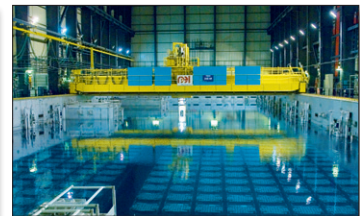


Trends towards Sustainability in the Nuclear Fuel Cycle



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Foreword

In 2002, the OECD Nuclear Energy Agency (NEA) published a report on *Trends in the Nuclear Fuel Cycle*, in which it examined current and expected changes in the fuel cycle, so as to lay the foundation for applying more quantitative approaches to assessing progress. Since that report, developments have occurred in connection with the development of nuclear energy and the fuel cycle. In particular, Generation IV reactor systems and research and development into fuel cycle concepts, such as partitioning and transmutation, have spurred new thinking. In addition, changes have occurred, and are expected to continue to occur, in approaches to uranium use, reprocessing, recycling and waste disposal. Furthermore, international initiatives have sought to co-ordinate and integrate work related to the fuel cycle, recognising the need to ensure that any such developments do not increase the potential for proliferation.

This report assesses trends in the nuclear fuel cycle over the past ten years, for the next ten years and for the longer-term future with a specific focus on considerations of sustainability. As part of that process, a number of criteria that define sustainability have been adopted for use in the comparative assessment. This is necessary since there is no single consensus on the meaning or evaluation of sustainability in the nuclear fuel cycle.

In performing the comparative assessment, a review was carried out of the trends towards sustainability that have been driven by changes in technologies and therefore largely stem from industry needs for improved performance and continued demonstration of progress towards economic, safety, environmental and safeguards goals. At the international level, the report considers the global efforts made in relation to the fuel cycle, which have become the dominant mechanism for bringing about major changes in how the fuel cycle is currently implemented.

However, there is a limit to what industry can achieve in these areas; so national strategies and policies in a range of representative countries have been examined to see how well, if at all, they have supported the trend towards more sustainable use of nuclear energy.

Overall the report identifies a range of improvements that have been evolutionary in nature and then considers the likelihood of more revolutionary changes such as moving towards closed fuel cycles, either partially (plutonium only) or completely (plutonium and minor actinides), and more advanced waste management approaches.

The current report forms part of the programme of work of the OECD/NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) and has been endorsed by that Committee.

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Executive summary

Over the last decade, there has been increased recognition of the role that civil nuclear power could play in terms of energy security and greenhouse gas reductions, especially if viewed over the long time frames of the expected lifetimes of current reactor technology. Nuclear energy presents a number of attractive features: it generates essentially no greenhouse gas emissions during production (limiting climate change) and no air pollution (avoiding very detrimental health effects); it is largely immune to the intermittency and unpredictability exhibited by wind and solar energy; it uses fuels with very high energy density (easing the establishment of significant strategic stockpiles) with resources and fabrication facilities distributed in diverse and (mostly) geopolitically stable countries. It therefore contributes to security of supply and offers a reliable energy source for countries where demand for electricity is growing rapidly. Such countries, including China and India, have thus been pursuing rapid deployment of nuclear energy and related fuel cycle elements, including reprocessing and recycling. Nuclear energy can be economically competitive, especially if carbon pricing is considered and financing costs are controlled. Certainly the sector still faces a number of challenges: first and foremost the requirement for continuous enhancement of safety and safety culture (reinforced in particular by the accidents of Three Mile Island, Chernobyl and the more recent accident at Fukushima Daiichi), the need to control the spread of technologies and materials that may be used for non-peaceful purposes and to implement final solutions for radioactive waste disposal and management. If the nuclear sector is to continue to make a substantial contribution to meeting the world's energy demand, such challenges require consistent effort, while developments in reactor and related nuclear fuel cycle technologies should be pursued to enhance longer-term sustainability.

It is in this context of sustainability that this report has been written, with the stated intent to consider the changes in the nuclear fuel cycle that have occurred over the last decade, or are expected to occur over the next few decades. An ad hoc expert group was established to undertake this task, comprising representatives from government agencies, research organisations and the nuclear industry involved in various aspects of nuclear fuel cycle development.

Naturally, in order to carry out an evaluation of whether and how fuel cycle developments affect the sustainability of nuclear energy, a definition of sustainability is required. The brief appraisal of some previous initiatives related to sustainability conducted in Chapter 1 showed no consensus on unequivocal definitions or approaches to a sustainability assessment of the nuclear fuel cycle. Therefore the following set of key elements defining sustainability were identified, in conformity with the methodology of the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles: environment, resource utilisation, waste management, infrastructure, proliferation resistance and physical protection, safety and economics. These selected elements provided a framework for a qualitative sustainability assessment of fuel cycle technologies and their expected future developments, forming the basis of the findings and conclusions of the study. Recognising that the selection of nuclear fuel cycle options is mainly driven by country-specific circumstances that ultimately determine national strategies, no comparative assessment of such national options has been undertaken.

Chapter 2 explores the role of nuclear power in the world's energy supply, before outlining the current fuel cycle, its constituent stages, its status of development and the options being considered. Chapter 3 provides an in-depth discussion of the technical developments over the past decade and those expected in the future. Chapter 4 considers developments in overall trends, technological aspects, national energy policies and international efforts, as set against the sustainability elements. Chapter 5 draws conclusions and recommendations.

The fuel cycle

The expression “nuclear fuel cycle” refers to the chain of processes whereby nuclear fuel is produced and managed before (front end), during (reactor operations) and after (back end) its use in a reactor for energy generation. Chapter 2 provides a description of these processes from uranium mining to fabrication into fuel assemblies, the trends in fuel utilisation and burn-up in the reactor, and the back-end processes of managing the spent fuel.

Currently there are two major options in commercial use for irradiated fuel management: the “once-through cycle”, where the fuel is used once and is then treated as a waste for subsequent disposal, and the partial recycling option where the spent fuel is reprocessed to recover unused uranium and the plutonium for eventual recycling in reactors, partially closing the fuel cycle.¹ Such partial recycling reduces the amount of spent fuel and high-level waste to be disposed of, while lowering the supply requirements for natural uranium.

Fast reactors, of which currently only a few are operational or are being deployed, are suited for multi-recycling of fissile and fertile materials. This is because they operate in fast neutron spectra, where fertile isotopes can be transformed into fissionable materials allowing a more effective use of the fuel. In such reactors it is even possible to generate more fissile material than the amount used, leading to a net increase of fissionable isotopes. This process is referred to as breeding and reactors designed to achieve it are termed fast breeder reactors. The ultimate goal of introducing fast reactors is to fully close the fuel cycle, where all actinides would be recycled continuously until they fission and only reprocessing losses go to waste, producing nearly actinide-free waste. However, even closing the fuel cycle leads to a need to manage residual actinides (from losses) and fission products, since the process is not completely efficient.

Developments in the fuel cycle and their impact on sustainability

Uranium – a key driver

As projections have not indicated immediate constraints in terms of available resources, there has been little incentive to close the fuel cycle or to invest significantly in advanced fuel cycle options. According to the 2009 edition of the NEA/IAEA *Uranium: Resources, Production and Demand*, uranium resources are expected to be sufficient for at least another 100 years of supply (at 2008 reactor requirement levels) and production is expected to be more than adequate to meet the demand in the near term, even for high growth scenarios, provided that existing and committed plans of capacity expansion are achieved in a timely manner.

However, the large number of new reactors in non-NEA countries, the recent plans for new build and the prevalent use of a once-through fuel cycle, combined with the

1. This “partially” closes the fuel cycle, in that U and Pu are recovered for recycling in LWRs. Currently only mono-recycling of U and Pu is being practiced.

generally increased mining costs and challenging approval processes, in association with the depletion of secondary uranium resources,² have caused significant changes in the uranium market over the last decade. Since the early 2000s, uranium prices have generally increased and become more volatile as the emphasis has turned to the need to increase primary resource capacity. The need for timely availability of natural uranium has played an increasingly important role in terms of security of supply for utilities and governments, as exemplified by the progressively longer-term supply contracts, the build-up of strategic stockpiles and the tendency of large reactor constructors to move into uranium mining in order to secure supply and to hedge against the rising prices of natural uranium. The demand from non-NEA countries for uranium resources will impact NEA countries during the next decade and certainly during the following decades. Further increases in the price of uranium and in price volatility will influence fuel cycle decisions in NEA countries.

In order to keep up with worldwide uranium demand and to adapt to these generally altered market conditions, uranium resources have to be developed through new mining projects or the expansion of existing capacity. Achieving existing and committed plans of capacity expansion in a timely manner is essential, but will require significant investment. Even with favourable market conditions, this will be very challenging for the industry, due to the scarcity of financial resources, but principally owing to the considerable time necessary for the development of uranium mines in most jurisdictions, and the challenge of keeping mine production at or near production capacity.

Although these conditions have not led to major breakthroughs in fuel cycle technologies and strategies to date, the nuclear sector has undergone a continuous evolution, driven mostly by the industry, with incremental changes in mainstream reactor design and operation, and associated fuel cycle facilities, aimed at their optimisation.

Evolutionary trends

In the **front end**, these changes include the development of *in situ* leaching in uranium mining and the promulgation of best practices, with improved environmental performance and reduced occupational radiation exposures. The expansion phase in mining spurred by the generally stronger uranium market has encouraged newer, less-established mining companies and producer countries to enter the market. This may pose challenges as new entrants may not be as aware of current international standards and optimal methods; in this sense the adoption and promulgation of best practices are of particular importance.

With regard to conversion, capacities appear adequate, as seems to be the case for enrichment, if the trend towards replacement of gaseous diffusion with centrifuges continues at the current rate, and will be enhanced if laser enrichment achieves commercial implementation. Centrifuge enrichment features high modularity and much lower relative energy consumption and carbon emissions in comparison to the diffusion process, and its increased use (from about 20% of the enrichment market in 2001 to nearly 40% in 2010) and eventual complete displacement of diffusion technology brings a number of benefits (notably in terms of environmental impact, waste management and the economics of the plants). However, the potential use of centrifuges for proliferation means that adherence to international safeguards is increasingly important.

In terms of **reactor operations**, light water reactors have remained the predominant reactor type worldwide. Such systems will continue to dominate up to the latter part of

2. Resources obtained from down blending of highly enriched uranium from nuclear warheads, stocks held by governments or utilities and recycled materials. Until recently these have significantly contributed to meeting uranium demand.

the century, with some prospective alternative uses such as small and medium reactors and high-conversion thermal reactors. The next few decades will also see the continued deployment of Generation III/III+ reactors and the phasing out of all but the newer Generation II designs. This, in itself, adds significantly to the enhancement of the sustainability elements in the areas of safety, economics and environmental protection, as these newer designs benefit from lessons learnt with the previous generations of reactors upon which they are based. However, their deployment will greatly depend on conducive market conditions favouring low-carbon technologies and means to ensure that nuclear construction risks are not perceived by investors as disproportionately high.

Partial recycling has seen some expansion in recent years (in France in particular, but also in other countries) and is expected to grow further, with improvements in resource utilisation and waste management. To date, nine countries have used or are using reprocessing. Further uptake of reprocessing/recycling in NEA countries has however been rather slow, held back essentially by political decisions and partly by limited reprocessing capacity (currently restricted to five countries) and issues regarding commercial competitiveness.

More decisive trends in reactor operations occurring in the last decade and expected to continue in the next decade include: the optimisation of fuel assembly designs and behaviour, the gradual increase of load factors and power upratings, the adoption of higher burn-ups and longer fuel cycles as well as system life extension in reactor operations. Whereas most of these changes have been motivated by the industrial drive to enhance efficiency, reliability and ultimately the economics of systems and facilities, in many cases they have also benefitted, to varying extents, sustainability aspects such as safety, environment, resource utilisation and waste management. Some of these changes have also posed new challenges: for instance those associated with increasing burn-up, including the potential impending requirements to re-license some enrichment plants (due to criticality constraints from higher initial fuel enrichment), or its back-end implications, as increased transuranic fission and activation product inventories are generated in spent fuel from higher burn-ups along with increased decay heat and neutron sources.

In the **back end** disposal of spent fuel and high-level waste remains the principal issue. Deep geological repositories have been widely accepted as the preferred option, but no repositories are yet in operation. Progress has been achieved in several countries (e.g. Canada, Finland, France, Sweden, Switzerland and the United Kingdom) through greater involvement of stakeholders in decision making, the reinforcement of legal and institutional frameworks, and further advancements in technologies through the experience acquired in underground laboratories. Concepts of retrievability and reversibility have been more widely considered.

As the implementation of permanent repositories is requiring very long time frames, extended operational periods of interim storage facilities are necessary, especially with an open fuel cycle. This raises the need for a better understanding of degradation mechanisms of the irradiated fuel in different storage systems, which may affect its longer-term integrity and retrievability. Further challenges include the regulatory activity (safety, security and safeguards) and capabilities to license repositories which will require new approaches, increased stakeholder confidence and knowledge retention throughout the very long periods needed for the repository development.

The concept of regional and transnational repositories has also been discussed in recent years, with particular significance for small and densely populated countries where siting a deep geological repository may not be either economical or environmentally possible.

Other evolutionary changes in the back end of the fuel cycle have occurred with reprocessing technologies, which have achieved greater efficiency, a reduction of the

level of discharges to the environment, higher flexibility and enhancements in the ultimate vitrified waste.

Overall impacts on sustainability

- Environment:** In general, the trends identified are either neutral or slightly beneficial with respect to environmental impact over the last decade or up to 2020. Of particular relevance to this sustainability element is progress in areas of mining (*in situ* leaching and much improved mining practices), enrichment (centrifuges displacing diffusion), reactor operations (higher load factors and upratings) and disposal of spent fuel and high-level waste (progress with deep geological repositories and stakeholder engagement). Further expansion in the adoption of recycling would also help reduce spent fuel interim storage needs.
- Resource utilisation (including availability of resources and security of supply):** In general, the trends identified are either neutral or towards improvements in resource utilisation (in particular for the next decade). Longer fuel cycles lead to slightly less efficient resource utilisation. Increased plant capacity has added to uranium ore, conversion and separative work unit demand. With the depletion of secondary uranium resources, demand for primary supplies has increased and higher uranium ore prices have stimulated new prospecting and commissioning of new mines, while *in situ* leaching has opened up new resources. A prospective increase in the use of mixed oxide and reprocessed uranium fuel would have a significant beneficial impact on resource utilisation and resource availability.
- Waste management:** The overall trend has been positive, with small incremental benefits having been achieved in most areas of the fuel cycle. In particular, in the front end, the consolidation of best practices and, increasingly, the introduction of less polluting technologies, such as *in situ* leaching and centrifuge enrichment, have reduced waste generation. In the back end, sustained efforts in reducing discharges to the environment from operation of nuclear reprocessing facilities have been significant. In addition, progress has been achieved in reducing the amount of low- to intermediate-level radioactive waste and the industry has been implementing methods that optimise volume reduction and conditioning of these wastes. Reprocessing and recycling in certain countries have also led to the reduction of spent fuel inventories and, in parallel, removal of most of the fissile material in the ultimate waste for disposal alleviates the long-term waste burden. However, clearly the implementation of deep geological disposal remains a key challenge for the industry and for governments, with opinion polls in many countries suggesting that this still represents a fundamental objection to the expanded use of nuclear energy.
- Infrastructure:** Over the last decade, new infrastructure has been required in a number of areas to meet changing demands in the fuel cycle (*in situ* leaching, centrifuges, fuel design for higher enrichment, dry storage). Strong pressure will derive from the expected trends to partially recycle in light water and heavy water reactors and further longer-term developments.
- Proliferation resistance and physical protection:** Overall the trends identified over the last decade or up to 2020 are either neutral or slightly beneficial with respect to proliferation resistance and physical protection. The only significant impact has been from the consolidation of mixed oxide fuel utilisation which has enabled the consumption of existing plutonium stocks while also degrading the isotopic composition of the remaining plutonium in the spent (mixed oxide) fuel, thus reducing its potential attractiveness for non-peaceful uses. In addition, the tendency to adopt centralised facilities for interim storage is favourable to proliferation resistance and physical protection. Any wider spread of reprocessing

or enrichment carries with it proliferation challenges, which continue to be the subject of national and international efforts to enhance the safeguards and non-proliferation regimes.

- **Safety:** For the last decade, most of the trends identified have had little impact on the safety of the fuel cycle, some of the main exceptions being:
 - A beneficial impact from the further spread and consolidation of best practices in mining and milling.
 - A positive effect from the move to centrifuge enrichment (centrifuge cascades can be considered slightly safer than diffusion cascades because the UF₆ inventory is orders of magnitude lower).
 - Benefits from improved fuel behaviour.
 - A slightly negative effect from higher initial enrichments, because of the unfavourable impact on criticality safety.
 - In terms of operation of facilities, a significant decrease in doses to workers and a reduction in off-site emissions.
 - In the back end, for countries implementing reprocessing and recycling, some relaxation in criticality constraints and safeguards requirements enabled by the removal of the majority of the fissile material in the final waste form going to a repository.

Improvements are expected from the introduction of Generation III reactors, which have much lower core damage frequencies than Generation II and utilise enhanced safety features, and in some cases more passive safety systems.

- **Economics:** For the last decade the overall trend has been positive, with beneficial effects deriving from a larger deployment of certain technologies (e.g. *in situ* leaching and centrifuge enrichment in the front end). Regarding the operation of reactors, improvements have been driven by the utilities aiming for incremental gains and leading to increased capacity factors. Higher uranium and conversion prices have been detrimental, but the effect on the overall economic competitiveness of nuclear energy is slight because they represent only a small proportion of the overall generating costs. Generation III/III+ reactors are designed to improve uranium utilisation and to reduce spent fuel, providing economic benefits to utilities. However, new build has seen a significant increase in costs and the industry is facing a major challenge to reduce construction times and capital costs.

National initiatives

Chapter 4 looks at progress at the national level in four groups of countries:

- Countries actively pursuing nuclear power programmes (e.g. China, India, Russia).
- Countries with a mature nuclear power programme and strong policy support (e.g. Finland, France, Japan and the Republic of Korea).
- Countries with a mature, stable and slowly evolving nuclear power programme (e.g. Canada, the United States).
- Countries where policies have not favoured, or have had a negative impact on the development of nuclear power programmes, or where there is not a clear policy (e.g. Belgium, Germany, Italy).

Generally, only the mature nuclear countries (other than the United States) or those with plans for major expansion have continued progress with introducing back-end

elements of the fuel cycle, partly driven by the need to manage the volumes of spent fuel and partly by the desire to re-use uranium and plutonium as fuels. Research and development has, however, been maintained in many countries.

Other countries have not formulated a final disposal policy, with many of these also contributing to international efforts looking at advanced options.

Overall, while technological progress has occurred across the fuel cycle, the enhancement of sustainability *per se* has not been a major driver of policy changes over the past decade and this is not expected to change significantly in the near future. Government initiatives to specifically foster sustainability have been very limited.

Advanced fuel cycles

The evolutionary trends described in this report, which have characterised fuel cycle technology over the last decade and which are expected to continue in that to come, are leading to continuous incremental improvements in sustainability. However, the advent of advanced fuel cycle technologies would lead to significant changes in sustainability. The commercial deployment of Generation IV nuclear reactors is a key step in this respect. Developed with the objective of enhancing safety, economics, sustainability, proliferation resistance and physical protection of future nuclear systems, these reactors also hold the promise of opening nuclear applications beyond today's electricity production (e.g. for process heat and hydrogen production). Several such reactors are based on fast neutron spectra and are intended to be operated within closed fuel cycles. Full closure of the fuel cycle through the introduction of fast breeder reactors and their fully integrated cycles would greatly decrease the requirement for fresh uranium, prolonging the lifetime of resources whilst offering waste minimisation advantages. Fast reactors used as burners in symbiotic configurations with light water reactors (for instance in "double strata" schemes) or with heavy water reactors can specifically target advanced waste management solutions, pursuing the sustainability objective of reducing the mass and radioactivity of wastes going to final disposal.

In any case, the deployment of fast neutron (including some Generation IV) systems and eventually the transition from thermal reactors to fast reactor fleets will require significant efforts of adaptation, increased investment and the commissioning of new facilities even in countries with well-developed nuclear industries. Infrastructures such as laboratories and other research equipment, legal and regulatory frameworks, facilities for the management of recyclable fissile and fertile materials as well as human resources will have to be reassessed and deployed.

Any transition towards Generation IV systems would occur progressively and over an extended time period. In addition, likely transition scenarios would encompass mixed reactor parks of light water and fast reactors, with reprocessing and recycling remaining key components.

Numerous countries have already devoted extensive efforts to the research and development of advanced reprocessing methods. These have often been aimed at the development of advanced processing techniques for the separation (partitioning) of minor actinides for their subsequent transformation (transmutation) into shorter-lived elements, either in fast reactors or in accelerator-driven systems. Research and development on advanced separation methods has also been driven by the interest in process optimisation and enhancement of proliferation resistance features by moving towards technologies that do not extract pure plutonium.

Another long-term option could be the use of thorium, and in particular the adoption of thorium-based fuels in closed fuel cycles, which is appealing in terms of resource utilisation. However, this will depend on the price of uranium as well as recycling and back-end costs, and still requires considerable research efforts and technological

developments, as well as feasibility and economic studies to prove their commercial viability.

In general, progress in most areas linked to the introduction of advanced options, including the development of Generation IV reactors, their advanced fuels, new conditioning processes, and the characterisation and optimisation of waste streams, will entail substantial research and development. Effective progress will need a holistic view of the overall economics of the fuel cycle and will crucially depend on co-ordinated research. This calls for continued international co-operation through programmes like the Generation IV International Forum and the International Project on Innovative Nuclear Reactors and Fuel Cycles, but also the support and involvement of governments in trying to secure the technological knowledge for new nuclear applications.

Recommendations

1. Work should continue towards developing a single set of simple and universally agreed upon indicators that can be used to assess the sustainability aspects of the nuclear fuel cycle.
2. To support nuclear development, governments would need to:
 - a) ensure that the necessary approval processes are as efficient as possible;
 - b) ensure that there is a longer-term plan for assuring resource sustainability, given the long timescales of nuclear power plant operations;
 - c) encourage efforts and technological investment to develop uranium from conventional and unconventional sources.
3. Governments and industry should work together to ensure that best mining practices are adopted by all players, especially new entrants to the market and developing countries with less established regulatory systems.
4. A holistic view of the overall economy of the fuel cycle (including long-term waste management) should be developed, which carefully assesses the respective advantages and disadvantages.
5. For those countries wishing to pursue nuclear development, government fiscal policy must support energy policy so that industry can better manage risk, particularly as it relates to the implementation of new technology characterised by long lead times. Market incentives could also be implemented to encourage investment in low-carbon technologies such as nuclear power.
6. Progress towards implementation of deep geological repositories must remain a high priority as it is crucial for the future sustainability of nuclear energy, regardless of the fuel cycle strategies adopted.
7. Research on spent fuel interim storage should continue, including comprehensive studies on degradation mechanisms as well as regular inspections of spent fuel (in particular that having been subjected to high burn-up).
8. Research, development and demonstration (RD&D) will still need to be carried out and in many instances further enhanced, in order to optimise solutions and to move from results obtained in laboratories and pilot facilities to industrial-scale implementation in waste repositories.

9. Governments will need to ensure that adequate regulatory frameworks and associated resources (both infrastructure and human) are available in those countries wishing to implement the transition to fast neutron systems.
10. International co-operation on advanced reactors and separation technologies should be further promoted as the most effective way of closing the fuel cycle and reducing long-lived radioactive waste inventories.
11. Research on advanced fuel cycles should seek integrated holistic approaches, encompassing assessments of system-wide technologies from advanced fuel development through to recycling (separation) and waste forms.

1. Introduction

1.1. Introduction

Over the last decade, the political and public attitude to nuclear electricity generation has seen marked changes; with increasing recognition of the role that civil nuclear power could play in terms of energy security and greenhouse gas (GHG) reductions. This has begun to translate into energy and environment policies embracing prospects of greater use of nuclear energy and new build projects. As a result, recent reports by the OECD Nuclear Energy Agency (NEA, 2008), the International Energy Agency (IEA, 2009; 2010) and the International Atomic Energy Agency (IAEA, 2008) had projected significant growth in the use of nuclear energy.

However, following the accident at the nuclear power plant of Fukushima Daiichi, in Japan, deviations from these predictions are likely to occur. Caused by the double natural catastrophe of a seismic event of very severe intensity and a consequent unprecedented tsunami, which hit the north-eastern coast of Japan in March 2011, the accident has affected public support and triggered immediate political and regulatory reactions, whose impacts have yet to be fully understood.

The event reinforces the overriding precedence of continuous enhancement of safety if the nuclear sector is to continue to make a substantial contribution to meet the world's energy needs, building on the sound foundation of existing reactor and fuel cycle technology, infrastructure and resources (natural resources and human capital). Developments in reactor and related nuclear technologies, including evolutions in the manner of implementing the nuclear fuel cycle (NFC) will be crucial for the longer-term sustainability.

Sustainability is a multi-faceted objective for any energy production technology covering economic, environmental and socio-political aspects, and elements of the nuclear fuel cycle have impacts across all facets. Currently the greater part of today's installed reactor base worldwide operates on a once-through nuclear fuel cycle using slightly enriched uranium fuel as uranium oxide (UOX) fuel. More than 25% of the total used fuel that has been discharged to date has been reprocessed with the separated uranium and plutonium being stored for future use or recycled in, respectively, reprocessed uranium oxide (REPU) and mixed oxide (MOX) fuels. Some 10% of all reactors use mixed oxide fuel with a slightly smaller percentage of reactors recycling reprocessed uranium into fuel. Future nuclear power programme decisions will increasingly be based on strategic considerations involving the complete nuclear fuel cycle, including requirements related to:

- availability of resources and fuel supply assurances;
- uranium utilisation;
- fuel cycle flexibility;
- waste minimisation;
- proliferation resistance (PR), safety and licensing and, obviously;
- cost competitiveness.

Several of these requirements relate to dimensions of sustainability which will constitute one of the focal points of this report. Its objectives are to update the 2002 NEA report *Trends in the Nuclear Fuel Cycle: Economic, Environmental and Social Aspects* (NEA, 2002) while evaluating whether developments in the nuclear fuel cycle have affected the sustainability of nuclear energy.

Naturally, in order to carry out this evaluation, a definition of sustainability is required against which an assessment of the developments can be conducted. In doing this assessment, the report considers what has been done in the NFC in the past ten years and what is expected to occur over the next ten years, as well as the longer-term prospects up to 2050. Recognising that the selection of nuclear fuel cycle options is driven by country specific circumstances that ultimately determine national strategies, no comparative assessment of such options has been undertaken. It should be noted that the bulk of the study was conducted prior to the Fukushima Daiichi accident and, at the time of publication of the work, the full implications of the event are still unfolding; thus the resulting impact on fuel cycle trends is difficult to predict.

This chapter provides a brief review of the previous report and some other relevant programmes and studies, before discussing and agreeing on a definition of sustainability. This definition will be used in the following chapters and will form the basis of the findings and conclusions. Chapter 2 explores the role of nuclear power in the world's energy supply, before outlining the current fuel cycle and the options being considered. Chapter 3 provides an in-depth discussion of the technical developments. Chapter 4 considers developments in the overall trends, in technological aspects, in national energy policies and through international efforts, against the sustainability elements. Conclusions and recommendations are drawn in Chapter 5.

1.2. Summary of the previous report

The previous NEA report (NEA, 2002) was based on work conducted in 1999-2000. The report described the various steps of the nuclear fuel cycle, giving a description of developments and trends at the time, and their potential for competitiveness and sustainability improvements. In conducting such an appraisal, the report focused on near-term (next 25 years) and mid-term (25-50 years) developments. It recognised the special characteristics and unique capabilities of nuclear energy that make many scientists and experts (as well as part of the public opinion) support the importance of its potential role in the world's energy supply mix. On the other hand, the previous report also discussed arguments used by opponents to the technology to claim that nuclear energy can never be considered sustainable.

The study noted that there was no agreed mechanism for assessing sustainability in a quantitative manner. It examined two techniques: the life cycle analysis (LCA) and the multi-criteria analysis (MCA). The former is based on the identification and use of a set of criteria to quantify and compare the multiple impacts that the energy systems exert on their surroundings. LCA consists of two parts: life cycle inventory (LCI) and life cycle impact assessments (LCIAs). LCI is an inventory method extensively studied in 1970s and 1980s (NEA, 2002 and OECD, 1980-1988). The difficulty of its application is that it involves the handling of a large amount of data covering all steps of an industrial process, i.e. nuclear power plants and their associated fuel cycle, throughout the whole lifetime of the various components of this cycle. LCI is in itself a complex assessment, although it has already been undertaken to cover nuclear energy systems and subsystems. The challenge is that resulting LCI data may not always be used at full in an LCIA as typically they are facility and site specific. As such a LCA requires the preliminary definition of numerous assumptions which will determine the final results and which are generally difficult to document in a clear and systematic manner. Based on a generic LCI method, the previous study defined and discussed relevant criteria grouped under three principles or categories: "no degradation of resources in the broadest sense", "no production of 'non

degradable' waste" and "high potential robustness/long term stability". Linked to the criteria, a set of more detailed measurable indicators was identified. The scope was limited to analysis of the applicability of such indicators and the description of the different fuel cycle options and developments according to the criteria; a full quantification was not undertaken.

In order to cope better with the inherent value judgements associated with the interpretation of LCI data, the study envisaged the parallel use of decision-aiding methods such as the MCA. Rather than embarking on a final and concrete selection and prioritisation process, the aim of the study was to lay the basis for the use of such techniques to provide an instrument that could be adopted by stakeholders for the assessment of sustainability characteristics. Results of work performed by other groups were essentially used, without engaging in a new, complete application of LCA and MCA techniques.

In reviewing fuel cycle developments, the report identified areas of continuous improvement but noted that communication of these developments remained a challenge. The major conclusions of the report were:

- Nuclear power shows a unique potential as a large-scale sustainable energy source.
- A global market for fuel supply exists but waste management issues remain on a national level.
- Appropriate measures have been put in place to protect the environment.
- The nuclear fuel cycle holds potential for further economic and environmental optimisation, especially in the areas of fuel performance, reprocessing techniques and waste disposal concepts.
- Work on finding disposal facilities has made progress but there is no societal consensus about the final implementation.
- A major issue of concern is the funding of long-term research and development in order to deploy the full potential of nuclear energy.
- The gap between expert views and the public perception calls for more work on stakeholder participation. A multi-criteria approach was investigated and considered to be an appropriate tool for allowing the public to participate in the assessment of options.

Since the previous report, progress has occurred and is expected to continue in connection with the sustainable development of nuclear energy and nuclear fuel cycle technologies. In particular, improvements of operational performance, safety, economics and fuel cycle flexibility have been achieved by the industry. Developments in Generation IV reactor systems, progress in various waste management programmes in a number of countries as well as research and development (R&D) including advanced fuel cycle concepts such as partitioning and transmutation (P&T) have been a spur to new thinking. With the advent of new generations of reactors, changes are occurring in approaches to uranium use, reprocessing, recycling and waste treatment and disposal. In addition, various international initiatives have sought to co-ordinate and integrate work related to the fuel cycle. Some of the most prominent are introduced below, whilst further programmes are discussed in Chapter 4.

1.3. International initiatives with a focus on sustainability

The GIF initiative

Generation IV International Forum (GIF) was initiated by the United States in 1997, when the US President's Committee of Advisors on Science and Technology reviewed national energy R&D and drew up a programme to address energy and environmental needs for the next century. This noted the importance of assuring a viable nuclear energy option to help meet future energy demands, and highlighted the need for properly focused R&D to address the principal obstacles. These obstacles included spent nuclear fuel management, proliferation risks, economics and safety.

GIF focuses on the collaborative development and demonstration of one or more fourth generation nuclear energy systems, further described in Section 2.9.1 (GIF, 2002). The main goals set for Generation IV nuclear systems are:

- Sustainability: meet clean air objectives and promote long term availability of systems and effective fuel utilisation for worldwide energy production; minimise and manage nuclear waste and reduce long-term stewardship.
- Economics: offer life-cycle cost advantage over other energy sources; offer a level of financial risk comparable to other energy projects.
- Safety and 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 and physical protection (PR&PP): represent a very unattractive and least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection (PP) against act of terrorism.

GIF has also been developing an evaluation methodology for PR&PP (GIF, 2006), as well as a cost estimating methodology and application (Rasin and Ono, 2010).

Joint study on Energy Indicators for Sustainable Development

In 2005, through their joint effort, several international organisations produced a study which provided guidelines and methodologies for the definition of energy indicators for sustainable development (EISD) (IAEA, 2005). Participating agencies were: the IAEA, the United Nations Department of Economic and Social Affairs (UNDES), the IEA, EUROSTAT and the European Environment Agency (EEA). These agencies had previously addressed their individual efforts to future energy needs and sustainability in a number of reports on the topic (e.g. UNDES, 2001). The final study (IAEA, 2005) identified EISD categorising, at increasingly more detailed levels of definition: dimensions, themes, sub-themes and finally energy indicators and their components. The three dimensions considered were social, economic and environmental, each cascading down into more detailed themes: e.g. under the environmental dimension the themes were atmosphere, water and land. In a similar manner, subthemes were identified under themes; e.g. subthemes under atmosphere were climate change and air quality.

The guideline provides a complex methodology that would have to be applied at country specific levels, as it is unlikely that all the indicators identified would be readily applicable for a global evaluation.

The INPRO methodology

The IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was initiated in the year 2000 based on a resolution of the IAEA General Conference [GC(44)/Res/21]. The aim is to promote international and national actions that will support innovations in nuclear reactors, fuel cycles and institutional approaches. In

particular, INPRO has defined a set of principles and requirements for assessing the sustainability of innovative nuclear systems, to guide members in their development efforts. INPRO is intended to help ensure that nuclear energy is available in the 21st century in a sustainable manner, seeking the co-operation of the IAEA member states to achieve desired innovations (IAEA, 2008a). INPRO was based on the member states' recognition that:

- A sustainable energy supply in 21st century will require the large-scale deployment of nuclear power as well as other energy sources.
- Nuclear power is an energy technology that offers practically unlimited resources whose deployment can reduce environmental pollution and the volume of waste needing management, including GHG emissions.

The INPRO manual is comprised of an overview volume (IAEA, 2008a) and 8 volumes dealing with the specific assessment topics which can also be interpreted as the elements of sustainability. The INPRO assessment methodology is hierarchical, composed of basic principles, user requirements and criteria. The criteria, in turn, consist of an indicator and an acceptance limit. Performing a complete INPRO assessment of any innovative nuclear system and its associated fuel cycle represents an enormous undertaking, well beyond the scope of this study.

1.4. Sustainability elements for the nuclear fuel cycle

This brief appraisal of some previous initiatives related to sustainability indicates the variety of approaches. In addition to these, there are several other projects both ongoing and completed undertaken by universities, research institutes and consortia (e.g. SPRING¹) and through the European Commission (e.g. NEEDS²).

The definitions of sustainability and associated criteria for evaluating nuclear energy systems show that multiple approaches can be adopted. These are often of cumbersome application and hardly ever offer simple unequivocal answers. In some cases (IAEA, 2005) methodologies have been proposed for the evaluation of country approaches to sustainability, which could be extrapolated at a regional and, perhaps, ultimately extended at a global level.

For the scope of this work a set of key elements defining sustainability are proposed in conformity with the INPRO methodology:

- environment;
- resource utilisation;
- waste management;
- infrastructure;
- proliferation resistance and physical protection;
- safety;
- economics.

A brief description how nuclear systems should address these elements is provided below, based on the INPRO definitions (IAEA, 2008a).

-
1. *Sustainability Assessment of Nuclear Power: An Integrated Approach*. Available at www.springsustainability.org/.
 2. *New Energy Externalities Developments for Sustainability*. Available at www.needs-project.org/.

Environment

Protection of the environment is a central theme in the concept of sustainable development and a major consideration in the deployment of industrial systems. Environmental stressors from nuclear systems include radioactive and non-radioactive chemical toxic emissions, heat discharges, mechanical energy, noise, odour, water and land use. All such stressors could lead to adverse environmental effects on a local, regional or even global scale, potentially causing harmful impacts on ecosystems. Such adverse environmental effects should be controllable over the complete life cycle of the nuclear system and kept to levels which fully comply with current (regulatory) standards and are kept as low as reasonably practicable.

Resource utilisation

Resource utilisation is strictly linked to the environmental component of sustainable development and, as such, it is addressed as an aspect of the environment in the INPRO methodology. A nuclear system should be able to generate energy while making efficient use of fissile/fertile material and other non-renewable materials and without giving rise to a substantial degradation of these resources. Hence long-term availability, and efficient use, of resources are a key component of sustainability.

Waste management

This element refers to waste generated by a nuclear system and all the steps necessary for its management whose main objective is to keep waste to the minimum level practicable, securing an acceptable level of protection of human health and the environment without undue burdens on future generations. Factors such as cumulative releases of radionuclides and related doses to the biosphere, heat generation and radiotoxicity, as well as costs of managing the waste over the life cycle of the system are all relevant parameters.

Infrastructure

This element considers firstly the establishment of adequate installations necessary throughout the lifetime of a nuclear system, such as physical capabilities for R&D and industrial deployment. This is the main aspect considered for the assessment conducted in the present study. Infrastructure can also refer to institutional and legal frameworks necessary for the deployment of a nuclear system/ programme as well as socio-political aspects such as available human resources.

Proliferation resistance and physical protection

The basic principle of proliferation resistance (PR) and physical protection (PP) considers the implementation, optimisation and cost effectiveness of intrinsic features, extrinsic measures and adequate PP regimes needed throughout the full life cycle of the nuclear system, in order to minimise the attractiveness and vulnerability of nuclear materials and technology for diversion to a nuclear weapons programme. PP is sometimes addressed in conjunction with PR, e.g. proliferation risk and physical protection assessment within GIF, as covering those measures required to avoid diversion of nuclear materials by sub-national or terrorist groups. However, PP has not been assessed in any detail in this report.

Safety

This element is related to potential health risks associated with specific technology systems. It looks at the enhancement of their safety and optimisation of protections of all nuclear facilities (including but not limited to reactors), namely through the adoption of

defence-in-depth and an increased emphasis on inherent and passive safety features, so that the risk from radiation exposures to workers, the public and the environment throughout their lifespan is comparable to that from other industrial facilities used for similar purposes.

Economics

For any nuclear or energy system to be viable for deployment, it must be available and economically affordable, having costs that are comparable to those of low-cost/priced alternatives. Capital costs, operating and maintenance costs, fuel costs, waste management costs, decommissioning costs and all external costs, must individually and collectively be sufficiently low to make the system competitive. Hence reductions in these costs will aid sustainability.

These elements will be adopted in the present study as key factors to provide a framework for a high-level, qualitative evaluation of effects and trends in the development of nuclear fuel cycle technologies.

It is apparent that several of the elements present common aspects and partly overlap. For instance, aspects related to waste management would also affect the environment element. Waste storage and disposal also impact infrastructure and safety. Resource utilisation (i.e. uranium mining and reprocessing) would influence the environment.

Metrics associated to these elements could eventually be developed to provide a framework for a quantitative evaluation of sustainability. At this stage, however, it would not be feasible to achieve quantification which would be sufficiently accurate and reliable. Where possible, an attempt will be made to establish qualitative trends of the implications that nuclear fuel cycle technologies may have on these elements of sustainability. This assessment is undertaken in Chapter 4.

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2. The nuclear fuel cycle in perspective

2.1. Introduction

This chapter provides an overview of the nuclear fuel cycle. It starts with a description of the context in which nuclear power is being developed, by reviewing its potential contributions to issues related to energy demand, climate change mitigation and security of supply. The chapter outlines the benefits nuclear power offers in helping to address these difficult issues and also the challenges facing a major expansion of nuclear energy. This is followed by a description of the nuclear fuel cycle and a more detailed examination of the status of each of its components, specifically the “front end” (uranium production and fuel manufacturing processes), the energy extraction stage (power reactors) and the “back end” (spent fuel management and radioactive waste disposal). The chapter closes with an overview of prospective future developments.

2.2. World energy and electricity demand

The quality of life in modern industrial society is critically dependent on a ready supply of energy at an affordable cost. In the *Nuclear Energy Outlook* (NEA, 2008a) the NEA looked at the drivers for the apparently inexorable growth in energy demand over recent decades. The world population has been steadily increasing and the United Nations (UN) expects that it will continue to do so, with the median expectation of a population increase from some 6.1 billion in 2000 to 8.3 billion in 2030 and over 9 billion in 2050 (UNPD, 2006). Fortunately, the world economy has been growing even faster, so that the standard of living for most of the world’s population is continuing to improve. The Intergovernmental Panel on Climate Change (IPCC) reported that from 1970 until the early years of this century, the world’s gross domestic product per capita was increasing at an annual rate of 1.8% (IPCC, 2007). Even with improving efficiency of the energy consumption for wealth production, the end result has been a rapidly growing demand for energy.

2.2.1. Energy demand

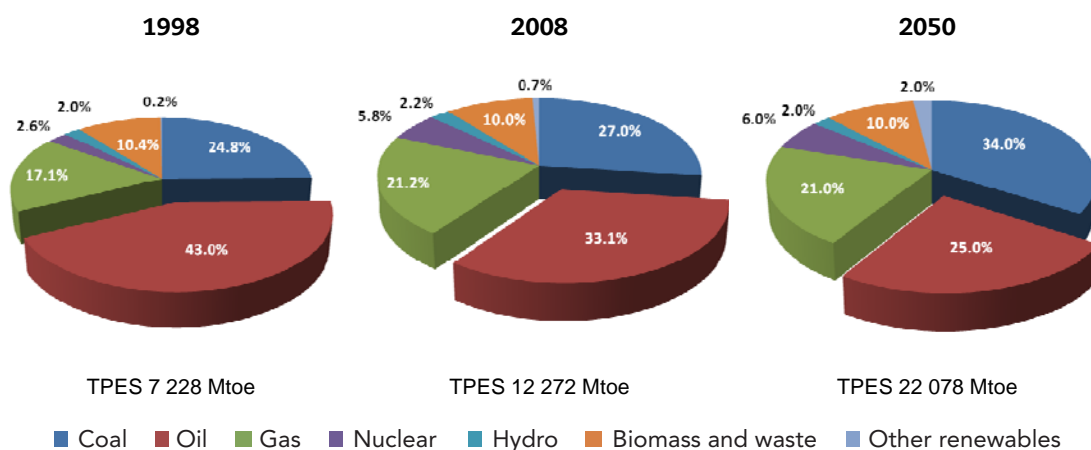
The *Nuclear Energy Outlook* reviewed a number of projections of energy demand to 2030 (from the IEA, the Energy Information Administration of the US Government and IAEA) and further out until 2050 (using the work of the IEA and the IPCC). The resulting projections obviously depend on a range of assumptions; in 2030 the outcome requires total primary energy supply (TPES) ranging from just over 17 000 Mtoe to just over 21 500 Mtoe compared with a level of around 12 272 in 2008. Not surprisingly, the spread on the outcomes in 2050 is much larger, ranging from 22 000 Mtoe to as much as 36 000 Mtoe. It therefore seems that, unless there are radical changes, TPES is expected to double or more by the middle of this century.

More recently we have seen what might appear to be a radical change in the form of the serious financial crisis that has overtaken the world economies since 2007. The IEA has provided updated projections (IEA, 2009a) taking account of the recent downturn in economic fortunes. Although the effect is noticeable in the near term (2009 TPES down by

2%, the first reduction since 1981) it is expected to have little impact by 2030 and the global energy demand is still set to keep soaring, despite various efforts with regards to energy demand management.

Most of the world's energy supply today is provided by fossil fuels. Figure 2.1 reports the world primary energy demand and different fuel shares in 1998 and 2008 (IEA, 2010a) along with projections¹ to 2050 (IEA, 2010b). In 1998 the TPES was 7 228 Mtoe, with fossil fuels comprising nearly 85% (43% from oil). In 2008 the fossil share came down only slightly to 81.2% of a growing TPES of 12 272 Mtoe.

Figure 2.1: Trend for world primary energy demand by fuel



Sources: Based on IEA, 2010a; 2010b.

