternative options and strategies for future nuclear energy development. While further efforts to implement fast neutron reactors with closed fuel cycles are important for effective utilisation of natural resources, the relevance of transition from thermal to fast neutron systems may vary from country to country.

Appendix 1

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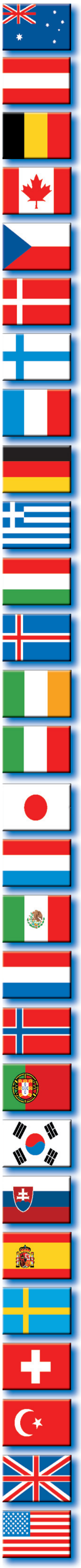
Appendix 2

GLOSSARY

ADS	Accelerator Driven System
EU	European Union
FR	Fast reactor
GAINS	Global Architecture of INS Based on Thermal and Fast Reactors Including a Closed Fuel Cycle
GFR	Gas-cooled fast reactor
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership
HLW	High-level waste
IAEA	International Atomic Energy Agency
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
INS	Innovative Nuclear Energy Systems
IPCC	Intergovernmental Panel on Climate Change
LFR	Lead-cooled fast reactor
LWR	Light water reactor
MA	Minor actinides
MDEP	Multinational Design Evaluation Programme
MOX	Mixed oxide fuel
MSR	Molten salt reactor
NDC	NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle
NWPA	Nuclear Waste Policy Act

PHWR	Pressurised heavy water reactor
PWR	Pressurised water reactor
P&T	Partitioning and transmutation
SCWR	Supercritical water-cooled reactor
SFR	Sodium-cooled fast reactor
SWU	Separative work units
TRU	Transuranic elements
USNRC	United States Nuclear Regulatory Commission
VHTR	Very high-temperature reactor

OECD PUBLISHING, 2, rue André-Pascal, 75775 PARIS CEDEX 16
PRINTED IN FRANCE
(66 2009 051 P) ISBN 978-92-64-06064-7 – No. 56711 2009



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

The renewed interest in nuclear energy triggered by concerns about global climate change and security of supply, which could lead to substantial growth in nuclear electricity generation, enhances the attractiveness of fast neutron reactors with closed fuel cycles. Moving from the current fleet of thermal neutron reactors to fast neutron systems will require many decades and extensive RD&D efforts. This book identifies and analyses key strategic and policy issues raised by such a transition, aiming at providing guidance to decision makers on the best approaches for implementing transition scenarios.

The topics covered in this book will be of interest to government and nuclear industry policy makers as well as to specialists working on nuclear energy system analyses and advanced fuel cycle issues.

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(66 2009 05 1 P) € 40
ISBN 978-92-64-06064-7

www.oecd.org

9 789264 060647