If current government policies are maintained, by 2050, the IEA's baseline scenario (IEA, 2010b) indicates a TPES of 22 078 Mtoe, 79% of which still coming from fossil fuels, although the relative share of oil will have dropped to 25%. Nuclear power is expected to grow enough to maintain its share at 6% while the share of renewables increases to 14%. However, within this renewable share biomass and waste² dominate at 10%, with hydro at around 2% and other renewables (wind, solar, etc.) also around 2%.

In addition to the reference scenario (no policy changes), the IEA has considered a new policies scenario, which quantified commitments made by governments and a 450 (or blue map) scenario, based on the intention to limit levels of CO₂ in the atmosphere to 450 ppm by 2050. Both affect the demand projections (see Table 2.1), but also the different fuel shares.

1. In the reference scenario, against which others are compared, which assumes continuation of current government policies and no new policies or measures.
2. Bioenergy feedstocks include solid biomass, wood wastes, agricultural wastes, wastes from the paper and pulp industry, energy crops, biogases, landfill gases, biodegradable components of municipal solid waste, and liquid biofuels (IEA, 2010b).

Table 2.1: World primary energy demand by fuel and scenario (Mtoe)

	1980	2008	New policies scenario		Current policies scenario		450 scenario	
			2020	2035	2020	2035	2020	2035
Coal	1 792	3 315	3 966	3 934	4 307	5 281	3 743	2 496
Oil	3 107	4 059	4 346	4 662	4 443	5 026	4 175	3 816
Gas	1 234	2 596	3 132	3 748	3 166	4 039	2 960	2 985
Nuclear	186	712	968	1 273	915	1 081	1 003	1 676
Hydro	148	276	376	476	364	439	383	519
Biomass and waste*	749	1 225	1 501	1 957	1 461	1 715	1 539	2 316
Other renewables	12	89	268	699	239	468	325	1 112
Total	7 229	12 271	14 556	16 748	14 896	18 048	14 127	14 920

* Includes traditional and modern uses.

Source: IEA, 2010b.

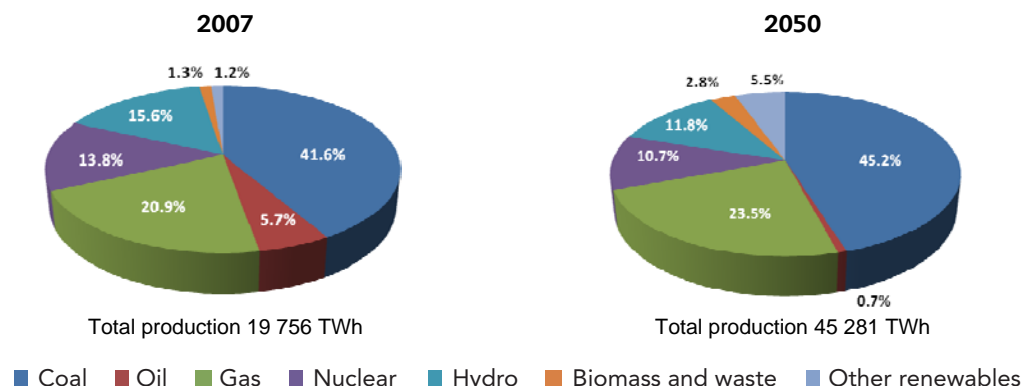
2.2.2. Electricity demand

With respect to electricity production, the projected growth rates are even more significant. Using the same sources as for TPES, the NEA explored projections of electricity consumption. In 2030 these ranged from nearly 25 000 to 39 000 TWh/y and in 2050 from 32 000 to 64 000 TWh/y, to be compared with a consumption of 17 400 TWh in 2004. Hence electricity consumption is growing even faster than TPES and might be expected to be somewhere between two and a half to three times as large in 2050. As for TPES, the IEA indicates that the current financial crisis will have only a small impact on the level of electricity demand in the longer term.

The IEA (IEA, 2010b) reports world electricity consumption of 19 756 TWh in 2007, with fossil fuels contributing 68%. By 2050, in its baseline scenario, IEA projects an increase of the world electricity consumption up to some 46 000 TWh, with a fossil fuel contribution to the much larger total undiminished at 69%. Figure 2.2 shows the global electricity production in 2007 and projections to 2050, with share contributions by each energy source.

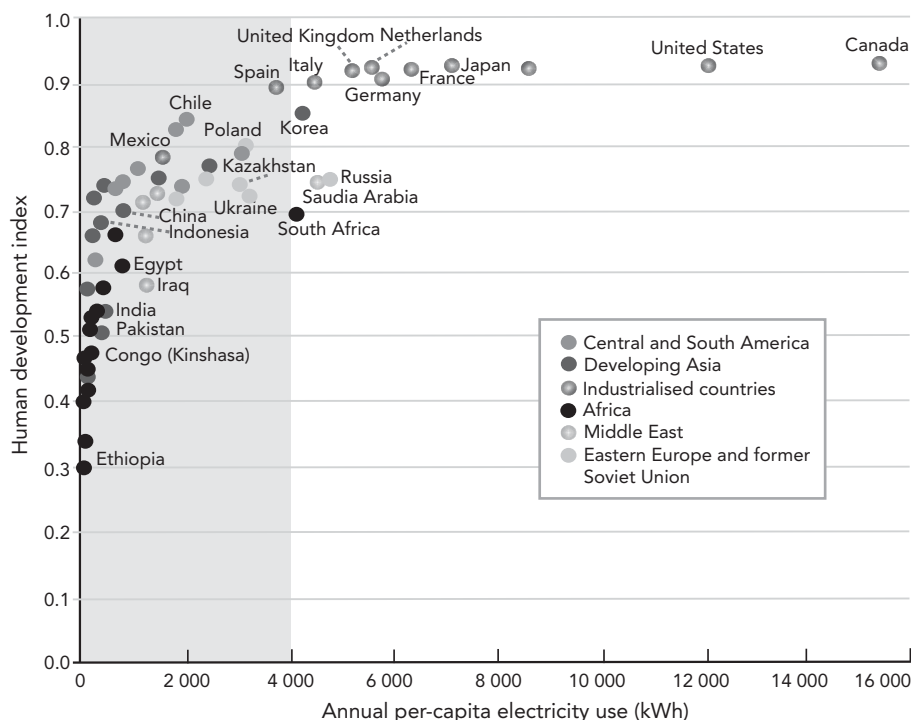
That electricity demand is expected to grow faster than TPES is perhaps not surprising. As the IPCC has observed (IPCC, 2007), "Electricity is the highest-value energy carrier because it is clean at the point of use, and can be used in so many end-use applications to enhance personal and economic productivity. Increased availability of electricity has a strong impact on the quality of life in developing countries". The United Nations human development index (HDI) is a quantitative measure of human well-being which combines human mortality, life expectancy, food supply, literacy rate, educational opportunities and political freedom. Figure 2.3 shows the relationship between electricity consumption and HDI. There appears to be a per capita threshold of around 4 000 kWh/y electricity consumptions for the HDI of a country to reach the level of the most advanced OECD economies. The IEA (IEA, 2010b) estimates that about a fifth (1.4 billion) of the world's population is currently without electricity supply, leaving plenty of scope for further demand growth.

Figure 2.2: Global electricity production by energy source



Source: Based on IEA, 2010b.

Figure 2.3: Relation between UN HDI and electricity use in 60 countries in 1997



Source: Pasternak, 2000.

2.3. The benefits of nuclear power

The IEA’s assessments of the availability of fossil fuels show that, at least for several more decades, there is sufficient oil to meet present and projected increases in consumption and other fossil fuels, particularly coal, are even more available. However, it is now almost universally accepted that continued consumption of fossil fuels is not sustainable in terms of its impact on the world’s environment. Neither is this the only concern with respect to increased fossil fuel use. Many policy-makers are beginning to regard nuclear energy as attractive again because:

- It produces very low quantities of GHG emissions in comparison to fossil fuels (see Section 2.3.1). It is therefore seen as having considerable benefits in limiting environmental impacts and climate change. Nuclear power does not suffer from the difficulties of intermittency and unpredictability that wind and solar energy exhibit. It has also an established position, being a proven technology that has been producing energy in significant quantities for over 50 years; it does not require any new technological breakthroughs (NEA, 2010a). These factors make it attractive as a predictable, reliable means to reduce GHG emissions.
- Major reserves of oil and gas are currently concentrated in a small number of countries, raising concerns with respect to security of supply and potential for political leverage. This has been illustrated in the first half of 2011 with the political crises in several north African countries, which led to rapidly increasing oil prices. Fossil fuel importing countries therefore will continue to face a significant outflow of financial resources in order to meet their energy needs. In addition to damaging the balance of payments of the importing country, the very considerable sums of money involved also have an impact on the balance of global financial power. Nuclear power, as a quasi-indigenous source of electricity has some significant advantages in terms of security of supply (see Section 2.3.2).
- In terms of economic competitiveness, nuclear power has been shown to offer attractive outcomes, especially if carbon pricing is considered and financing costs are controlled. Oil and gas prices have been extremely volatile in recent times. More recently, the estimates of increased gas supply from shale and coal seam gas have acted to decrease gas prices, but the duration of this gas “bubble” is not known (nor is its longer-term environmental impact). While uranium prices have also been volatile, the cost of production of nuclear energy depends only to a very small extent on the cost of the uranium for the fuel ($\leq 5\%$), insulating the cost of the electricity produced from the fuel price volatility. This is discussed in Section 2.3.3.
- Somewhat less well recognised are the benefits that nuclear energy can bring in the avoidance of air pollution, which has very detrimental health effects (see Section 2.3.4).
- A distinctive feature of nuclear energy is the very high energy density of its fuels (a factor of approximately 10^5 greater than fossil fuels), which results in a significant reduction of fuel volumes used, and transport needs, while easing the establishment of significant strategic energy stockpiles (in the form of fresh or spent fuel).

However, the expansion of nuclear energy presents its own challenges that should not be overlooked. These are discussed in Section 2.4.

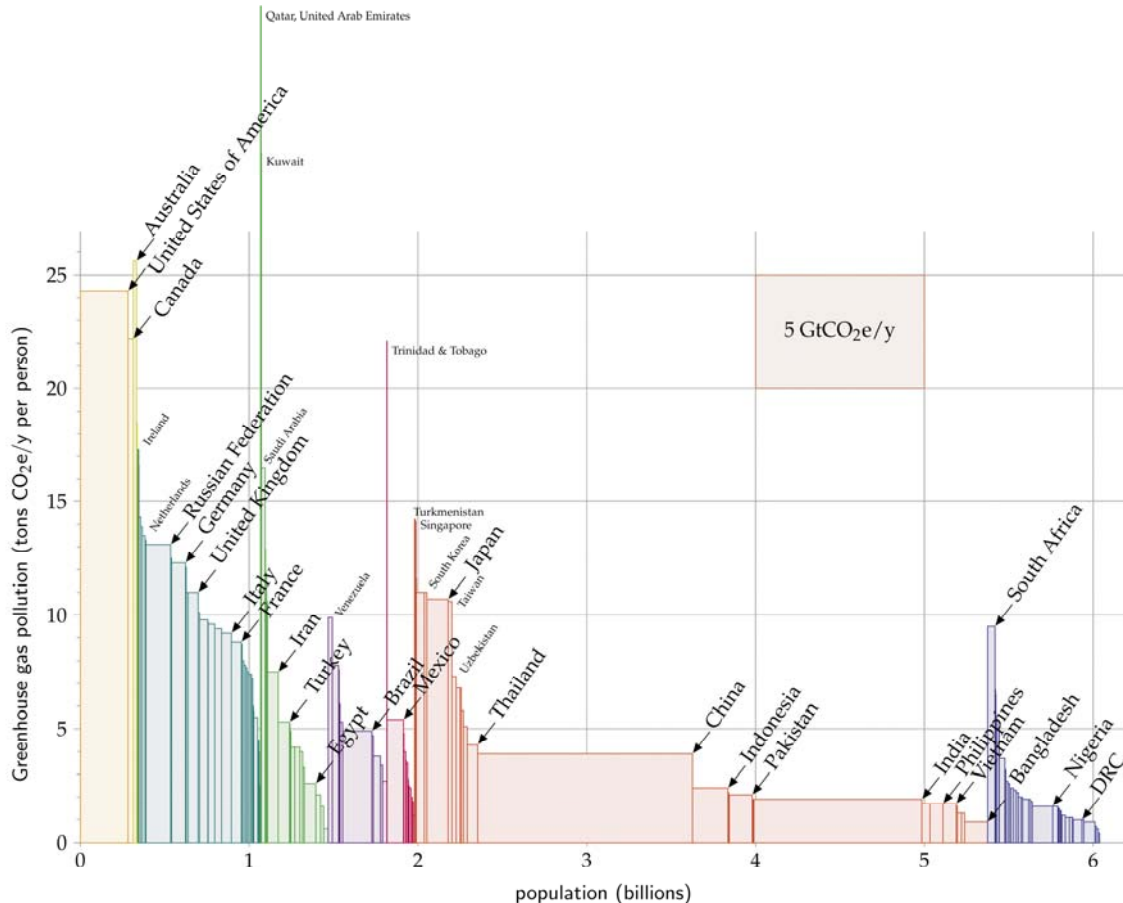
2.3.1. Climate change

The massive body of work reported by the IPCC in its fourth assessment report (IPCC, 2008) has been subjected to criticism in some detailed aspects, but the main outcomes continue to be regarded as robust. The IPCC concluded that climate change is a reality and that the main cause is anthropogenic releases of greenhouse gases,³ the principal contributor being carbon dioxide. The report recommends that, in order to avoid the worst consequences of climate change, the average global temperature increase should

3. While carbon dioxide is the biggest anthropogenic contributor to atmospheric greenhouse gases, there are other contributors and some of these other gases have a greater warming potential per unit mass. It is normal practice to convert these contributions to “CO₂ equivalent”. Methane (CH₄) currently contributes around 15% to anthropogenic CO₂ equivalent releases and nitrogen dioxide (NO₂) around 8%. Other contributions are relatively small.

be limited to no more than 2 °C.⁴ In order to have a 50% probability of achieving this, the analysis proposes that atmospheric concentrations of GHGs should be limited to 450 ppm (parts per million) of CO₂ equivalent. This requires CO₂ releases to be reduced to around 13 Gt/y by 2050, half of that released in 2005. Figure 2.4 shows how difficult this will be to achieve. For each country the height of the bar in the chart gives the annual per-capita GHG emissions, which, for less industrialised countries, is only a fraction of that generated in rich countries. The width of the bar represents the country’s population. Hence the integrated value given by the area of the bar indicates the total yearly amounts of CO₂ equivalent generated by that country. Some 1.4 billion people worldwide are still without electricity supply (IEA, 2010b) and, as conditions in developing countries improve, the global energy demand is bound to increase substantially, particularly to foster the fast economic growth and meet the needs of a greatly increasing population in countries such as India and China. Without changes in the way primary energy is converted into energy services, a massive increase of GHG emissions is inevitable. In addition, the initial higher investments required to switch towards “zero-emission” energy technologies might not be viable in all markets.

Figure 2.4: Per capita greenhouse gas emissions by country



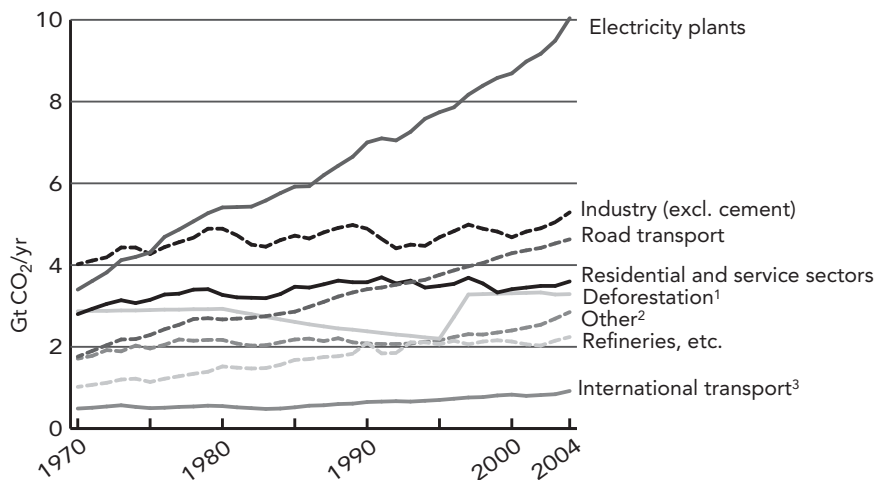
Source: MacKay, 2009.

4. The Copenhagen Accord set out in December 2009 has provided international recognition of the 2 °C limit target.

In its *Energy Technology Perspectives* publication (IEA, 2010b), the IEA shows baseline (i.e. current policies remain unchanged) projections of CO₂ emissions rising from 29 Gt in 2007 to 40 Gt by 2030 and continuing to increase to 57 Gt by 2050, close to a 100% increase, in sharp contrast to the 50% reduction regarded as essential.

Figure 2.5 shows the origins of global CO₂ emissions over the past three decades. Clearly, the largest source of CO₂ emissions is electricity generation, contributing some 27% of the total. This is twice the size of the next largest contributor (industry) and it is increasing at twice the rate of the next fastest growing source (road transport). As we have seen in Section 2.2.1, demand for electricity will continue to grow over the coming decades. A key challenge in combating climate change is therefore the decarbonisation, to the greatest extent possible, of electricity production.

Figure 2.5: Sources of global anthropogenic CO₂ emissions



1. Includes fuel wood and peat fires.

2. Includes other domestic surface transport, cement making, venting/flaring gas from oil production, non-energetic use of fuel.

3. Includes aviation and marine transport.

Source: IPCC (2007).

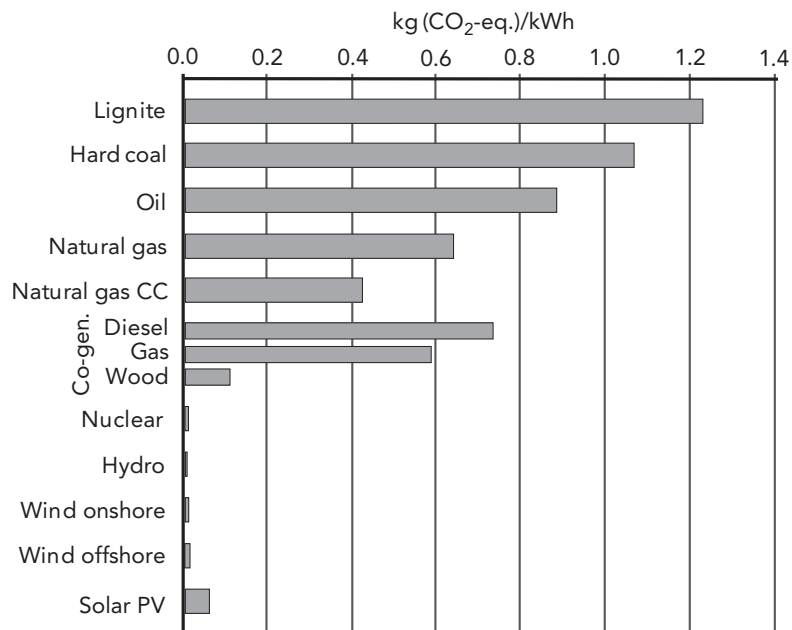
In order to make an appropriate comparison of emissions from different sources of power generation it is necessary that the assessment includes the full life cycle of the power production systems including the provision of the necessary facilities as well as the fuel itself. Figure 2.6 shows such an assessment. Amongst the fossil fuel sources, gas produces roughly half the life cycle emissions of coal, but nuclear energy and the renewables⁵ produce considerably less.

The small quantities of emissions associated with nuclear and the renewables come from the life cycle analysis where, for example, some fossil fuels are used in the production of construction materials. In the case of nuclear power, the assessments include fossil fuel used to provide power for uranium enrichment. Modern centrifuge enrichment technologies use much less energy than gaseous diffusion plants and so the life cycle emissions from nuclear power will fall further as these older facilities are phased out (see Section 2.6.3). It has been claimed that the emissions from nuclear

5. Without taking into account the back-up power needed to cover when these are not available, due to the variability of the meteorological agents renewable sources rely upon (e.g. when the sun does not shine or the wind does not blow, etc.).

energy will rise dramatically if uranium producers are forced to process lower grades uranium ores. As will be seen in Section 2.6.1 there is no evidence to support such a contention; uranium seems to be in plentiful supply for future needs.

Figure 2.6: Greenhouse gas emissions of selected energy chains



Note: The data are for the average emissions of the UCTE (Union for the Coordination of Transmission of Electricity, part of the European Network of Transmission System Operators for Electricity since 2009). At the time of the data collection, UCTE member countries were: Austria, Belgium, Bosnia-Herzegovina, Croatia, Denmark (associated member), France, Former Yugoslav Republic of Macedonia, Germany, Greece, Italy, Luxembourg, the Netherlands, Portugal, Serbia and Montenegro, Slovenia, Spain and Switzerland.

Source: Based on Dones *et al.*, 2004.

2.3.2. Security of energy supply

With respect to gas, the IEA (IEA, 2009a) reported that proven reserves⁶ can sustain current extraction rates for 58 years. Proven reserves continue to increase, having more than doubled since 1980; over the last five decades the volume of newly discovered gas fields has consistently exceeded the volume of gas produced. However, 70% of this is located in the Middle East (41%) and Eastern Europe/Eurasia (30%) and just three countries, Iran, Qatar and the Russian Federation, hold more than half. Looking beyond proven reserves to remaining recoverable resources,⁷ the remaining reserves to current production ratio extends to 130 years, with around two thirds in Eastern Europe/Eurasia and the Middle East. However the more recent discovery of the potential reserves of shale and coal seam gas in North America will be a significant issue over the next decade.

6. Hydrocarbons remaining in gas fields that have been discovered and for which there is a 90% probability that they can be extracted profitably on the basis of current assumptions.

7. The remaining total volume of resource that is technically and economically recoverable; this includes both proven and probable reserves in discovered fields and hydrocarbons that have yet to be found.

Moving to consider the position with respect to oil, the IEA (2010a) reported estimates of the proven conventional oil reserves⁸ of 1 354 billion barrels at the end of 2009. It further reported that the reserves to production ratio, which had fluctuated within a range of 39 to 43 years over the previous 20 years (IEA, 2006), have increased in the last two years as a result of the recession-induced drop in demand for oil and continuing modest increases in reserves. Almost half of the increase of the additional reserves had been coming from revisions to estimates in fields already in production or undergoing appraisal. Although discoveries have picked up in recent years with increased exploration activity (prompted by higher oil prices), they continue to lag production by a considerable margin.

However, the distribution of reserves was of more concern from an energy security perspective. Countries in the Middle East held around two thirds of the conventional reserves with Saudi Arabia alone holding more than 20%. Adding the other OPEC countries shows that the OPEC group controlled some 80% of the world's conventional oil reserves. The largest non-OPEC reserves were held by the Russian Federation (5%). The narrow geographical distribution of oil and gas reserves and the propensity for supply interruption that results are not the only factors of potential instability. Increasingly large quantities of oil and gas are being transported, via pipelines and shipping, across large distances. These supply routes are also vulnerable to disruption.

In contrast to oil and gas, nuclear energy has less potential for disruption. Uranium is produced by a diverse range of countries (see Section 2.6.1) with no one geographical area or group of countries dominating. It also has a very high energy density; 1 tonne of uranium used in light water reactors in open cycle has the energy equivalent of 10 000-16 000 toe or 14 000-23 000 tce (tonnes of coal equivalent) (NEA, 2008b). It therefore requires significantly smaller quantities of fuel to be used and material to be transported. Further, given that the cost of the uranium itself is small in comparison to the cost of the final electricity, it is reasonably easy in both physical quantity and financial terms for a country or individual utility to hold a considerable stock in energy terms. In contrast to all other energy resources, uranium and plutonium (bred in the reactor) may be recycled. Already with current LWR systems, this feature adds a net gain to the resource base, which would be greatly increased with fast spectrum reactors, thus further reducing vulnerability to resource supply uncertainties.

The increasing cost of oil and gas from around 2000 onwards until the recent recession had an obvious impact for countries dependent on energy imports. For the United States and the European Union (EU) the percentage of GDP spent on oil and gas imports rose from around 1% to around 2.5%; for Japan, more dependent on energy imports, the increase was from 1.5 to 4% (IEA, 2009a). In the IEA's reference case scenario these percentages will remain significant at around the 2-3% level for the United States and the EU and 3% for Japan. The developing economies of China and India have fractions of GDP devoted to oil and gas imports which are more demanding as their development continues, reaching more than 3.5% for China by 2030 and approaching 6.5% for India. By 2030 spending on oil and gas imports is expected to be around USD 670 billion/y in the EU, USD 570 billion/y in China, USD 430 billion/y in the United States, USD 290 billion/y in India and USD 180 billion/y in Japan.

For the fossil fuel exporting countries, the period of 2008-2030 will see a cumulative inflow for OPEC countries of USD 30 trillion and USD 7 trillion for the Russian Federation. For OPEC this would represent a five-fold increase compared with the cumulative earnings of the previous 23 years and for the Russian Federation a factor of 3.5.

Some commentators attribute a significant, albeit secondary, role to the increase in oil price up to 2008 as a cause of the current financial downturn. If policies remain

8. Oil that has been discovered and is expected to be economically producible.

unchanged the scale of the money flows from importing to exporting countries is set to increase dramatically.

Therefore nuclear energy is increasingly seen as an attractive means of enhancing security of supply. Recent analyses done by the NEA shows that the move to nuclear has enhanced indices of security of supply in many NEA countries (NEA, 2010g).

2.3.3. Financial competitiveness of nuclear power

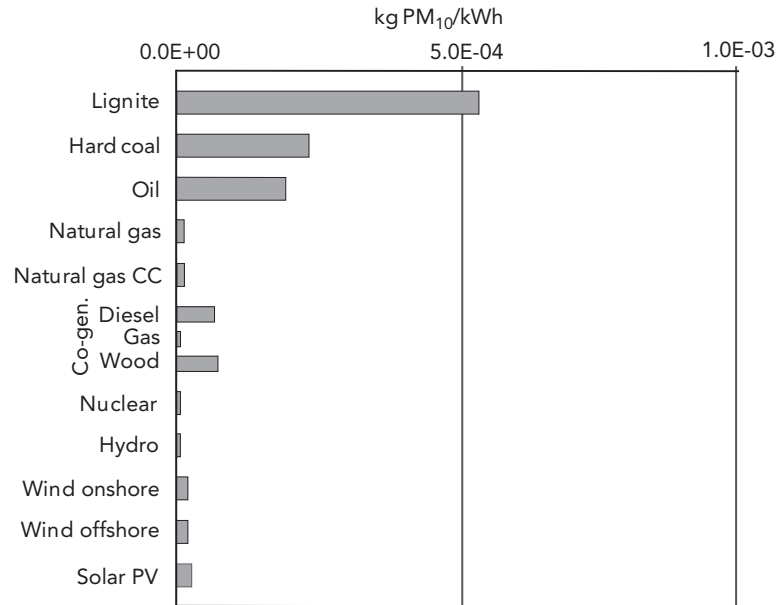
The competitiveness of nuclear power is a key issue for many countries and especially for developing countries, many of which may not have the means of financing the initial investments needed to introduce nuclear power. It is important, therefore, that nuclear power is attractive to investors. A recent study by the NEA (IEA/NEA, 2010) considered the lifetime (levelised) cost of nuclear in comparison with other sources of electricity. The results indicated that nuclear power is the most competitive option at a discount rate of 5% and assuming a carbon price of USD 30 per tonne of CO₂ emitted. This was true for all regions. At a 10% discount rate, the competitiveness of nuclear fell behind gas in Europe but remained the most competitive in Asia.

For nuclear power the levelised cost of electricity splits typically into 60% investment (overnight construction cost) plus interest during construction (IEA/NEA, 2010), 25% operations and maintenance costs and 15% fuel cycle (uranium, enrichment, fuel fabrication, spent fuel management); only about 5% is the cost of the uranium itself. Hence, the cost of nuclear energy is very heavily capital dominated. From a national perspective the outflow of money for energy from this source depends mainly on how much of the construction and financing of the plant is sourced locally and how much is imported. Given the nature of nuclear plant construction, it is common to find much of the construction cost is locally sourced. Domestic nuclear power can therefore be beneficial in terms of balance of payments, avoiding a transfer of very significant financial resources to fossil fuel exporting countries.

2.3.4. The health benefits of avoiding air pollution

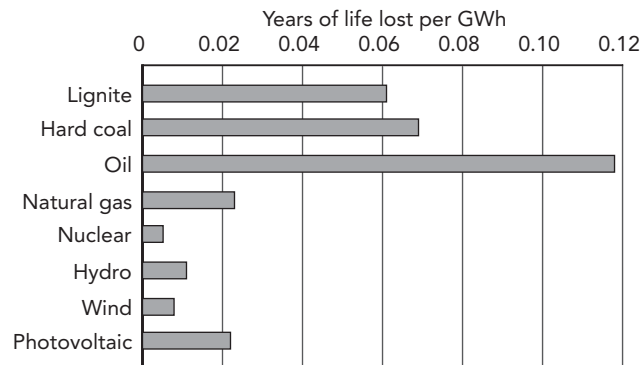
While GHG emissions have a worldwide impact, other pollutants from fossil fuel use, particularly fine particulate matter, sulphur dioxide and nitrogen oxide have regional or local impacts. Various studies have been carried out in different countries and regions on the health impacts of outdoor air pollution. The study *The Health Costs of Inaction with Respect to Air Pollution* (OECD, 2007) concludes that air pollution may be a significant contributor to ill health and death in NEA countries due to cardiovascular diseases, cancer and diseases of the respiratory system. A recent analysis at the global level estimates that outdoor air pollution is responsible for approximately 800 000 premature deaths (i.e. 1.2% of global deaths) and 6.4 million years of life lost per year (Cohen *et al.*, 2005).

Figure 2.7 shows comparative data for particulate releases from various sources of energy production, again based on a full life cycle analysis; PM₁₀ refers to particles of less than 10 microns in size. It is clear that coal and oil are significant polluters (note the logarithmic scale of the abscissa) while gas, alone among the fossil fuels, ranks with nuclear and the renewables as a non-polluting technology. A similar pattern occurs for SO₂ emissions. For NO₂ nuclear and the renewables again give excellent performance, but in this case gas has somewhat higher emissions.

Figure 2.7: PM₁₀ releases of selected energy chains

Source: Based on Dones *et al.*, 2004.

Integrating the effects of these pollutants, Figure 2.8 shows the resulting mortality from German energy chains as an example. Nuclear, wind and hydro power lead to very few mortalities, those due to natural gas and solar photovoltaics are slightly higher but comparable. The fossil fuels other than gas exhibit much higher impacts. For the avoidance of doubt, the study did include the effects of radioactive emissions, which can attract significant public attention. Further, the authors of the study point out that for all chains, mortalities due to accidents (which again attract a great deal of public attention) are practically negligible as compared with the corresponding effects of normal operation (Hirschberg *et al.*, 2004).

Figure 2.8: Mortality resulting from the emissions of major pollutants from German energy chains during normal operation in 2000

Source: Based on Hirschberg *et al.*, 2004.

2.4. The challenges to nuclear power expansion

From Section 2.3, it is clear that nuclear energy appears to have many advantages to offer over other energy sources. From 1960 up to the mid-1980s, its contribution grew rapidly, but then stalled in many countries of the world and has grown only slowly since. Only now is it beginning to see a revival, especially in those countries experiencing enormous energy demand growth, i.e. Asian countries such as China and India. Challenges to the growth of nuclear power can be grouped as follows.

- Public and political attitudes, expressed in concerns:
 - About the safety of nuclear installations, exacerbated in particular by the accidents of Three Mile Island in the United States, Chernobyl in the former Soviet Union (Ukraine) and the more recent accident at Fukushima Daiichi (Japan).
 - About the spread of technologies (enrichment and reprocessing) that may be used for non-peaceful purposes and result in nuclear weapons proliferation.
 - Particularly after the attack on the World Trade Centre in New York of 11 September 2001, that nuclear installations or materials could be a focus for terrorist attacks. This also includes the risk of diversion of nuclear materials to make “dirty bombs”.
 - That radioactive waste disposal was an unsolved problem and would leave a serious environmental management issue for future generations.

While there is no doubt that the public in many countries continue to be wary, there was also evidence that attitudes have been slowly moving to be more pro-nuclear, or at least neutral in their acceptance (NEA, 2010c). Time will tell if the recent event at Fukushima Daiichi has had a material effect on this trend.

- Investor confidence:
 - Following the Three Mile Island accident in the United States, reactor construction programmes in the leading nuclear nations of the time saw extensive delays due to design modifications and had to sustain large interest charges. Operating plants also incurred significant costs due to safety upgrades prompted by the accident.
 - Many electricity markets were liberalised, such that there was no guaranteed market returns on a nuclear investment within a short-time horizon, typically less than 7 years investment horizon for venture capitalists. The upfront capital costs of a nuclear plant are very large⁹ and the balance sheets of many utilities could not support such a project. This means that investors withdrew from equity funding for nuclear projects.
 - Nuclear construction timescales are long, with the attendant risks that changes during the construction period (regulatory changes, political policies, fossil fuel prices, etc.) may endanger the project and damage its economics.
 - Gas became a relatively cheap energy source and gas-fired power plants are cheap and quick to construct, minimising the amount of capital at risk and the project delay risks.

9. By way of example, the overnight construction cost of a modern nuclear plant in the United States is of the order of USD 4-5 billion (IEA/NEA, 2010).

- Once construction experience was lost in many countries and new designs emerged, utilities were reluctant to carry alone the risk related to the deployment of a first-of-a-kind (FOAK) system.
- Delivering the merits that policy-makers might see in nuclear energy (reduced GHG emissions and improved security of national energy supply) provided no returns for investors. More recently carbon markets with carbon trading is attempting to correct this in part but many governments have still to settle on guarantees of a process for carbon pricing. Hence, there is no investor confidence in the stability of carbon markets and the long-term price for carbon.
- Government responsibilities:
 - Governments of those countries already having a nuclear programme and wishing to expand it need to ensure that the existing legal, regulatory and institutional frameworks are effective and optimised. Clear, harmonised provisions and rulings help in minimising uncertainties, including risks of construction delays, which strongly affect capital costs.
 - In addition to these issues of public, political and investor confidence, governments wishing to see nuclear development for the first time need to put in place these essential legal, regulatory and institutional frameworks. This includes an effective system of licensing and regulatory oversight and a strategy for radioactive waste management. These can take some time to establish and are, of themselves, a disincentive.

If nuclear energy is to make a major contribution to resolving the world's energy issues by a second wave of rapid expansion, there are a number of challenges to which the industry must respond.

- Operational safety performance. Nuclear energy is a very sensitive technology in terms of the attention it receives from the media, which in turn drives public and political sensibilities. Although its safety performance in comparison with fossil fuel energy chains is excellent (see Section 2.7.2) an event anywhere in the world has an impact everywhere in the world, as evidenced by Three Mile Island and Chernobyl. The more recent events at Fukushima Daiichi are also likely to have an impact, despite today's changing perception on the role of nuclear energy as part of sustainable "zero GHG-emission" strategies for several countries. It is essential that the highest safety performance is maintained everywhere if there is to be a further expansion worldwide.
- Construction performance (see also Section 2.7.4).
 - Given the high capital cost of a nuclear power plant, delays in construction can have a significant adverse impact on the project economics, which discourages investment. In order to restore investor confidence, construction timescales and costs must be closely managed to ensure timely and within budget delivery.
 - First-of-a-kind construction. Project delays are much more likely with the construction of the first build of a new design. The industry must continue the efforts to minimise any project risks before construction of first-of-a-kind reactors commences, by standardising designs so that there are fewer FOAKs and possibly by more modular and factory construction, as difficulties may be exacerbated with "on-site" activities.
 - Reduction of capital cost. The more that can be done to reduce capital costs the more attractive nuclear energy will become, both in terms of the levelised cost of generation and in terms of reduction of investor risks from project delays.

With an increasing concern on the part of many governments that the energy issues they face cannot be overcome without a significant contribution from nuclear power, there are actions being undertaken to alleviate a number of these obstacles. In the United States and the United Kingdom design, licence and planning approval processes have been revisited to ensure that they deal as quickly and efficiently as possible with any applications whilst maintaining appropriate rigour. Regulatory bodies are collaborating in programmes such as the Multinational Design Evaluation Programme (NEA, 2010b), to harmonise design approval and in the first tentative steps towards internationally approved designs (leading to faster project approvals and greater assurance of the construction of safe designs across many nations). Governments are collaborating in the research and development necessary to further improve new reactor and fuel cycle system designs with respect to proliferation resistance, security, safety and economics, through programmes such as the GIF and the INPRO (see Sections 1.3 and 2.9.1). In the United States there are government incentives to reduce the financial risks of first-of-a-kind and early investment in new plants. Governments and the IAEA are exploring nuclear fuel supply security measures¹⁰ and multinational fuel cycle arrangements such that there will be reduced need for individual countries to deploy their own enrichment and reprocessing infrastructure, thereby reducing the risk of nuclear weapons proliferation.

2.5. The nuclear fuel cycle: an overview

The commonly used term, “the nuclear fuel cycle” refers to the chain of processes whereby nuclear fuel is produced and managed before, during and after its use in a reactor for generating energy. In practice many of the world’s reactors currently employ what is termed the “once-through cycle”, which in reality is not a cycle at all; the fuel is used once and is then treated as a waste for subsequent disposal, nothing being recycled.

Figure 2.9 shows a schematic of the main options in the nuclear fuel cycle.

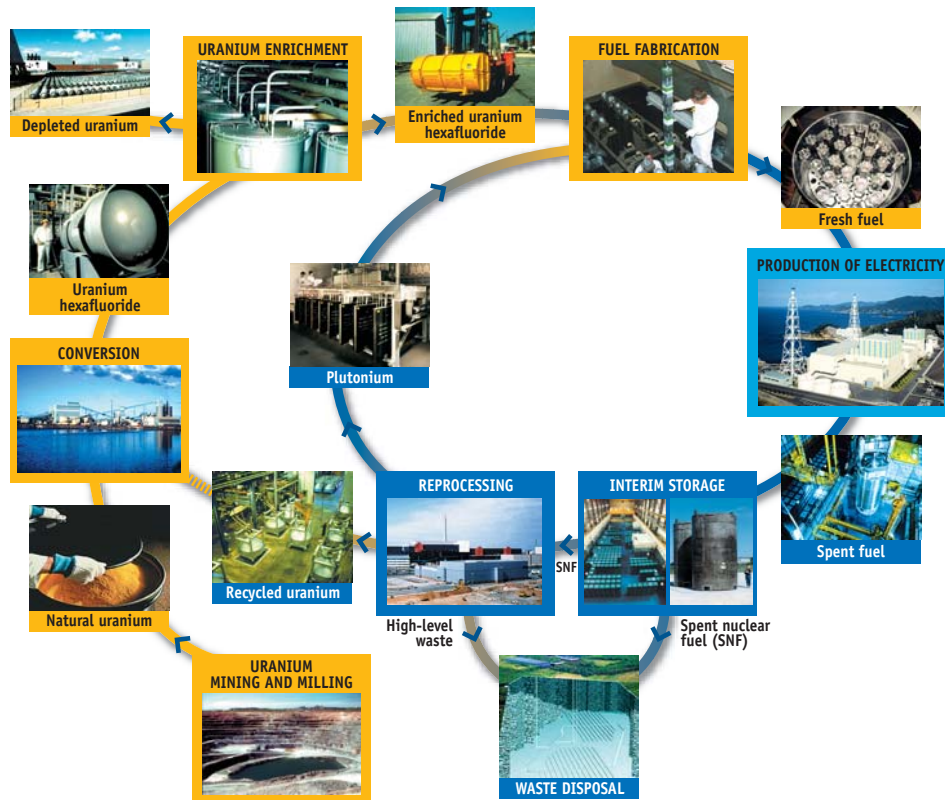
In the “front end” of the cycle, the extraction of uranium ore from the earth is conducted in much the same manner as the recovery of other mineral resources, such as copper. Around 55% of current uranium production is achieved by the extraction of ore using conventional open pit or underground mining methods. The remainder is mainly accounted for (36%) by *in situ* leaching (ISL), a method whereby a solvent is injected underground, dissolves the uranium and is recovered from wells and pumped to the surface for further processing. Some uranium is also obtained as a by-product of the extraction of other minerals (~8%).

The next step of the fuel cycle is milling, the process through which mined uranium ore is physically reduced to a suitable size and chemically treated to extract and purify the uranium. The resulting solid product (U_3O_8) is of a colour and consistency such that has been commonly termed “yellowcake”, even though it can sometimes be grey in colour.

Conversion, the next step, is the chemical process that transforms yellowcake into uranium hexafluoride (UF_6). This is solid at room temperature but readily turns into a gas at a temperature below the boiling point of water. In the gaseous form it is very suitable for the following process of enrichment.

10. For example, in December 2010 the Board of Governors of the IAEA adopted a resolution establishing an international low-enriched uranium (LEU) fuel bank and a framework is being drawn up to define the structure, access and location of the fuel bank.

Figure 2.9: The nuclear fuel cycle – once-through and closed options



Uranium enrichment involves the partial separation of uranium into its two main naturally occurring isotopes (^{235}U and ^{238}U). Natural uranium contains a low concentration of ^{235}U (0.711%), the fissionable component, capable of being used to produce energy in a reactor. The enrichment process enhances the percentage of ^{235}U in the usable product, with the result that a rejected stream of “depleted” uranium¹¹ contains less than the natural ^{235}U concentration. Most commercial reactor fuels have enrichments to 5% or less of ^{235}U ; heavy-water moderated reactors use, however, natural uranium and do not require enrichment.

Most reactors use uranium dioxide as their fuel. Its production in fuel form involves the transformation of UF_6 into uranium dioxide (UO_2) powder which is then pressed and heated (sintered) into small cylindrical pellets. These are loaded into hollow metal tubes (fuel rods/pins), typically of highly corrosion resistant stainless steel or zirconium alloy. A number of these rods are arranged in a carrier structure, collectively termed a fuel assembly. A typical boiling water reactor (BWR) contains over 730 assemblies containing about 46 000 fuel rods.

Fuel assemblies are typically irradiated in a reactor for 3-4 years, during which some of the ^{235}U is consumed (fissioned) to produce energy. Furthermore some ^{238}U undergoes fertile conversion yielding ^{239}Pu , which is also fissionable and which is also partially consumed to produce energy. The ^{238}U fertile conversion rate is approximately the same in all reactors in the current fleet, with typical values ranging from 0.6 to 0.7. This means that for every fissile nucleus undergoing fission or neutron capture, 0.6 to 0.7 fertile capture events also take place, leading to the generation of useful ^{239}Pu . Only a fraction of

11. This depleted material is commonly referred to as “tails” or “tailings”. It amounts to ~85% by weight of the input uranium to the enrichment process.

the ^{239}Pu so produced fissions, thus contributing to about 30% to 40% of the energy output over the lifetime of the fuel.¹² The fertile conversion mechanism is therefore a valuable means by which the useful energy extracted from uranium is enhanced.

The majority of the uranium in the fuel also remains unused and, at discharge, irradiated fuel still contains fertile ^{238}U and residual quantities of different fissile nuclides: ^{235}U , ^{239}Pu and ^{241}Pu . The precise amounts vary depending on the reactor type and the burn-up history of the fuel, but for light water reactors (LWRs) the residual ^{235}U is typically between 0.6 and 1.0%, while the fissile plutonium content ($^{239}\text{Pu} + ^{241}\text{Pu}$) is typically between 0.7 to 0.8%.

The “back end” of the fuel cycle starts when the irradiated or “spent” fuel is unloaded from the reactor for interim storage, a necessary step in all fuel cycles (as discussed in Section 3.2.3.). Typically radioactive spent nuclear fuel (SNF) is transferred from the reactor core to water filled pools at the site, where the water provides cooling and radiation shielding. After this initial cooling period some of the radioactivity has declined (although the spent fuel is still highly radioactive) and the fuel temperature is much reduced. SNF is then ready for longer-term interim storage, which may be at the site or at a centralised storage facility, either in a pool or using specially designed storage units, where it can remain awaiting eventual packaging for disposal (the once through cycle) or for sending to a reprocessing facility (closed fuel cycle).

Transport of SNF is typically done in heavy steel casks, whose walls provide radiation shielding and dissipate radioactive decay heat through conduction. Transport of SNF as other nuclear materials, is also an important integral part of the fuel cycle, quite focal from the socio-political perspective. Subject to stringent national and international regulations (IAEA), nuclear transport is however a very safe and mature industry, as shown by the experience in many countries (NEA, 2010g).

Reprocessing is the operation by which the unused energy content of spent fuel is recovered for future re-use or where various constituents in the spent fuel are separated for waste management reasons (e.g. partitioning and transmutation discussed in Section 2.9.2). Reprocessing as done today already significantly reduces the volume and the long-term radioactivity of material that requires disposal. The separation of the uranium and plutonium is achieved commercially using a chemical process called plutonium and uranium extraction (PUREX). The rejected high-level fission product waste stream which also contains the minor actinides is stored for subsequent solidification in a highly leach resistant glass matrix (vitrified high-level waste – VHLW). During the vitrification process molten VHLW is poured into stainless steel canisters, where it solidifies. The canisters are then sealed and sent to a cooled storage facility until they are eventually sent for deep geological disposal. The metal fuel rod tubes and the other components from the fuel assemblies form other waste streams which are also conditioned in canisters for storage and final disposal. An important facet of reprocessing is that the ultimate waste, i.e. the vitrified glass canisters, no longer contains any fissionable materials, allowing some relaxation of criticality constraints and safeguards requirements after its disposal.

REPU can be recycled (with some additional measures, see below), following re-enrichment. Some reactors are also partially fuelled with pellets containing a mixture of uranium and plutonium dioxides (MOX) using recycled materials recovered during reprocessing (see Figure 2.9). At present about 40 LWRs worldwide use MOX fuel to meet part of their fuel requirements. MOX fuel requires some more elaborate precautions in fuel manufacturing than uranium fuel, to contain the plutonium and guard against radiological dose uptake for the operating staff. The possible number of plutonium recycles is limited by the build up of even-numbered Pu isotopes that are not fissionable

12. Pu accounts for about 50% of the energy produced in HWRs.

by the thermal neutrons found in LWRs and by the build up of undesirable elements, especially curium. After two to three cycles (depending on how much spent MOX fuel is diluted with spent UOX fuel) the MOX-fuel cannot be recycled within LWRs, whilst further use of the still valuable U and Pu in the MOX-fuels can be pursued in fast spectrum reactors (see below).

Thus, there are two major options currently in commercial use for irradiated fuel management in light water reactors, the “once-through cycle” and the partial recycling option where the unused uranium and the plutonium in spent fuel are recycled in light water reactors.

REPU from LWRs typically contains slightly more ^{235}U than natural uranium and, with suitable adjustments to allow for the presence of neutron absorbing non-fissile ^{236}U , it can be used as a direct substitute. In principle, REPU can be recycled without re-enrichment in pressurised heavy water reactors (PHWRs) but this is not yet commercially implemented.¹³ As for MOX, REPU fuel manufacture also requires special provision to deal with the high gamma field from the decay chain of ^{232}U , which, although present only at very low levels (parts per billion), is nevertheless a significant gamma source.

Other types of reactors – fast reactors (FRs) – which operate with fast neutron spectra are more suited for multi-recycling of fissile and fertile materials. This is because, in a fast neutron spectrum, fertile isotopes behave as and/or transform to fissionable materials so that, compared to LWRs, the effective use of the fuel is much enhanced. In such reactors it is even possible to generate more fissile material than the amount used; this process which leads to a net increase of fissionable isotopes is referred to as breeding. Reactors designed to achieve this are termed fast breeder reactors (FBRs).

Given FRs potential for multi-recycling of plutonium and uranium, such reactors consume much reduced uranium resources. From a given quantity of natural uranium the energy content extracted through FRs can be some 60 times greater than in open fuel cycles. Although a number of FRs have been constructed and operated they have so far not been deployed in significant numbers; they are a more complex technology and uranium has so far been plentiful and relatively inexpensive. From a waste management perspective, FRs are also very suited for the recycling of minor actinides (MAs) to pursue a reduction of decay heat and radiotoxicity of waste (see Section 2.9.1).

These advantages have led to a continuing interest in their development as, for example, in the Generation IV programme (see Section 2.9.1). Many studies have been and are still conducted on the transition scenarios from today’s LWR-driven nuclear reactor park towards a mixed LWR-FR or full FR reactor parks and the various fuel cycle choices these may induce (NEA, 2006; 2009 and RED-IMPACT, 2008). During the 1990s and early 2000s important activities relating to the use of FRs were undertaken in the context of furthering the sustainability of the waste management component, i.e. the reduction of minor actinides¹⁴ in the final waste. It should be noted that sustainability, including optimised fuel utilisation to provide long-term availability and minimisation and effective management of waste, is one of the goals for the new systems supported by GIF.

13. The first power reactor demonstration irradiations of REPU-derived fuel have been completed in China.

14. The actinide series encompasses the 15 chemical elements with atomic numbers from 89 to 103, actinium through lawrencium. The minor actinides are the actinide elements in used nuclear fuel other than uranium and plutonium, which are termed the major actinides. The minor actinides include neptunium, americium, curium, berkelium, californium, einsteinium and fermium. It is generally only the first three of these that need to be considered as significant.

2.6. The nuclear fuel cycle: front end

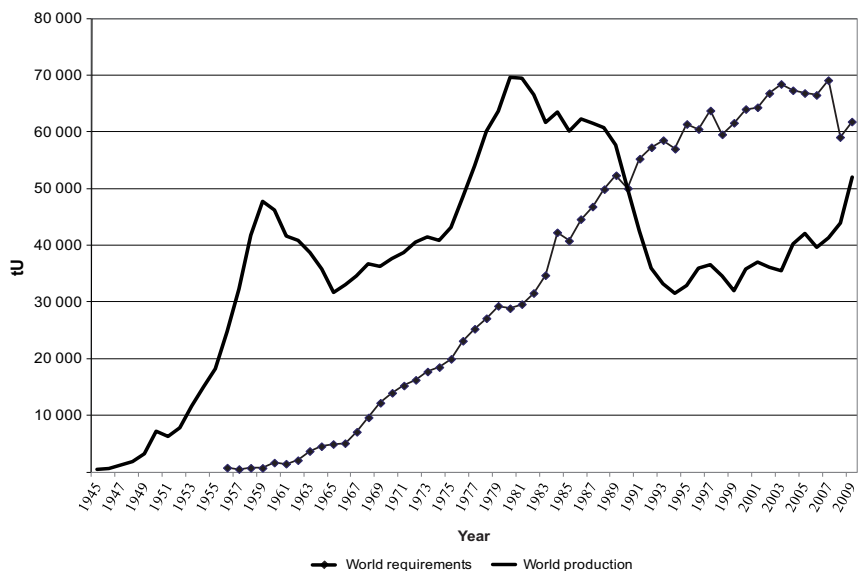
2.6.1. Uranium supply and demand

The uranium market

Market conditions are the primary driver in the determination of resources and the development of uranium production capacity. Many aspects of the current uranium market have been shaped by a 20-year period of low prices (~1983-2003) that followed a period of high prices and intensive exploration and production in the 1970s. Since production in these early years of the industry greatly exceeded subsequent requirements for electricity generation a large inventory of “secondary supplies” accumulated.

This inventory, held in various forms by governments and civil industry, was a critical factor in keeping prices low in subsequent years. When the 2002 *Nuclear Fuel Cycle Trends* report was published, uranium prices had been mostly below USD 30/kgU since 1989, also due to a combination of other factors (Price *et al.*, 2006). Drawing from this accumulated inventory and from blending down the weapons grade highly enriched uranium (HEU) from the Russian Federation and the United States that became available around the same time, reduced demand for fresh uranium resulted in two decades of low uranium prices. This led to the closure of all but the lowest cost mining facilities, stimulated market consolidation and curtailed investment in exploration and mine development. From the early 1990s until the middle of the current decade, around half of annual requirements has been met by these secondary sources (see Figure 2.10).

Figure 2.10: Annual uranium production and requirements, 1945-2009

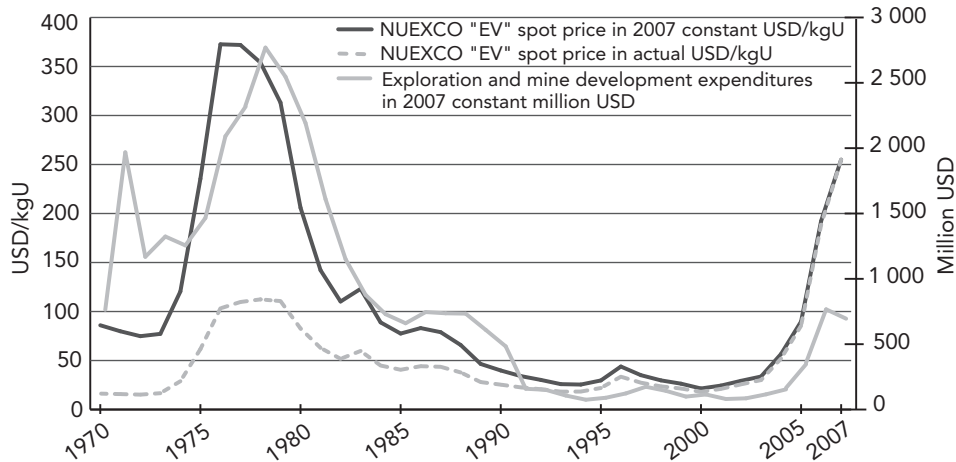


Note: 2009 values are estimates.

The situation changed dramatically in 2003/2004 when uranium prices rose in response to changing market conditions. First, demand increased as new reactors came on-line and as old reactors achieved increased capacity factors through improvements in operations and up-ratings. Second, it became evident that the historic uranium stocks were nearing the point at which they would soon be used up and the HEU down-blending programme was drawing to a close. The more widespread recognition of the potential contribution nuclear could have in the generation of low-carbon energy needed for a

global development has likely contributed to strengthening the market through to 2007. Additional factors influencing the market were some temporary difficulties experienced at existing and developing uranium mines and mills as well as purchases by speculators. Uranium spot market prices increased considerably and became volatile, peaking many times higher than their previous long-term plateau (between the early 1990s and 2000s, as shown in Figure 2.11).

Figure 2.11: Average annual uranium spot price, exploration and mine development expenditures, 1970-2007



Notes: The 2007 exploration and mine development value is an estimate. NUEXCO exchange value ("EV") spot price data courtesy of Trade Tech (www.uranium.info).

In 2007 following the peak, uranium spot prices experienced a downturn. This has been attributed to the reluctance of traditional buyers to engage in transactions at such high prices (NEA, 2010d). Ultimately the global financial crisis has contributed to the downturn stimulating sales by distressed sellers needing to urgently raise capital (NEA, 2010d). Spot prices rose steadily again during 2010 but, following the accident in Fukushima Daiichi, they fell quite dramatically,¹⁵ on concern that lost generating capacity in Japan and possibly other European countries would reduce uranium demand. However, spot prices have since climbed back and, while in the short term the uranium market is expected to be volatile and perhaps somewhat depressed, the fundamental market and social forces are still there to drive the market higher again in the medium to longer term.

It should be noted that the quantity of uranium traded on the spot market in a given year is usually equivalent to under 15% of the total quantity of uranium traded. For example, in 2009 only 5.2% of all uranium deliveries to EU utilities were purchased under spot contracts (the European nuclear market makes up around 30% of the world market). Long-term contracts account for most uranium ore transactions and prices for these have been less volatile, although still subject to substantial increase.

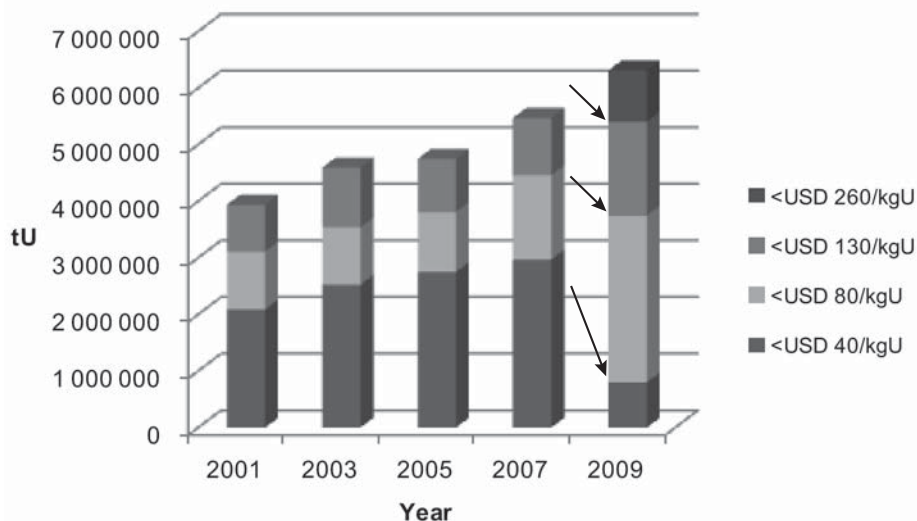
Uranium exploration and resources

Although the decline of market prices since 2007 and the rising mining and development costs have caused at least some of the planned developments to be delayed, it is clear that the generally stronger market of recent years, compared to the last two

15. Ux Consulting Company (www.uxc.com/review/uxc_PriceChart.aspx?chart=spot-u3o8-2yr).

decades of the 20th century, has spurred increased exploration and the development of production capability (NEA, 2010d) (see Figures 2.11 and 2.12).

Figure 2.12: Total identified resources by cost category from 2001 to 2009



Sources: Based on NEA, Uranium Resources, Production and Demand: 2001-2009.

According to the NEA (2010d), significant new production capability is planned for the near term, both through the opening of new mines and the expansion of existing production centres which has been ongoing since 2003. It seems that investment in exploration and mine development follows spot price increases with a lag of around two years. Since uranium is a relatively common element of the earth's crust, renewed investment in uranium exploration can be expected to result in the discovery of new resources of economic interest.

As exploration activity increases, so does the resource base, despite continuous draw-down through mine production. In 2009, total identified resources¹⁶ (reasonably assured and inferred) amounted to about 5 400 000 tU in the <USD 130/kgU category and to about 6 300 000 tU in the <USD 260/kgU category (NEA, 2010d).

The total of the so-called undiscovered resources (prognosticated resources and speculative resources) amounted to some 10 500 000 tU, increasing by 485 000 tU from that reported in 2005, even though some countries, including major producers, do not report resources in this category. Some of these countries, such as Australia, Gabon and

16. Uranium resources are classified by a scheme (based on geological certainty and costs of production) developed to combine resource estimates from a number of different countries into harmonised global figures. "Identified resources" (RAR and inferred) refer to uranium deposits delineated by sufficient direct measurement to conduct pre-feasibility and sometimes feasibility studies. For RAR, high confidence in estimates of grade and tonnage is generally compatible with mining decision-making standards. Inferred resources are not defined with such a high degree of confidence and generally require further direct measurement prior to making a decision to mine. "Undiscovered resources" (prognosticated and speculative) refer to resources that are expected to occur based on geological knowledge of previously discovered deposits and regional geological mapping. Prognosticated resources refer to those expected to occur in known uranium provinces, generally supported by some direct evidence. Speculative resources refer to those expected to occur in geological provinces that may host uranium deposits. Both prognosticated and speculative resources require significant amounts of exploration before their existence can be confirmed and grades and tonnages can be defined.

Namibia, are considered to have significant resource potential in as yet sparsely explored areas. Table 2.2 shows the quantities of uranium reported in each of the categories in 2009.

Table 2.2: Uranium resources

Resource category	Quantity: 1 000 tU at <USD 130/kgU	Quantity: 1 000 tU at <USD 260/kgU
Identified (reasonably assured and inferred)	5 404	6 306
Reasonably assured	3 525	>4 004
Inferred	>1 879	2 302
Prognosticated	2 815	2 905
Speculative*	3 778	3 902
Total	11 997	13 113

* Plus a further 3 594 with a cost range unassigned, totalling 7 496 tU.

Source: NEA, 2010d.

It should be noted that, whilst total identified resources have increased overall, there has been a significant reduction in lower cost resources owing principally to increased mining costs. In the 2009 edition of *Uranium Resources, Production and Demand* (NEA, 2010d) a new high-cost category (of <USD 260/kgU) was added in response to both the overall increase in market prices for uranium since 2003 and increased mining costs. Though a portion of the overall increases in the new high-cost category relate to new discoveries, the majority results from re-evaluations of previously identified resources.

The introduction of fast breeder reactors on a commercial scale would dramatically expand the amount of energy that could be extracted from the available uranium resources (Table 2.3). As discussed in Section 2.5, by converting non-fissile ²³⁸U to fissile ²³⁹Pu, the requirement for fresh uranium could be greatly reduced (NEA, 2006); a factor of up to 60 is considered in NEA, 2008a. This would enable the production of largely CO₂-free energy for many thousands of years.

Table 2.3: Lifetime of uranium resources
(years of supply at 2008 reactor requirements)

	Identified resources	Total conventional resources	Total conventional resources plus phosphates
Present reactor technology	100	~300*	~700**
Introduction of fast neutron systems	>6 000	~17 000	~40 000

* Total conventional resources include all cost categories of reasonably assured resources (RAR), inferred, prognosticated and speculative resources for a total of about 16 706 300 tU. Significant exploration and development would however be required to move these resources into more definitive categories (NEA, 2010d).

** Estimates of uranium resources associated with phosphates are very uncertain and the development of more rigorous estimates is needed (NEA, 2010d). However, almost 9 million tU is estimated in four countries alone, Jordan, Mexico, Morocco and the United States. According to previous reviews (NEA, 2006a), worldwide totals of phosphate-related resources could total as much as 22 million tU.

Source: Based on NEA, 2010d; 2006a; and 2008a.

The uranium resource figures presented here should not be regarded as an inventory of total amount of mineable uranium contained in the earth's crust. Should favourable market conditions continue to stimulate exploration additional discoveries may be

expected, as was the case during past periods of heightened exploration activity. Given the limited maturity and geographical coverage of uranium exploration worldwide, there is considerable potential for the discovery of new resources of economic interest.

As seen in Table 2.3, employment of advanced reactor and fuel cycle technologies could also add significantly to world energy supply in the long term. Moving to advanced technology reactors and recycling fuel could increase the long-term availability of nuclear energy from hundreds to thousands of years. In addition, thorium, which is more abundant than uranium in the earth's crust, is also a potential source of nuclear fuel, if alternative fuel cycles are developed and successfully introduced. Thorium-fuelled reactors have been demonstrated in the past but require further development, especially with respect to recycling technologies.

There are also considerable unconventional resources, including phosphate deposits (see Table 2.3), which, if potential barriers such as regulatory requirements and availability of qualified personnel are overcome, could be utilised to significantly lengthen the time that nuclear energy could supply energy demand using current technologies. While phosphate rocks are believed to be the largest source of the unconventional U resources, there is also a considerable quantity of uranium (approximately 4.2 million tU) in the black shales of Chattanooga (United States) and Ronneburg (Germany) and uranium recovery from coal and coal ash is under consideration. Extraction from seawater, in which there is an estimated 4.6 billion tU, has also been explored and research has continued in Japan to find methods to make this economically exploitable.

Geographical distribution

Geopolitically, uranium resources and fuel fabrication are very different from fossil fuels. One big advantage of nuclear power is the high energy density of the fuel and the consequent ease with which strategic stockpiles of fuel can be maintained,¹⁷ combined with the diverse and stable geopolitical distribution that has characterised uranium resources and fuel fabrication facilities. Identified resources amongst 14 countries that are either major uranium producers or have significant plans for growth of capacity are reported in Figure 2.13, which illustrates their widespread distribution. Together, these 14 countries are endowed with about 97% of the identified global resource base in this cost category (the remaining 3% is distributed among another 19 countries). The widespread distribution of uranium resources is an important strategic aspect of nuclear energy in respect of security of energy supply, which is a cornerstone of national energy policies and is receiving increasing attention from the public and policy-makers. It should be noted, however, that uranium mining has recently seen a gradual move towards countries that are either new in mining and/or have increased geopolitical risks. This may have negative implications, including on the predictability of uranium prices.

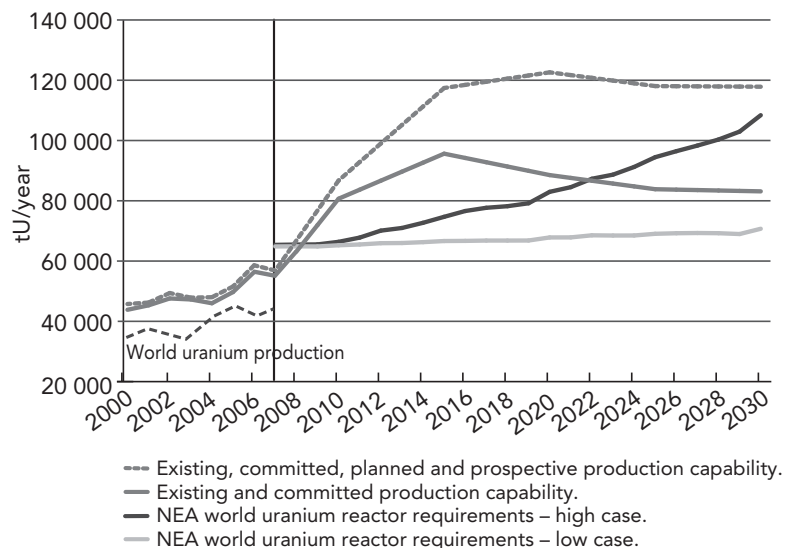
17. One tonne of uranium used in a light water reactor with open fuel cycle (once through) has the energy equivalent of 10 000-16 000 tonnes of oil or 14 000-23 000 tonnes of coal (NEA, 2008b).

Figure 2.13: Global distribution of identified resources (<USD 130/kgU)

Uranium demand

Worldwide uranium demand is almost entirely set by the nuclear industry fuel requirements; the latter totalled approximately 67 300 tonnes in 2008. This demand is matched by uranium production (mining, ISL, etc.) combined with secondary supplies (down blending of highly enriched uranium from nuclear warheads, stocks held by governments or utilities and recycled materials). Uranium acquisitions have declined in recent years due to inventory drawdown and because increased uranium costs have motivated utilities to specify lower tails assays at enrichment facilities in order to reduce uranium consumption (see Section 3.2.1).

A global picture of uranium supply and demand balance (see Figure 2.14) can be derived by considering plans for new production capacity together with the production capacity of mines in operation and the identified conventional resource base (as of 1st January 2007), combined with future uranium demand based on NEA scenarios of growth in nuclear generating capacity to 2030 (404 GWe and 619 GWe in the low and high scenarios, respectively). The *Nuclear Energy Outlook* shows the response of the industry to higher prices from 2003 to 2007 and demonstrates the power of the market in driving the development of uranium production capacity. With firmer world uranium prices, it has now become easier for primary producers to compete with the remaining secondary supplies, the production costs of which are largely sunk. To meet the upper demand scenario, a significant increase is warranted, moving towards a tripling of world uranium production by 2030 from the current level of 40-45 000 tU per annum (see Table 2.4). In the reference scenario of the NEA, production must at least double. Both of these are clearly possible given the strong resource base, but will mean a substantial break with the history of the industry in the 1980s and 1990s. Indeed the build up needs to be along the lines of the huge expansions of the 1950s (for military requirements) and the late 1970s (to satisfy rapidly rising civil demand).

Figure 2.14: Annual world uranium production capacity and NEA projected world uranium reactor requirements,* 2007 to 2030

* Includes all existing, committed, planned and prospective production centres supported by reasonably assured and inferred resources recoverable at a cost of <USD 80/kgU.

Table 2.4: Uranium production by country in 2008

Country	Uranium production (tonnes)	Total production (%)
Australia	8 433	19
Brazil	330	1
Canada	9 000	21
China	770	2
Czech Republic	275	1
India	250	1
Kazakhstan	8 512	19
Namibia	4 400	10
Niger	3 032	7
Russian Federation	3 521	8
South Africa	565	1
Ukraine	830	2
United States	1 492	3
Uzbekistan	2 340	5
Others	130	<0.5
Total	43 880	100

If achieved, plans for a rapid expansion of existing and committed uranium production capacity are expected to be sufficient to meet NEA high demand requirements until 2022. If planned and prospective centres are considered, production capacity is expected to be more than adequate to meet even the NEA high demand scenario through 2030; but these centres must be completed on schedule and production must be maintained at or near full capacity throughout the life of each facility. Considering the recent record of uranium mine development, delays in the establishment of new

production centres can reasonably be expected, reducing and/or delaying anticipated production from planned and prospective facilities. Moreover, as noted in NEA (2006a), world production has never exceeded 89% of reported production capacity (since 2003, production has varied between 73% and 84% of capacity). Hence, even though industry has responded vigorously to the market signal of higher prices, achieving market balance will likely require additional primary production and secondary supplies, supplemented by uranium savings achieved by employing low enrichment tailings levels, to the extent possible given the limited excess enrichment capacity available today (reducing enrichment tailings levels from 0.3% to 0.25% would, all other things being equal, reduce uranium demand by 9.5% but increase enrichment requirements by 11%). After 2013, following the expiration of the HEU disposition agreement between the governments of the United States and the Russian Federation, secondary sources of uranium are expected to decline in availability and reactor requirements will have to be increasingly met by primary production.

Research and investment will be very important to develop new mining projects in a timely manner and a market price for uranium that stimulates investment will be required. Moreover, in the last couple of years the recent financial crisis steadily occupied the financial markets worldwide as it spread across the world economy. The uranium market was not immune to its effects. The scarcity of financial resources has led to some decisions to reduce, postpone or even stop production; because of the squeeze on sources of finance, some companies might even abandon new mining projects.

Hence, while the availability of uranium in the ground is not in question, the rate at which it can be extracted and made available to the market is in more doubt. In the near term much now depends on the speed of the financial recovery and the perceived longer-term demand for uranium post the Fukushima Daiichi event. Even with favourable market conditions, the industry will be challenged to meet high demand scenarios, principally because of the considerable time that it takes to develop a uranium mine in most jurisdictions and the challenge of keeping mine production at or near production capacity and also because of the gradual reduction in average ore-grade in mines explored. There is a key role for governments here in ensuring that the necessary approval processes are as efficient as possible, while still maintaining the necessary rigour.

2.6.2. Conversion

At around the turn of the century (2000) uranium conversion prices were quite low (<USD 5/kgU¹⁸), but on a rising trend. At these prices it was difficult for conversion plants to make a return and there was an expectation that some producers might withdraw their plants and cease production. However, coincident with the rise in uranium prices in 2004 there was a sharp increase in conversion prices to a high of USD 12/kgU between 2005 and 2007, followed by a slight downwards trend in 2008/2009.

In 2009, total world conversion capacity was estimated at 76 000 tU as UF₆ (see Table 2.5). Large conversion plants are operating in Canada, France, the Russian Federation, the United Kingdom and the United States, with four companies accounting for more than 90% of nominal capacity and production. Kazatomprom is likely to become a major provider of conversion services, having signed an agreement with Cameco to build a UF₆ conversion facility with a potential capacity of 12 000 tonnes in Kazakhstan using Cameco technology.

During 2008, AREVA announced plans to invest another EUR 610 million in modernising and increasing its conversion capacity at the Tricastin and Malvési plants, a project known as Comurhex II and currently being constructed with gradual startup by

18. Ux Consulting Company, available at www.uxc.com.

2015. Completion of these installations is scheduled in 2012, adding a conversion capacity of 15 000 tonnes (and possibly up to 21 000 tonnes) per year.

Table 2.5: Major uranium conversion companies

Company	Nominal capacity in 2008 (tU as UF ₆)	Share of global capacity (%)
Atomenergoproj (Russian Federation)	25 000	33
Cameco (Canada and United Kingdom)	18 500	24
AREVA (France)	14 500	19
ConverDyn (United States)	15 000	20
CNNC (China)	3 000	4
World total	76 000	100

Source: Based on WNA, 2011.

Normally conversion facilities can be expected to have averaged throughputs of some 90% of nominal capacity. Comparing these conversion capabilities with the demand for uranium in the NEA scenarios shows that additional conversion capacity will be needed in the near future if the high projection materialises. The timing depends on the amount of secondary uranium supplies continuing to reach the market. Building additional capacity should not cause difficulties and, as indicated here, significant new capacity is already under construction.

2.6.3. Enrichment

In the years leading up to 2000, enrichment separative work unit (SWU)¹⁹ prices had been declining steadily, but in 2001 stepped up to USD 100-110/kgSWU, remaining stable thereafter, until 2006. From 2006 onwards, SWU prices have risen and in 2010 were at about USD 160/kgSWU. This coincided with the rise in primary uranium price and a corresponding rise in enrichment requirement. SWU costs contribute a few percentage to overall generating costs, roughly comparable to uranium ore, so the potential for SWU price volatility to deleteriously affect overall generating costs is limited.

The main commercial-scale uranium enrichment facilities currently in operation worldwide are located in China, France, Germany, Japan, the Netherlands, the Russian Federation, the United Kingdom and the United States (see Table 2.6).

The World Nuclear Association (WNA) also reports a number of projects and developments that are targeted to add new enrichment capacity over the next 10 years (WNA, 2009):

- USEC plans to replace the existing Paducah gaseous diffusion plant with the American Centrifuge Plant based on the AC100 series centrifuge (USEC, 2010). As of 30 September 2010, USEC had invested approximately USD 1.9 billion in the project and had secured USD 3.1 billion in committed sales for the output of the plant. However, USEC needs additional financing to complete plant construction and has significantly demobilised construction and machine manufacturing activities for the project until that is available. The capacity of the American Centrifuge Plant will be equal to about one-third of the fuel requirements for the commercial power reactors in the United States.

19. SWU: separative work unit. This is the standard measure for enrichment. It is commonly expressed as kgSWU or tSWU.

- The Georges Besse II programme in France will replace the existing gaseous diffusion plant with gas centrifuge production. The construction at the Tricastin nuclear site began in the second half of 2006 and is continuing in a stepwise fashion, through progressive connection of modular centrifuge cascades. This AREVA group new uranium enrichment plant, which will include two enrichment units, was inaugurated in December 2010, with the first production of enriched UF₆ in April 2011. Completion of the plant is expected for 2014, with a total production capacity of 7 500 tSWU extendable according to market demands.

Table 2.6: Major enrichment companies with approximate 2010 capacity

Country	Company and plant	Capacity (tSWU)	Share of global capacity (%)
France	Areva, Georges Besse I & II	8 500	14.8
Germany-Netherlands-United Kingdom	Urenco: Gronau, Germany; Almelo, Netherlands; Capenhurst, United Kingdom	12 800	22.3
Japan	JNFL, Rokkaasho	150	0.3
United States	USEC, Paducah & Piketon	11 300	19.7
United States	Urenco, New Mexico	200	0.3
United States	Areva, Idaho Falls	0	0.0
Russian Federation	Tenex: Angarsk, Novouralsk, Zelenogorsk, Seversk	23 000	40.1
China	CNNC, Hanzhun and Lanzhou	1 300	2.3
Others	Various	100	0.2
World total		57 350	100.0

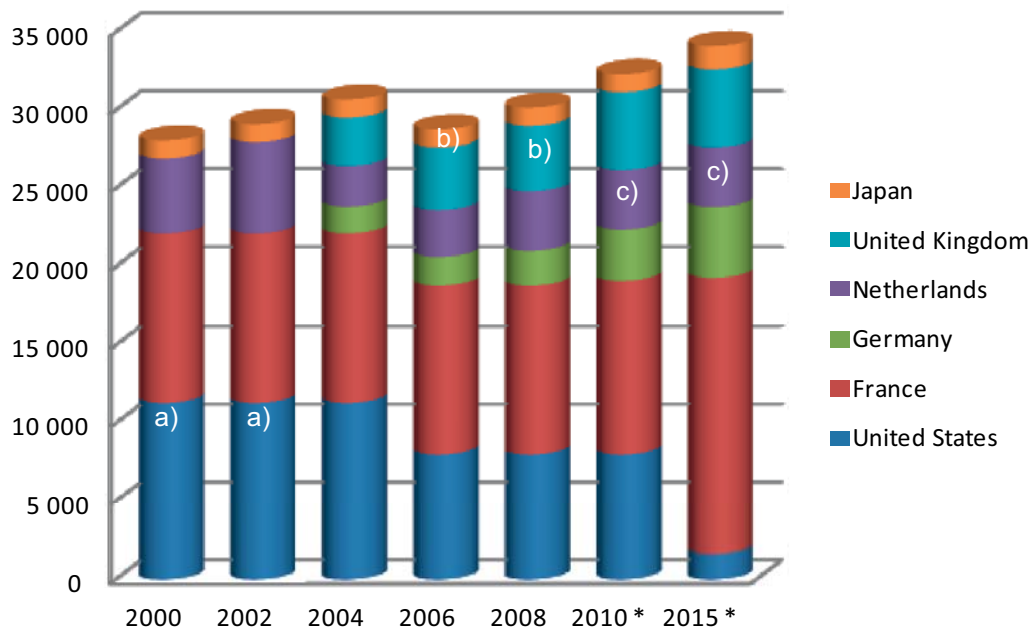
Source: Based on WNA.

- The National Enrichment Facility (NEF), to be constructed by Urenco's subsidiary Louisiana Enrichment Services (LES), is targeted to add an initial capacity of 3 000 tSWU by 2013. In November 2008, LES announced plans to expand NEF's capacity to 5 900 tSWU by 2015, pending US Nuclear Regulatory Commission (NRC) licence approval.
- The Eagle Rock Enrichment Facility will produce 3 300 tSWU for the United States market with the potential to expand to 6 000 tSWU. AREVA has targeted start of production by 2014 with full production by 2017. A loan guarantee (USD 2 billion) for the project has been provided by DOE and construction is expected to begin in 2012 subject to licensing and the necessary diplomatic agreements.
- GE Hitachi (GEH) Global Laser Enrichment (GLE) in the United States has outlined plans to commercialise the SILEX laser isotope enrichment technology. In July 2009, GLE announced the start-up of the test loop which will be used to provide information for the design of a future commercial facility. GEH expects to have the GLE commercial facility in operation by 2013/2014. Plans are for initial production of 500 tSWU per annum, with an eventual target of 3 500-6 000 tSWU for the final commercial facility.
- Urenco continues to increase its capacity at its European facilities and plans to have a capacity of 12 000 tSWU by the end of 2015.

- Japan Nuclear Fuel Ltd. (JNFL) continues to enhance the design of its centrifuges and is planning to install new machines to achieve a targeted capacity of 1 500 tSWU by around 2020.
- CNNC will have a fourth unit of the gas centrifuge uranium enrichment plant at Hanzhong with 500 tSWU capacity.
- In May 2007, Russia's Tenex and Kazakhstan's Kazatomprom signed an agreement on the creation of the International Uranium Enrichment Centre (IUEC) located in Angarsk in Siberia. The IAEA Board of Governors approved this initiative in November 2009, with the aim of providing assured access to uranium enrichment to interested parties without transferring the sensitive technology. Following negotiations, in March 2010 the IAEA Director-General and the Director-General ROSATOM signed an agreement to establish the LEU reserve for supply to the IAEA for its member states. The IUEC storage facility was inaugurated in December 2010 following the first IAEA inspection and after completion of all formal procedures, the March 2010 agreement entered into force in February 2011. Since then the LEU reserve in Angarsk has been available for IAEA member states (120 tonnes of LEU up to 4.95%). It is expected that IUEC will start commercial supplies of enriched uranium to Ukraine in 2012.

Figure 2.15 represents the changes in enrichment capacity within NEA countries in the last decade and expected projections up to 2015.

Figure 2.15: Enrichment capacity in NEA countries (tSWU/year)



* Expected; a) nameplate capacity; b) provisional data; c) not available – assumed as per 2008. It should be noted that additional capacity is expected to become available in the United States after 2015.

Source: Based on NEA Nuclear Energy Data: 2001-2010.

According to industry estimates, by the end of 2015, planned enrichment capacity worldwide (including non-NEA countries and notably the Russian Federation and China) could reach a total of ~69 000 tSWU. This includes new centrifuge enrichment facilities,

expansion of existing facilities and the closure of the two remaining gaseous diffusion plants (see Table 2.7).

The WNA estimates that enrichment requirements will grow to 66 535 tSWU in 2020 and 79 031 tSWU in 2030, under its reference scenario (WNA, 2009). In its upper-case scenario, those figures are 77 651 tSWU in 2020 and 105 715 tSWU in 2030. Given the modular expansion capability of enrichment plants and the required timelines for building new ones, WNA concluded that enrichment capacity should be able to meet worldwide requirements under any current projection of demand in the forecast period.

Table 2.7: Projected enrichment plant capacity at the end of 2015 and 2020 (tSWU)

Country	Company and plant	Enrichment capacity (tSWU)	
		2015	2020
France	AREVA, Georges Besse I	7 000	7 500
Germany, Netherlands, United Kingdom	Urenco: Gronau, Germany; Almelo, Netherlands; Capenhurst, United Kingdom	1 000	12 300
Japan	JNFL, Rokkaasho	750	1 500
United States	USEC, Paducah & Piketon	12 100	3 800
United States	Urenco, New Mexico	5 900	5 900
United States	AREVA, Idaho Falls	3 800	3 300
United States	Global Laser Enrichment	2 000	3 500
Russian Federation	Tenex: Angarsk, Novouralsk, Zelenogorsk, Seversk	33 000	30-35 000
China	CNNC, Hanzhong & Lanzhou	750	6 000-8 000
Brazil, Iran, Pakistan	Various	300	300
Total		69 000	74-81 000

Source: WNA, 2011.

2.6.4. Fabrication

Information supplied to the IAEA identified 40 commercial-scale fuel fabrication facilities in operation in Argentina, Belgium, Brazil, Canada, China, France, Germany, India, Japan, Kazakhstan, Pakistan, the Republic of Korea, Romania, the Russian Federation, Spain, Sweden, the United Kingdom and the United States (IAEA, 2011a). Table 2.8 provides an update on the status of these commercial plants. The main fuel manufacturers are also the main suppliers of nuclear power plants or closely connected to them. The largest fuel manufacturing capacities can be found in France, Kazakhstan, the Russian Federation and the United States, but fuel is also manufactured in other countries, often under licence from one of the main suppliers.

Fuel assemblies from different suppliers are not easily interchangeable, although many utilities do periodically change suppliers to maintain competition. Entering the fabrication market is especially challenging because the fuel assembly itself is a highly engineered, technologically specific product with significant intellectual property behind it. In addition, the fuel assembly is a component affecting the overall safety of the plant and requires extensive licence approval.

Table 2.8: Commercial fuel fabrication plants

Country	Facility name	Fuel type	Reactor type	Design capacity (tHM/year) (*)	Start of operation
Argentina	Ezeiza – Nuclear Fuel Manufacture Plant	U Assembly	PHWR	270	1982
Belgium	FBFC International – LWR	U Assembly	PWR	500	1961
Brazil	FCN Resende – Unit 1	U Assembly	PWR	240	1982
Canada	N. Fuel PLLT. OP. – Toronto	U Pellet-Pin	PHWR	1 300	1967
Canada	General Electric Canada	U Assembly	PHWR	1 200	1956
Canada	Zircotec Precision Ind. – Port Hope	U Assembly	PHWR	1 200	1964
China	CANDU Fuel Plant	U Assembly	PHWR	200	2003
China	Yibin Nuclear Fuel Element Plant	U Assembly	PWR	200	1998
France	FBFC – Romans	U Assembly	PWR	1 400	1979
Germany	Advanced Nuclear Fuels GmbH Lingen Plant	U Assembly	LWR	650	1979
India	NFC – Hyderabad	U Assembly	BWR	24	1974
India	NFC – Hyderabad	U Pellet-Pin	BWR	335	1998
India	NFC – Hyderabad	U Assembly	PHWR	270	1974
India	NFC – Hyderabad-2	U Assembly	PHWR	300	1997
Japan	Global Nuclear Fuel-Japan Co., Ltd. (GNF-J)	U Assembly	BWR	750	1970
Japan	Mitsubishi Nuclear Fuel Ltd. (MNF)	U Assembly	PWR	440	1972
Japan	Mitsubishi Nuclear Fuel Ltd. (MNF)	Re-conversion to UO ₂ powder	PWR	450	1972
Japan	Nuclear Fuel Industry Ltd. (NFI Kumatori)	U Assembly	PWR	284	1972
Japan	Nuclear Fuel Industry Ltd. (NFI Tokai)	U Assembly	BWR	250	1980
Kazakhstan	Ulba Metallurgical Plant (UMP)	U Pellet-Pin	WWER, RBMK,	2 800	1949
Korea, Rep.	PWR Fuel Fabrication Plant	U Assembly	PWR	400	1989
Korea, Rep.	CANDU Fuel Fabrication Plant (2)	U Assembly	PHWR	400	1998
Pakistan	Chashma	U Assembly	PHWR	20	1986
Romania	Pitesti Fuel Fabrication Plant (FCN)	U Assembly	PHWR	200	1983
Russian Fed.	Machine – Building Plant	U Assembly	FBR	50	1953
Russian Fed.	Machine – Building Plant	U Assembly	RBMK	900	1953
Russian Fed.	Machine – Building Plant	U Assembly	WWER	620	1953

Table 2.8: Commercial fuel fabrication plants (continued)

Country	Facility name	Fuel type	Reactor type	Design capacity (tHM/year) (*)	Start of operation
Russian Fed.	Machine – Building Plant	Fuel fabrication (U Pellet-Pin)	WWER, RBMK, FBR	800	1953
Russian Fed.	Novosibirsk Chemical Concentrates Plant (Assembly)	U Assembly	WWER	1 000	1949
Spain	Fabrica de Combustible Juzbado (ENUSA)	U Assembly	LWR	400	1985
Sweden	Westinghouse Electric Sweden AB	U Assembly	LWR	600	1971
United Kingdom	NDA Springfields OFC AGR Line	U Assembly	AGR	290	1996
United States	Columbia (Westinghouse)	U Assembly	PWR	1 150	1986
United States	Lynchburg – FC Fuels	U Assembly	PWR	400	1982
United States	Richland (ANF)	U Assembly	LWR	700	1970
United States	Wilmington (GNF)	U Assembly	BWR	1 200	1982

* Please note that the list might not include all of the facilities in the world due to the unavailability of the data.

Source: Based on data from IAEA, 2011a.

In the western world alone, fabrication capacity currently outweighs requirements by approximately 40%. Hence, existing fuel fabrication capacity is more than sufficient to meet current requirements and this is likely to be the case under all scenarios until at least 2020. Investments, consolidation and partnerships in fuel fabrication are being pursued by the major players (notably AREVA). The lead time for increasing capacity of existing fabrication plants or even for constructing new fabrication plants is shorter than the licensing and construction period for new reactors. A new fabrication line can satisfy the reload demand of 20 to 30 new reactors.

It follows that fuel fabrication should not become a bottleneck in the supply chain in any conceivable nuclear expansion. However, in the vast majority of current and future nuclear reactor designs, zirconium is widely used as a material for cladding and structural elements in fuel assemblies, due to its specific characteristics, such as low absorption of thermal neutrons, an excellent resistance to corrosion in water and high-pressure steam, good mechanical strength and stability under radiation. Nuclear grade zirconium is only supplied by 4 or 5 main companies around the world and, in a prospective global nuclear expansion, its fabrication is likely to come in the critical path. Consolidation and the establishment of joint ventures among zirconium suppliers are being established to increase the capacity.

One area of the market where growth remains a possibility is in MOX fuel fabrication. Existing plans by the limited number of countries that have to date committed to using MOX fuel will require the expansion of capacity at existing MOX fuel fabrication facilities, along with the construction of new plants. However, while decisions on changes within the LWR market are increasingly based on commercial considerations, future decisions related to MOX fuel fabrication are likely to depend as much on political factors as on economic ones.

Since 2001, MOX fuel production has increased largely through the increased capacity that was installed at the MELOX plant in France, which can now produce MOX fuel at the rate of 195 tHM/year. Other MOX production plants, such as Sellafield MOX Plant (SMP) in the United Kingdom, that were expected to contribute to world production have been

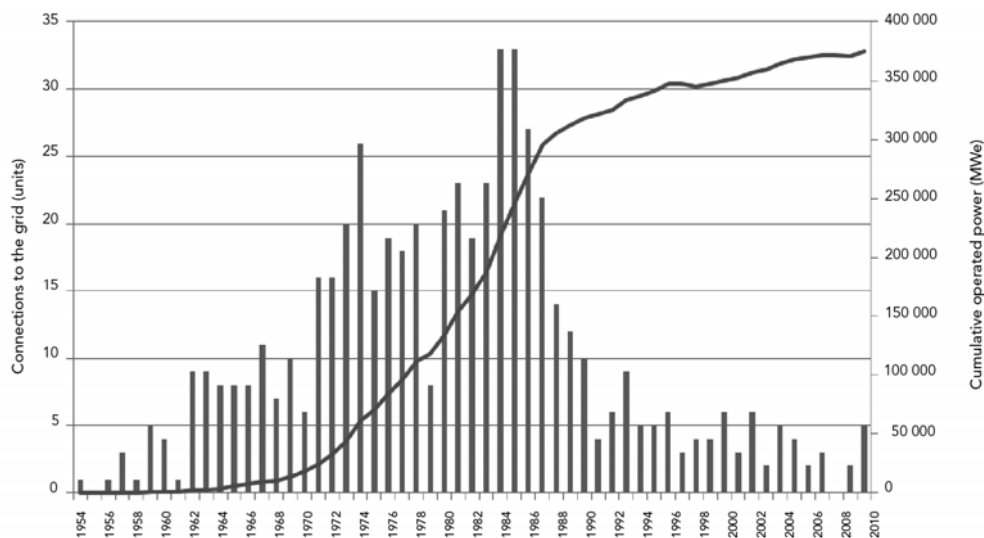
slower than expected to reach full production capacity. In 2010, the Nuclear Decommissioning Authority (the United Kingdom owner of SMP) agreed on a plan to refurbish the SMP, and this work was being undertaken over three years by Sellafield Ltd, using technology from France's AREVA (WNN, 2011a). However, closure of the Sellafield MOX Plant was announced in August 2011, as a result of increased uncertainties in future use, deriving from the Fukushima Daiichi accident, for the ten Japanese utilities that had placed contracts for supplies of MOX fuel at SMP.²⁰ A USD 4.8 billion MOX plant is being built in the United States at Savannah River by Shaw AREVA MOX Services to combine 34 tonnes of surplus military plutonium with uranium oxide and create fuel for conventional power reactors; operation is expected to start in 2016 (WNN, 2011). JNFL is developing a plan to construct a MOX fuel fabrication plant (the J-MOX plant) in Rokkasho-mura which will start operation in June 2015. The plant is the first commercial MOX plant in the country and will have a capacity of 130 tHM/y.

2.7. The nuclear fuel cycle: irradiation stage – reactor operations

2.7.1. The evolution of reactor technology

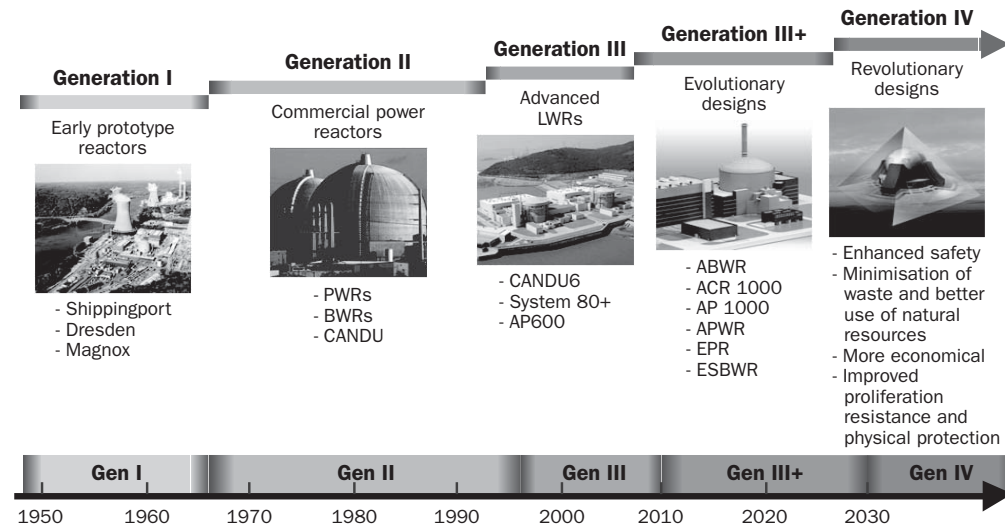
The first electricity producing reactor was connected to the grid in 1954 at Obninsk in the Soviet Union, with a very modest power output of 5 MWe. It was a graphite moderated, water-cooled reactor, the forerunner of the RBMK design. This was soon followed by others in the United Kingdom of a graphite moderated, gas-cooled design (Calder Hall, 1956, four reactors of 50 MWe each) and the United States (1957 Shippingport, 60 MWe), the world's first pressurised water reactor. As shown in Figure 2.16, since these early beginnings there was at first a rapid growth, which then levelled out in the mid-1980s to a much slower level. This slower growth rate has continued until present times.

Figure 2.16: Nuclear growth from 1954 to 2010 – annual statistics
(excluding unfinished constructions)



Source: Based on IAEA, 2011.

20. www.world-nuclear-news.org/WR_Sellafield_MOX_plant_to_close_0308111.html.

Figure 2.17: The evolution of nuclear power plant designs

Source: GIF, 2002.

Throughout this time the design of reactors has been evolving and improving; Figure 2.17 illustrates this evolution. As shown in the figure, the evolution is commonly described by designating reactors into generations. Generation I were mainly prototype reactors and many different designs were built, as illustrated by the earliest reactors at Obninsk, Calder Hall and Shippingport. Most of these have now been shut down with the exception of the Magnox series (graphite moderated, gas cooled) in the United Kingdom, where two reactors at Oldbury (1968) and two at Wylfa (1972) are still operating. Generation II designs were the main wave of reactors constructed during the big expansion of the 1970s and 1980s. The more recent Generation III and III+ reactors are designed for higher availabilities and longer lives, typically 60 years, but perhaps extendable to well beyond that.

Design improvements over the evolution have enhanced the protection against external hazards (earthquakes, aircraft impacts, floods, etc.), reduced the Generation III/III+ probability of core melting to very low levels and the probability of large releases of radioactivity to even lower levels. Most Generation III/III+ designs make use of improved safety features combining active and passive safety systems to mitigate all envisageable incident and accident conditions. Some designs incorporate passive safety features which require no active controls or operational intervention in the event of reactor malfunction.

While today's designs are more than fit for purpose, the radical Generation IV designs (see Section 2.9.1), for which the research and development is being conducted today, are aiming to further improve sustainability, economics, safety and reliability, proliferation resistance and physical protection. Generation IV reactors are intended to become available for deployment beyond 2030.

2.7.2. The current fleet

At the time of the publication there are 433 if we count the fast reactors in operation worldwide (IAEA, 2011). LWRs comprise the largest grouping, made up of 268 pressurised water reactors (PWRs) and 84 BWRs. There are 47 PHWRs and the balance is comprised of 17 gas-cooled reactors (GCRs), 15 light water-cooled graphite-moderated reactors (LWGRs) and 2 fast reactors. A further 65 units are under construction.

All the commercial power reactors currently in operation are dependent on uranium as their fissile material. Most of the world's reactors operate with low-enriched uranium (LEU), characterised by initial enrichments of less than 5%, requiring an enrichment stage in the FC. Only HWRs, notably CANDU reactors, operate with natural uranium and do not require the enrichment stage,²¹ but the other aspects of the front-end FC still apply. While, for the same amount of energy produced, CANDU reactors generate larger amounts of spent fuel due to the lower achievable burn-up in comparison to reactors that are fuelled with LEU, they allow a more efficient utilisation of uranium, requiring smaller quantities of natural uranium. This is because, by separating a significant fraction of the ²³⁵U in the original uranium ore into the depleted tails stream, the enrichment operation required for LEU fuels used in LWRs introduces an unavoidable inefficiency. This ²³⁵U in the tails stream is largely unused at present in the fuel cycle and can amount to as much as 30% or 35% of the original ²³⁵U mass.

Challenges

The need for continued safety vigilance. For the sustained use of nuclear power, let alone its expansion into the future, it is clear that continued safe operation of the existing reactors is of critical importance. Large accidents in all the energy industries, especially in the more advanced economies of the OECD, are relatively rare. Indeed, although this is not widely appreciated, premature deaths from emissions from fossil fuel consumption are large, as reported in Section 2.3.4, greatly outweighing those from all energy chain accidents. Nevertheless, accidents seem to galvanise public and political attention, defining the social acceptability of any technology and particularly that of nuclear energy.

The Paul Scherrer Institut in Switzerland has built up a database of energy-related accidents from the 1970s onwards, by which technologies can be compared in terms of accident statistics. The Nuclear Energy Outlook (NEA, 2008a) presents a review of this work. From this impressive collection of real accident data it is clear that nuclear energy is far safer than all of the fossil fuel technologies (liquid petroleum gas, coal, oil and natural gas) in terms of prompt deaths from accidents. The well known accident at Three Mile Island (TMI) in the United States resulted in no deaths and the Chernobyl accident in the former Soviet Union caused 31 prompt deaths and a similar number of deaths over the following years. No deaths from radiation have been reported for the Fukushima Daiichi accident (Japanese Government, 2011) at the time of publication of the work.

Latent deaths from Chernobyl, the world's most severe nuclear accident, are much harder to estimate, with estimates ranging up to 9 000 (with dose cut-off) to 33 000 (summed over the entire northern hemisphere with no dose cut-off). Given the high natural incidence of cancer, these incidences will be difficult, if not impossible, to detect. As a comparison, the larger number is similar to the prompt deaths from the world's worst hydroelectric accident (Banqiao/Shimantan, China²²) and the rate per GWe-year much lower than other energy forms. Further, on a like for like basis for health effects, the estimated latent deaths **per year** from fossil fuel consumption are larger than all the long-term latent Chernobyl deaths.

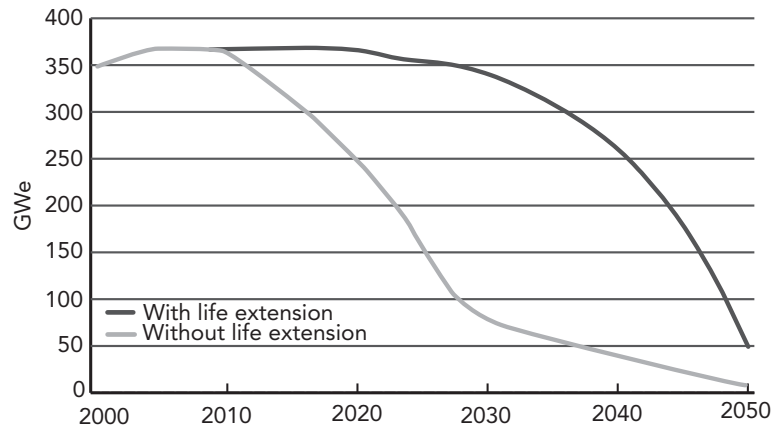
While, in terms of mortality statistics, it makes no sense to replace one technology with others that are more dangerous, any nuclear accident of moderate severity, anywhere in the world, could impact on the continued operation of the current fleet and halt the possibility of a further major expansion of nuclear power, just as TMI and Chernobyl were major contributors to the end of the rapid growth phase of the 1970s and

-
21. With the addition of the last three Magnox reactors operating in the United Kingdom, which are all due to close by 2012.
 22. This caused 26 000 deaths from the flood, an additional 145 000 from epidemics and famine (NEA, 2010f).

1980s. It remains to be seen what the final impact of events at Fukushima Daiichi will be, although there will undoubtedly be a slowdown in development and many countries will review their proposed programmes.²³

Reactor life extension. Given the slow nuclear construction in the 1990s and the first decade of the current century, the average age of the world's reactor fleet has been increasing. The ages of those reactors constructed in the 1970s are now, or are approaching, 40 years or more; this was often set as the length of their expected economic life. However, most of the designs were robust and many countries are undertaking safety case re-evaluations and plant upgrades to extend the operating period. As of April 2011, in the United States, for example, regulatory approvals have already been given to continue operation to 60 years for 62 reactors with approximately 20 more applications under review by the US NRC and a further 16 reactors expected to apply for license renewal (NEI, 2011). This process is of considerable importance, as can be seen from Figure 2.18. With no new build and no life extension the world's nuclear power capacity would drop rapidly from 2010 onwards. With life extensions, some 350 GWe will be maintained until 2030, allowing time for a regrowth of construction capacity.

Figure 2.18: The effect of reactor life extension on world nuclear capacity



2.7.3. New reactors under construction

At the beginning of 2011, 65 new power reactors were officially under construction in 16 countries (Table 2.9), although 13 of these have been under construction for some time. Of these, China had the largest programme, with 27 units under construction. The Russian Federation also had several large units under construction. Among NEA countries, the Republic of Korea had the largest expansion underway with 5 units, but Finland, France, Japan and the Slovak Republic were each building one or two new units. In the United States, a long-stalled nuclear project has been reactivated. In total, these new units can be expected to add around 50 GWe of new capacity to existing capacity of 370 GWe (although a few gigawatts of older capacity are also expected to close over the next few years).

23. Germany and Switzerland have already committed to shutting down their programmes, and Italy has voted not to renew theirs.

Table 2.9: Nuclear power plants under construction, as at the start of 2011

Location	No. of units	Net capacity (MWe)
Argentina	1	692
Brazil	1	1 245
Bulgaria	2	1 906
China	27	27 230
Finland	1	1 600
France	1	1 600
India	5	3 564
Iran	1	915
Japan	2	2 650
Korea (Republic of)	5	5 560
Pakistan	1	300
Russian Federation	11	9 153
Slovak Republic	2	782
Chinese Taipei	2	2 600
Ukraine	2	1 900
United States	1	1 165
Total	65	62 862

Source: IAEA, 2011.

2.7.4. Commercially available designs

Each of the latest Generation III/III+ designs available from the main suppliers offers a comparable level of technology. As discussed briefly in the previous section, the aim has been to “design out” many of the issues encountered in the construction and operation of existing plants. Design simplification and the use of advanced construction techniques (such as modular construction) are important themes, with the goal of reducing construction times and costs. The designs offer improved performance and reliability, greater fuel efficiency, enhanced safety systems, and produce less radioactive waste. The plants are designed from the outset to operate for up to 60 years with availability factors exceeding 90%.

The intention of each supplier is to offer, as far as possible, one or more standardised designs worldwide, to reduce the risk of construction delays caused by design changes. Standardisation will also offer benefits during operation, from exchange of information and experience between operators and easier movement of personnel and contractors between similar plants. The leading designs presently being offered by the major nuclear power plant suppliers worldwide, which are expected to provide the great majority of new nuclear capacity at least until 2020, are described in Table 2.10.

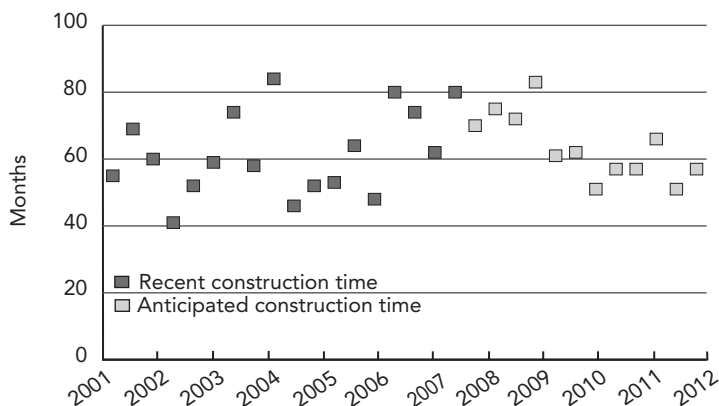
Table 2.10: Main designs for nuclear power plants for deployment by 2020
(status in 2011)

Design	Description
AP1000	is the flagship design from Westinghouse. Although majority owned by Toshiba of Japan, Westinghouse is headquartered in the United States. The AP1000 is an advanced PWR with a capacity of about 1 200 MWe, the first three examples of which are at an early stage of construction in China. The design has also been selected for the largest number of potential new US plants, and is being offered in the United Kingdom and other markets.
EPR™	is the main offering from AREVA, the main European nuclear industry group. Also an advanced PWR, it has an output of 1 600 to 1 750 MWe. The first units are now under construction in Finland and France with two others being constructed in China, with a further order due shortly in France and India. Up to four orders are expected in the United Kingdom, while others are under consideration in the United States.
ATMEA™	is an AREVA and Mitsubishi Heavy Industries (MHI) jointly developed 1 000-1 150 MWe Generation III+ 3-loop PWR. The design is based on PWR technology but adding more passive safety systems. The core can allow a 100% MOX core loading and the reactor is designed for load following.
KERENA™	is an AREVA-designed Generation III+ design. With a 1 250 MWe output, KERENA is based on existing BWR-technology with a safety concept based upon active and passive safety systems. The reactor can run on enriched uranium (up to 5%) and MOX fuel.
ABWR	is the only advanced BWR of the recent designs already in operation, with four units in Japan. Two further ABWRs are under construction in Chinese Taipei. These units have outputs in the 1 300 MWe range, but up to 1 600 MWe versions are offered. The basic design was developed jointly by General Electric (GE) of the United States and Toshiba and Hitachi of Japan. GE and Hitachi subsequently merged their nuclear businesses.
ESBWR	a further development of the ABWR concept, is the latest offering from GE-Hitachi. Its output will be in the region of 1 600 MWe. No orders have been secured to date, but the design has been selected for some potential new US plants.
APWR	the advanced PWR has been developed for the Japanese market by MHI, with two units expected to begin construction in the near future. Output will be around 1 500 MWe per unit. MHI is also offering a version of the APWR in the US market, and has been selected for one potential project.
VVER-1200	is the most advanced version of the VVER series of PWR designs produced by the Russian nuclear industry, now organised under state-owned nuclear holding group Rosatom. Four VVER-1200 units are under construction in the Russian Federation, each with a net power output of about 1 100 MWe. Additional designs are also offered in other markets, including the VVER-1000, which has been exported to several countries, including China and India.
ACR	is the newest design from Atomic Energy of Canada Ltd. (AECL), owned by the Canadian Government. Most Canada Deuterium Uranium (CANDUs) use heavy water to moderate (or slow) neutrons, making it possible to use natural uranium fuel. However, the 1 200 MWe ACR will use enriched fuel, the first CANDU design to do so. AECL also offers the Enhanced CANDU 6, a 700 MWe unit using natural uranium. No orders for either design have been placed so far.
APR1400	is the latest Korean PWR design, with four 1 400 MWe units under construction and several more planned. It is based on original technology now owned by Westinghouse. This has been further developed by Korean industry in a series of more advanced designs. The licensing agreement still limits its availability in export markets, but in late 2009 a Korean-led consortium (with Westinghouse participation) won a contract to build four APR1400 in the United Arab Emirates.
CPR1000	is currently the main pressurised water reactor design being built in China, with 16 units under construction. This 1 000 MWe design is an updated version of a 1980s AREVA Generation II design, the technology for which was transferred to China. China recently announced that they will not build further CPR1000 plants.
India's PHWR	designs are based on an early CANDU design exported from Canada in the 1960s. The latest units have a capacity of 540 MWe, and 700 MWe units are planned. Although further developed since the original design, these are less advanced than Generation III designs. In addition to building PHWRs, India has imported two VVERs from the Russian Federation, and is expected to place further orders for nuclear imports in the near future.

Around the world, further designs are under development. For example, since 2008, the Japanese METI, electric utilities and plant vendors have been designing next-generation systems of 1 700-1 800 MWe (one PWR and one BWR), based on ABWR and APWR technologies. These include designs with higher enriched fuel, more use of passive safety systems and materials designed for longer lifetimes.

One issue troubling potential investors, as discussed in Section 2.4, is the timescale that it can take from utility project decision to first generation for nuclear plants. The early stages of public enquiries and regulatory approvals can be moderately expensive, but the major expenditure begins when construction commences. Delays in construction can have a significant impact on project economics and, of course, this is particularly so where the interest charges are high (IEA/NEA, 2010). Time to construction is therefore a matter of considerable interest. In NEA, 2008a, data were analysed for construction times in those Asian countries that had continued to construct nuclear reactors on a frequent basis; Figure 2.19 shows this data.

Figure 2.19: Recent and anticipated construction times in Asia, as of 2007



For these countries the recent historic data and the anticipated construction times were good, averaging around 60 months. However, in those countries where construction has not been so frequent and experience has been lost, recent history is not encouraging, as exemplified by the experience in Finland for the construction of Olkiluoto III. Construction delays are exacerbated by projects that involve first-of-a-kind where regulatory or construction difficulties can be experienced in the erection of a new design.

The lessons to be learnt are the need for fully completed and approved designs before construction commences, ensuring that the supply chain is fully educated in the quality standards required in nuclear construction. Modular and factory construction as much as it can be arranged, and the employment of standard designs that can be repeated many times can minimise novel difficulties.

2.8. The nuclear fuel cycle: back end

2.8.1. Reprocessing

Reprocessing is the process of separation of various constituents in the used fuel with the aim to further condition these or to recycle some of them via fabrication of new fuels. Reprocessing consists of separating uranium, plutonium and a combination of fission

products (FP) and minor actinides²⁴ allowing the recycle of uranium and plutonium or even transuranics²⁵ in reactors. The attractions of reprocessing are that it reduces natural uranium requirements and considerably decreases the quantities of radioactive waste which have to be safely stored awaiting subsequent disposal. Closing the fuel cycle also leads to a decrease in the radiotoxicity of the waste. Reprocessing can therefore enhance sustainability by reducing the use of natural uranium resources while ultimately assuring improved waste management. Nevertheless, there is awareness at the international level of the potential use of reprocessing for non-civil purposes, although, with the effectiveness of current international safeguards, no known diversion of fissile material from the civilian fuel cycle under safeguards has occurred to date. Many countries have avoided domestic development or use of reprocessing for reasons of non-proliferation.

Today there are reprocessing plants in France, India, Japan, the Russian Federation and the United Kingdom (smaller pilot plants exist in China). The countries which have used or are using reprocessing are Belgium, France, Germany, India, Japan, the Netherlands, the Russian Federation, Switzerland and the United Kingdom. Table 2.11 summarises the reprocessing capacities in 2000, 2004 and 2010 (estimated) in NEA countries. No significant changes are apparent, which reflects the discussion in Chapter 4 of the policy stances in different countries.

Table 2.11: Reprocessing capacities in NEA countries (tonnes HM/year)

Country	Fuel type	2000	2002	2004	2006	2008	2010 [*]
OECD America		0	0	0	0	0	0
United States	LWR	0	0	0	0	0	0
	FBR	0	0	0	0	0	0
OECD Europe		4 100	4 100	4 100	4 100	4 100	4 100
France	LWR	1 700	1 700	1 700	1 700	1 700	1 700
United Kingdom	LWR	900	900	900	900	900 ^(a)	900
	Magnox	1 500	1 500	1 500	1 500	1 500 ^(a)	1 500
OECD Pacific		14	29	39	26	40	160
Japan	LWR					0	120
	MOX	14	29	39	26	40	40
Total		4 114	4 129	4 139	4 126	4 140	4 260

* Estimates. (a) Provisional data.

Source: Based on NEA Nuclear Energy Data: 2001-2010.

Adding non-NEA countries, the spent fuel reprocessing capacity worldwide reaches approximately 5 150 tHM/y [including current capacities in the Russian Federation and India which account for 400 and 260 tHM/y respectively²⁶ (IAEA, 2008), but excluding the Rokkasho facility in Japan which, when operational, would account for some further 800 tHM/y²⁷]. Of this capacity approximately 3 000 tHM/y is being used. As yearly

24. Advanced reprocessing techniques under development allow even further separation of elements, particularly minor actinides.

25. Transuranics = plutonium + minor actinides (neptunium, americium, curium).

26. Additional capacities of some 1 600 and 300 tHM/y are planned in the Russian Federation and in India respectively.

27. Commencement of commercial operations is expected in 2012.

discharges of spent fuel have been approximately 10 500 tHM/y for several years, it can be inferred that just under 30% of fuel discharged from reactors is currently being reprocessed (IAEA, 2008).

The most advanced MOX recycle programme is in France, which places value on the strategic benefits of recycling (see Section 3.2.1). In Japan, LWR MOX utilisation is seen in much the same way and a gradual expansion of LWR MOX utilisation is anticipated. In Europe, some countries which have used MOX fuel in their LWRs have done so because of an obligation to consume plutonium from historical reprocessing contracts. In other countries, however, the motivation to utilise MOX fuels or reprocessed uranium has been the reduction of natural uranium needs and of ultimate waste volumes, whilst pursuing improved characteristics for the waste. These countries intend the irradiated MOX fuel assemblies to be reprocessed and to provide fissile and fertile material for the fast reactors under development.

Conversely, for the group of countries which see MOX utilisation as a necessary commitment until their separated plutonium has all been recycled, the irradiated MOX fuel assemblies would then join irradiated UO₂ assemblies for interim storage and eventual geological disposal. For a long time the United States have had a policy of direct disposal of irradiated fuel, but is now considering again the possibility of reprocessing and MOX recycle. The United States have already started to implement a limited MOX recycle programme as a means of using surplus weapons grade plutonium. The United Kingdom also has a stock of separated plutonium from historic reprocessing operations and MOX utilisation in LWRs is one option that is being considered for the purpose of reducing plutonium stocks.

In order to make maximum use of uranium resources in a closed fuel cycle, however, use of fast breeder reactors or other advanced systems is being actively considered for longer-term deployment in a number of countries.

2.8.2. Waste management

Radioactive waste is defined by IAEA as “any material that contains or is contaminated by radionuclides at concentrations or radioactivity levels greater than the exempted quantities established by the competent authorities and for which no use is foreseen”. Most civil radioactive waste arises from nuclear power production but a wide variety of industries, including medicine, agriculture, research, industry and education, use radioisotopes and produce radioactive waste.

Several classifications are possible when categorising radioactive waste. The system adopted by IAEA, which is the most internationally accepted, combines the type of radiation emitted, the activity of the waste, its half-life and the best disposal option to present an easy method of classification based on the main following categories (IAEA, 2009):

- Exempt waste (EW): excluded from regulatory control because radiological hazards are negligible.
- Very short-lived waste: can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control. This class includes waste containing primarily radionuclides with very short half-lives.
- Very low-level waste (VLLW): waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control. Concentrations of longer-lived radionuclides in VLLW are generally very limited.
- Low-level waste (LLW-SL): waste with limited amounts of short-lived radionuclides (SL) that requires robust isolation and containment for periods of

up to a few hundred years. LLW may include short-lived radionuclides at higher levels of activity concentration, and also long-lived radionuclides, but only at relatively low levels of activity concentration.

- Intermediate-level waste (ILW-LL): waste that, because of its content, particularly of long-lived radionuclides (LL), requires a greater degree of containment and isolation than that provided to LLW. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal.
- High-level waste (HLW): waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste.

All stages of the nuclear fuel cycle produce wastes. Low-level waste and short-lived intermediate-level wastes are generated at all stages. Low- and intermediate-level waste with long-lived radionuclides (LILW-LL) is almost entirely generated by reprocessing. HLW is almost entirely generated from the fission product residue of reprocessing or the packaging of spent fuel for direct disposal. Conservative values for the quantities of waste generated per GWe-year are given in Table 2.12, which includes an annual allocation for eventual decommissioning wastes.

Table 2.12: Approximate quantities of radioactive waste and spent fuel per GWe-year (2005 base data)

Waste categories	Quantities
LILW-SL ⁱ	410 m ³ /y or 980 t/y
LILW-LL ⁱ	120 m ³ /y or 290 t/y
Committed ⁱⁱ decommissioning waste	90 m ³ /y or 210 t/y
Spent fuel	30 tHM/y
Committed ⁱⁱⁱ vitrified HLW	12 m ³ /y
Milling ^{iv} waste	45 000 m ³ /y
Total	~630 m ³ /y (or 1 500t/y) plus 45 000 m ³ /y of low-level milling wastes

- i) These values are now likely to be a significant overestimate as they average the quantity of waste generated over the history of nuclear power plants over the total power produced; better management practices have greatly reduced the quantities of waste produced as time has progressed.
- ii) Committed decommissioning waste: the quantity of decommissioning waste that will be generated at the end of life of the world fleet and its support facilities is accounted for here by allocating equal quantities over each of the assumed 40y lives of the power plants.
- iii) This is the quantity of HLW that would be generated if the whole of the spent fuel were eventually to be reprocessed. Note that this waste has already been included as part of spent nuclear fuel.
- iv) Milling wastes are generally of low radioactivity and are not always included in radioactive waste classification systems. If secondary sources were not available, this value would rise to 80 000 t/y.

Source: NEA, 2010e.

While these numbers may seem large, they are very small compared to the waste generation rate from coal-fired electricity generation. Nuclear power produces <0.2 kt/TWh of solid waste (including accounting for decommission wastes that will eventually arise). Coal produces ~1 600 kt/TWh. Both coal and nuclear power produce additional wastes from fuel mining and primary production processes. For nuclear energy this is <8 kt/TWh of lightly radioactive milling wastes and a similar quantity of non-active mining wastes. For coal these wastes amount to ~3 000 kt/TWh (NEA, 2010e).

Technology for the treatment, storage and disposal of low-level and short-lived intermediate-level wastes is well developed and almost all countries with a major nuclear programme operate disposal facilities for such wastes (Table 2.13). While these

represent the largest volumes of radioactive waste, the great majority of the radioactivity is contained in the relatively small volumes of spent nuclear fuel and, for countries that have recycled nuclear fuel, high-level waste from reprocessing.

Table 2.13: VLLW, LLW and ILW repository sites and projects in selected NEA countries

Country	Site (start year)	Waste category and capacity	Type	Status
Belgium	Dessel and Mol area (TBD)	LILW-SL	ENSF	Public inquiry
Canada	Kincardine (TBD)	LILW 160 000 m ³	GR	Under construction
Czech Republic	Richard II (1964)	LILW-SL 8 500 m ³	RC	Operating
	Bratrstvi (1974)	LILW-SL 1 200 m ³	RC	Operating
	Dukovany (1994)	LILW-SL 55 000 m ³	ENSF	Operating
Finland	Loviisa (1998)	LILW	RC	Operating
	Olkiluoto (1992)	LILW	RC	Operating
France	Centre de l'Aube (1992)	LILW-SL 1 000 000 m ³	ENSF	Operating
	Centre de la Manche (1979)	LILW-SL 527 000 m ³	ENSF	Closed in 1994
	Centre de Morvilliers (2003)	VLLW 650 000 m ³	SNSF	Operating
Germany	Konrad (2013)	LILW	GR	Under construction
	Morsleben (1981)	LILW	GR	Closed in 1998
Hungary	Bátaapáti (2009)	LILW	GR	Under construction
	RWTDF, Püspökszilágy (1976)	LILW-SL 5 040 m ³	ENSF	Operating
Japan	Rokkasho (1992)	LLW-SL 80 000 m ³	ENSF	Operating
	TBD	LILW-LL	RC	Site-selection
Korea (Republic of)	Wolsong, Gyungju (2010)	LLW-SL 160 000 m ³	RC	Under licensing
Slovak Republic	Mochovce (2001)	LILW-SL 22 300 m ³	ENSF	Operating
Spain	El Cabril (1992)	LILW-SL	ENSF	Operating
	El Cabril (2007)	VLLW	SNSF	Operating
Sweden	SFR (1988)	LILW-SL	RC	Operating
United Kingdom	Drigg (1959)	LLW-SL 1 400 000 m ³	E/SNSF	Operating
United States	Barnwell, South Carolina (1971)	LLW-SL 890 000 m ³	ENSF	Operating
	Richland, Washington	LLW-SL	SNSF	Operating
	Clive, Utah (1988)	LLW-SL and NORM	SNSF	Operating
	Andrews, Texas	LLW-SL and NORM	SNSF	Under licensing
	WIPP (1999)	TRU (LILW-LL) 175 000 m ³	GR	Operating

Notes: SNSF = simple near-surface facility; ENSF = engineered near-surface facility; E/SNSF = ENSF and SNSF; RC = rock cavern or intermediate-depth geological repository; GR = deep geological repository; TBD = to be determined.

Source: NEA, 2008a, Table 8.1.

The main challenge for the future of radioactive waste management is to develop and implement plans for the eventual disposal of spent fuel and VHLW. Long-lived intermediate-level waste may also be disposed of by the same route. There is a worldwide consensus amongst technical experts in the field that properly established deep geological disposal is an entirely appropriate management approach for HLW/SNF. While, as Table 2.13 shows, commercial facilities exist in many countries for LILW-SL there is, as yet, no facility for HLW/SNF.

Several countries have built underground research laboratories in different geological settings to develop HLW/SNF repository concepts and investigate factors affecting their long-term performance. The scientific and technological bases for implementing

geological disposal are thus well established. Several countries presently have active research, development and deployment (RD&D) programmes aimed at opening repositories before 2050. If successfully implemented, these ongoing projects and plans will provide disposal routes for much of the spent fuel and high-level waste already accumulated and expected to be produced up to 2050. Sweden and Finland are among the leaders in advancing plans to build and operate repositories. In both countries, sites have been selected and it is expected that the facilities will be in operation by around 2020. France is expected to follow by around 2025. Meanwhile, however, a policy decision has been taken to abandon a long running programme to develop a geological repository at Yucca Mountain in the United States of Nevada.

In the longer term, if recycling of spent fuel is introduced on a wide scale, then existing stocks of spent fuel, often treated as waste at present, could become an energy resource. The use of advanced fuel cycles could also reduce significantly the amounts of spent fuel and high-level waste to be disposed of. There would still be a need for some disposal facilities, but they could be smaller and/or fewer in number.

2.9. The nuclear fuel cycle: future developments

2.9.1. Generation IV systems

Launched in 2001, the GIF²⁸ is a co-operative international endeavour, initiated by the United States and organised to carry out the R&D needed to establish feasibility and performance capabilities of the next generation nuclear energy systems. Its membership comprises 12 leading nuclear energy countries (including Canada, China, France, Japan, the Republic of Korea, the Russian Federation and the United States) plus European Atomic Energy Community (Euratom – representing the EU). The major goals set out in the GIF roadmap (GIF, 2002) are summarised in Table 2.14. The prime objective is to improve sustainability of the nuclear option through a better use of resources and better management of radioactive wastes, together with improved economics, safety and reliability, proliferation resistance and physical protection.

The GIF goals were used to guide the selection of the six most promising systems for further collaborative R&D (GIF, 2002):

- gas-cooled fast reactor (GFR);
- very high-temperature reactor (VHTR);
- supercritical-water-cooled reactor (SCWR);
- sodium-cooled fast reactor (SFR);
- lead-cooled fast reactor (LFR); and
- molten salt reactor (MSR).

28. Available at www.gen-4.org.

Table 2.14: Goals for Generation IV nuclear energy systems

Goals	Description
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 their 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 and 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 and physical protection	Increase the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

Table 2.15: Characteristics of Generation IV nuclear energy systems

System	Neutron spectrum	Coolant	Outlet coolant temperature (°C)	Fuel cycle	Size (MWe)
VHTR	Thermal	Helium	900-1 000	Open	250-300
SFR	Fast	Sodium	550	Closed	30-150, 300-1 500, 1 000-2 000
SCWR	Thermal/fast	Water	510-625	Open/closed	300-700 1 000-1 500
GFR	Fast	Helium	850	Closed	1 200
LFR	Fast	Lead	480-800	Closed	20-180, 300-1 200, 600-1 000
MSR	Epithermal/fast	Fluoride salts	700-800	Closed	1 000

Sources: GIF, 2002; Bouchard and Bennett, 2009.

The main characteristics of each system are summarised in Table 2.15. In parallel to R&D topics specifically identified for each of the systems, cross-cutting issues have been identified for horizontal R&D efforts, addressing goals common to all the GIF systems. Currently, three working groups are developing common methodology related to economics (GIF, 2007a), risk and safety (GIF, 2007b), and proliferation resistance and physical protection (GIF, 2006).

Five of the designs are fast neutrons reactors, either as the base design or as an alternative. This allows the potential exploitation of the full energy content of uranium, both fissile and fertile isotopes, and also of all actinides (inbred ²³⁹Pu as well as other actinides found in the waste) through their recycling. The transmutation of actinides and fission products to shorter-lived isotopes will also allow the reduction of radiotoxicity and heat generated by the waste, potentially reducing the burden on disposal.

Very high-temperature reactors

Very high-temperature reactors (VHTRs) designs are based on the development of the high-temperature reactors which were studied in the 1960s-1980s in Europe (Germany, the United Kingdom) and the United States but interrupted after the mid-1980s. More recently there has been a renewed interest in high-temperature reactors (HTRs) firstly in South Africa, although the plans to build a prototype pebble bed modular reactor (PBMR) have now been abandoned, and in China,²⁹ where construction of a first twin unit PBMR (2 x 210 MWe) was due to start in April 2011, but is currently deferred. In Japan, HTTR (now part of Japan Atomic Energy Agency – JAEA), which achieved first criticality in 1998, reached a high temperature of 950 °C in 2004.

These reactors are graphite moderated (thermal neutron flux) helium cooled reactors with a ceramic fuel form, capable of very high coolant outlet temperatures (~1 000 °C) and therefore very high thermal efficiencies. Producing electricity using a direct cycle turbine in the primary circuit could allow efficiency levels as high as 50%. Furthermore, the high temperature coolant opens the possibility of nuclear energy providing industrial process heat. In particular, through the GIF, special attention is being given to hydrogen production processes with high efficiency and no CO₂ emission using thermo-chemical cycles or high-temperature steam electrolysis.

Among the challenges being addressed for the development of VHTR is the development of materials which can be used at the very high operating temperatures (graphite, ceramics, metal alloys for heat exchangers) as well as the ceramic fuel (TRISO particle). Particle fuel technology is central to VHTRs. Indeed, only ceramic materials are resilient to the temperatures foreseen. The TRISO particle consists of a fissile or fertile kernel up to 0.5 mm (500 µm) diameter, encapsulated with a buffer layer of porous pyrolytic carbon. This is then coated with a layer of high density pyrolytic carbon, a silicon carbide layer (“pressure vessel” around each fuel particle) and an outer layer of pyrolytic carbon. TRISO particles are then embedded in 6 cm diameter graphite spheres (pebble bed core design) or in cylindrical fuel compacts incorporated in hexagonal graphite fuel blocks (prismatic block design). The stable and robust characterisation of TRISO fuel particles in core also applies to spent fuel in a repository, so that, with a minimum of encapsulation, the fuel would form a very stable repository medium to retain the radiotoxic content.

VHTR fuel can also be recycled, but this is complicated by its design: the TRISO particles need first to be separated from the much larger volume of graphite matrix (which is another issue for sustainability, currently under study); dissolution of the fuel kernels cannot then proceed until the tough SiC outer layer has been mechanically breached.

Sodium-cooled fast reactor

Sodium-cooled fast reactor (SFR) technology was recognised early on in the history of nuclear power as a viable system for establishing a breeding cycle and considerable progress was made towards developing the technology to commercial readiness. SFRs were built and operated in France, Germany, Japan, the Russian Federation (former Soviet Union), the United Kingdom and the United States, ranging from 1.1 MWth to 1 200 MWe. GIF is building on this historic SFR knowledge base to develop designs which would best meet the Generation IV strategic goals. Today such reactors are still operated in Japan and the Russian Federation, while China and India recently joined the SFR operators and

29. In November 2005, a first twin unit PBMR (2 x 210 MWe) was initially approved to be built at Shidaowan, Shandong province. Its construction, due to start in April 2011, has been deferred following the accident at Fukushima Daiichi, but is still intended to begin soon, with commercial operations expected to start around 2015 (www.world-nuclear.org/info/inf63.html#HTR_PM).

France is planning to build a new prototype by 2020. India has an ambitious independent SFR programme based on the long-established experience with the experimental fast breeder test reactor. The construction of a 500 MWe prototype fast breeder reactor (PFBR) unit in Kalpakkam should be completed and the reactor put into operation by 2012, with the plan to build five additional units similar to this first by 2022.

The SFR system uses liquid sodium as the reactor coolant, allowing high power density with a low coolant volume fraction. With the developments currently achieved, the primary coolant system can either be arranged in a pool configuration (all primary system components are housed in a single vessel), or in a compact loop layout. However, sodium reacts chemically with water and air and it is therefore important that the design limits the potential for such reactions and their consequences. In past and present designs, a secondary sodium system acts as a buffer between the radioactive sodium in the primary system and the steam or water used in the conventional Rankine cycle, in order to avoid any radioactive release if a sodium-water reaction occurs. Ongoing studies include the development of alternative energy conversion system, such as using supercritical CO₂ cycle.

Beside the production of electricity and possibly process heat, the primary mission set for the SFR (as with the other fast neutron reactors) is a better use of resources and the management of high-level wastes, in particular the management of plutonium and other actinides. This comes with the development of the whole fuel cycle, able to both reprocess existing thermal reactor fuel and to serve the needs of SFR. At the moment there are two primary fuel cycle technology options: advanced aqueous process and pyrometallurgical process. Both processes could allow recovering and recycling 99.9% of the actinides, with final waste under the form of vitrified glass or glass bonded mineral.

Lead-cooled fast reactor

As far back as the 1950s, both the United States and the Russian Federation (then USSR) were investigating different options for reactors running with a fast neutron spectrum. While the United States abandoned lead coolant in favour of the sodium option, the Russian Federation decided to focus on lead-based reactors and developed lead-bismuth reactors to a mature stage. Seven lead-bismuth reactors in submarines and two on-shore prototypes were built and operated. Lead-cooled reactor technology was then transferred from military application to civil application with the design of the BREST reactor, a lead-cooled commercial power-generating reactor. Unfortunately, much of this Russian technology is unknown outside of the Russian Federation. Today, the main designs are the United States small secure transportable autonomous reactor, and the designs developed by the EU under the Euratom Framework Programme (ELSY, followed by LEADER).

When compared to sodium, lead (and lead bismuth) is far less reactive with air or water, so that the adoption of a buffer circuit between the primary circuit and the energy conversion system can be avoided. However, lead is much more corrosive, and extensive research in material technology and corrosion prevention under lead-alloys is ongoing, including the characterisation of candidate materials and coolant chemistry as well as radiochemistry control.

Gas-cooled fast reactor

Like the VHTR, the gas-cooled fast reactor (GFR) uses pressurised helium as the coolant, which is advantageous in that it has only a slight moderation effect, it is a single phase coolant, allowing high operating temperatures and high thermal efficiencies with direct cycle power conversion (i.e. using the primary circuit gas to drive a gas turbine and the compressors used to re-pressurise the working gas). There is no prior experience of operating GFR plants, but many features are similar to the VHTR. A commercially ready

design will certainly not be available within the next ten years, with perhaps more realistic timeframes of the order of 20 years or more.

One major difference between VHTR and GFR is the absence of the graphite moderator in the core of the latter. The fuel has to withstand very high operating temperatures. Ceramic forms are therefore required for cladding and several candidates are being investigated. Developing a satisfactory fuel design is one of the principal technical challenges to overcome. Core configurations may be based on prismatic blocks, pin or plate-based assemblies. The GFR reference design has an integrated, on-site spent fuel treatment and refabrication plant.

Molten salt reactor

The molten salt reactor (MSR) system uses a molten salt fuel circulating in a fast, thermal or epithermal spectrum reactor and operates with an integrated (on-line) fuel cycle. The fuel is a circulating liquid of lithium – beryllium fluorides or lithium or sodium and zirconium fluorides, with uranium or plutonium fluorides providing the fissile charge and thorium fluorides as the fertile material. In thermal or epithermal MSR systems the molten salt fuel flows through graphite channels in the core, with the graphite moderating the neutron flux. The fast MSR system has a core made from nickel alloy channels. Heat transfer from the molten salt to the power conversion system is obtained by means of secondary (molten salt) and tertiary (gas) coolant systems through heat exchangers. MSR can operate with a high thermal efficiency because the primary coolant can reach temperatures in the region of 700 or 800 °C.

The integrated fuel cycle is potentially very flexible and the elimination of fuel fabrication from the fuel cycle is a major benefit in this respect. Unlike the solid fuel reactors, the possibility of MSR liquid fuel on-line reprocessing enables the use of the thermal spectrum MSR as very effective thorium breeder. In the case of the double-fluid MSR core design, with separate fissile (^{233}U) and fertile (^{232}Th) fuel channels, MSR can reach attractive breeding factor of 1.13-1.15. It enables operation of MSR in a pure thorium – uranium (233) fuel cycle with minimised production of plutonium and no production of transplutonium elements. The key factor for future industrial deployment of MSR is the successful development of the pyro-chemical on-line reprocessing technology of its hot liquid fuel.

Supercritical-water-cooled reactor

The supercritical-water-cooled reactor (SCWR) system is a light water reactor that operates above the thermodynamic critical point of water (374 °C, 22.1 MPa). Supercritical fluids do not exhibit a phase transition and the use of supercritical water enables a thermal efficiency about 30% higher than current light water reactors (up to 50% thermal efficiency), as well as simplifying the balance of plant. Indeed, much of the technology base for the SCWR can be found in the existing LWRs and in commercial supercritical-water-cooled fossil-fired power plants. The main development issues are then associated to the core design and materials. There are currently two main designs under development, the pressure-vessel and the pressure-tube designs, plus a tentative combination of both concepts.

One of the advantages of the supercritical water technology is the possibility of designing a fast neutron spectrum reactor (allowing the implementation of a closed fuel cycle) as well as the thermal spectrum reactor.

2.9.2. Advanced fuel cycles

While sustained R&D has been conducted by the industry and research organisations to continuously improve today's fuel cycle technologies, including reprocessing and recycling, significant effort has also been geared towards the development of advanced

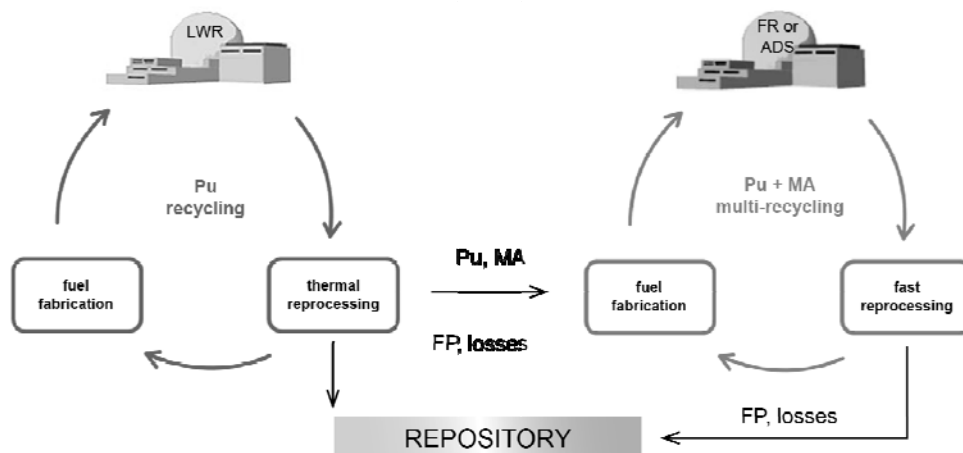
fuel cycle technologies. These advanced fuel cycle concepts, designed for the longer term have been studied theoretically or on a laboratory scale, principally with the dual objective of reducing the mass and radioactivity of wastes going to final disposal and optimising the use of natural resources.

While highly active but short-lived fission products dominate the activity of spent fuel in the shorter term, transuranics including plutonium and the minor actinides, together with a few long-lived fission products, are largely responsible for the long-term radiotoxicity and heat load of spent fuel. By burning minor actinides the long-lived component of high-level waste can be reduced, decreasing the long-term radiotoxicity and residual heat of HLW, hence providing a possible means to minimise the volume and cost of the repository for its disposal.

Current reprocessing and recycling methods allow some reduction of the volumes of high-level radioactive waste for eventual repository disposal through the removal of the U and Pu, with MAs and FPs remaining in the waste stream. Further reductions depend therefore on the ability of advanced cycles to remove these residual long-lived heavy isotopes from the irradiated fuel through the use of advanced reprocessing technologies (partitioning), and then dispose of them separately (this reduces long-term radiotoxicity and decay heat of the bulk of the waste, but not that of the partitioned stream) or “burn” them through nuclear reactions (transmutation). Essentially, two major families of such advanced fuel cycles can be considered, which can incorporate to different degrees P&T.

A first category aims at the separate treatment of minor actinides by transmuting them either homogeneously in the fuel, or heterogeneously in dedicated targets. Such fuel cycles would typically consist of a first stratum, relying on LWR technology, and a second stratum where low conversion ratio³⁰ FRs or accelerator driven systems (ADS) are deployed for the transmutation of the MAs (and possibly the recycling of Pu). The transmutation of minor actinides is also being explored in the heavy-water moderated CANDU reactors, in which the high neutron economy enables a high degree of fuel cycle flexibility. This “double strata” configuration is schematically depicted in Figure 2.20 (see also Section 3.3.4 for further details).

Figure 2.20: Double strata scheme



A second family of advanced fuel cycles (FCs) allows a combined treatment of transuranics including MAs together with plutonium as fuel in fast reactor systems

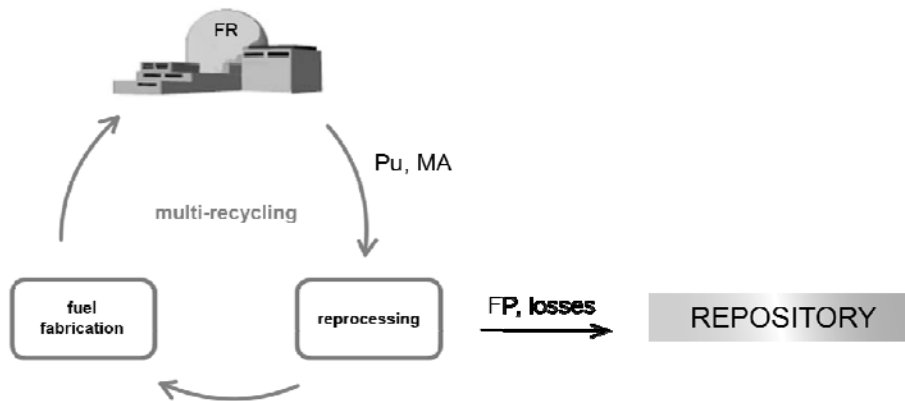
30. The conversion ratio is the ratio of new fissile nuclei to fissioned nuclei.

(although this cycle could also be envisaged as the second stratum in double strata schemes).

The “double strata” fuel cycle has the advantage of concentrating hazardous highly radioactive radionuclides in a separate part of the fuel cycle. However, the front end of the fuel cycle is not improved significantly, as natural uranium consumption remains mainly dictated by the less efficient fuel use in LWRs and fertile breeding (i.e. the production of fissile materials in greater quantities than those burned in the reactor) is not pursued in the low conversion ratio FRs adopted in these schemes.

The introduction of fully integrated cycles of fast reactors (Figure 2.21) could combine waste minimisation with the optimisation in the use of natural resources. As discussed in more detail in Chapter 3 (Section 3.3.4), TRU transmutation is more efficient in fast reactors. As most of the transuranics become fissionable in fast neutron spectra, they also contribute to the energy production while less of them will go to waste. Furthermore, with their ability to multi-recycle plutonium and uranium, FRs hold the promise of greatly prolonging the lifetime of uranium resources (as shown in Table 2.3).

Figure 2.21: Fast reactor cycle



Another potential long-term option consists in moving from U/Pu fuelled systems to a thorium cycle. Thorium is a more abundant element than uranium and, due to its important neutronic advantages (see Section 3.3.6), its use as a fertile material has been considered since the dawn of nuclear power technology. In principle, the use of thorium fuel could reduce the fuel cost and the amount of spent fuel per unit of energy generation (NEA, 2002). This potential, together with the enhanced proliferation-resistant character of its spent fuel (significantly reduced plutonium production and high-energy gamma emissions), could provide very important advantages in terms of sustainability.

Most countries' R&D efforts on advanced nuclear systems are being pursued in the context of one or more co-operative programmes (e.g. GIF, INPRO, the International Framework of Nuclear Energy Cooperation – IFNEC, etc.). India is separately pressing ahead with the demonstration of a sodium fast reactor, with a prototype currently under construction. The aim is to follow this with a fleet of larger SFRs within the next 10 to 20 years. In addition, India is the main country currently developing the potential of thorium fuel cycles, with some ongoing effort in Canada leading the development of the pressure-tube based supercritical-water-cooled reactor design.

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3. Technical progress

3.1. Introduction

Chapter 3 gives an update on the technical developments in the fuel cycle since the 2002 report (NEA, 2002a) and provides a commentary on the prospects for the near-term future (to 2020) and in the longer term. In the near term, LWRs will remain the predominant reactor type worldwide. Prospective programmes of new build will be mostly based on LWR systems, with every possibility that this established technology will continue to dominate up to the latter part of the century; this will be reflected in world fuel cycle facilities. Progress continues with Generation IV fast neutron reactors and, in the longer term, their possible introduction has the potential to have an important effect on the nuclear fuel cycle.

Section 3.2 reviews the status of current and future fuel cycles. No major breakthroughs in technology have occurred in the past ten years and none are expected in the next ten years, with only incremental changes in mainstream water-cooled reactors,¹ aimed at their optimisation.

Section 3.2 is organised into three sub-sections each covering one broad stage in the fuel cycle (FC):

- Front end of the FC: including mining and milling, conversion, enrichment and fuel design and fabrication.
- Irradiation stage: including reactor operations and in-core fuel management.
- Back end of the FC covering the management of radioactive waste, high-level waste and spent fuel (including interim storage), as well as low and intermediate waste disposal.

Advanced fuel cycle options that may become available in the long-term future beyond 2020 are considered in Section 3.3. Beginning with an analysis of prospects in the front end, this section considers unconventional uranium resources and the developments and ongoing research in fuel design and fabrication. Further, progress on fuel processing R&D is illustrated, addressing advanced separation options under development, P&T of minor actinides and long-lived fission products. Consideration is given to the potential impact that such options may have on waste management as well as to reactor physics and the adoption of ADS for transmutation. Additional future options are assessed, such as small and medium reactors, high conversion light water reactors, possible alternative uses of nuclear energy, namely for desalination and hydrogen production, as well as, in the longer term, the thorium fuel cycle.

The principal trends are highlighted in summary boxes at appropriate points in the text.

1. See also Section 2.7.1 for the evolution of reactor technology and the trend in new reactor designs to include passive safety features.

3.2. Evolution trends in the current fuel cycle

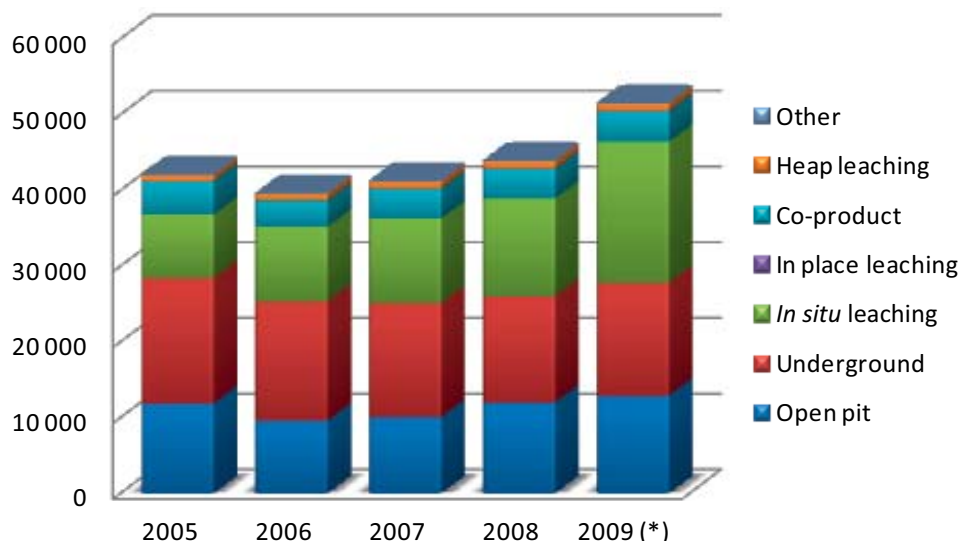
3.2.1. Front end

Mining and milling

Changes in uranium demand and supply market and their impacts have been discussed in Chapter 2 (Section 2.6.1).

Historically, uranium production has principally involved open-pit and underground mining. The relative contributions of different uranium mining methods have continued to evolve, as shown in Table 3.1 (NEA, 2010) and Figure 3.1.

Figure 3.1: Uranium production by mining methods



* Expected.

Source: Based on NEA, Uranium Resources, Production and Demand, 2006 to 2010.

Table 3.1: Percentage distribution of world uranium production by production method

Production method	2005	2006	2007	2008	2009 (expected)
Open-pit	28.1	24.2	24.4	27.3	25.0
Underground	39.4	39.8	36.5	32.0	28.9
<i>In situ</i> leaching	20.0	25.0	27.2	29.5	36.3
In place leaching*	<0.1	<0.1	<0.1	<0.1	<0.1
Co-product/by-product	10.3	8.6	9.5	8.9	7.8
Heap leaching**	1.9	2.2	2.3	2.3	1.9
Other methods***	0.3	0.2	0.1	<0.1	0.1

* Also known as stope leaching or block leaching.

** A subset of open-pit mining, since it is used in conjunction with open-pit mining.

*** Includes mine water treatment and environmental restoration.

Source: NEA, 2010, Table 23.

The rise of the relative share of *in situ* leaching (ISL) over recent years is significant. Having reached some 25% in 2006 (Kok, 2009), ISL is expected to become the dominant method of uranium mining, owing primarily to the increased production in Kazakhstan, where over 95% of mining is through ISL (but also in Australia, China, the Russian Federation, the United States and Uzbekistan).

The ISL technique involves leaving the ore where it is in the ground and using liquids that are pumped through it to recover the minerals by leaching. Consequently, there is little surface disturbance (simple multiple boreholes) and no tailings or waste generated. The basic requirement for ISL mining is that the mineralisation is located in water-saturated permeable sands within sediments that allow effective confinement of mining solutions (commonly confined between impermeable clay-rich strata) (Commonwealth of Australia, 2010). Techniques for ISL have evolved to the point where this is a controllable, safe and environmentally benign method of mining which can operate under strict environmental control, offering simpler rehabilitation and, often, cost advantages (Kok, 2009).

Driven by generally higher uranium prices since 2003, an expansion in production capability is underway, albeit not as rapid as originally anticipated. Turning stated production capability increases into production takes time and is dependent on continuing suitable market conditions. As reported in Section 2.6.1, a significant rise in production capability is expected in the next few years in Kazakhstan, Namibia and Niger and, to a lesser extent, in other countries.

Commissioning an ISL site can be done in a reasonably short time. This is one reason why Kazakhstan has been able to increase its uranium capabilities so significantly in the span of a few years. Another factor behind the expansion in Kazakhstan is that the new mining sites have been in the vicinity of areas with easy access to the necessary infrastructure (e.g. water and electricity). The insufficient availability of acid² for ISL mining in Kazakhstan has been successfully addressed.

The consolidation and spreading of best practices in the uranium mining and milling industry is, perhaps, the principal development in the last decade (IAEA, 2010). The uranium mining industry was first established in the middle of the 20th century, at a time of rapid industrial and social change. In the context of that time, when nuclear weapon development was a major driver, the need for production meant that insufficient attention was paid to environmental and health impacts of mining. Only in the last quarter of the 20th century did the improvement of environmental management standards begin to receive increased attention in corporate planning strategies, with the introduction of legislation and the development of environmentally sound operating procedures. In spite of the cyclical slowdown the industry suffered in the 1980s and 1990s, the surviving uranium producers continued to develop and implement a series of procedures in environmental management, to meet more stringent regulatory requirements and to demonstrate to governments, the public, stakeholders and consumers that mining operations were being run in a fashion that minimises potential adverse impacts.

This century, with the resurgence of uranium mining activities, the uranium mining industry continues to improve environmental standards through the introduction and development of best practices. From the establishment of the site and onset of mining activities through to full production, waste management and closure, these best available and most practicable methods enable the operator to achieve production goals and

2. This was a serious production constraint in Kazakhstan over the period 2007-10. In 2009, Kazatomprom with other mining companies and acid producers set up a co-ordinating council to regulate acid supplies and infrastructure (WNA, 2010a).

develop and run site/operations in ways that minimise social, environmental and economic impacts.

This important matter has recently been addressed by international organisations (IAEA, 2010; WNA, 2008a). In particular, in its technical report *Best Practice in Environmental Management of Uranium Mining* published in 2010, the IAEA considered relevant country experience through case studies. Some of the principal best practices figuring in the IAEA appraisal are summarised in Table 3.2 below for different stages in the lifespan of mining/milling sites.

As newer, less established mining companies and producer nations are entering the market in the present expansion phase, the development and adoption of such best practices are of particular importance. New entrants may not be as aware of current international standards and optimal methods and may have more limited access to resources (e.g. financial resources, expertise, etc.) to adopt and sustain such best practices. Failure to maintain the current high levels of environmental management may hamper the development of the uranium mining industry, resulting in adverse reactions from the public and regulating authorities.

Key trends:

- Increase in uranium demand (See Section 2.6.1).
- Secondary sources of uranium from historic stocks and HEU diminishing (See Section 2.6.1).
- General increase in uranium prices (See Section 2.6.1) with the following potential impacts:
 - Negative for short-term economic competitiveness of nuclear power.*
 - Positive for resource availability (high uranium ore prices encourages new exploration and development of known resources).
- Increasing utilisation of ISL:
 - Generally positive for environmental impact.
 - Techniques for ISL have evolved to the point where this is a controllable, safe and environmentally benign method of mining which can operate under strict environmental control, offering simpler rehabilitation and, often, cost advantages.
- Consolidation and spread of best practices in the uranium mining and milling industry leading towards better safety and environmental standards as well as greater and more efficient public involvement and stakeholder consultation processes.
- New companies and countries entering the market.

Possible bottlenecks:

- Increasingly challenging mine developments and approval processes combined with public resistance to mining in some areas.

* But the effect is small given the low percentage contribution of uranium price to the levelised cost of nuclear generation (~5%).

Table 3.2: Best practices in uranium mining and milling for different stages in the lifespan of facilities

Phase	Practice	Details/description
Exploration/ conceptual design	Baseline data collection	<ul style="list-style-type: none"> Socioeconomic characterisation, including current and historic land and water uses, archaeological and heritage surveys, documentation of regulatory regime, etc. Environmental characterisation, including: hydrological and hydrogeological conditions, geological and geochemical characterisation, soil as well as flora and fauna surveys, climate data, radiological surveys and contaminated site assessments.
	Public and stakeholder consultation processes	<ul style="list-style-type: none"> Involvement of stakeholders in a full and interactive participation throughout all levels and stages of the planning process. Negotiation of economic, employment and/or environmental agreements with stakeholders. Extensive training and education programmes. Community sustainable development plan e.g. through the construction and management of infrastructure (airstrips, roads, power, water supply systems, etc.).
	Adequate planning of infrastructure and other activities related to exploration	<ul style="list-style-type: none"> Designing for access routes, drilling sites, etc. Test pitting, bulk sampling, etc. to minimise erosion and prevent the release of contaminants. Remediation plans for exploration activities.
	Impact assessment (IA)	<ul style="list-style-type: none"> IA is a process of identification, communication, prediction and interpretation of information to identify potential (both adverse and beneficial) impacts through the life of a project (i.e. construction, operations, and closure) and determining measures to manage these impacts.
	Risk assessment	<ul style="list-style-type: none"> Risk assessment and management is an iterative process consisting of a series of well-defined steps to evaluate the likelihood of an event occurring, potential consequence of that event and management measures to reduce the residual risk to an acceptable level. Many jurisdictions have formalised risk assessment tools tailored to their local standards.
	Developing closure and sustainable remediation objectives	<ul style="list-style-type: none"> Objectives will reflect the overall values of the operator, stakeholders, regulators and the community, addressing points such as: sustainability, final or sequential land use, human health and safety, social impacts, ecosystem impacts, regulatory requirements and cost optimisation. Most effective when financial guarantees are set by operators to ensure that funds for closure costs are available.
Operation	Mining safety	<ul style="list-style-type: none"> Ensure safe, well maintained site conditions for the protection of employees and the public from all conventional mining hazards, including but not limited to those related to airborne contaminants, ground stability and structure, geological and hydro-geological conditions, storage and handling of explosives, mine flooding, mobile and stationary equipment, ingress and egress, and fire.
	Radiation safety	<ul style="list-style-type: none"> Optimise radiation exposure to as low as reasonably achievable, taking into account all socio-economic factors. Plan and carefully monitor employee and contractor doses. Estimate potential radiological impacts on the public and the environment.

Table 3.2: Best practices in uranium mining and milling for different stages in the lifespan of facilities (continued)

Phase	Practice	Details/description
Operation	Management systems	<ul style="list-style-type: none"> Implementation of an environmental management system – two series of ISO standards, ISO 9000 and 14000, are particularly relevant in the area of management systems for environmental performance improvement. Establishment of key performance indicators.
	Monitoring	<ul style="list-style-type: none"> Impact or compliance monitoring – regular checks of operational impacts on the receiving environment, ensuring compliance with commitments and statutory obligations. Performance monitoring – check performance of remediation works against predicted or required outcomes.
	Risk assessment and emergency response plan	<ul style="list-style-type: none"> Take all reasonable precautions to eliminate undesirable environmental events. Have plans in place to mitigate and contain the consequences should such events occur.
Waste management and closure	Implementation of a regional milling facility	<ul style="list-style-type: none"> Development of a regional milling facility and associated tailings management to limit the number of mills and tailings disposal sites in a particular area.
	Implementation of a centralised waste disposal facility.	<ul style="list-style-type: none"> Transport of potential contaminants (e.g. waste rock, domestic waste or industrial waste) to a centralised waste disposal location.
	Management of waste water	<ul style="list-style-type: none"> Implement water systems designed to divert, collect, isolate, recycle and treat all potentially contaminated wastewater. Establish restricted release zones (RRZs) as water control areas.
	Management of waste rock	<ul style="list-style-type: none"> Waste rock/overburden is the material excavated during mining containing less than economic amounts of the target commodity and requiring specific characterisation and handling e.g. through: <ul style="list-style-type: none"> storage on pads with impermeable base to minimise movement of contaminated leachate into groundwater; the application of cover systems to minimise water and air ingress and the potential for significant contaminated surface runoff; disposal in zone with limited/controlled oxygen and water content to further reduce the risk of contamination through waste rock seepage.
	Management of process residues (primarily tailings)*	<ul style="list-style-type: none"> Geochemical and radiological characterisation and appropriate management of tailings e.g. through the enhancement post-closure physical and chemical stability of the tailings, the optimisation of tailing settled density, the minimisation of radon release rate and potential release of contaminants in air, groundwater and surface water.
	Management of contaminated equipment	<ul style="list-style-type: none"> Segregation of radiologically and chemically contaminated materials in a purpose-built area separate from other non-contaminated wastes. Capping: placement of a cover to encapsulate wastes to control infiltration into and radon emanation from waste.

* Tailings from the milling of uranium ore comprise leached solids, process water and sometimes chemical precipitates created during recovery. Disposal of mill tailings often represents the greatest challenge in a conventional uranium processing operation. Approximately 85% of the radioactivity in the original mill feed remains in the tailings after the ore has been processed and the uranium recovered. The tailings also contain heavy metals and process chemical contaminants from the production process.

Source: IAEA, 2010, summary of Chapter 3 with permission.

Conversion

Beside the variations in prices, which, as reported in Chapter 2 (Section 2.6.2), have stabilised at a higher level than previously, no substantial changes have taken place in the conversion sector over the last decade. The higher prices have encouraged the

retention of existing capacity and may stimulate new capacity. Most western conversion plants are aged and will have to be replaced over the next 10-15 years and considerable investment will therefore be needed.

As reported in Chapter 2 (Section 2.6.2), in France a recent project has been launched, COMURHEX II, which aims to replace and modernise existing installations in the conversion sites of Tricastin and Malvési. New installations are based on proven technology but also integrate further recent R&D developments that will allow improvements in production and plant safety, as well as the reduction of the environmental impact of activities. The capability also exists for treatment of recycled uranium, which increases fuel cycle flexibility.

Key trends:

- Prices for conversion services have stabilised at a higher level:
 - Negative but small³ impact for economic competitiveness of nuclear power.
 - Retention to date of existing capacity and potential development of new capacity.
- Need to replace and modernise existing installations.
- Potential need for new conversion capacity (see Chapter 2).

Enrichment

A general outlook of the uranium enrichment capability and projects under development worldwide is provided in Chapter 2 (Section 2.6.3). Today two main technologies are practised for the commercial enrichment of uranium (IAEA, 2009a):

- Gaseous diffusion, where separation of isotopes of uranium in the form of gaseous UF_6 is achieved by using the faster diffusion rate of ^{235}U through a porous membrane as compared to ^{238}U . This process is very energy intensive and requires very large plants for commercial operation.
- Centrifuge enrichment, which separates the lighter ^{235}U by applying very high rotational speeds, again using uranium in the form of gaseous UF_6 .

As Figure 3.2 illustrates, centrifuge capacities have been increasing steadily in response to increasing demand, displacing ageing diffusion installations. One of the characteristics of centrifuge enrichment is its modularity; with parallel cascades, this technology allows for incremental expansion to meet higher demand scenarios, should market demand warrant an increase (including the replacement of secondary supply sources). Recent announcements by USEC and the Enrichment Technology Company⁴ also show that improved centrifuge designs can produce significantly more SWU than existing machines. Crucially, the specific consumption of electricity is considerably reduced, by approximately a factor of 50 in comparison with diffusion plants, so that the cost per SWU is drastically reduced, as are the associated CO_2 emissions. Given the modular nature of centrifuge technology compared with the massive gaseous diffusion facilities, a further advantage is that re-enrichment of reprocessed uranium can be conducted in “dedicated” cascades, avoiding the contamination of the entire plant by traces of fission products and ^{236}U , hence enhancing flexibility. However, centrifuge enrichment is also well suited for the production of highly enriched uranium. This latter

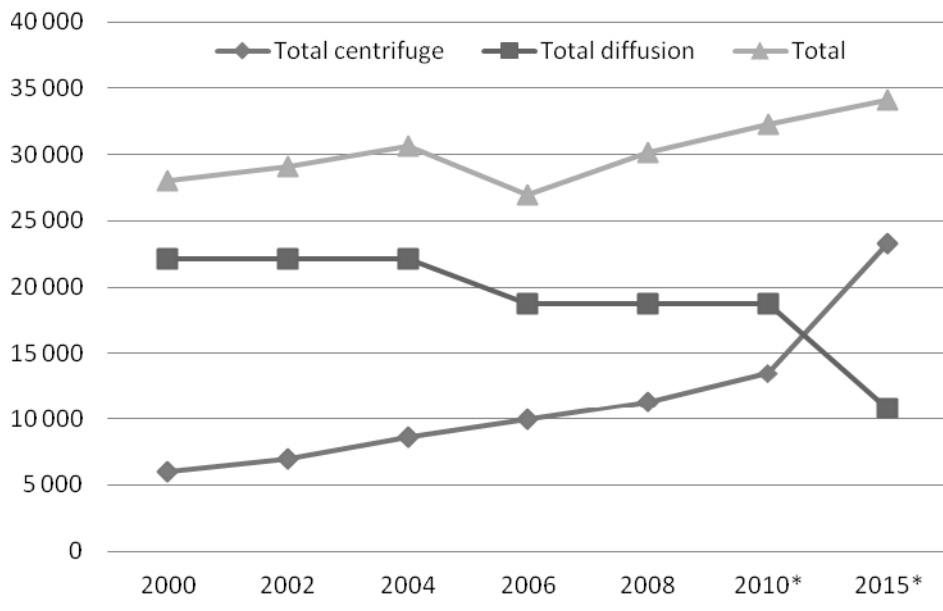
3. But again the effect is small given the low percentage contribution of conversion to the levelised cost of generation (~6%).

4. ETC is a centrifuge development company jointly owned by AREVA and URENCO.

characteristic along with the high modularity of centrifuge installations (and hence the possibility of small plant size) enhances proliferation risks (Patarin, 2002).

Western diffusion plants, such as those operating in France and the United States are now nearing the end of their useful lifetimes and are likely to be phased out within the next few years.

Figure 3.2: Enrichment capacity in NEA countries by method (tSWU/year)



* Estimates.

a) Assume constant centrifuge capacity in the Netherlands as more accurate data are not available.

b) It should be noted that the estimates for the 2015 do not consider the forthcoming closure of the GB1 facility in France, which will occur before 2015 and will cause a further reduction of the diffusion enrichment capacity.

Sources: Based on NEA Nuclear Energy Data 2001-2010.

Once replacement of the gaseous diffusion plants has been achieved, the potential for incremental expansion to enhance overall capacity remains. Two thousand tSWU of enrichment capacity is sufficient to supply the annual fuel requirements for 15 000 MWe of nuclear generating capacity.

Historically, commercial enrichment suppliers have always worked to a 5% enrichment limit, which has been sufficient to meet all LWR fuel requirements. In view of future moves to higher burn-ups and higher initial enrichments, some enrichment suppliers are now anticipating the requirement for higher enrichments by licensing their plant for 6% or more (e.g. Georges Besse II).

The development of other enrichment technologies has not progressed since 2001, with the exception that laser enrichment has progressed from laboratory/pilot plant stage to pre-industrial and possibly industrial readiness, the latter is to be confirmed in the coming years. As mentioned in Section 2.6.3, in June 2009 Global Laser Enrichment (a consortium led by General Electric) submitted an application to build the world's first commercial enrichment plant based on laser technology using the SILEX process. If the decision is made to proceed with construction, this will be a very significant step for the world enrichment market, introducing a competitor technology to centrifuge process.

Laser enrichment methods are also being investigated in the Russian Federation, primarily at the Russian Research Centre of Kurchatov Institute (IAEA, 2009a).

Another trend singled out in Chapter 2 (Section 2.6.1) and linked to the recently established uranium market conditions is the adoption of lower enrichment tailings levels, down from typically 0.3% to 0.25% and expected to go even further down to 0.15%. This practice allows uranium savings (to the extent possible given the limited excess enrichment capacity available today).

Key trends:

- Western diffusion plants nearing the end of their useful lifetimes.
 - Increased use of centrifuge process: from just about 20% in 2001 to nearly 40% in 2010 and expected to displace diffusion technology. Centrifuge enrichment features high modularity and much lower energy consumption and carbon emissions in comparison to the diffusion process.
- The resulting effects are:
- Positive with respect to the environment.
 - Positive with respect to the plant economics.
 - But potentially negative in terms of proliferation resistance.
- Laser enrichment under continuous development and approaching pre-industrial/industrial readiness.
 - Reduced enrichment tails assays (down from 0.3% to 0.25% – expected to go even further down to 0.15%).
 - Anticipated requirement for higher enrichment with consequent changes in licensing requirements.
 - Potential need of further enrichment capacity (see Chapter 2).

Fuel design and fuel fabrication

Since 2001 there have been no major step changes in fuel design and fabrication, only a continuation of the steady evolutionary modifications that applied previously aimed towards improved fuel behaviour in line with reactor technology developments. The available fuel fabrication capacity has remained steady, with only one plant coming on line since 2000 and some consolidation and mergers occurring between fuel vendors. Now that production of uranium metal fuel for the UK Magnox plants has ceased (with the two remaining Magnox plants utilising pre-manufactured stocks), oxide fuel is the only fuel type used for commercial power plants.

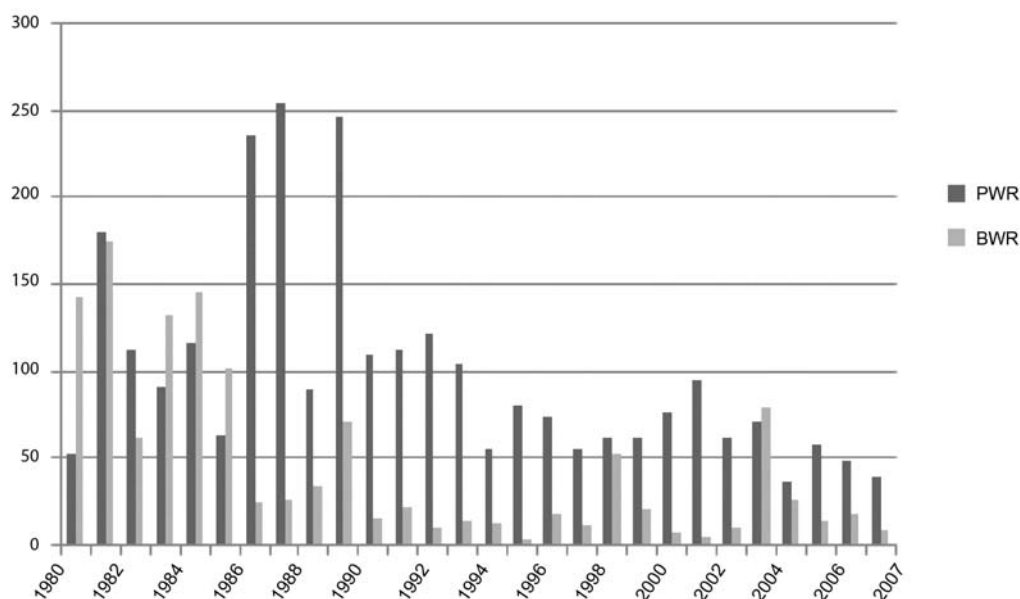
■ Improved fuel behaviour

Good improvements have been registered with fuel reliability, which is critical to the safe and economic operation of nuclear power plants. High reliability depends on the integrity of the plant nuclear fuel rods. Fuel failures, or a breach in the cladding, can lead to radioactive material leakage, lost plant generation, increased inspection and repair activities, premature removal of fuel assemblies and increased radiation exposure, with significant cost impacts on individual utilities and a negative influence on public perception.

The nuclear industry has devoted considerable effort to understanding and eliminating the causes of fuel failures, and has adopted long-term strategies focused on operation with a defect-free core. Thanks to these efforts, the number of fuel failures per plant is significantly lower today than in past decades. Figure 3.3 shows a clear pattern of improvement in the United States nuclear fuel performance.

A noteworthy example of industry initiative is that undertaken in recent years in the United States (EPRI, 2008). In late 2005, the Institute of Nuclear Power Operations (INPO) set a zero fuel failure goal for all operating US plants. Collectively the US industry has responded by committing to a Fuel Integrity Initiative based on understanding the underlying failure mechanisms and root causes for all fuel failures, assessing fuel reliability margins and developing fuel integrity guidelines to ensure all utilities have adequate margins to failure. For the first time, industry executives endorsed a series of mandatory good practice elements for fuel reliability that all US utilities were expected to implement, also adopted by other utilities worldwide. The US nuclear power industry has since made significant progress in achieving its goal of zero fuel failures, with a clear upward trend in the number of units without failures. As of July 2010, US facilities have operated at unmatched fuel reliability levels, with slightly more than 90% being failure clear (EPRI, 2010).

Figure 3.3: Fuel failures in US facilities from 1980 to 2007



Note: Note that the typically higher numbers for PWRs do not necessarily reflect poorer fuel performance for this design; there are more PWRs than BWRs in the US fleet (as of 07/2011 there are 69 operating PWRs and 37 operating BWRs).

Source: EPRI, 2008.

- Greater design complexity

Fuel designs have gradually become more complex since 2001. In BWR fuel assemblies there has been a trend towards increased heterogeneity due to a combination of axial and radial enrichment zoning, heterogeneous integral burnable poison loading, part length fuel rods and unvoided water channels.⁵ In PWR fuel assemblies the trend has been to adopt increased loadings of integral burnable absorber and axial enrichment heterogeneity (e.g. use of natural or low-enrichment axial blanket zones). The use of discrete burnable poison rods in PWRs is now virtually obsolete and it is likely that future first cores for PWRs will rely on integral poisons instead.

5. Channels with single-phase water flow (no void fraction).

- Standardisation

The UK's advanced gas reactor (AGR) plants have made demonstrable savings by rationalising the initial enrichments used in seven of the eight twin-unit plants. Originally, each plant had its own specific initial enrichment set (there being different enrichments for the inner and outer core fuel). These have now been replaced by a smaller number of standard enrichments that are sufficient to meet the demands of the different plants. By rationalising the ordering of enriched UF₆ supplies and by reducing the number of enrichment campaigns that need to be processed through fuel manufacturing, there are significant operational savings to be made in the fuel fabrication plant. A change of enrichment requires down time in fuel fabrication to purge the plant equipment of material from the previous campaign. The purged material also needs to be recycled, which may require blending.

There may be scope for similar rationalisation of LWR initial enrichments and greater design standardisation that would help to further optimise the front-end fuel cycle costs.

- Higher burn-ups

Burn-up refers to the amount of energy generated per initial mass of fuel (metric tons of initial heavy metal). In a power station, high fuel burn-up is desirable for:

- reducing downtime for refuelling;
- reducing the number of fresh nuclear fuel elements required;
- reducing spent nuclear fuel elements generated for a given amount of energy produced;
- reducing the potential for diversion of plutonium from spent fuel for use in nuclear weapons.⁶

Higher mean discharge burn-ups can be attained through a combination of measures: higher capacity factors, longer intervals between refuelling outages and a reduction in the fraction of fuel assemblies discharged. All of these tend to drive in-core fuel management towards increasing complexity to meet the increased demands imposed on the fuel and core. For this purpose, fuel vendors and core designers will need to make further progress in some or all of the following aspects:

- fuel assembly neutronic design optimisation, such as increasingly complex heterogeneity of fissile material and burnable poison distributions;
- further optimisation of core loading patterns to maximise margins to limits;
- continuing development of fuel assembly mechanical and thermal-hydraulic designs to maintain and increase design and safety margins;
- improved understanding of design and safety margins to allow a relaxation of operating envelopes.

Since 2001, UOX fuels for LWRs have continued to trend steadily upwards in burn-up. Mean discharge burn-ups for PWRs and BWRs approaching 50 GWd/t are routinely being achieved, with peak rod burn-ups in the region of 60 GWd/t or more licensed. For US LWRs, for example, there has been a trend to increase mean burn-ups by about 5 GWd/t every 10 years, however the NRC has set a legal limit of 62 GWd/t on peak rates. Fuels for

6. Higher burn-up results in more of the higher isotopes of plutonium, particularly non-fissile ²⁴⁰Pu. This isotope has a higher heat production and neutron emission, making it more hazardous to any illicit bomb maker, as well as making the plutonium unreliable as a weapons material.

the Russian-built VVERs are approaching parity with those of Western PWRs, with similar discharge burn-ups.

In the longer term, some advanced light water reactor designs are expected to achieve over 90 GWd/Mt using higher-enriched fuel (WNA, 2011). As experience accumulates, there is every prospect that burn-ups will continue their upward trend, subject to continued improved economic performance with respect to lowest energy generation cost.

Safety aspects related to burn-up extension were considered and effects on loss-of-coolant accident and on reactivity initiated accident by rod-ejection in PWRs and rod-drop in BWRs, respectively, were intensively discussed during the 1990s. The broad consensus is now that no real danger exists for plant operation, based on the results obtained through the combined approach of improved analytical methods and re-evaluation of experimental data (IAEA, 2009a). Fuel reliability continues to be good at very high burn-ups and some fuel vendors are striving to further reduce their already very low failure rates. There is no suggestion that fuel reliability issues are limiting the outputs achievable. Various advanced zirconium alloy materials (with niobium) developed by the different fuel vendors have proven to perform well under new burn-up conditions, with improved behaviour achieved mainly towards corrosion, hydriding, creep and pellet-cladding interaction (PCI) (Thibault *et al.*, 2009).

An NEA report (NEA, 2006) made an in-depth technical and economic study of very high burn-ups in LWRs and concluded that there are operational benefits to utilities to extend average burn-ups beyond 50 GWd/t but for much higher values benefits are not quite as marked. The direct fuel cycle cost benefits of a sustained increase in burn-ups are small and may even reverse at some point, but the indirect benefits for plant and fuel cycle operations are the dominant factor that will continue to drive utilities towards higher burn-ups.

The CANDU reactors worldwide continue to use un-enriched fuel bundles with mean discharge burn-ups of approximately 7 GWd/t and excellent fuel reliability.⁷ To extend burn-ups beyond this value, MOX, REPU and LEU fuels could be used, which have a higher initial fissile loading, compared with natural uranium. AECL has developed an advanced CANDU bundle called CANFLEX (AECL, 2009) specifically capable of achieving higher burn-ups (up to about 20 GWd/t) and accommodating MOX, REPU or LEU fuels. Relative to the normal natural uranium fuel bundle, in the CANFLEX bundle the number of fuel rods is increased. In addition, small diameter fuel rods are used in the outer ring of CANFLEX to help increase its rating capability. In such CANDU reactor designs the outer ring of fuel rods tends to operate at a higher rating than the inner rings because of the thermal flux gradient from the outside to the inside of the fuel bundle. Decreasing the diameter of the outer rods increases their rating capability by spreading the power loading in the outer ring over a higher number of rods. A central dysprosium rod is used to ensure a negative void reactivity coefficient.

The impact of higher burn-ups on the management of spent fuel are discussed in Section 3.2.3.

- Higher enrichments

As burn-ups increase, mean initial enrichments for LWR fuel need to go up. All current commercial fuel fabrication plants are limited by the 5% enrichment limit imposed by criticality restrictions on finished fuel assemblies during washing and storage. With past burn-ups, this threshold was not a limiting factor, but as mean initial

7. Note that CANDU reactors are designed for on load refuelling, so that lower burn ups do not carry the same availability penalty experienced with reactors which need to be shut down for refuelling (e.g. LWRs).

enrichments approach 5% this is increasingly becoming an issue. For the time being, this concern is less pressing for PWRs because the initial enrichment required to attain 50 GWd/t mean burn-up or slightly higher is less than 5%. While the same is also true of BWRs, the fact that BWRs use enrichment zoning implies maximum enrichments closer to 5% and even if the 5% limit is currently not restrictive, very soon it is likely to become so.

Therefore, as further increase in burn-up is achieved, there is the possibility that fuel fabricators may soon face a pressing technological challenge to re-license fuel fabrication plants for higher enrichments. To achieve a mean discharge burn-up of 75 GWd/t, initial enrichments between 6.0 and 6.5% will be required (NEA, 2006), depending on the details of the fuel management scheme. Manufacturing fuel with such levels of enrichment may demand design and operational modifications and possibly the use of different licensing approaches to criticality safety.

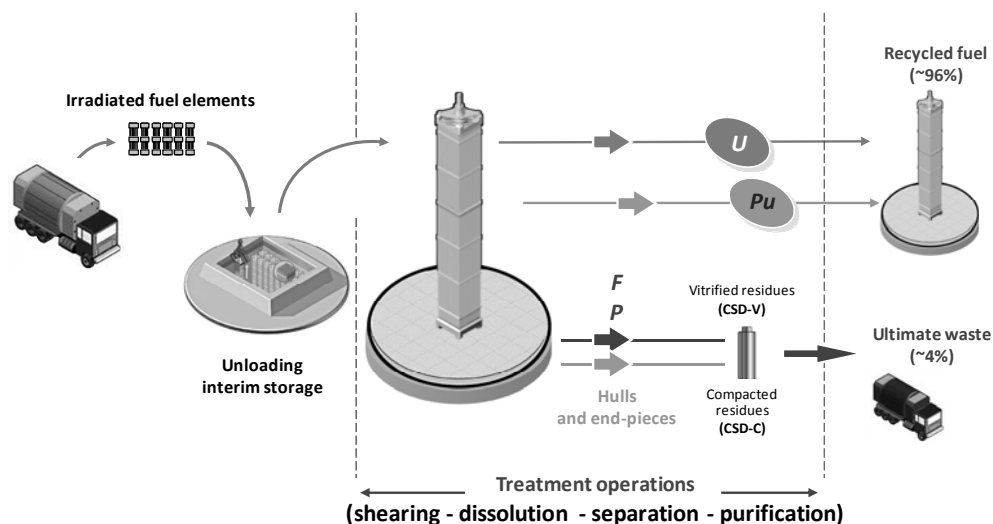
In terms of in-core fuel management, higher enrichments require higher initial reactivity hold-down and therefore higher burnable poison loading.

▪ Partial recycling

One PWR fuel assembly contains approximately 500 kg of uranium before irradiation in the reactor. After irradiation it will contain some 475 to 480 kg of U plus about 5 kg of Pu; hence more than 96% of material in used nuclear fuel is recyclable, as shown in Figure 3.4. Residual contents of useful uranium and plutonium can be separated from other elements in the spent fuel through reprocessing and used to produce MOX and REPU, both recyclable materials. Typically, one new MOX fuel element and one REPU fuel element can be obtained from the recycling of eight LWR spent fuel assemblies. Details on current reprocessing capacities are provided in Chapter 2 (Section 2.8.1).

The utilisation of recycled fuels, namely MOX and REPU, has not developed as extensively as envisaged in the 2002 report (NEA, 2002). This general stagnation has been driven by a combination of factors and particularly political constraints with regard to reprocessing of fuel and the low uranium prices that prevailed up to 2001, which made the use of recycled fuel barely competitive for those utilities not yet exposed to waste management storage limitations or not seeking to take advantage of back-end fuel cycle management benefits offered by such recycling.

Figure 3.4: Used fuel: residual fissile content and post-irradiation treatment



Source: L. Van Den Dурpel, AREVA, 2010.

REPU recycling involves the conversion of UO_3 ⁸ recovered from irradiated fuel to UF_6 and its re-enrichment prior to use for the fabrication of REPU fuel assemblies. This process brings benefits, in that it reduces the immediate uranium requirements by approximately 15% (about the same magnitude as for plutonium recycle) and, potentially, the fuel costs for the utility, depending on market prices for uranium and front-end fuel cycle services (conversion, enrichment and fuel fabrication). It also reduces the quantities of material for subsequent disposal (see Section 3.2.3).

Since 2001, this technology has been demonstrated at commercial scale with no significant technological hurdles to be overcome and with resulting fuel performance comparable to that of natural uranium UO_2 fuels. The REPU market has been constrained primarily because of limited conversion capacity (to convert REPU oxide to UF_6) and because, until recently, low uranium prices made REPU only marginally competitive. Higher uranium prices have now increased REPU economic competitiveness, prompting some new activity. Notably, in the United Kingdom, some 16 000 tonnes of REPU have been recycled into enriched AGR fuel and REPU is now being used for the first time in the Sizewell B PWR. In 2010, a sizeable increase in recycled REPU has been reported in France. The new French enrichment plant George Besse II will also be able to re-enrich uranium from spent fuel. Greater competitiveness may persuade increasing numbers of LWR operators to adopt REPU fuel assemblies for their fuel requirements, driving the REPU market towards commercial maturity.

Mono-recycling of plutonium is currently being carried out in some 40 nuclear power plants (NPPs) in the world to partly realise its energy potential, while stabilising the plutonium inventory. Pu separated by reprocessing irradiated UO_2 is mixed with depleted uranium to prepare MOX that is subsequently burnt in LWRs licensed for this type of fuel. Typically MOX core fractions in LWRs are between one third and one half, with a total demand for MOX fuel assemblies which is therefore a fraction of the UO_2 demand. Modern plants such as the ABWR, the AREVA EPR and Westinghouse AP1000 will be able to accommodate higher MOX fractions; for instance EPRs are designed to operate with 100% MOX fuel cores. This ability improves the overall flexibility of fuel cycle management.

Although technical demonstration programmes may still be required in some countries, technical limitations do not generally constrain LWR MOX utilisation. With the significant irradiation experience accumulated, the use of MOX can be regarded as a mature technology, fully established commercially. MOX fuel performance has matched the excellent record of UO_2 fuel assemblies reaching parity, in most instances, also in terms of high discharge burn-ups.

Similarly to REPU recycling, MOX utilisation is, at present, held back essentially due to political considerations with regard to fuel cycle policy as well as limited MOX fabrication capacity and commercial competitiveness for utilities not seeking the benefits in spent fuel and waste management. MOX fuel has been used primarily in Europe. Earlier plans to increase MOX utilisation in Japan were delayed for many reasons, but finally began implementation in 2009. The most advanced MOX recycle programme is running in France, where this practice has recently seen a considerable extension. The WNA reports that, in 2010, 17% of French electricity generation was obtained from recycled products, with a substantial number of PWRs operating with approximately one third MOX loading. MOX recycle in PWRs in France is seen as a valuable intermediate stage on the way to full recycle in fast reactors, with the following perceived benefits (WNA, 2011b):

- LWR MOX minimises the stored inventory of separated plutonium, since the plutonium recovered from the reprocessing plants is promptly recycled as MOX. This ensures any remaining plutonium in the subsequently discharged spent MOX

8. While UO_2 is the form in which uranium is used in LWR fuel, UO_3 is the form in which uranium is recovered in the PUREX process.

fuel is subject to a high degree of self-protection from the radiation field, reducing proliferation risks.

- At equilibrium, the use of MOX in LWRs gives typically a reduction of about 15% in immediate uranium requirements, also helping to hedge against uranium price fluctuations.
- LWR MOX demonstrates elements of recycle technology that will be required later for full recycle in fast reactors.
- Interim storage of the irradiated MOX fuel assemblies constitutes a reserve of plutonium that in future could be accessed via reprocessing to feed the initial cores of a fast reactor fleet.
- Due to the reprocessing of the original UO₂ fuel, an improved ultimate waste matrix is obtained, which may have advantages for geological disposal in the very long term; waste volumes and radiotoxicity are also reduced, alleviating requirements for long-term safeguarding of the disposed waste (see Section 3.2.3).
- For countries using existing reprocessing facilities, recycling alleviates the need for their own longer-term interim spent fuel storage and reduces the investment needs for additional back-end fuel cycle facilities.

In the coming decade there is the potential for MOX utilisation to increase: as new MOX fabrication plants become available more utilities might adopt MOX purely for commercial reasons. The fissile fraction of Pu decreases with discharge burn-up. Consequently, MOX fabricated with Pu from reprocessing spent fuel with higher burn-up will need higher initial concentrations of this element, limited by the need to ensure negative reactivity coefficients. This restricts the achievable discharge burn-up for MOX assemblies and new technical solutions will have to be developed to change this threshold. Overall the possible additional costs related to reprocessing and MOX manufacture might limit the benefits resulting from adopting higher burn-ups and they should be considered in the evaluation of its economics in a closed fuel cycle policy (Druenne, 2009).

MOX and REPU usage in CANDU reactors through the deployment of the CANFLEX bundle (as discussed above) can be viewed as a form of partial recycle; both recycling practices reduce primary uranium demand by an amount that depends on the availability of plutonium and REPU. MOX and REPU for CANFLEX would be sourced from LWR fuel reprocessed elsewhere. This synergistic approach involving LWRs and CANDU is referred to as DUPIC (Direct Use of PWR fuel in CANDU) fuel cycle.

One of the major advantages of this concept is that it does not require separation of the irradiated fuel constituents, avoiding any chemical reprocessing. In addition, significant uranium saving (40%) can be achieved with the DUPIC fuel cycle, while at the highest burn-ups envisaged for CANFLEX irradiated fuel volumes could be reduced by a factor of ~3. The spent DUPIC fuel would have to be cooled for 50 years prior to geological disposal.

The CANFLEX bundle design has been developed over a number of years and this technology is considered ready for commercial deployment. The necessary commercial drivers have not yet been sufficient for CANDU utilities to adopt the new fuel design. This could change in the next ten years and the widespread deployment of the CANFLEX bundle with either MOX, REPU or LEU fuel is a realistic prospect.

In the Republic of Korea, where a joint research programme with Canada was initiated in 1991 to develop the DUPIC concept, a fuel fabrication campaign was launched in 2000. Used fuel pellets from PWR fuel are size reduced, heated to drive off radioactive fission products, and then reformed for use in CANDU fuel (WNA, 2010). Small-size elements fabricated by the Korea Atomic Energy Research Institute (KAERI) are being

irradiated in the HANARO research reactor and full-size DUPIC elements have also been fabricated (NEA, 2008).

In 2010, a one-year trial was started in the CANDU NPP of Qinshan in China, where natural uranium equivalent (NUE) bundles are being used in two of the reactor fuel channels. NUE is derived from mixing REPU with some depleted uranium to achieve a mix with the same overall characteristics as natural uranium. Chinese plans to build another two CANDU reactors figure as part of their used fuel management strategy. Using CANDU reactors in a similar way is also under investigation in Ukraine (WNA, 2010).

▪ Multiple recycling

Strategies for multiple-recycling of Pu and REPU in LWRs have been also investigated in order to further the efficiency gains of natural uranium use obtained from mono-recycling of reprocessed REPU and Pu. Multi-recycling of Pu is theoretically possible although not yet industrially implemented. An NEA study (NEA, 2002b) reviewed multiple plutonium recycle in LWRs and carried out core physics benchmarks for conventional MOX and high moderation MOX (HM-MOX) assembly designs. This study found that the fissile fraction of plutonium degraded very rapidly after the second recycle (i.e. after the irradiated MOX assemblies had been reprocessed and the plutonium recycled for a second time), such that further recycle brought limited benefits, raising, in turn, additional technical issues. The HM-MOX design was intended to overcome this limitation, by using assembly designs with a much higher moderator/fuel ratio. In effect, it was found that HM-MOX designs are less sensitive to degradation of the fissile content, but result in reduced fertile production of ^{239}Pu , with a final performance which deteriorated about as quickly as the conventional MOX assembly, bringing hardly discernible benefits.

Multiple recycle of REPU assemblies has not been considered very extensively. While theoretically possible, this presents similar problems to those discussed for Pu multi-recycling, with a degradation of the fissile fraction. The difficulty is the very high ^{236}U content of spent REPU fuel, which is a neutron absorber. When REPU is re-enriched for recycle, the ^{236}U is further concentrated in the product stream causing significant technical challenges and possibly invalidating any benefit from multiple recycle.

Key trends:

- Improved fuel behaviour.
- Continued fuel fabrication over-capacity (see Chapter 2):
 - Downward pressure on fuel fabrication services beneficial for economic competitiveness of nuclear power.
- Continued evolutionary development of fuel design including:
 - Greater design complexity with increased heterogeneity in BWR fuel and increased loadings of integral burnable absorber and axial enrichment heterogeneity in PWR fuel.
 - Standardisation, e.g. through the introduction of rationalised, smaller number of standard enrichments.
- Continued increase in mean discharge burn-ups:
 - Beneficial with respect to lower fuel demand and lower spent fuel volumes.
 - Back-end complicated because of increased specific activity, heat load and neutron source (see Section 3.2.3).
 - Beneficial in terms of proliferation resistance as the potential for diversion of plutonium from spent fuel is reduced (due to the increased specific activity and neutron source).

- Continued increase in mean initial enrichments:
 - Maximum enrichment level approaching 5% fuel fabrication limit with implications in criticality safety and the possible need to re-licence enrichment and fuel fabrication facilities, which may have a short-term impact on infrastructural requirements.
- Slightly increased activities in REPU utilisation with possible further expansion in the near-term future with higher uranium prices:
 - Beneficial with respect to resource utilisation (as it reduces the immediate uranium requirements).
 - Potentially beneficial with respect to economics as it could reduce the fuel costs to utilities (depending on market conditions).
- Stabilisation and, in some cases, expansion of MOX utilisation:
 - Beneficial with respect to maintaining future options (including elements of technology that will be required for full recycle in FRs).
 - Beneficial with respect to resource utilisation (as it reduces the immediate uranium requirements).
 - Potentially beneficial with respect to economics as it could reduce the fuel costs to utilities (depending on market conditions).
 - Beneficial in terms of proliferation resistance as the inventory of separated plutonium is minimised.
 - Potential benefits through synergistic recycling approaches with MOX and REPU recycled in CANDU reactors.

Possible bottlenecks:

In a prospective global nuclear expansion, zirconium fabrication is likely to come in the critical path (see Section 2.6.4).

3.2.2. Irradiation stage – reactor operations (including in-core fuel management)

This section discusses technical developments in the irradiation stage of the fuel cycle. This refers to the irradiation of the nuclear fuel in the reactor and the associated in-core fuel management. Some of the trends described in Section 3.2.1, such as higher burn-ups and recycling, are also related or affect in-core fuel management. These will not be discussed further in the present section.

Longer fuel cycles

In 2001 most LWR utilities had already started adopting longer fuel cycles for in-core fuel management. Today long cycles can be considered the norm, with typical durations of 18 months or more, in some cases approaching 24 months (Thibault *et al.*, 2009). Some countries still favour 12-month fuel cycles; for example, in France among the plants run by EDF, some continue adopting a 12-month fuel cycles, although many have now converted to 18-month cycles. Longer cycles have slightly negative effects on uranium and SWU utilisation. However, while short cycles are neutronically more efficient, they are becoming less prevalent. The reason is that longer cycles reduce operating and maintenance costs, as refuelling outages are spread further apart. At the same time, refuelling down-time is reduced so that higher load factors can be achieved. These benefits outweigh the loss of neutronic efficiency.

Increased load factors and power uprating

In many countries, most notably the United States, there has been a large improvement in load factors that has been achieved through improved plant

management and operational practices; additional generation has been achieved by plant upratings.

In BWR fuel assembly designs, the power rating capability can be enhanced by increasing the number of fuel rods, although the benefits need to be balanced against higher fabrication costs. For BWR cores, each fuel assembly is a self-contained unit, which gives BWR fuel vendors the potential to continue increasing the number of fuel rods by decreasing the lattice spacing and fuel rod diameter. For PWR cores however, the need to maintain compatibility with the control rod guide tubes of the existing control rod mechanisms will prevent any increase in the number of fuel rods per assembly.

Load following

Load following is increasingly becoming an important requirement for nuclear systems as the amount of renewable energy on, or targeted for, electricity grid systems increases. In Europe, under UCTE/ENTSO-E rules, generators are required to provide a certain level of load following (e.g. frequency response) nationally (Claverton Energy, 2011) and plants being built today have load-following capacity fully built in, according to European Utilities' Requirements (WNA, 2011b). In countries with mature and interconnected energy markets this may become a trend and affect the operation of reactors. In France, where some 80% of electricity is produced by nuclear plants, reactors have to match grid demands and operate using frequency control. Similar arrangements are in place in Belgium.

Flexible load following from the nuclear fleet can be needed to contribute to power regulation at three different levels (WNA, 2011a): primary power regulation for system stability (when frequency varies and power must be automatically adjusted by the turbine); secondary power regulation related to trading contracts; and, thirdly, power adjustment in response to demand. In flexible operation mode, systems may sacrifice a couple of percentage points of load factor. As an example, for French and Belgian units it is essentially a commercial decision whether to reduce output instead of exporting the excess at a low price, or using it for pumped storage.

A number of physical features of nuclear systems have to be considered in flexible operation. Temperature and pressure ranges and rates of change, as well as the number of their acceptable cycles, potentially place limits on how much, how quickly and how often the power output of a reactor can be changed (Claverton Energy, 2011). This forms part of the safety case assessment that needs to be adapted to operations in load following.

One of the most important fuel performance aspects linked to load following operations is the potential for PCI (IAEA, 2010b). Recent experience shows that, in PWR fuel of modern design, only a very limited numbers of failures can be attributed to PCI. In France, daily load following and extended reduced power operations have shown that the fuel failure rate is not affected by these operations or by the control rod movements associated with them. In addition, R&D programmes have been launched to test improved cladding materials and doped pellets to achieve greater margins against PCI, although these may take some time before industrialisation (Thibault et al., 2009).

Xenon poisoning is a further aspect that needs to be considered in load following operations. Some fission products are neutron absorbers, the main one being the isotope ^{135}Xe (Claverton Energy, 2011). At steady state the concentration of ^{135}Xe reaches equilibrium, but if reactor power is reduced this equilibrium is disturbed and the ^{135}Xe concentration rises, increasing the absorption of neutrons, hence contributing to a further reduction of power. The build-up of ^{135}Xe has to be balanced by adjustments of the control rods or other neutron control mechanisms, but the ability to do this depends on there being sufficient spare reactivity in the reactor core.

Reactors such as PWRs are nevertheless able to achieve fast load changes by temporarily further inserting or partially extracting one or several groups of control rods (called grey banks) and borating or de-borating⁹ the primary circuit coolant, as necessary. Grey control rods are less absorbing, from a neutronic point of view, than ordinary control rods and allow sustained variation in power output, without undue local power perturbations. Moreover, the most modern plants are equipped with a sophisticated or even automatic control system for power distribution using direct input from in-core detectors. There are few restrictions on load following operation except for starting up after refuelling¹⁰ and at the end of cycle, when the reactivity margin is reduced.

However, the load following capability is dependent on the condition of the core. In France, once the reactor attains more than 65% cycle burn-up, PWR units can no longer be used for load-following manoeuvres linked to demand change response because of limitations on the rate of boration and de-boration achievable. Indeed, when PWRs get to around 90% cycle burn-up they can only respond to frequency regulation, and essentially no power variation is allowed (unless necessary for safety).

Plant ageing and life extension

With many existing nuclear plants having entered operation in the 1970s, a very significant proportion of the current nuclear fleet will reach an age of 40 years between 2010 and 2020. Typically the originally intended economic lifetime of these plants was 30 or 40 years. The lifetimes of many existing LWRs are being extended to as much as 60 years and serious consideration is being given to extending lifetimes even further. Hence, management of component ageing and plant life extension have increasingly acquired greater interest and importance (as also discussed in Chapter 2).

In-core fuel management in LWRs has played a role in managing the effects of plant ageing. The widespread adoption of low (neutron) leakage loading patterns was in part driven by the need to minimise pressure vessel exposure to fast neutrons, which have a role in vessel embrittlement. In early LWR pressure vessels there was a specific issue with longitudinal welds becoming embrittled. In-core loading patterns were adopted for such plants in which the fast neutron fluence at the welds was reduced by selective positioning of irradiated fuel assemblies near the weld locations and by the use of steel dummy rods to provide an element of shielding. There may be a requirement to adjust core loading patterns to further reduce pressure vessel damage. This represents an aspect in the overall system optimisation, trading off a likely decrease of in-core fuel efficiency in favour of longer operational lifetime.

Lifetime assessment programmes have been initiated in recent years to further understand factors affecting the lifetime extension of existing nuclear power plants and associated management practices, in order to facilitate their safe and economic long-term operation. Under the Euratom Framework Programme, for instance, the European network of excellence for nuclear plant life prediction (NULIFE) has been launched with a clear focus on integrating safety-oriented research on materials, structures and systems and the production of harmonised lifetime assessment methods. NULIFE activities are aimed at maintaining the sustainability and safe and economic operation of nuclear power towards 60+ years. NULIFE includes programmes such as LONGLIFE, research directed at the accurate prediction and surveillance of reactor pressure vessel (RPV) neutron irradiation embrittlement and its effects in RPV safety assessments, and STYLE,

9. Boron is a neutron absorber.

10. After refuelling, in PWRs and BWRs new fuel has to be “conditioned” when the reactor returns to power, which means that in the first few days after return to service, the reactor power has to be kept steady and increased slowly, so the reactor cannot operate flexibly during this period of a few days at the beginning of the fuel cycle (Claverton Energy, 2011).

looking at structural integrity assessments of non-RPV components such as reactor coolant systems and piping (Rintamaa and Aho-Mantila, 2009).

Key trends:

- Continued trend to longer fuel cycles:
 - Beneficial for economic competitiveness.
 - Slightly negative effect on uranium utilisation and SWU utilisation.
- Increasing load factors and power upratings:
 - Increased generation.
 - Increased uranium and enrichment demand.
 - Cost savings in new power capacity (power upratings).
- Load following.
- Plant ageing and approach to end-of-life.
- Lifetime extensions:
 - Need to review safety assessment and licensing
 - Near-term cost savings – delay of need for new build.

3.2.3. The back end

With respect to the back end of the fuel cycle, as reported in Section 2.8.1, traditionally there has been a clear divide among countries that have adopted a reprocessing policy and those who have not. This will be discussed further in Chapter 4. The once-through fuel cycle is the most widely adopted strategy, while a few countries have chosen to reprocess and recycle spent fuel to make use of its residual energy content.

However, the deployment of final waste disposal routes has been slow and, in many cases, decisions have been postponed, with the spent fuel discharged and stored in the interim, pending a final decision, either towards permanent disposal of spent fuel or reprocessing and recycling of fissile materials.

This section discusses technical aspects of the back end of the fuel cycle; it considers impacts from trends upstream in the fuel cycle, such as the use of MOX and REPU or the adoption of higher burn-ups, and evaluates progress in the back-end technologies, e.g. in the interim storage and permanent disposal of SNF and HLW, as well as in the management of LLW and LILW.

Reprocessing and recycling and impacts in waste management

The adoption of reprocessing derives primarily from energy policy considerations, but it can also be seen as a waste management strategy, as it contributes to the decrease of the long-term radiotoxicity of the spent fuel and the reduction of heat and volume of the original waste, alleviating any long-term post-closure safeguarding needs at the disposal site. As already mentioned in Section 3.2.1, the next decade holds the potential for some expansion in MOX and REPU utilisation in existing LWRs.

The PUREX process is the most commonly used method to separate U and Pu from SNF containing natural, low or high enriched uranium, and is the reference process for LWR/UOX and LWR/MOX reprocessing (IAEA, 2009a).

The main developments in aqueous reprocessing technology have been mostly oriented towards a continuous optimisation of the process and reduction of the level of

discharges to the environment, providing higher flexibility of the process and improving the ultimate vitrified waste resulting from reprocessing.

The generation of pure plutonium is perceived as the main disadvantage of the PUREX process, from a proliferation perspective. In addition to the need to manage uranium and plutonium, future nuclear energy strategies may seek to manage minor actinides. The PUREX process as such is not suited to the separation of individual MAs (e.g. neptunium, curium, and americium) and specific long-living fission products (e.g. ^{137}Cs , ^{90}Sr , ^{99}Tc , ^{14}C , ^{129}I). During the last decades substantial R&D has been performed to recover minor actinides (and fission products) in advanced aqueous processing schemes, these will be further discussed in Section 3.3.3.

During reprocessing with PUREX techniques, MAs and FPs are separated together, to be subsequently vitrified and placed in an interim storage. Although in principle it is possible to recycle nuclear fuel many times, in practice only mono-recycle has been implemented and, after irradiation, the recycled fuel is stored indefinitely pending a decision on its final disposal or further reprocessing.

For a given amount of energy produced, when compared with a straight once-through cycle, mono-recycling of Pu yields already to a reduction in overall waste volumes (according to AREVA, 2010, less than 0.5 m³/tU are generated, including both the vitrified waste and the compacted technical waste, which compared to 2 m³/tU for once-through fuel cycle). In terms of high-level waste, the reduction would be between four and five, depending on the optimisation of MOX disposal packages. Total decay heat is initially similar in the two options, although a higher decay heat (due to the higher actinides content) is observed for MOX-fuel after some years of discharge. If MOX fuel is sent for disposal (rather than stored as a potentially useful fuel source), this could result in the need to increase the spacing between waste packages which depends on the duration of the interim storage (NEA, 2006a; Wigeland, 2007). Even so, an overall reduction in the repository footprint would still be achieved, due to the significant decrease in the waste volume obtained through the UOX-fuel reprocessing. Mono-recycling of Pu can also provide a lower inventory of radiotoxicity in the long term, approaching a factor of 2, due to the removal of Pu from the disposed waste. Some of these conclusions for mono-recycling of Pu can be extrapolated to any nuclear fuel cycle strategy intended to maximise the recycle of Pu. In general, the maximum dose reduction achievable in such scenarios is about a factor of 10¹¹ (NEA, 2006a; RED-IMPACT, 2008).

Impact of higher burn-up on radioactive waste management

Increasing the discharge burn-up of nuclear fuel impacts on some key elements that provide the basis for the configuration of facilities and practices in the back end of the fuel cycle. The following aspects are sensitive to higher burn-up rates:

- SNF volumes;
- isotopic inventory;
- heat output;
- neutron emissions;
- criticality considerations concerning transport, storage and disposal;
- long-term integrity of fuel cladding and fuel assemblies.

Per unit of energy produced, the volume of SNF varies inversely to its discharge burn-up: a 50% increase in burn-up decreases SNF volumes by 33%. However high burn-up

11. The lower dose mainly results from the removal of ^{129}I from the high-level waste during reprocessing.

spent fuel assemblies are hotter, both radioactively and thermally (Dixon and Wigeland, 2008). According to recent modelling (NEA, 2006) higher discharge burn-ups lead to increased amounts of fission products, transuranics and activation products in spent fuel. With respect to fission products, shorter-lived isotopes reach saturation when their decay rate matches their production rate, so that their inventory at discharge is roughly independent of discharge burn-up (NEA, 2006). However, the overall mass of fission products is expected to increase almost proportionally with increasing discharge burn-up, due to larger yields of the longer-lived fraction (^{137}Cs , ^{90}Sr , etc.) that accumulates roughly linearly with increasing discharge burn-up (NEA, 2006). Inventories of many transuranics tend to grow with burn-up and, as for long-lived FPs, activation products build up proportionally to burn-up levels.

Modelling developed in NEA (NEA, 2006) shows that for different discharge burn-ups (i.e. ranging from 45 GWd/t to 95 GWd/t), variations in the decay heat output at short cooling times (a few days) are negligible (a few percent), both for PWR UOX and MOX assemblies. However, the heat output at high burn-ups is significantly higher for longer periods, so that, for a given threshold heat output for transport or transfer to interim storage, longer cooling times are required at high burn-ups (NEA, 2006). A similar conclusion applies to MOX fuels, although these are more sensitive to burn-up than UO₂ fuels.

Neutron emission in UOX fuels is always higher for high burn-up fuels, roughly following a linear trend for a given cooling time. MOX fuels exhibit a similar behaviour, with even higher neutron activities.

With respect to spent fuel and radioactive waste management, a key benefit of high burn-up fuels is the reduction in the total mass of SNF resulting for the same energy produced. Current assessments and experience indicate, however, that this advantage has to be weighed against the impacts, potentially very substantial, that higher burn-ups may have on the design and features of existing or planned facilities, including systems for storage and transport, and hence on costs.

As high burn-up fuels are subject to more challenging conditions during reactor operation and subsequent storage, structural elements of cladding or assemblies may deteriorate affecting their integrity and potentially compromising their retrievability, handling and transport. At present, limited research and testing on degradation mechanisms of high burn-up fuel has been performed. High confidence in the integrity of SNF after a century of storage, adequate for transportation and possibly reprocessing, and the possibility for even longer storage times are important considerations for informed fuel cycle decisions (MIT, 2011). Confirmatory research involving spent fuel inspections of high burn-up fuel in dry casks and more extensive degradation modelling to provide adequate justification for expected periods of storage of the order of 100 years or more will need to be undertaken.

Increased decay heat output and neutron emissions will require adaptation of strategies, facilities and equipment used during storage, transport, reprocessing, conditioning and disposal of spent fuel and HLW. Higher burn-ups require longer cooling periods or, alternatively, reconsideration of licensing conditions of dry storage casks. The capacity of existing transport flasks would be reduced and a greater number of shipments required, unless increased cooling times are adopted. Optimisation may be different for each national waste management programme (or even each NPP).

Existing reprocessing and plutonium recycling systems could also be affected by a shift to high burn-up fuels. In the case of reprocessing, very high burn-up fuel will lead to different design and operational conditions. Neutron shielding requirements would have to be reconsidered and the degradation rate of solvent will increase. Higher temperatures will also modify operational requirements. Higher neutron outputs, higher inventories of heavy nuclides and especially higher decay heat (NEA, 2006) will limit the incorporation rate of waste to glass matrices. However, continuous developments in vitrification

technology may compensate for these effects, so that the number of HLW glass canisters per mass of used fuel reprocessed should remain fairly constant. The recent installed cold furnace vitrification technology in the La Hague plant provides such capability next to a higher flexibility in vitrifying different waste compositions.

If spent fuel management follows the once-through option with direct disposal, higher heat and neutron emissions arising from higher burn-up will impose higher shielding requirements in conditioning plants. Consequently, there will be higher construction costs and more demanding operational conditions.

The design of underground repositories for directly disposing of spent fuel inevitably depends on the fuel characteristics, so its heat output and neutron emissions determine the lay-out of the canisters, dimensions of disposal galleries and the required minimum distance among them. Although higher burn-up produces proportionally smaller volumes of spent fuel to be disposed, the size and dimensions of the repository would not decrease linearly; on the contrary, they may need to be enlarged. The need for larger repositories could be avoided through the provision of longer cooling and interim storage periods.

Having a greater inventory of long-lived fission products and transuranics per unit mass of unprocessed spent fuel disposed would also mean having higher levels of radiotoxicity per unit mass for disposal. The change in the relative composition of the isotopic inventory, with a higher proportion of fission products, may have some impact on the safety case for the particular site where the repository is planned to be built.

These arguments reveal the complexity and interdependency of factors deriving from the adoption of higher burn-ups and which strongly influence the back end of the fuel cycle. While the main driver to higher burn-ups has been the economics of NPP operations, a holistic view of the overall economy of the fuel cycle should be developed, which carefully assesses the pros and cons. To this end analyses of the fuel cycle in its entirety are expected to become increasingly important in the future. The prevailing trend will be to include benefits and costs from the back end of the fuel cycle in the scope of the analysis carried out.

Interim storage of spent fuel and high-level waste

At reactor shut-down SNF is intensely radioactive and generates decay heat equivalent to approximately 6% of the reactor thermal output. The residual decay heat and gamma radiation decrease rapidly with time; hence, for any fuel cycle, safety and economic benefits are obtained by allowing for this decay to occur in an interim storage facility before transport, processing, or disposal of the SNF, reducing repository costs and performance uncertainties (MIT, 2011).

The interim storage of spent fuel and HLW is therefore a key step in any fuel cycle strategy. No final repository for SNF and HLW has been put into operation in the world thereby reinforcing the importance of carefully improving the existing options and capacities for interim storage. While in most cases interim storage facilities were initially licensed to operate for periods up to 50 years, now operation periods up to 100 years or longer are increasingly being considered.

The integral planning of longer-term interim storage of spent nuclear fuel is also important in that it gives additional flexibility for future fuel cycle decisions (MIT, 2011) (where recycling is not currently considered). Interim storage also provides a safe transient solution during possible fuel cycle transitions (which, for the deployment of advanced fuel cycles could still require up to some 100 years). For these extended operational periods, it becomes crucial to predict the longer-term integrity and retrievability of SNF and the mechanisms that may degrade the fuel and fuel structure in the different storage systems.

The two main options adopted so far for interim storage are pool storage and dry cask storage (both either at the reactor or at a centralised site). With the greater use of MOX and high burn-up fuels resulting in higher decay heat levels, wet storage will remain the preferred approach for interim storage during the first decade after discharge¹² (IAEA, 2009a). Furthermore, pool storage is often used at reprocessing plants because it allows easy retrieval of specific fuel assemblies to be reprocessed as a batch. France, Russia, Great Britain and Japan have centralised pool storage of SNF to support their associated reprocessing plant operations (MIT, 2011).

After sufficient decay of fission products and especially where long-term storage is foreseen (up to and beyond 100 years), dry storage under inert conditions or in air becomes the preferred option. This past decade has seen the extraordinary development of dry storage. This modular technology is often used to complement the capacity of NPP pools, providing a system of easy implementation and extremely low operational costs. After Fukushima Daiichi dry storage technologies may see further impetus.

Choosing between a centralised facility for long-term interim storage or retaining SNF stored at the individual NPPs has been the subject of policy debates during the past decade. Generally those countries using or operating reprocessing services have a single storage facility to keep all the vitrified HLW which has been produced or has been shipped back. In some cases the same location could also be used to centrally store spent fuel destined to be directly disposed. Since 2000, new facilities of this type entered in operation (e.g. in Vlissingen, in the Netherlands and Würelingen in Switzerland). Germany decided in 2002 to abandon its former policy of centralising SNF and HLW storage in three facilities and reverted to storage at the reactor sites. Risk minimisation by avoiding transporting these materials was cited as the reason for favouring at-reactor storage. Accordingly NPPs should have to take care of these wastes in near-site interim storage facilities until their dispatch to a would-be federal repository (BMU, 2008).

Among countries with direct disposal strategies, the Swedish centralised storage facility that has been operational since 1985 was granted a licence extension in 2008 for an additional storage pool. The need for a centralised facility was also the subject of extensive discussions in Spain and the United States. In the United States, different private attempts to implement a monitored retrievable storage (MRS) have been dismissed. In Spain, the government launched a siting process in 2006.

Disposal of spent fuel and high-level waste

Underground emplacement of waste in stable geological formations continues to be the preferred disposal option for SNF and HLW. All technologies being developed for geological disposal take into account the fact that the selected host rock is the central element or barrier to provide isolation and containment of the waste radioactivity for very long periods of time. Each national programme on SNF/HLW repositories tends to concentrate its effort on a particular type of rock. Granite, clay, salt and tuffs are the most frequently selected rock formations. Most countries have retained their preferred host rocks since the very beginning of their research programmes (Belgium, Canada, Finland, Germany, Sweden, etc.). Only France and Switzerland have had a significant shift in the last 20 years from mainly working with granites to more recent research totally oriented to clay.

Research has focused on a variety of different repository designs, specific to each type of rock. Their evaluation and safety assessment are being regularly reported and, in many cases, peer-reviewed internationally. In the past decade, the development of technologies for geological disposal has benefited from the experience acquired in underground laboratories, especially those constructed and operated within the

12. Although this may be challenged as a result of the incident at Fukushima Daiichi.

designated sites. The possibility of experimenting in places with the same geological features of the final repositories has widely improved the characterisation, as well as construction and monitoring techniques, providing a deeper understanding of the long-term behaviour of the different barriers involved.

Some countries have reached important milestones:

- In Finland, as in Sweden, a repository design has been developed, a site selected in granite formations and safety cases have been submitted to the authorities. If the reviews from the safety authorities are favourable, these repositories are expected to become operational in the early 2020s.
- In France and Switzerland:
 - Safety cases for the geological disposal of various high-level and intermediate-level waste types in a clay formation have been submitted and reviewed by national and international committees.
 - In France, research is ongoing for the site selection, design and development of the disposal facility, with a safety case for licence application due for submission in 2015. In 2009, an area of 30 km² was officially selected. Depending on the decision of the authorities, the facility should be operational in 2025.
 - In Switzerland, the first phase of the site selection process was initiated in 2008.
- In the United States, a licence application for a geological repository at Yucca Mountain was developed and submitted to the regulator in 2008, but its withdrawal was requested in the following year by the United States administration. Nevertheless, studies performed for the Yucca Mountain repository have allowed important advancements in safety cases of geological disposal systems, particularly for the consideration of human intrusion scenarios.
- In Canada, in June 2007, the government of Canada selected Adapted Phased Management as its approach for the management of HLW, at the recommendation of that country's Nuclear Waste Management Organization. Canada is currently undergoing preliminary site selection for a deep geological HLW repository.

Between 1996 and 2008 a strong harmonisation in the requirements imposed by national regulations in various countries and in the treatment of future human actions in the safety cases developed was pursued (NEA, 2011a).

Given the times anticipated for the start of operation of the most advanced projects, RD&D will still need to be carried out and in many instances, further enhanced. It is generally recognised that further RD&D is needed in order to optimise solutions and move from results obtained in laboratories and pilot facilities to industrial scale implementation.

Key concepts introduced in the recent technological development of geological repositories have been reversibility and retrievability.¹³ These features, required by stakeholders in some countries, are fundamentally motivated by three considerations: the possibility of benefiting from future scientific and technical progress; the potential economic valuation of the waste; and the ethical mandate of providing freedom of decision to future generations. Reversibility and retrievability have thus impacted on the requirements of new designs. Among countries interested in pursuing retrievability and reversibility, several stances have been adopted, mostly during the last few years. In

13. According to NEA, retrievability is “the possibility of reversing the waste emplacement” while “reversibility” is defined as “the possibility of reversing one or a series of steps in repository planning or development at any stage of the programme” (NEA, 2001).

Finland and Sweden, these features are simply built into the design of geological repositories and they are part of the current national debate in the United Kingdom. In France, Switzerland and the United States retrievability is required by law and it is stated in government policies in Canada and Japan.

Notwithstanding the points discussed above and the political aspects covered in Chapter 4, to achieve the required disposal capacity decisive activity will certainly be necessary in the coming years to address some key outstanding issues:

- **Licensing.** Regulatory activity and capabilities to license repositories will require new developments both on the side of regulators as well as on that of implementers of radioactive waste management.
- **Stakeholder confidence.** Public acceptance of waste management activities and especially of HLW and SNF disposal will continue to be crucial. A less contentious atmosphere would be required to get a more positive attitude from potential host communities. In the past decade, methodologies to improve the confidence of stakeholders have been developed and implemented. Legal instruments such those that could derive from the Aarhus Convention or the strategic environmental assessment (SEA) will inevitably bring additional opportunities to have a more balanced and composed debate.
- **R&D.** The technical basis for implementing geological disposal is well established and the necessary technology is available. On the other hand there is little experience in the application of these technologies and their adaptation to the particular conditions of sites selected to host the final repository. Together with the possibility of R&D *in situ*, knowledge retention through the long periods of time involved in repository development will be a further challenge (Ahn and Apted, 2011).

Developments in LLW and LILW waste management

LLW and LILW waste management in NEA countries is a well established practice that benefits from extensive experience. As already seen in Chapter 2 (Table 2.12), most NEA countries have a repository for LILW in operation or, in a few cases, the licensing process to construct a facility is underway. For instance, Belgium has designated a site at Dessel; Canada is licensing Kincardine; in Germany, a repository for non-heat generating waste is being constructed in Konrad; in Hungary, operations at surface storage and control facilities at the Bataapati site were inaugurated in late 2008 (WNA, 2008b); the Republic of Korea has selected Wolsong; and in the United States, a licensing process is underway for a new repository at Andrews in Texas.

The past decade has proved LILW disposal technologies to be well-defined and established. Near-surface disposal is the most frequent choice for LILW, given the short times required for the construction of these facilities. Shallow underground disposal has also been adopted in certain countries, like the Czech Republic, Finland and Sweden, as it seems to be a more accepted practice by the public.

In parallel, an important milestone was achieved in 1999 with the start of operation of WIPP (New Mexico, United States), the first underground repository to receive long-lived LILW generated by the US defence programme. Confirming the maturity of LILW disposal technologies the disposal centre of La Manche in France, which was closed in 1994, continued its planned programme of institutional surveillance with no particular concerns with respect to the safety of the facility.

During the past decade, efforts in LILW management have mostly focused on volume reduction. Effective improvements have been obtained and some countries are reporting average reductions in the range of 30 to 50%. A second area of development has been the recycling of some forms of waste which, after being subject to decontamination and

subsequent melting, can be compacted in volume or even used in special systems for the casing of other more active wastes. This is, for instance, the case of scrap metals arising in large volumes from decommissioning activities. A practice that has been adopted and that is receiving more attention¹⁴ is smelting. Through this process various types of contaminated metals can be recycled following decontamination and are ultimately converted into ingots that can be reused or released as conventional scrap metal. Although some secondary waste requiring disposal as LLW is still generated in the form of “slag”, this is still significantly less than the original volume of metal scraps.

In some countries, a significant advancement in terms of safety and economics has been the establishment of a lower category of waste, identified as VLLW within the wider classification of LILW. VLLW is defined as waste that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control (IAEA, 2009b). VLLW disposal sites can be released some decades after closure. Near-surface repositories for VLLW result in a significant reduction of costs in comparison with the traditional near-surface vault systems for LILW. This is particularly important when considering the large amounts of waste arising from decommissioning operations. France (at the Morvilliers site, which started operation in 2003) and Spain (El Cabril, which started operation in 2007) have opted for this technology which is expected to be most likely extended to other countries in the near future.

Key trends and impacts on waste management from upstream trends:

Reprocessing:

- Continued reduction in the level of discharges to the environment from reprocessing and increased operational performance of the commercial reprocessing plants.

Impact of reprocessing and recycling in waste management (mono-recycling of Pu):

- Can reduce total volumes of waste (up to a factor of 2) with a reduction of about 4 to 5 in the amount of high-level waste.
- Generates a similar amount of total decay heat but with higher density of thermal power.
- Reduces radiotoxicity (by a factor of 2) in the long term – up to 1 000 years – the total radiotoxicity is slightly higher.

Impact of higher burn-up on radioactive waste management:

- Reduction in spent fuel mass in inverse proportion to mean discharge burn-up.
- Higher isotopic inventory (increased amounts of fission products, transuranics and activation products) per tonne of spent fuel.
- Higher heat output: for a given heat output longer cooling times are required at higher burn-ups.
- Higher neutron emissions, with associated implications on criticality and shielding considerations concerning transport, storage and disposal (as well as separation facility design, including considerations on degradation rate of solvent, if high burn-up spent fuel is reprocessed).
- Long-term integrity of fuel cladding and fuel assemblies could be compromised due to more challenging fuel duties.

Interim storage of spent fuel and high-level waste:

- Consolidation of commercially available dry storage systems.
- Steady trend to implement centralised storage facilities for HLW and SNF.

14. See for example www.technologiya-metallov.com/englisch/oekologie_5.htm.

Disposal of spent fuel and high-level waste:

- Positive progress in some countries towards deep geological repositories for spent fuel.
- Progress of research on repository designs, specific to different host rocks, including implementation of underground laboratories.
- Increasing weight attached to reversible/retrievable repositories, with the following advantages:
 - Benefit from future scientific and technical progress.
 - The potential of benefitting from the economic valuation of the waste.
 - Entrust freedom of decision to future generations.
- Progress with establishing legal frameworks and public involvement practices.

Developments in LLW and LILW management:

- Consolidation of LILW disposal, with facilities operational in many countries.
- Steady trend towards optimisation of existing disposal capacities.
- Advances in waste categorisation with establishment of VLLW.

3.3. The longer-term future, options and R&D trends

This section considers fuel cycle options that may become available in the long-term future, beyond 2020. It starts, in Section 3.3.1, with a review of unconventional uranium resources that may become economically viable, if market conditions become sufficiently conducive. Sections 3.3.2 through to 3.3.5 consider various stages of advanced fuel cycles, emerging issues and associated R&D; Generation IV systems introduced in Chapter 2 are not discussed further. The thorium fuel cycle is separately addressed in Section 3.3.6, while Section 3.3.7 considers other innovative nuclear energy applications and concepts.

Through greater recycling of spent fuel, advanced fuel cycles would allow a better use of the energy potential of natural uranium. In particular, closed fuel cycle schemes based on fast reactors could greatly decrease the requirement for fresh uranium. At the same time, the volume and radiotoxicity of waste could be decreased significantly, through a selective separation (partitioning) of the long-lived elements, including minor actinides (e.g. neptunium, americium and curium) and possibly some fission products from spent fuel. Mixed directly with the fuel (homogeneous transmutation) or incorporated in separate targets (heterogeneous transmutation), these separated isotopes could then be transformed into shorter-lived elements (transmutation) by fissioning or neutron capture either in reactors or in specifically designed systems (e.g. ADS). Alternatively the partitioned isotopes could be vitrified as waste in special matrices and separately conditioned and disposed of.

The deployment of these advanced cycles, including Generation IV systems (see Section 2.9.1) and P&T technologies, requires significant R&D advances, with some important challenges still laying ahead. Some of these are listed below and discussed in the forthcoming sections:

- R&D on novel fuel separation methods, including processing techniques, for waste streams that can be destined to disposal, or re-processing followed by transmutation (see Section 3.3.3).
- Advances in transmutation technologies (see Section 3.3.4).
- Addressing emerging waste management issues linked to new systems and advanced separation technologies (see Section 3.3.5), such as the development of new conditioning processes, a better characterisation and optimisation of composition and quantities of waste streams (including LILW).

3.3.1. Unconventional uranium resources

Conventional resources are defined (NEA, 2010) as resources from which uranium is recoverable as a primary product, a co-product or an important by-product, while most unconventional resources are those from which uranium is only recoverable as a minor by-product; principally uranium associated with phosphate rocks, but also non-ferrous ores, carbonatite, black schists, and lignite and other potential sources (e.g. seawater and black shale). A brief overview on the status and prospects of unconventional resources is provided in this section, based on the review conducted in the last edition of the IAEA/NEA publication *Uranium: Resources, Production and Demand* also known as the Red Book (NEA, 2010). Recently, in November 2009, an IAEA Technical Meeting on unconventional resources was convened and covered a broad spectrum of issues, including their potential, research and technological developments as well as related environmental aspects (IAEA, 2009).

Phosphate deposits are the only unconventional resource from which a significant amount of uranium has been historically recovered, notably in the United States, Belgium (with the processing of Moroccan phosphate rock) and in Kazakhstan from processing marine organic deposits (essentially concentrations of ancient fish bones). As the price of uranium dropped in the 1990s, these operations became uneconomic and consequently most of the plants were shut down; those operating in the United States were decommissioned and demolished. However, with expectations of rising demand and the generally increase of uranium prices since 2003 partly linked to this, a variety of projects and alternative technologies are being investigated by both governments and commercial entities and unconventional uranium resources are gaining more attention again.

In Brazil, development of the St. Quitéria Project is ongoing, with production of as much as 1 000 tU/yr from phosphoric acid produced from the Itataia phosphate/uranium deposit expected to begin as early as 2012. In the Red Book 2010 (NEA, 2010) the long-term potential of uranium recovery from phosphate deposits is also considered for other non-NEA countries such as Egypt, Peru and South Africa. Furthermore, Jordan, Morocco and Tunisia have expressed an interest in recovering uranium from phosphate rocks during fertiliser production; uranium is now being dispersed in very low concentrations on the land surface in fertiliser. In the future, uranium could be extracted during fertiliser production and used in the nuclear fuel cycle. In November 2009, Cameco invested USD 16.5 million in Uranium Equities to develop and commercialise the company's PhosEnergy process.

By-product recovery of uranium from unconventional resources and in particular phosphate processing facilities is likely to become economically viable if uranium prices reach levels in excess of USD 260/kgU (USD 100/lb U₃O₈). In this case, by-product uranium production from phosphoric acid could again become an important, competitive source of uranium, provided barriers such as regulatory requirements and qualified personnel development are overcome. However, given that uranium market prices may justify the exploitation of these deposits, the development of more rigorous estimates of uranium in phosphate rocks is needed to define the extent of these resources, their accessibility and the economics of uranium production.

Interest is not restricted to phosphate rocks alone. In Finland, low-grade polymetallic sulphide ores in the Talvivaara black shales have been in commercial production since October 2008. Whilst at present the extraction process does not include recovery of uranium contained in the ore, under favourable market conditions this may be extracted in the future. Also in Finland, in 2007, the Ministry of Employment and the Economy granted a two-year extension of the Sokli mining concession on phosphate ore containing niobium, thorium and uranium, with an option for uranium production. Canadian-based Spartan Resources has been actively developing the technology for the recovery of uranium from coal ash, focusing efforts on a Chinese coal-fired power station, but also exploring other potentially suitable ash disposal sites. Although the process has been conducted on a limited scale in the past, strong uranium prices will be necessary for

such extraction technologies to become commercially viable. In any case, uranium recovery from tailings and coal ash could only contribute small amounts to the annual uranium production, on the order of a few hundred tU/year from each operation.

Seawater has long been regarded as a possible source of uranium, due to the large amount of uranium contained (some 4.6 billion tU) and its almost inexhaustible nature. However, because of the low concentration of uranium in seawater (3-4 parts per billion) it would require the processing of about 350 000 tonnes of water to produce a single kilogram of uranium. Nonetheless, with the exception of its high recovery cost, there is no intrinsic reason why at least some of these significant resources could not be extracted from various coast-lines at a total rate of a few hundred of tonnes annually. Research on uranium recovery from seawater was carried out in Germany, Italy, Japan, the United Kingdom and the United States in the 1970s and 1980s, but is now only known to be continuing in Japan, through pilot trials, aimed at improving the recovery factor and lowering costs towards competitive ranges.

3.3.2. Fuel design and fuel fabrication research and development

The development of advanced fuels with a system-wide integrated view taking into account recycle (separations) and waste forms is crucial for the implementation of advanced fuel cycles. The recent NEA study *Nuclear Fuel Cycle Transition Scenario Studies – Status Report* published in 2009 (NEA, 2009), identifies areas of fuel development. Tables 3.3, 3.4 and 3.5 below, extracted from the study, summarise advanced fuels for LWR (for which standard fuels such as UOX and MOX currently available are also listed), fast reactor and HTGR respectively. The tables provide also an estimate of implementation times, development needs and perceived advantages, as well as a list of countries interested in each specific technology (NEA, 2009).

Table 3.3: Fuels for LWRs

Fuel type	Perceived advantage	Countries interested	Development needs	Time envisaged for industrial availability ¹	Comments
U oxide	Current industrial practice; potential for decreasing waste; impact large scale commercial deployment.	All countries.	Increased burn-up and continued reliability at high burn-up.	Industrially available today	Standard burn-up fuel (>70 GWd/t) is available now.
U-Pu oxide	Considerable industrial experience; way to reduce Pu stockpiles.	Belgium, France, Germany, India, Japan, the Republic of Korea, the Russia Federation, Switzerland and the United States.	Improved remote fabrication methods.	Industrially available today	Fuel performance parity with UOX achieved.
U-Pu-Am oxide	Reduced attractiveness ² of recycled material; some level of management of MA stockpiles.	No one actively pursuing industrially at this time. R&D ongoing in France within context of French waste law 2006.	Chemical method for separation of Am from Cm developed at lab-scale; development of remote fabrication methods; complete fuel qualification testing programme; special plant needed.	2030-2040	May meet with resistance from utility operators; benefits for minor actinide management limited.

Table 3.3: Fuels for LWRs (continued)

Fuel type	Perceived advantage	Countries interested	Development needs	Time envisaged for industrial availability ¹	Comments
U-TRU oxide	Reduced attractiveness ³ of recycled material; only losses at reprocessing sent to repository.	Research mode only.	Development of remote fabrication methods; complete fuel qualification testing programme.	2035	Very high neutron dose from fuel assembly will require remote handling at all times.
Pu oxide inert matrix	Efficient consumption of Pu, essentially to get rid of fissile Pu.	Switzerland (paper study), some studies sponsored by EU countries. One fuel irradiation study underway.	Development of inert matrix material and of reprocessing methods; development of fabrication methods.	2030	Very limited irradiation performance data for inert matrix fuel.
TRU oxide inert matrix	High burn-up capability.	Research mode only.	Development of inert matrix material and of reprocessing methods; development of fabrication methods.	2045	Currently very limited irradiation performance data. Build-up of higher mass actinide. Neutron dose from fuel assembly will require remote handling at all times. Only calculations performed with very limited experimental work.

1. These are estimates from NEA, 2009 but may change as technologies develop.

2. In terms of illicit diversion for weapons use.

3. As for previous note.

Table 3.4: Fuels for FRs

Fuel type	Perceived advantage	Countries interested	Development needs	Time envisaged for industrial availability ¹	Comments
Oxide (U-Pu)	Already industrialised technology; current industrial practice.	China, France, India, Japan, the Republic of Korea, the Russian Federation, the United Kingdom.	None.	2025	Not on critical path; availability of fast irradiation facility (20 years) more limiting.
Oxide (U-TRU oxide)	Highest level of technological maturity of non-industrialised processes.	France, Japan, the United Kingdom and the United States. Gen-IV irradiation project in MONJU.	Validation of ceramic properties with minor actinide content (fabrication issue); fast reactor irradiation of minor actinide bearing fuels. Irradiation facilities availability.	2030	Homogeneous TRU recycle. MA content (3-10%) depends on reactor size and coolant technology. Neutron dose increase at fuel fabrication.

Table 3.4: Fuels for FRs (continued)

Fuel type	Perceived advantage	Countries interested	Development needs	Time envisaged for industrial availability ¹	Comments
Metal (U-TRU-Zr)	High level of technological maturity; highly favourable safety characteristics in SFR application.	France, Japan, the Republic of Korea and the United States.	Demonstration of fabricability of minor actinide (i.e. Am) bearing fuels; fast reactor irradiation of minor actinide bearing fuels. Irradiation facilities availability.	2030	Homogeneous TRU recycle. MA content (3-10%) depends on reactor size and coolant technology. Utilisation in lead-cooled reactor would require use of different thermal bonding material and confirmation of chemical compatibility with fuel. Know how to do Na bonding – not Pb or Pb-Bi. Neutron dose increase at fuel fabrication.
Nitride (UN-TRU N-ZrN)	Complete solubility of actinide nitrides; irradiation stability of fuel at normal operating temperatures; amenable to aqueous or non-aqueous reprocessing.	The Russian Federation.	Development of efficient fabrication methods; fast reactor irradiation testing. Irradiation facilities availability.	2040	Potential issue with dissociation of nitrides at accident temperatures. Might require 15N enrichment. Neutron dose increase at fuel fabrication.
Carbide (UC-TRU C-SiC)	High-temperature capability.	France.	Development of new fuel forms and efficient fabrication methods; fast reactor irradiation testing. Irradiation facilities availability.	2040	Homogeneous TRU recycle. MA content depends on reactor size and coolant technology (3-10%). If used for GFR, new fuel forms are possible: advanced fuel particles, cellular plate fuel concept, advanced pin fuel concept. Neutron dose increase at fuel fabrication.

Table 3.4: Fuels for FRs (continued)

Fuel type	Perceived advantage	Countries interested	Development needs	Time envisaged for industrial availability ¹	Comments
Targets for heterogeneous MA recycling	Separation (in the reactor core and in the fuel cycle) of “standard” Pu-bearing fuel and (high concentration) MA-bearing fuel. Potentially, only a fraction of the fast reactor to be deployed should be loaded with MA targets in special fuel subassembly.	France.	Development of appropriate matrix: inert or uranium. Fabricability in presence of high content of MA (Cm). Need for irradiation tests. Irradiation facilities availability.	2035-2040	Potential difficulties related to high thermal power (both at beginning and end of irradiation), and high He production. A larger part of the fast reactor fleet to be loaded with MA targets, if MA content should be limited.
Dedicated fuels for MA transmutation	Can be used for MA transmutation in a separate stratum of the fuel cycle. If ADS are used, practically any MA/Pu ratio can be envisaged. Dedicated fuels can in principle be oxide, metal, nitride or carbide.	Belgium, France, Germany, Japan, the Republic of Korea, the Russian Federation, Spain, and Sweden.	Development of appropriate matrix: inert or uranium. Fabricability in presence of high content of MA (Cm). Need for irradiation tests. Irradiation facilities availability.	2035-2040	If U-free fuel, inert matrix choice should accommodate fabrication, spent fuel processing and core constraints. U matrix can allow up to 80% of maximum theoretical MA consumption.

1. These are estimates from NEA, 2009 but may change as technologies develop.

Table 3.5: Fuels for HTGRs

Fuel type	Perceived advantage	Development needs	Time envisaged for industrial availability ¹	Comments
TRISO UO ₂	Prior experience with this fuel type in Germany and the United States.	Development of fuel fabrication technology; irradiation testing to confirm fuel integrity. Determination of fuel behaviour in repository in case of direct disposal.	2017	May be prone to kernel migration during irradiation to high burn-up.
TRISO UCO oxy-carbide	Similarity to TRISO UO ₂ fuel; resistance to kernel migration.	Development of fuel fabrication technology; irradiation testing to confirm fuel integrity. Determination of fuel behaviour in repository in case of direct disposal.	2022	More complex kernel preparation method required (essentially a mixture of UC ₂ and UO ₂).
TRISO PuO ₂	Potential high burn-up capability.	Development of fuel fabrication technology; irradiation testing to confirm fuel integrity. Determination of fuel behaviour in repository in case of direct disposal.	2025	Plutonium consumption application.
TRISO U/TRU oxy-carbide	Deep burn concept.	Development of fuel fabrication technology; irradiation testing to confirm fuel integrity. Determination of fuel behaviour in repository in case of direct disposal. Development of reprocessing technology for two-pass case.	2030	Validation of core physics analysis required. Potential high build-up of higher mass actinides.

1. These are estimates from NEA, 2009 but may change as technologies develop.

3.3.3. Separation – fuel processing research and development

With the current reprocessing techniques based on the PUREX method (as discussed in Section 3.2.3), uranium and plutonium are separated from FPs and MAs which are vitrified as high-level waste. Advanced processing techniques are aimed at the separation of some of these other radioisotopes (in particular MAs but possibly some FPs too), or their incorporation in the plutonium stream. The chemistry of minor actinides is not as conducive to separation as that of uranium and plutonium and the development of satisfactory flow sheets is not straightforward. Potential flowsheets have been developed at laboratory scale, but have yet to be demonstrated at industrial scale, with likely times for commercialisation of the order of 20 years or even longer for some processes geared towards full separation of actinide streams.

Research and development performed on advanced separation methods is however progressing, with extensive effort, over the past decade, in different countries across the globe, including in North America (Canada and the United States), Europe (EU, France, the United Kingdom), and Asia (China, India, Japan, the Republic of Korea and the Russian Federation). This research can be classified into a few broad categories:

- modifications to the PUREX process;
- alternative aqueous (hydrometallurgical) processes to recover uranium;
- advanced hydrometallurgical processes to recover the minor actinides (Am, Cm);
- hydrometallurgical processes to remove fission products for waste management purposes; and

- pyrochemical methods of recovering uranium and transuranics.

Technical details of these different categories are provided below.

Modifications to the PUREX process

Modifications to the PUREX process have been developed primarily to improve performance including reducing the amount of secondary waste arising, while also allowing the treatment of a larger variety of fuels (e.g. fuels with higher burn-up, different compositions, etc.). Another significant progress at the vitrification stage involves the industrial use of the cold crucible technology at La Hague since 2010. Other R&D has also addressed changes to the original PUREX process, providing options for the processing of spent nuclear fuel without separating pure plutonium. Two primary approaches to this have been developed. In one approach, only uranium is extracted, and plutonium is left with the other fission products and actinides. This process is called the uranium extraction (UREX) process and was developed in the United States within the last decade. The other approach is to co-extract uranium and plutonium (as is done in the PUREX process) but to then co-strip a fraction of uranium with the plutonium so that pure plutonium is never separated in the process. This process has been studied as a variation of the UREX process in the United States, developed as the COEX™ process in France, and as the NUEX process in the United Kingdom.

▪ UREX process

Uranium and technetium are separated from the dissolved spent fuel solution by employing the tri-*n*-butyl phosphate (TBP) in a normal paraffin hydrocarbon (NPH) diluent. Chemical additives are used to reduce plutonium in the acidic feed solution to the trivalent state, and to form complexes of plutonium and neptunium, inextractable by TBP. Depending on the residual level of TRU elements, the solid uranium product might be disposed as low-level waste. The uranium product could also be utilised in the fabrication of new nuclear fuels. Plutonium and other TRUs remain with the fission products and may be incorporated in the process waste or removed for transmutation. The UREX process has been studied extensively for the past several years, including several flowsheet demonstration tests in small-scale centrifugal contactors using spent light water reactor fuel. Results of the demonstration tests were very promising, and indicate that the process may be a viable technology for treating spent nuclear fuel. The process to date has been studied only on a laboratory scale using a few kilograms of fuel.

▪ Co-decontamination, COEX™ or NUEX processes

The second modified PUREX technology is referred to as the co-decontamination process, COEX™ or NUEX process. Both uranium and plutonium are simultaneously extracted from the dissolved spent nuclear fuel in 30% TBP and a hydrocarbon diluent. In this process, the valence of neptunium may be adjusted from (V) to (IV) or (VI) using a reductant or oxidant. In the COEX™ process, the ratio of uranium and plutonium can be adjusted and the product converted to oxides for use in MOX fuel. In the co-decontamination process, plutonium and neptunium are stripped from the solvent in dilute nitric acid containing AHA and uranium. Following the Pu/Np/U strip, the remainder of the uranium and technetium are stripped in 0.01 M nitric acid. Technetium is removed from the uranium product by an ion exchange column.

These processes also require a relatively high nitric acid concentration in the feed (~3 M), which may improve spent fuel dissolution efficiency and dissolver solution stability. Each of the three processes has unique characteristics, but has been demonstrated in small-scale extraction tests with spent nuclear fuel.

Alternative processes to recover uranium

There are a few processes under investigation that could be used in place of the PUREX process for the recovery of uranium. The first process is very similar to PUREX, but uses a malonamide extractant rather than the tri-butyl phosphate extractant used in the PUREX process. Performance of the malonamide extractant is similar to the TBP, but has the advantage that the solvent does not contain phosphorus, which complicates solvent disposal options. Research on this new extractant has been primarily carried out in France.

Another method of removing uranium is crystallisation. Research into uranium crystallisation has been carried out in the United States and the Russian Federation, but the largest ongoing research effort is in Japan (with the so-called NEXT process which includes crystallisation and U/Pu/Np coextraction). Manipulating uranium concentration and temperature, about 70% of the uranium can be effectively separated from the dissolved spent nuclear fuel solution. U/Pu/Np are co-extracted from the resultant solution after the crystallisation step. Pilot-scale demonstrations of the technology are in progress, but the technology has yet to be demonstrated in actual production-scale operations.

Processes to remove the minor actinides

Separation of the transplutonium actinides from the lanthanides and remaining fission products for possible transmutation in fast spectrum reactors has received significant attention in several national spent nuclear fuel strategies for the middle of the 21st century. As such, it has been the subject of a substantial amount of research over the past decade in nearly every nuclear developed country.

Two processes that have been extensively developed and tested are the transuranium extraction (TRUEX) process and the diamide extraction (DIAMEX) process for separation of the actinides and lanthanides together. Both processes would produce a relatively pure TRU/lanthanide fraction and the raffinate would contain transition and noble metals. The primary difference between the processes is the composition of the extractants, with the diamide extractants following the C, H, O, N principle of containing only carbon, hydrogen, oxygen and nitrogen atoms to allow ease of incinerating spent solvent and the TRUEX extractant containing phosphorous. Another extractant that exhibits high separation efficiencies for TRUs and lanthanides is N,N,N',N'-tetraoctyldiglycolamide or TODGA developed in JAERI. The development of this extractant is relatively new, but it is under investigation by a number of research laboratories around the world.

The TRUEX process uses a solvent comprised of octyl (phenyl)-N,N-diisobutyl-carbamoylmethylphosphine oxide (CMPO), and tri-*n*-butyl phosphate in a paraffin hydrocarbon diluent. The TRUEX process is very effective at extracting 3, 4 and 6 valent metals from nitric acid solutions. Complexants, such as oxalic acid, can be added to reduce the extraction of transition metals, such as zirconium and molybdenum.

The DIAMEX process originally utilised dimethyl-dibutyl-tetradecylmalonamide (DMDBDMA) as the extractant in a hydrocarbon diluent. Recently, a new extractant, dimethyl-dioctyl-hexaethoxymalonamide (DMDOHEMA) has been developed that appears to have better extraction properties than DMDBDMA. This new extractant has been tested in a countercurrent flowsheet test with actual concentrated high activity PUREX process raffinates.

Following the separation of the TRU/Ln fraction, an additional process after the TRUEX or DIAMEX process would be required to separate trivalent actinides from lanthanides. An/Ln partitioning technologies are at an earlier stage of development than the other technologies described above.

Trivalent actinide/lanthanide separation is difficult to accomplish due to the similarities in the chemical properties of the trivalent actinides and lanthanides. Various

solvent extraction processes have been studied including: the extraction of the lanthanides from the trivalent actinides with the TALSPEAK process; the coextraction of the trivalent actinides and lanthanides, with selective stripping of the actinides from the lanthanides with the reverse TALSPEAK process; the di-isodecylphosphoric acid (DIDPA) process; the SETFICS process; the PALADIN process; selective actinide extraction (SANEX) processes using Cyanex 301; the SANEX-III and SANEX-IV processes; as well as processes utilising bis-triazinyl-1,2,4 pyridines (SANEX-BTP). Additional research is being conducted on the GANEX process (group actinide extraction), which is similar to the combined DIAMEX-SANEX approach, but attempting to combine them into a single process.

Fission product separation

Shorter-lived fission products account for the majority of heat generation for the first 100 years after spent fuel is discharged from the reactor. Caesium and strontium are the primary heat generating isotopes in this time frame. Several technologies have been developed to separate either caesium or caesium and strontium together. Methods to extract caesium from spent nuclear fuel were developed in France using calixarene extractants. Calixarene molecules can be tailored to be highly selective for caesium over other alkaline and alkaline earth elements. A similar process was developed in the United States to extract caesium from alkaline high-level tank waste at the Savannah River Site using calixarenes. Extraction of caesium and strontium together has been demonstrated in two different processes. The first utilising cobalt dicarbollide and polyethylene glycol extractants was initially developed by Czech and Russian scientists, and later modified for possible use in the United States. The second process (called fission product extraction) utilises a combined solvent containing a calixarene extractant for caesium extraction and a crown ether extractant for strontium extraction.

Pyroprocessing

Pyroprocessing is another separations method for the recovery of uranium and, if desired, transuranic elements. Pyroprocessing comprises several dry separation methods, first of all electrochemical separations from molten chloride or fluoride salts, molten salt/liquid metal extraction and fluoride volatilisation.

Electrochemical pyroprocessing was originally developed for processing of metal fast reactor fuel. After chopping, fuel is anodically dissolved into a bath of molten salt, such as lithium chloride-sodium chloride eutectic. Once dissolved, the uranium is electrochemically deposited on a cathode, as uranium metal. Transuranics (with some uranium) can be recovered by use of a liquid metal cathode, such as cadmium. The electrical potential, applied to the anode and cathode, determines what metals are recovered on the cathode. The product metals, such as uranium dendrites, are removed from the molten salt, and processed to separate the uranium from salt adhered to the metal. This is typically done by vacuum distillation at about 1 200 °C to volatilise the salt. The salt is recovered and returned to the electrorefiner. The uranium metal can be cast into pins or ingots for potential recycle into new fast reactor fuel.

The pyroprocess produces two high-level waste streams. One is a metal waste stream that contains undissolved metals (such as fuel hulls, etc.). The other is a ceramic waste used to immobilise the spent electrorefiner salt. Recent developments have been made on methods to reduce oxide fuels to metals as an additional head-end process to prepare oxide fuels for treatment by pyroprocessing. Research on electrochemical pyroprocessing is being performed in numerous countries around the world, including India, Japan, the Russian Federation, South Korea and the United States.

The molten salt/liquid metal extraction method was originally proposed for the separation of uranium and thorium from fission products in the on-line reprocessing of liquid fuel from molten salt reactors. The method is also considered promising for the separation of actinides from fission products within the uranium-plutonium fuel cycle.

The method is based on the successive countercurrent reductive extraction of dissolved fuel components from carrier molten salt into liquid metal (usually bismuth, cadmium or aluminium). The typical reductive agent is lithium, which is progressively added in the liquid metal. The partitioning of individual components or chemical element groups from the carrier salt is dependent on the distribution coefficients. This technology was originally developed in the United States, but present studies are performed primarily in France.

The fluoride volatility method is the only pyrochemical process under present development that is not based on the use of molten salts. The process derives from the specific property of uranium, neptunium, and plutonium to form volatile hexafluorides, whereas most fission products (in particular lanthanides and the transplutonium elements Am and Cm) present in the irradiated fuel form non-volatile trifluorides. The process is based on direct fluorination of powdered spent fuel with pure fluorine gas in a flame reactor, where the volatile fluorides (mostly UF_6) are separated from the non-volatile ones. Subsequent separation of plutonium from the volatile fluorides stream is done by thermal decomposition of gaseous PuF_6 to solid PuF_4 . Purification of uranium from neptunium and other volatile impurities is done by condensation/evaporation, sorption and final distillation of uranium hexafluoride. The fluoride volatility method should be primarily suitable for reprocessing advanced oxide fuels with inert matrices, carbide fuels and fast reactor oxide fuels of very high burn-up and short cooling time. This method was originally studied in Czechoslovakia, France, the Soviet Union and the United States; the present development is performed primarily in the Czech Republic, with further ongoing investigation in Japan (Fluorex method).

3.3.4. Transmutation

Transmutation in reactors – reactor physics

The transmutation potential of each TRU isotope depends on its specific neutron cross-sections in a particular neutron spectrum. Ideally, for an isotope “A” (with A being the isotope atomic number) to be transmuted effectively, the following conditions should be met:

1. The fission of “A” should be favoured against (n,) and (n,xn) reactions.
2. “A” reactions giving rise to “A +1”, “A +2”, etc., should be minimised (the radioactive properties of these resulting isotopes need to be carefully investigated).
3. As far as possible, isotopes that undergo full fission should be “neutron producers” rather than “neutron consumers”, in order to achieve a viable core neutron balance.

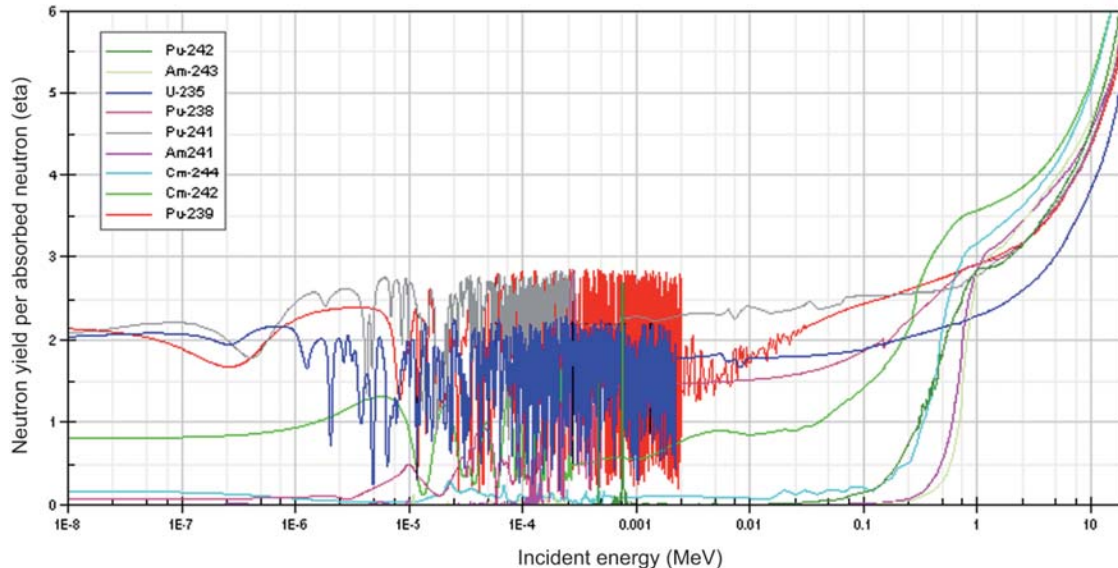
A simple indicator of the influence of the neutron energy spectrum is the reaction ratio α =capture/fission. For most TRU, the most favourable (i.e. low) ratio values are obtained in a fast neutron spectrum. Instead, in a thermal neutron spectrum MAs act as “neutron poisons”, presenting high α ratios where reactions of capture prevail over fissions. This is illustrated in Figure 3.5, where the η factor¹⁵ – neutron yield per neutron absorbed – is reported as a function of the energy of the incident neutron.

High η factors realise the condition expressed in 3. This indicates that if these isotopes are loaded into a thermal core, in order to achieve a self-sustained fission chain,

15. η represents the number of fission neutrons generated per thermal neutron absorbed by the isotope: $\eta=v/(1+\alpha)$, with v being the average number of neutrons generated per fission by the given isotope.

additional fissile enrichment would, in principle, be required. In addition, MA behaviour as neutron poisons in thermal spectra also implies build-up of higher mass isotopes. In a fast neutron spectrum, as TRU isotopes are less likely to absorb neutrons in sterile captures, there will be less build-up of higher mass isotopes.

Figure 3.5: Neutron yield per neutron absorbed $\eta=v/(1+\alpha)$, for ^{235}U and selected plutonium and minor actinide isotopes



Source: Based on JEFF 3.1.

The presence of high quantities of higher mass TRU isotopes (especially the shorter-lived Am and Cm isotopes) is undesirable as it increases the decay heat of the spent fuel and the “transmuter” fuels in which the TRU is incorporated, posing challenges in their treatment and fabrication, respectively.

The drawbacks outlined in the previous analysis and based on physics arguments have been confirmed by detailed studies. Some of these, still ongoing, are aimed at identifying optimised strategies for TRU transmutation in thermal neutron spectrum reactors. However, most of the leading research, both theoretical and experimental, is focused on TRU transmutation in fast neutron spectrum reactors. A comprehensive analysis of the physics of transmutation can be found in Salvatores, 2009.

Fast reactor programmes

All research programmes related to advanced fuel cycles which encompass transmutation are geared towards fast-spectrum systems and primarily fast reactors, with some effort continuing in investigation of specific accelerator-driven systems.

More suited for multi-recycling of fissile and fertile materials (as discussed in Chapter 2) their future deployment offers also the prospect of closing the fuel cycle, which would greatly improve the efficiency in the use of uranium resources.

Motivated by this potential as well as their breeding ability and their higher thermal efficiency, efforts to develop fast-spectrum reactors have been undertaken since the early days of nuclear energy. Several fast-spectrum research reactors, mainly sodium cooled, were constructed in the 1950s and 1960s in the United States, the United Kingdom, the Soviet Union and France, with larger sodium-cooled fast reactors developed in the 1970s (e.g. BN-600 – 600 MWe in the Soviet Union and Superphénix – 1 200 MWe in France). However, the pursuit of FR designs slowed, partly due to the technical and materials

problems encountered in FR development, but especially as a consequence of uranium abundance, which averted immediate concerns on resource availability.

Today, ongoing international programmes such as INPRO and Generation IV have placed renewed emphasis on fast neutron reactors, while R&D also continues at the national level in some countries such as France, Japan, the Russian Federation, India and China and through multilateral agreements. In the Russian Federation, designs for large sodium reactors (1 200 and 1 800 MWe) are being developed, while the construction of BN-800, a 800 MWe FBR, is well advanced at Beloyarsk (completion is expected by 2014). Two reactors of the same design have been ordered by China, which, in collaboration with the Russian Federation, has recently constructed a small research sodium-cooled reactor (China experimental fast reactor – CEFR, 20 MWe).

Supported by the government, France is developing the advanced sodium technical reactor for industrial demonstration (ASTRID), a 250 to 600 MWe sodium fast reactor prototype. France is also pursuing a second line FR: ALLEGRO, a gas-cooled fast reactor in the framework of a European project.

India is currently building a 500 MWe PFBR at Kalpakkam. Fuelled with uranium-plutonium oxide and including a breeding thorium blanket, the PFBR is expected to reach operation by 2012.

In Japan, JAEA is working on the design of a demonstration reactor to succeed the prototype 280 MWe FBR Monju, which, after a long period of shut-down following a sodium leakage, restarted operations in May 2010.

In some cases (notably in the United States and the Russian Federation), interest in FRs has also been linked to the development of small and medium reactors.

Accelerator-driven systems

Accelerator-driven systems (ADS) are being researched in some countries essentially for minor actinide incineration. An ADS consists of a sub-critical core which is maintained in steady-state high power operation by means of a spallation neutron source driven by a proton beam from an accelerator. Spallation is the physical process by which, as a result of an impinging high energy particle, a heavy nucleus emits a number of nucleons. The accelerator, which may be a cyclotron or a linear accelerator, provides a strong current of protons at energies between 600 MeV and 1 GeV, which impinges on a heavy material spallation target. As a result, the target produces about 15-20 neutrons for every incident proton (depending on initial proton energy). Entering the subcritical core (often referred to as blanket), the neutrons produced by spallation trigger fission reactions and undergo multiplication, based on the effective multiplication factor of the core k_{eff} . The neutron multiplication factor is given by $1/(1-k_{\text{eff}})$; as k_{eff} usually ranges from 0.95 to 0.98, the external neutron source can be multiplied by a factor of 20 to 50. As the core is subcritical, with criticality being maintained by the accelerator, its operation stops as soon as the accelerator flux is interrupted. This alleviates some safety issues associated with criticality,¹⁶ and, in principle, such systems do not require shut-down mechanisms (e.g. control rods).

ADS generate energy through the fission of plutonium, thorium or uranium, although they are not aimed at the commercially competitive production of energy. Deemed particularly suited to transmutation, they would be adopted as dedicated burners for MAs. Part of the interest in them relates to the ability to produce neutrons with wide energy spectra, depending on the energy of the impinging protons from the accelerator. This gives access to fission cross-sections that are not accessible in thermal spectra and that

16. Other important safety aspects such as the requirement of post-irradiation cooling or negative reactivity feedback remain fundamental for ADS as for all critical systems.

allow the incineration of lighter isotopes (including long-lived fission products). Another advantage is that, compared to critical reactors, ADS' are less limited by reactivity feedback effects, allowing the core to be loaded with larger inventories of minor actinide fuels. After some time, nuclei that have undergone transmutation need to be removed from the core to avoid undesirable activation; long-lived fission products and actinides still present in targets can be returned to the blanket, while short-lived fission products, stable isotopes and fission poisons are separated and processed for storage (IAEA, 2009a).

In some countries ADS are envisaged to form part of a multi-tier fuel cycle, together with a mix of thermal and fast reactors. ADS would be used to burn minor actinides produced in the recycling of fuel from the thermal and fast reactors, thereby reducing the radiotoxicity and heat load of nuclear waste committed to the geological repository.

Investigations on ADS were essentially undertaken during the 1990s, with some R&D now continuing in countries such as in Belgium, the Russian Federation, the United States, as well as in China, India, Japan and the Republic of Korea. ADS designs are currently at the conceptual design stage; much work remains to be done to develop detailed engineering designs and demonstrate satisfactory performance, and their commercial deployment is not envisaged before 2050.

Examples of European research projects which are designed to demonstrate the performance of ADS at prototype scale are MYRRHA and VENUS-F. MYRRHA (Ait Abderrahim, 2008) is designed as a flexible fast-spectrum irradiation facility, capable of operating as a sub-critical (accelerator-driven) system and also as a critical reactor for material and fuel developments for Generation IV and fusion reactors. In March 2010, the Belgian government officially expressed their support for the MYRRHA project and committed to a contribution of approximately EUR 400 M to the project. The GUINEVERE project (Generator of Uninterrupted Intense NEutrons at the lead VEnus REactor) (Baeten, 2008) aims at providing a zero power experimental facility to investigate reactivity on-line monitoring and absolute measurement for ADS systems; these are major issues for ADS safety. VENUS-F reached first criticality in March 2011 and licensing for sub-critical operation is ongoing.

3.3.5. Waste management

Advanced fuel cycles are still at an early stage of development and many questions remain open, including the management strategies for wastes produced. For any given scenario involving advanced reprocessing (advanced PUREX, pyroprocessing, etc.) and P&T in FRs and/or ADS several waste streams are produced:

- HLW resulting from reprocessing plants and containing fission products, fuel impurities and their activation products and U, Pu and MA reprocessing losses.
- LILW-LL produced during the reprocessing operation.
- New waste streams resulting from spallation targets and ADS fuel matrices, when ADS are deployed.

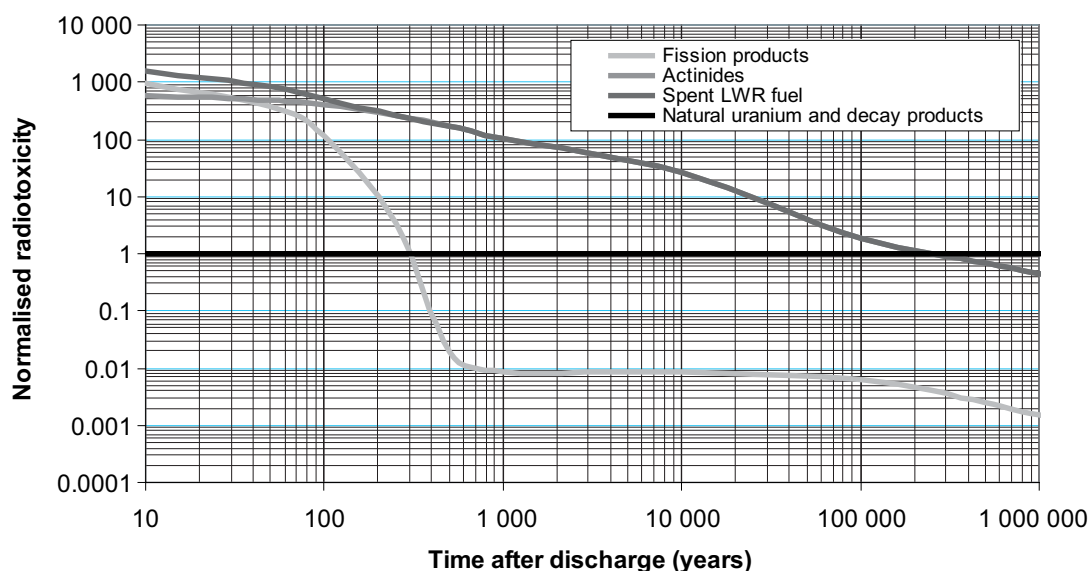
A significant source of LILW-LL could derive from the decommissioning processes of P&T facilities. If the total system includes upstream Generation III reactors, then the more familiar wastes from the reprocessing of their fuels must also be considered in the total picture.

While it is generally recognised that, by reducing the TRU waste mass, the introduction of P&T has the potential to positively affect public perception as to the ability to effectively manage radioactive waste (NEA, 2011a), further investigation is required for a better understanding and characterisation of the different arising waste streams. This has been the subject of a number of recent studies of different configurations of partitioning processes and reactors fleets. International assessments have been carried out by NEA (NEA, 2006a and 2010a), the European Union (RED-IMPACT,

2008 and PATEROS, 2008), JAEA (Nishihara, 2008 and Oigawa, 2008), ANL (Wigeland, 2006 and 2007) and IAEA (IAEA, 2010a).

An NEA Task Force on “the Potential Benefits and Impacts of Advanced Fuel Cycles with Partitioning and Transmutation”¹⁷ has compared the results of the different studies (NEA, 2011a). A consensus view of this task force is that, in any advanced fuel cycle scenario, a deep geological repository will still be needed to dispose of the remaining high-level waste and, most likely, some of the long-lived intermediate level waste. As schematically shown in Figure 3.6, actinides dominate the spent fuel radiotoxicity in the long term, which therefore could be substantially reduced through partitioning. Levels of radiotoxicity of HLW expected at $\sim 10^5$ years in a direct disposal configuration could be reached at less than 1 000 years when actinides are removed.

Figure 3.6: Radiotoxicity of 51 GWd/MtHM spent UOX fuel showing primary contributors as a function of time after discharge



However, industrial achievement of this reduction is currently seen as extremely challenging. It would require that all minor actinides were removed from the ultimate waste and recycled. Actual results are very sensitive to the real separation factors in the fuel reprocessing stage and total incineration of separated minor actinides cannot realistically be achieved in the transmutation stage. This results in a significant inventory of separated minor actinides in the fuel cycle or in-core. The radiotoxicity of the core (waste at the end of life of the system) for instance, would be dominated by separated actinides (and in particular plutonium) accumulated over the years (David, 2011).

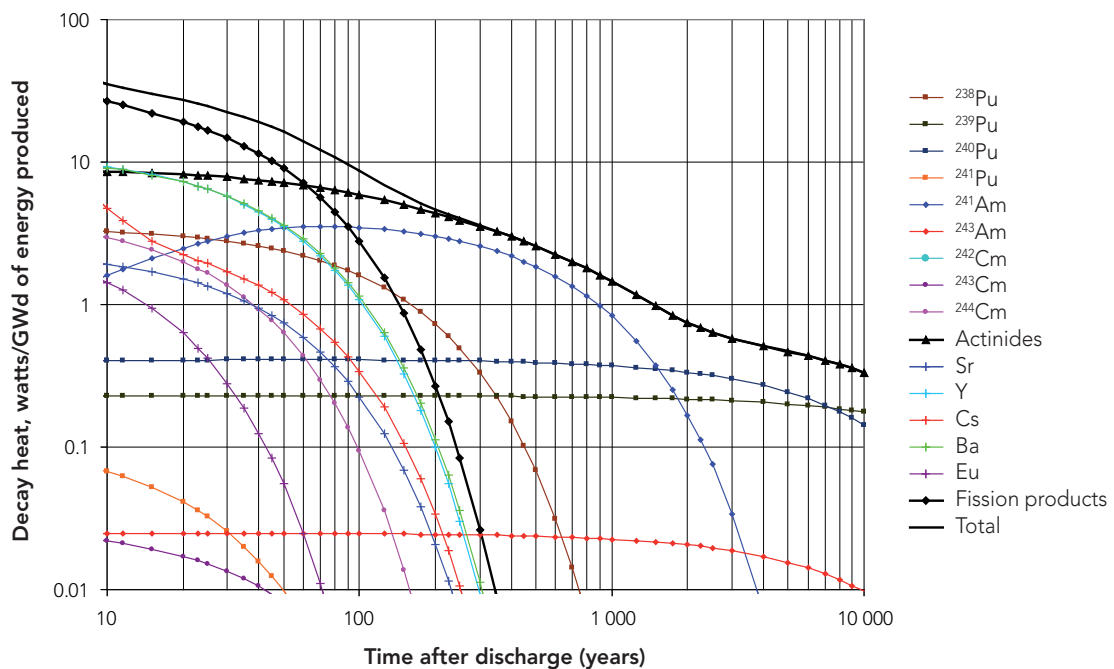
The final impact on the repository performance from radiotoxicity reduction in the HLW varies with the different repository environments and depends upon the approach and assumptions in the performance analysis (NEA, 2011a). It is generally expected that lower actinide inventories would lead to a significant reduction of the consequences of low probability accidents (i.e. increase of actinide mobility in certain geochemical situations; radiological impact of human intrusion) and might diminish the impact of uncertainties about repository performances. As P&T of actinides reduces the hazard (radiotoxicity) of the emplaced materials, it lessens the consequences of strongly

17. Established within the Working Party on Scientific Issues of the Fuel Cycle (WPFC) of the Nuclear Science Committee.

disruptive scenarios that can bring man in direct contact with the disposed waste (NEA, 2011a). No significant advantages would, however, derive from the adoption of P&T strategies in relation to doses to the biosphere from the normal evolution scenarios of geological repositories. This is due to the dominating influence of long-lived fission and activation products on total doses.¹⁸

A further benefit of P&T on the management of HLW is that heat generation is significantly less than in the spent fuel arising from a once-through fuel scheme. Figure 3.7 shows the contribution to decay heat from different radionuclides in spent LWR fuel as a function of time for a discharge burn-up of 51 GWd/MtHM (NEA, 2011a). The lower thermal output of HLW achievable with P&T is expected to result in a significant reduction of the total length of disposal galleries needed. For example, in the case of disposal in a clay formation the gallery length needed for HLW disposal could be reduced by a factor of 3.5 through a fully-closed cycle scheme as compared with the reference PWR once-through scheme and by a factor of 9 through a scheme including separation of caesium and strontium (NEA, 2006a).

Figure 3.7: Decay heat contributors in spent LWR fuel, 51 GWd/MtHM discharge burn-up



On the other hand, the radiation levels of HLW packages after standard cooling times (50 years) will still require heavy shielding when handling.

With respect to the management of fission products, R&D effort has been directed towards the possibilities and advantages of separating the main fission products, either those which are heat-generating (Sr and Cs) or those (I, Tc) which are long lived and highly mobile in geological environments. By separating heat-generating fission products,

18. In various repository geologies (e.g. with reducing water conditions) many actinide ions are generally found to be quite immobile. Mobile fission and activation products dominate the total dose rates in the reference scenario and the altered evolution scenarios assumed in the performance analysis of such repositories, while the dose contribution from actinides is a few orders of magnitude lower. Hence, in these cases, a large reduction of MA inventory would bear negligible reductions of the dose to the biosphere (NEA, 2011a).

thermal load could be greatly diminished, leading to significant reductions of the volumes of vitrified HLW (25-40%) (NEA, 2010a). This would further reduce (by a factor of 9, as indicated above) the requirements for repositories capacity and contribute to a more sustainable use of nuclear energy. While much progress has been achieved in this area over the past decade, the need for caesium and strontium separation appears to be uncertain. The cost of additional processing, as well as storage and disposal, is likely to be more than simply including these fission products in the high-level waste fraction and storing this for 50-100 years until that of the waste has cooled (assuming heat management is an issue in the geologic disposal system).

Removing long-lived fission products (I, Tc) and subsequently placing those in specially adapted waste matrixes could have a dramatic impact on the expected doses from the repository, but these are already low.

Achieving the potential optimisation objectives of closing the fuel cycle by means of P&T technologies requires decisive R&D actions to address the challenges and uncertainties, some of which are:

- The incorporation of heavy MA inventories in fuels (homogeneous transmutation) and particularly targets (heterogeneous transmutation) will involve the handling of materials with very high activity levels, requiring new handling techniques and enhanced radioprotection measures. The same is applicable for the HLW packages in most of advanced scenarios.
- LILW-LL volumes arising from advanced reprocessing as well as from ADS targets and decommissioning of P&T facilities are not yet well understood, but some early estimates show that they could largely exceed those resulting from the equivalent open cycle. Further investigation is needed, as impacts on geological repositories where this waste is disposed could be significant, offsetting the potential advantages of P&T. New materials will probably be needed, such as low activation steels with stronger specifications on impurity content.
- Potential transmutation of fission products, particularly those that are long lived, remains an open issue. A roadmap to explore potential ways of managing fission products would be desirable. The removal or destruction of some of these nuclides could have significant consequences on the design and performance of geological repositories (capacity, configuration, heat load, long-term behaviour, etc.).

The considerations above mostly concern implications of advanced fuel cycles and P&T schemes on the disposal of resulting wastes. An important factor that should also be considered is the very long transition time (several decades) required to reach a state of equilibrium for advanced schemes. Reducing waste inventories as much as possible will require new attention to interim storage facilities; longer storage times will also be needed if maximum inventory reduction or maximisation of repository capacities is the objective.

3.3.6. Thorium fuel cycle

The thorium fuel cycle presents an alternative to the uranium/plutonium fuel cycle that has long been advocated and researched but has not yet been adopted on a commercial scale.

Naturally occurring thorium consists entirely of ^{232}Th , which is a fertile nuclide. Through neutron capture and subsequent decay ^{232}Th is transformed into fissile ^{233}U , following a process similar to that of the uranium cycle: as illustrated in Figure 3.8, ^{232}Th can be considered as the analogue of ^{238}U and ^{233}U the analogue of ^{239}Pu . However, in the thorium cycle there is no analogue of ^{235}U and a fissile isotope needs to be added to thorium fuelled reactors to provide the original source of neutrons which trigger the process; this could be either ^{235}U or ^{239}Pu .

In its simplest form of implementation, with a once-through fuel cycle, the thorium fuel cycle can be adopted to enhance the useful energy produced per tonne of uranium. However, with the reprocessing of thorium fuel and the recycling of ^{233}U , it is theoretically possible to achieve a breeding cycle in a thermal reactor, which is difficult to achieve with the uranium/plutonium fuel cycle (except with high conversion thermal reactors).

Figure 3.8: Comparison of thorium and uranium cycles

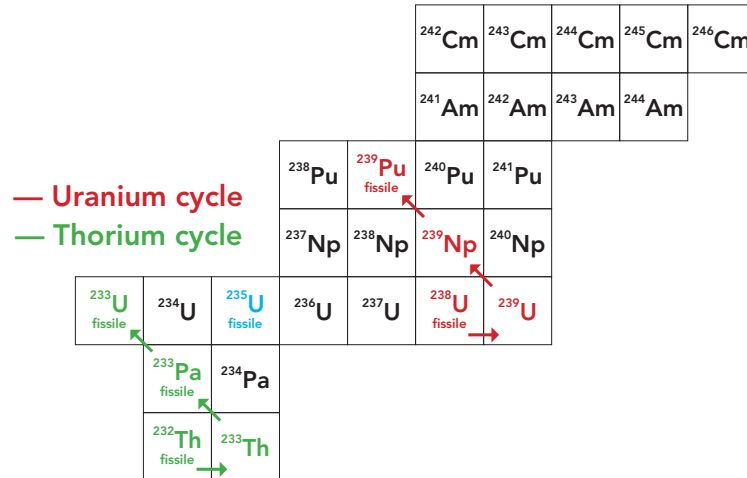
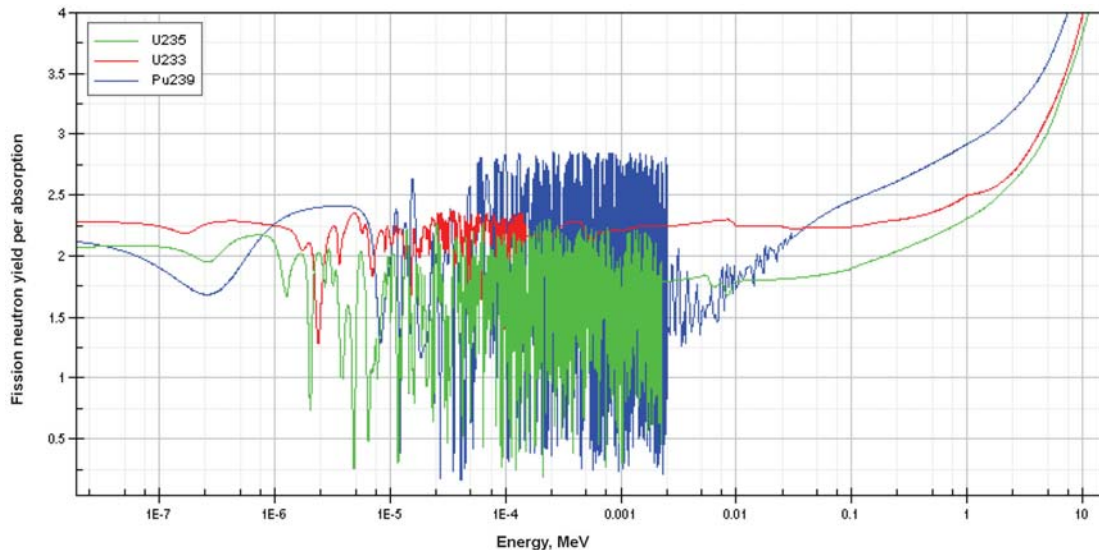


Figure 3.9: Fission neutron yield per absorption for ^{233}U , ^{235}U and ^{239}Pu



Source: Based on JEFF 31.

The superior thermal breeding capability of ^{233}U arises from the high value of its thermal η factor (η , already introduced in Section 3.3.4, is the number of fission neutrons generated per thermal neutron absorbed). For a breeding cycle, the minimum threshold value of η is 2.0 (one neutron removed to initiate the fission event and one neutron left over for fertile conversion). In practice, higher values are needed to allow for neutron losses due to absorption in non-fuel materials and leakages.

As shown in Figure 3.9, all common fissile isotopes exhibit a similar increase in the η factor at high energies. However, for ^{233}U , unlike ^{235}U and ^{239}Pu , η is sufficiently higher than 2.0 in the thermal neutron energy region (below 1 eV) to enable breeding also in thermal reactors. Thus, self-sustainable Th-U fuel cycles can operate at any neutron spectrum, while the U-Pu fuel cycle unavoidably requires a fast spectrum (MIT, 2011).

The thorium fuel cycle is claimed to be advantageous in generating very low quantities of transuranic materials, in particular plutonium. This enhances proliferation resistance and decreases the long-term radiotoxicity burden after fission products have decayed. However, reduction of transuranics calls for recycling highly ^{233}U enriched uranium which may cause risks of proliferation.

The greater chemical and irradiation stability of ThO_2 enhances fuel behaviour in the core and in the repository. The same characteristics, on the other hand, complicate fuel reprocessing, thus escalating the costs associated with ^{233}U recycling. This is equally affected by the high radiation dose rates of separated ^{233}U deriving from daughter nuclei of ^{232}Th and ^{233}U . Conversely, such higher radiotoxic inventory can be seen as a favourable proliferation resistance feature, as it provides self-protection against diversion and misuse of the separated fissile material.

There have been many studies on thorium fuel, performed internationally, including several demonstration programmes in the Shippingport prototype PWR (WNA, 2011a and DOE, 1987) and HTRs (WNA, 2011a). In Canada, AECL has long recognised the potential flexibility of CANDU reactors to utilise alternative fuels, including thorium (as well as plutonium/uranium MOX, REPU, LEU as discussed in Section 3.2.1). One approach to initiating the thorium fuel cycle in CANDU reactors is to add the fissile component as LEU in separate elements in a mixed LEU/Th fuel bundle (Boczar, 2002).

Recently there has been some renewed interest in Europe as well as in the United States in the use of thorium in LWRs. Various proposals are being considered to further this approach by performing irradiation tests of some U/Th and Pu/Th-fuel samples in material test reactors in order to investigate the irradiation behaviour of such fuels before undertaking more significant irradiation tests in power reactors.

Most of the recent work has been done, however, in India, a country which until very recently¹⁹ had limited known uranium resources but very large thorium resources. India's nuclear power programme has proceeded independently from other countries and has focused on energy self-sufficiency, based on the synergies between HWRs (including advanced HWRs – the AHWR) and FBRs with advanced fuel cycles using uranium, MOX and thorium (Banerjee, 2009). In India, commercial utilisation of thorium for large-scale energy production has been set as a major goal of the nuclear power programme and Th-assemblies have already been used in several PHWR to flatten the neutron flux in the initial core during start-up. Th-fuel has also been used as blanket in the fast reactor design.

The most expedient means of implementing thorium fuel cycles would be in existing LWRs or HWRs. A particular application for thorium fuels in countries concerned with excess plutonium may be as the matrix used to eliminate this plutonium.

This route would not demand the implementation of new reactors and would require changes only to the fuel cycle infrastructure (though this itself is not an insignificant challenge).

The successful large-scale reactor technology demonstration efforts conducted in the past suggest that there should not be insurmountable technical obstacles preventing the use of Th fuel and its fuel cycle in the existing and evolutionary LWRs. However, the

19. On 29 July 2011 it was reported that a large low-grade deposit of uranium was found in a southern state of India that could be among the larger in the world. Available at www.reuters.com.

industrial infrastructure, research, design and licensing data are not in place to warrant a rapid deployment of thorium fuels in current reactors in the short term. Reprocessing and refabricating of UTh-fuels call for significant research and development efforts, including the implementation of remote fuel fabrication capabilities and adequate radiation protection and non-proliferation measures.

The commercial viability of such use of thorium depends on the price of uranium as well as recycling and back-end costs. So far the technology has not offered sufficient incentives to easily penetrate the market, as it competes with the uranium/plutonium fuel cycle, already mature both technologically and commercially.

Options for the use of thorium-based fuels in closed fuel cycles in light or heavy water reactors alone or in symbiotic generating fleets with fast reactors are more appealing in terms of resource utilisation. The Generation IV International Forum considers molten salt reactors operating with a uranium-thorium fuel cycle as a potential long-term alternative to uranium-plutonium fuelled fast neutron reactors. A thorium-based fuel is also the reference fuel design in the pressure-tube based supercritical-water-cooled reactor, the development of which is led by Canada. However, advanced applications of thorium with full recycle of ^{233}U are only achievable in the long term, as they still require significant research efforts and technological developments, as well as feasibility and economic studies to prove their commercial viability.

3.3.7. Other technology developments impacting the fuel cycle

This section considers advanced technologies and prospective alternative uses of established technologies, whose adoption holds the potential to impact the fuel cycle and, notably, the use of resources: uranium and other supply.

Small and medium reactors

Nearly all nuclear units in operation or under construction make use of light or heavy water reactors. These established technologies and evolutionary designs based on them are expected to dominate nuclear capacity up to 2050. As discussed in Section 2.7.1, a few advanced Generation IV systems could be available for commercial deployment in the 2030s, and such systems could become more widely available on the market after 2040.

Most of the available designs currently being marketed by the leading reactor vendors are for large units, of 1 000 MWe or more. It is generally acknowledged that, in developed countries with mature electricity distribution grids compatible with large plant sizes, there are benefits from the economies of scale associated with such large capacity plants. However, for many developing nations with less mature electricity distribution grid systems, large capacity plants are not easily accommodated and small or medium capacity plants are more suited. Such reactors could be deployed as single or double units in remote areas without strong grid systems, or to provide small capacity increments on multi-unit sites in larger grids. They feature simplified designs and would be mainly factory fabricated, potentially offering lower costs for serial production. Their much lower capital cost (per unit as opposed to per MWe installed) and faster construction than large nuclear units should make financing easier. Small- or medium- sized plants require a significantly lower initial investment that is more likely to be affordable for developing countries.

Other advantages for widespread deployment could be in the area of proliferation resistance, as some designs would operate autonomously or semi-autonomously for very long periods (many concepts are able to rely on passive heat removal and passive safety systems) and would require no on-site refuelling, while others would only require refuelling after several years. In many cases, the reactor core is envisaged as a self-contained module that will be delivered with loaded fuel and which would operate without the need to access the core. When the core is depleted (after a period of 10 to 15

or more years), its module would be recovered by the supplier and be replaced with a new module.

Designs for small and medium reactors (SMRs), with generating capacities ranging from tens to a few hundred megawatts, continue to be developed, often through co-operation between government and industry. Slow progress over the past two decades has resulted in about a dozen new SMR concepts reaching advanced design stages. Several such designs are already being considered or even promoted by nuclear industry companies, including AREVA, Babcock & Wilcox, General Atomics, NuScale, Westinghouse and DCNS. Others are being developed by national research institutes in Argentina, China, Japan, the Republic of Korea and the Russian Federation.

Two small units designed to supply electricity and heat are under construction in the Russian Federation, based on existing ice-breaker propulsion reactors; these will be barge-mounted for deployment to a remote coastal settlement on the Kamchatka peninsula. Some other designs are well-advanced, with initial licensing activities underway. One of the furthest developed is the 4S design from Toshiba of Japan, a sodium-cooled “nuclear battery” system capable of operating for 30 years with no refuelling. It has been proposed to build the first such plant to provide 10 MWe to a remote settlement in Alaska, and initial licensing procedures have begun. Three other designs are undergoing a formal licensing process in Argentina, China and the Republic of Korea and several others are under pre-licensing negotiations in India and the United States. Demonstration plants could potentially be in operation before 2020, if funding becomes available. However, no firm commitments beyond those in the Russian Federation have been made to date.

Beyond the advantages of allowing the safe and proliferation resistant spread of nuclear power to less developed regions, SMRs are allowing designers to develop more advanced and innovative concepts. Many SMR plant designs are not fundamentally different from designs for large reactors; the majority of the near-term advanced SMRs are pressurised water reactors. However SMRs present, in general, a higher degree of innovation in their designs, as well as being tailored for the conditions and requirements specific to their intended target niche markets. Designs encompass a range of technologies, some being variants of the six Generation IV systems selected by GIF. Several SMR designs are HTRs. HTRs are suited to heat or co-generation applications, as discussed below. There are also several other concepts for advanced SMR designs, including liquid metal-cooled fast reactors, such as the HPM, a uranium nitride (UN)-fuelled, lead-bismuth (Pb-Bi)-cooled, fast reactor developed by Hyperion Power Generation, and the TerraPower Travelling Wave Reactor pool-type, liquid sodium-cooled reactor. These are generally at an earlier stage of development, with some being the subject of GIF collaborative R&D efforts.

With respect to fuels, the majority of the near-term LWR based designs are fuelled with traditional uranium oxide fuel, with less than 5% enrichment. The performance of medium-sized plants is likely to be very similar to those of the larger plants currently favoured so that parameters such as the uranium requirement per GWe and waste volumes per GWe are likely to be comparable. The average projected fuel burn-up is between 30 and 70 GWd/t, but typically around 40 GWd/t or slightly above. The spent fuel from these reactors can be reprocessed using the existing aqueous process.

Other designs, however, use cermet (ceramic-metal) fuel with higher enrichment (15-20%). Some designs could be used with advanced fuel cycles, burning recycled materials. Other concepts for advanced metal-cooled SMRs may also adopt different advanced fuels such as uranium nitride or metallic U-Zr fuel, as it is the case for the Toshiba 4S design. The utilisation of the MOX fuel is being considered for SMR reactors, with some designs operating in a closed nuclear fuel cycle, using U-TRU fuel loads. However, the adoption of advanced FCs is most likely to occur once the technology is well

established for the more standard designs. The main innovative feature of most SMRs is that they are designed to adopt long refuelling intervals (from 7 to 30 years).

In summary, if multiple modular units on a single site were to become a competitive alternative to building one or two large units, then SMRs could eventually form a significant component of nuclear capacity. They could also enable the use of nuclear energy in locations unsuitable for large units, and some designs could extend its use for non-electricity applications. However, whether SMR designs can be successfully commercialised, with an overall cost per unit of electricity produced that is competitive with larger nuclear plants and other generating options, remains to be seen.

It should be noted, however, that none of the smaller reactors has yet been licensed for operation (although a barge-mounted small reactor is under construction in the Russian Federation) and there remain both development challenges to overcome, regulatory approvals to obtain and legal issues to consider before deployment, especially in light of the recent accident at Fukushima Daiichi. Regulatory issues and delays regarding SMR licensing may occur due to their use of innovative features. With regard to economic competitiveness, a NEA study published recently (NEA, 2011) indicates that while SMRs do not appear to be competitive with state-of-the-art large NPP reactors,²⁰ they could however be of interest for private investors or utilities in specific market circumstances²¹ and be competitive with many non-nuclear technologies in those cases where large NPPs are, for whatever reason, unable to compete (NEA, 2011).

High conversion thermal reactors

High conversion thermal reactors are able to achieve enhanced fertile ²³⁹Pu production by modifying the thermal neutron spectrum so that the peak neutron density occurs at higher energies. This increases ²³⁸U resonance captures relative to thermal neutron absorption in the fuel, thereby enhancing the conversion ratio.

The reduced moderation water reactor (RMWR) is an example of a high conversion thermal reactor for which extensive studies have been carried out (Akie *et al.*, 2001) in Japan. The design objective was to overcome the limitations of partial recycle in LWRs by reducing the moderator/fuel ratio to increase the conversion ratio to 1.0 or greater. Plutonium fuelled RMWR core concepts were developed for both PWR and BWR cores with very narrow fuel rod spacing and hence reduced volume of water. The neutron spectrum is much less thermalised than in a normal LWR core. These studies demonstrated that in principle it is possible to achieve conversion ratios of 1.0 or more, which would allow a breeding cycle. Therefore, RMWR represents a possible alternative to fast breeder reactors.

RMWR requires very major changes to the design of the fuel assemblies. The packing density of fuel is increased by adopting a triangular lattice arrangement in place of the normal square lattice, with the rod to rod spacing reduced. In addition, it is necessary to radically change the radial and axial distributions of fissile material by adopting a very wide and flat (pancake) core configuration. This kind of configuration increases neutron leakage and ensures that the moderator void coefficient is negative. A heterogenous axial configuration is used with the various axial layers containing fissile driver and fertile blanket regions and in some cases, two fissile driver layers.

Such radical changes in core design would make RMWRs an option for the long-term future only. The experience from existing LWRs would only be of very limited relevance to RMWR, thus a very extensive development programme would be required in order to

20. Based on a levelised cost basis at 5% discount rate (NEA, 2011).

21. That is to say in liberalised energy markets for which small upfront capital investments, short on-site construction time, and flexibility in plant configuration matter more than the levelised unit electricity cost (NEA, 2011).

demonstrate satisfactory feasibility of the design, including reactor physics, thermal-hydraulics, mechanical design and fuel behaviour.

RMWR R&D has not yet been taken beyond the conceptual stage and there are no immediate plans to do so. Hence RMWRs may be an option only for the long-term future.

Non-electric uses of nuclear

Since nuclear power plants are generally operated continuously to produce base-load electricity, they will increasingly contribute to the transportation sector as a low-carbon source of mainly off-peak electricity for charging electric and plug-in hybrid vehicles, as the use of such vehicles grows over the coming decades. Nuclear energy also has considerable potential to penetrate non-electricity energy sectors in the 2050 time frame. Possible applications include industrial process heat (including for petro-chemical industries), district heating, seawater desalination, and electricity and heat for hydrogen production.

There are a few examples of heat from nuclear plants being used for such purposes,²² but the potential of nuclear energy in non-electricity energy markets has so far remained largely unrealised. If this is to change, nuclear energy systems will need to be adapted to the requirements of these markets. In particular, the commercialisation of HTRs could extend the heat applications of nuclear energy. Small prototype HTRs are in operation in China and Japan, and larger prototypes were built in Germany and the United States some years ago. The construction of a pair of demonstration HTRs in China was due to start in April 2011 but has been recently deferred; when operational these would provide heat plus 200 MWe of electricity. In the United States, the Next Generation Nuclear Plant (NGNP) project aims to demonstrate the feasibility of using HTR technology for hydrogen production and high-temperature process heat. Subject to funding, the NGNP could be in operation before 2025. Development of HTR technology is also being pursued in Japan, the Republic of Korea and Europe. However, plans to build a demonstration modular HTR in South Africa have been shelved due to lack of financial support.

Key trends:

- Renewed interest in unconventional resources (phosphates, coal ash, black shales, etc.), prompted by increased uranium prices (compared to the period 1983-2003).
- Continued R&D into advanced fuel designs:
 - Current reactors.
 - Advanced reactors (FR and P&T systems).
- PUREX expected to dominate reprocessing for next two decades or more:
 - Cold crucible technology introduced to improve vitrification.
- R&D progress on advanced separation techniques for MA and some FPs:
 - Wet chemistry and pyroprocessing.
 - Objectives:
 - co-extraction of uranium and plutonium;
 - manage MA and FP (transmutation and bespoke waste matrices).
- Continued R&D for recycling and transmutation towards FC closure:
 - FRs.
 - ADS systems.

22. For instance, the feasibility of integrated nuclear desalination plants has been proven with over 150 reactor-years of experience, mainly in India, Japan and Kazakhstan (NEA, 2008).

- Continued (albeit limited) interest in thorium use to use complement U/Pu-cycles (except in India where there is greater interest).
- Renewed interest in SMR designs:
 - Advantages for developing countries and remote locations (small size, proliferation resistance, lower initial investment).
 - Some reaching licensing and commercial maturity.
 - Commercial attractiveness yet to be established.
- Non-electric uses of nuclear energy – probable growth in coming decades:
 - Process heat.
 - Hydrogen production for transport.
 - Desalination.

Among the Generation IV designs selected by GIF for further development, the VHTR is specialised for high-temperature heat applications. This will be a development of HTR designs, adapted for even higher temperatures. Achieving these higher temperatures will require further R&D, especially of heat-resistant materials. Several other Generation IV designs are also capable of producing higher temperatures than existing reactors, extending the scope of their potential non-electricity applications.

Expanding nuclear power applications outside electricity production will increase the potential contribution that nuclear can make towards the reduction of GHG emissions. This is especially the case for the hydrogen economy, because transport is already one of the major sources of carbon emissions which is expected to continue substantial growth. Meeting demand for small-scale non-electricity applications, such as distributed hydrogen production or desalination in sparsely populated areas, could eventually be an important role for these small modular reactors.

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4. Progress towards sustainability: technology, policy and international trends

The previous chapter described the technical developments that have occurred, or are expected to occur in the nuclear fuel cycle, many of which have supported the move towards sustainability. In this chapter a qualitative assessment is made of these developments against the sustainability principles outlined in Chapter 1:

- environment;
- resource utilisation;
- waste management;
- infrastructure;
- proliferation resistance and physical protection;
- safety; and
- economics.

Specific trends related to sustainability progress are summarised in Section 4.1 below. Section 4.2 extends the thinking and examines trends in countries and global efforts for nuclear fuel cycle developments, with comments on policies summarised in Section 4.3.

4.1. Sustainability of trends in nuclear fuel cycles

4.1.1. Evolutionary trends of current fuel cycles and sustainability

Chapter 3 assessed technical progress in the nuclear fuel cycles over time. Evolutionary changes during the past ten years and up to 2020 were characterised in the areas of mining and milling, conversion, enrichment, fuel design and fabrication, reactor operations, spent fuel reprocessing and spent fuel and waste management. Later developments expected for the longer-term future were considered separately.

Table 4.1 analyses the evolutionary trends (during the past ten years and up to 2020) against the seven sustainability elements listed above. For each component of the fuel cycle the table identifies the main trends, in relation to the two time periods, indicating the direction of the trend and, where available, numerical changes in related parameters. The qualitative impact of trends is indicated against each of the sustainability elements with a check symbol when the effect is deemed positive, a cross when it is considered negative and a dash when the effect is neutral or very minor. In the case of infrastructural requirements, a tick merely indicates that new infrastructure will need to be developed. The table was compiled by the working group from discussion on trends derived in Chapters 2 and 3, based on their expert judgement and knowledge in relation to such developments.

In some cases the scoring reported may not be immediately obvious or it may involve negative as well as positive aspects at the same time. In these cases footnotes are

introduced to provide further explanation; and, for greater clarity, reference is made to the sections of the report where the specific trend is discussed (last column of the table).

It is noted that the ratings were largely developed in advance of the Fukushima Daiichi events of March 2011; however, the outcomes for the next decade are expected to be generally correct with the understanding that some details may be affected by post-Fukushima Daiichi reviews and assessments.

Table 4.1: Impact of evolutionary trends (during the past ten years and up to 2020) on sustainability elements

Fuel cycle step	Parameter	Period	Trend - data or trend direction	Environment	Resource utilisation-availability	Waste management	Infrastructure	PR&P	Safety	Economics	Section		
											Section	Page(s)	
FRONT END	Availability of uranium resources	2000-10	↕	-1	-2	-	-	-	-	x ³	2.6.1	44-48	
		2010-20	↕										
	Uranium prices	2000-10	↕	-	✓	-	-	-	-	-	x	2.6.1	44-45
		2010-20	↕										
	Use of ISL	2000-10	↕	✓	✓	✓	✓	-	✓	✓	✓	3.2.1	80-81
		2010-20	↕										
	Consolidation of best practices	2000-10	↕	✓	-	✓	✓	-	✓	✓	✓	3.2.	81-84
		2010-20	↕										
	New companies/ countries entering the sector	2000-10	↕	↕									
		2010-20	↕	↕	-4	✓	-4	✓	-4	-4	-4	3.2.1	82
	Conversion prices	2000-10	↕	↕	-	-	-	-	-	-	x	2.6.2	51
		2010-20	↕	↕									
Conversion	Replace and modernise existing capacity	2000-10	↕	✓	-	✓	✓	-	✓	✓	3.2.1	84-85	
		2010-20	↕										
	Need for new conversion capacity	2000-10	-				n/a						
		2010-20	↕				No or marginal impacts				3.2.1	85	

Table 4.1: Impact of evolutionary trends (during the past ten years and up to 2020) on sustainability elements (continued)

Fuel cycle step	Parameter	Period	Trend - data or trend direction	Environment	Resource utilisation-availability	Waste management	Infrastructure	PR&PP	Safety	Economics	Section		
											Section	Page(s)	
Enrichment	Use of centrifuge enrichment (displacing diffusion)	2000-10	↕	✓	-	✓	✓	x ⁵	✓	✓	3.2.1	85-86	
		2010-20	↕								3.2.1	87	
	Levels of tails enrichment	2000-10	↕	3% → .25%	✓	✓	-	-	-	✓	3.2.1	87	
		2010-20	↕	.15%	✓	-	-	-	-	✓	3.2.1	87	
FRONT END	Enrichment capacity	2000-10	-				n/a				2.6.3	52-55	
		2010-20	↕								2.6.3	52-55	
	Optimisation of fuel assembly designs	2000-10	↕		-	-	-	-	-	✓	3.2.1	88-89	
		2010-20	↕		-	-	-	-	-	✓	3.2.1	88-89	
	Burn-up	2000-10	↕	50 GWd/t	-	-	-	-	-	✓	3.2.1	89-90	
		2010-20	↕	75 GWd/t	-	-	-	-	-	✓	3.2.1	89-90	
	Initial enrichments	2000-10	↕	→ 5.0%	-	-	-	-	-	✓	3.2.1	90-91	
		2010-20	↕	→ 6.5%	-	-	-	-	-	✓	3.2.1	90-91	
	MOX fuel utilisation	2000-10	↕		-	✓	✓	✓	✓	✓	✓	3.2.1	91-94
		2010-20	↕		-	✓	✓	✓	✓	✓	✓	3.2.1	91-94

Table 4.1: Impact of evolutionary trends (during the past ten years and up to 2020) on sustainability elements (continued)

Fuel cycle step	Parameter	Period	Trend - data or trend direction	Environment	Resource utilisation-availability	Waste management	Infrastructure	PR&PP	Safety	Economics	Section		
											Section	Page(s)	
FRONT END	Recycling of REPU (and, in HWR, depleted uranium)	2000-10	-	-	-	-	-	-	-	-	3.2.1	91-94	
		2010-20	↑	-	✓	✓	-	-	-	✓	3.2.1	91-94	
	Further improvements in fuel behaviour	2000-10	↑	-	-	-	-	-	-	✓	3.2.1	87-88	
		2010-20	↑	Up to 18 months	-	-	-	-	-	-	✓	3.2.1	87-88
MIDDLE	Fuel cycle duration	2000-10	↑	-	-	-	-	-	-	✓	3.2.2	95	
		2010-20	↑	Up to 24 months	-	-	-	-	-	-	✓	3.2.2	95
	Increasing output through higher load factors and upratings	2000-10	↑	↑	✓	-	-	-	-	-	✓	3.2.2	95-96
		2010-20	↑	↑	-	-	-	-	-	-	✓	3.2.2	95-96
	Load following (Belgium, France, Germany and Hungary)	2000-10	↑	↑	-	-	-	-	-	-	-	3.2.2	96-97
		2010-20	↑	↑	-	-	-	-	-	-	-	3.2.2	96-97
	Lifetime extension	2000-10	↑	↑	-	-	-	-	-	-	-	3.2.2	97
		2010-20	↑	>60y	-	-	-	✓	-	-	✓	3.2.2	97

Table 4.1: Impact of evolutionary trends (during the past ten years and up to 2020) on sustainability elements (continued)

Fuel cycle step	Parameter	Period	Trend - data or trend direction	Environment	Resource utilisation-availability	Waste management	Infrastructure	PR&PP	Safety	Economics	Section	
											Section	Page(s)
Reprocessing	Reprocessing capacities	2000-10	-	-	-	-	-	-	-	-	2.8.1	65
		2010-20	↑	-	✓	✓	✗ ¹²	-	-	-		
Spent fuel and waste management	Dry storage capacity and centralised facilities (for interim storage of spent fuel and HLW)	2000-10	↑	-	-	✓	✓	✓ ¹³	✓ ¹⁴	✓	3.2.3	101-102
		2010-20	↑	-	✓	✓	✓	✓	✓	✓ ¹⁶	3.2.3	102-104
BACK END	Progress with deep geological repositories for the disposal of SNF and HLW ⁵	2000-10	↑	✓	-	✓	✓	✓	✓	✓	3.2.3	103-104
		2010-20	↑	-	-	-	-	-	-	-		
Spent fuel and waste management	Reversibility/retrievability ⁷	2000-10	-	-	-	-	-	-	-	-	3.2.3	103-104
		2010-20	↑	-	-	✓ ¹⁸	-	-	-	-		
LILW disposal	LILW disposal	2000-10	↑	✓	-	✓	✓	-	✓	✓	3.2.3	104-105
		2010-20	↑	✓	-	✓	✓	-	✓	✓		
Implementation of new waste categorisation for LLW and LILW	Implementation of new waste categorisation for LLW and LILW	2000-10	↑	✓	-	✓	✓ ¹⁹	-	✓	✓	3.2.3	105
		2010-20	↑	✓	-	✓	✓	-	✓	✓		

1. Greater utilisation of resources will probably mean greater generation of tailings, except for higher grade uranium and/or ISL.
2. The discovery of new uranium resources will likely lead to their expanded exploitation, however mining companies may face challenges in developing new mining projects in a timely manner to respond to increased demand.
3. Lower cost resources have been significantly reduced as mining costs increase and re-evaluations have increasingly resulted in identified resources being moved towards higher cost categories.
4. The adoption of best practices by new entrants is fundamental to avoid detrimental effects on these sustainability parameters. The gradual move towards countries that are either new in mining and/or have increased geopolitical risks may have a negative impact on the predictability of uranium prices.
5. Concerns regarding the ease of producing HEU with centrifuge enrichment.
6. Waste volumes at enrichment facilities are expected to decrease. However, tails would contain depleted uranium with lower content of ^{235}U , less amenable to re-enrichment.
7. See also comments on increased use of centrifuge enrichment.
8. Higher burn-up can cause both positive and negative effects on resource utilisation and waste management – these are difficult to quantify and, in any case, are considered rather marginal. Hence it was deemed appropriate to consider an overall neutral impact for the two sustainability elements.
9. Higher burn-ups could mean starting with higher boron content, hence less negative moderator temperature coefficient – but this is manageable.
10. Extended use of MOX favours the consumption of existing Pu stocks alleviating related waste management and proliferation issues at the possible expense of reducing Pu for the start-up of fast reactors.
11. Marginal impacts on a global basis – few countries are introducing this practice which is to deal primarily with the increased use of renewables.
12. Initial moves to introduce a process that separate U and Pu as a mixture have not been commercialised. In Japan separated Pu solution is mixed with reprocessed U solution and is obtained as MOX product, within the processes of Tokai reprocessing plant and Rokkasho reprocessing plant.
13. Through the adoption of centralised facilities, transport of spent fuel is reduced.
14. Dry storage is completely passive (no use of active components) and packaging of fuel is less tight than for wet storage.
15. It should be noted that no disposal facilities are operational (or will become operational in the next decade). Research and studies have been and (will be) oriented towards the improvement of sustainability elements as identified in the table. These benefits will realise only when repositories are opened.
16. Diminishes uncertainties in the overall economy of the cycle. Helps making more accurate financial provisions for waste disposal therefore releasing financial resources in corporations and funds.
17. The application of reversibility/retrievability criteria is considered to play a role in improving public acceptance.
18. If spent fuel is retrieved for future re-use this could result in a better use of resources.
19. This optimises the use of facilities through the release of capacity of existing valuable waste management facilities with stricter requirements, which are needed for higher level waste.

Overall, incremental changes or improvements towards sustainability were observed during the last ten years, and are expected in the foreseeable future. Selected key trends are summarised below by technology area to highlight progress and ongoing challenges.

Fuel cycle front-end processes

- There has been a steady increase in uranium demand that is expected to continue into the future. Secondary sources of uranium from historic stocks and HEU are diminishing. However, primary supplies have increased and overall uranium resources have continued to expand as a result of exploration motivated by the rise of uranium prices. The investment required to mine deposits is also increasing with a particular focus on extraction from lower grade ores using ISL. While positive impacts on safety and the environment (e.g. no tailing and lower radiation doses to workers) are associated with this method, ISL is not suitable everywhere and its application in inappropriate circumstances could impact water quality. Overall, for uranium supplies, there is a slightly positive trend to improved environmental sustainability.
- Uranium ore prices are expected to continue to rise during the next decade if the demand grows as several studies (NEA, 2008; IEA, 2009 and 2010; IAEA, 2008) have

projected. Price volatility may also increase. To meet projected market requirements beyond 2030, all existing and committed production centres, as well as a significant proportion of the planned and prospective production centres, must be completed on schedule and production must be maintained at or near full capacity throughout the life of each facility. This could negatively affect economics.

- Prices for conversion services have slowly increased during the last ten years and are expected to slowly increase over the next decade. This has some positive and some negative impacts but overall is not greatly significant.
- In the enrichment market, centrifuge capacities have been increasing steadily in response to increased demand (and are displacing the diffusion process). Laser enrichment is reported to be approaching industrialisation but is not expected to play a significant role in the foreseeable future. This trend is generally positive for sustainability although some concerns are raised over the potential for production of HEU with centrifuge and especially laser technologies.
- With respect to fuel design and fuel fabrication technology, continued evolutionary design improvements were made and are expected in the future with increased design complexity and standardisation, which have had positive impacts on the economics.
- Within the fuel fabrication market, the overall objective remains to deliver tailored high-quality products addressing the objectives of safety, reliability and performance with ongoing continuous improvements of pellet designs (e.g. doped pellets), enhanced fuel debris resistance, improved fuel assembly structure (for instance, new spacer designs) and advancements in material. All such improvements are geared towards providing utilities with “zero-failure” fuels.

Reactor operations

- In reactor operations and in-core fuel management, a continued increase in mean discharge burn-ups and associated increase in mean initial enrichments have occurred over the last decade and are expected to continue well into the future with upper limits approaching 75 GWd/t.
- The utilisation of MOX fuels in LWRs has not developed extensively and MOX utilisation has consolidated at a level only slightly higher than a decade ago. MOX use is expected to stabilise during this decade in Western countries. Further increases may however occur thereafter if more countries choose the recycling options and/or the use of MOX to burn Pu from former military applications. The market for REPU has not developed significantly during the last decade. Increased uranium prices may however lead to its greater use during the next decade, as initial trends seem to indicate.

Spent fuel and waste management

- Reprocessing capacity has not changed significantly since 2000. The commercial process has remained the same during the decade with improvements mostly oriented to improving efficiency and reducing the level of discharges to the environment. Several countries have deferred their decisions; availability of uranium has certainly contributed to the tendency of not actively pursuing closure of the fuel cycle.
- In the area of interim storage of spent fuel and high-level waste, there has been a steady trend to use commercially available dry storage systems, and also a steady trend to implement centralised storage facilities for HLW and spent fuel. This is partly due to economic considerations and partly to political decisions, the latter related to delays in implementing ultimate disposal. The trend to higher fuel burn-up will result in increased challenges associated with increased transuranic fission

and activation product inventories along with increased decay heat and neutron sources. The higher burn-up is beneficial with respect to lower fuel demand and lower volumes of spent fuel.

- With respect to disposal of spent fuel and high-level waste, there has been positive progress towards deep geological repositories with a trend towards greater stakeholder engagement and moves to partnerships with potential host communities, which have enhanced public acceptance. However, as yet, no country has succeeded in opening a repository over the last decade. The legal and institutional framework for spent fuel and radioactive waste management has been further strengthened. Increasing weight has been attached to reversible/retrievable repositories.
- Efforts in LILW management have mostly focused on volume reduction during the last decade with facilities in many countries operational. A second area of development has been the implementation of a new waste categorisation which has favoured recycling of some forms of waste and the release of capacity of waste management facilities.

Discussion of impacts on sustainability elements

Selected comments on progress towards sustainability from evolutionary trends are summarised below by sustainability area to highlight progress (qualitatively) and ongoing challenges. This can be derived by reading Table 4.1 by column for each sustainability element.

- **Environment:** Overall the trends identified are either neutral or slightly beneficial with respect to environmental impact over the last decade or up to 2020. Of particular relevance to this sustainability element is progress in areas of mining (*in situ* leaching and much improved mining practices), enrichment (centrifuge displacing diffusion), reactor operations (higher load factors and upratings) and disposal of spent fuel and HLW (progress with deep geological repositories and stakeholder engagement).
- **Resource utilisation (including availability of resources and security of supply):** Overall the trends identified are either neutral or towards improvements in resource utilisation (in particular for the next decade). Longer fuel cycles lead to slightly less efficient resource utilisation. Increased plant capacity has added to uranium ore, conversion and SWU demand. With the depletion of secondary uranium resources, demand on primary supplies has increased and higher uranium ore prices have stimulated new prospecting and commissioning of new mines, while *in situ* leaching has opened up new resources. A prospective increase in MOX and REPU fuel use would have a significant beneficial impact on resource utilisation and resource availability.
- **Waste management:** The overall trend has been positive, with small incremental benefits having been achieved in most areas of the fuel cycle. In particular, in the front end, the consolidation of best practices and, increasingly, the introduction of less polluting technologies, such as ISL and centrifuge enrichment, have benefitted the environment. In the back end, efforts in the reduction of discharges to the environment from reprocessing facilities have been significant. The trend to higher burn-up has an ambiguous impact, with reduction in spent fuel mass offset by challenges associated with increased fission product, transuranic and activation product inventories along with higher decay heat and neutron sources. The recycling of some forms of LILW has also benefitted the environment. However, clearly the implementation of deep geological disposal remains a key challenge for the industry and for governments, with many opinion polls

suggesting that it still represents a fundamental objection to the expanded use of nuclear energy.

- **Infrastructure:** Over the last decade, new infrastructure has been required in a number of areas to meet changing demands in the fuel cycle (*in situ* leaching, centrifuges, fuel design for higher enrichment, dry storage). Strong pressure will derive from the expected trends to partial recycle in LWRs and HWRs and further longer-term developments.
- **Proliferation resistance and physical protection (PR&PP):** Overall the trends identified over the last decade or up to 2020 are either neutral or slightly beneficial with respect to PR&PP. The only remarkable impact has been from the consolidation of MOX fuel utilisation which has enabled the consumption of existing Pu stocks while significantly degrading the isotopic composition of the remaining plutonium in the spent (mixed oxide) fuel, thus reducing its potential attractiveness for non-peaceful uses. In addition, the tendency to adopt centralised facilities for interim storage is favourable to PR&PP. Many of the trends identified will have implications for future infrastructural requirements with the opportunity to consider PR&PP design improvements. Further increase of MOX use and the implementation of other advanced fuel cycles are likely to significantly enhance proliferation resistance in the future. Any wider spread of reprocessing or enrichment technologies carries with it proliferation challenges, which are however continuously addressed through international effort.
- **Safety:** For the last decade, most of the trends identified have little impact on the safety of the fuel cycle, some of the main exceptions being:
 - Beneficial impact from the further spread and consolidation of best practices in mining and milling.
 - Positive effect from the move to centrifuge enrichment (centrifuge cascades can be considered slightly safer than diffusion cascades because the UF₆ inventory is orders of magnitude lower).
 - Benefits from improved fuel behaviour.
 - Slightly negative effect from higher initial enrichments, because of the unfavourable impact on criticality safety.
 - In terms of operation of facilities, doses to workers have significantly decreased and off-site emissions have reduced.
 - Effects of some trends on the back end (e.g. higher activities from increased burn-ups) also have slightly negative implications for safety.

Improvements are expected from the introduction of Generation III reactors, which have much lower core damage frequencies than Generation II and utilise improved safety features and in some cases more passive systems.

- **Economics:** For the last decade the overall trend has been positive, with beneficial effects deriving from a larger deployment of certain technologies (e.g. ISL and centrifuge enrichment in the front end). In operation of reactors, improvements have been driven by the utilities aiming for incremental gains and leading to increased capacity factors. Higher uranium and conversion prices have been detrimental, but the effect on overall economic competitiveness of nuclear is slight because they represent only a small proportional of the overall generating cost. Generation III/III+ reactors are designed to improve uranium utilisation and reduce spent fuel providing economic benefits to utilities. However, new build has seen a significant increase of costs and the industry is facing the major challenge to reduce construction times and to build within budgets.

4.1.2. Trends for longer-term options

Based on the trends seen and foreseen, the major changes expected over the longer term will be driven from the work of the Generation IV International Forum on reactor technologies, which require closure or partial closure of the fuel cycle through reprocessing and use of fast reactors for recycle and breeding of reactor fuel. The renewed interest in small- and medium- sized reactors and high conversion thermal reactors as a complement to fast reactors is also expected to lead to more focus on fuel and fuel cycle R&D.

Linked to the fuel cycle work with Generation IV is the research on the use of partitioning and transmutation for the reduction of high-level waste. Although this has not advanced significantly in the last ten years, it is expected to reach an implementation stage, driven mainly by the need to have solutions for the increasing volumes of spent fuel.

Further progress or deployment will require policy choices, which today are not defined or internationally consistent. These include such issues as the degree of partitioning, recycling modes and timetable for introduction of Generation IV systems.

Impact on sustainability

In terms of the sustainability criteria introduced in this report, advanced fuel cycles featuring P&T and Generation IV systems will result in more pronounced progress towards sustainability. The two major benefits to sustainability obtained through the introduction of advanced fuel cycles would be a significant reduction of waste volumes and radiotoxicity and a more efficient use of existing resources. This would have a positive impact on a number of the sustainability elements considered, including reduced environmental impacts and enhanced safety, resource availability and waste management.

- **Environment**

Reductions in accidents frequencies, radioactive emissions and waste arisings will be positive for the environment. The goals of Generation IV systems and of waste reductions are directed towards enhanced environmental performance (although such systems have not yet been commercially demonstrated).

- **Resource utilisation**

Generation IV systems were described in previous chapters and are fundamental to a sustainable nuclear industry by ensuring long-term availability of fuel, options for non-electric uses of nuclear energy, potentially more efficient and economic systems and enhancements in safety through design.

- **Waste management**

In terms of the impact of recycling and P&T, a recent study carried out by IAEA in the framework of the INPRO project (IAEA, 2010) provided a comparative assessment of parameters linked to the sustainability aspects mentioned above. Five different scenarios were considered, including the reference case of current open fuel cycles, some evolutionary options with REPU and MOX recycling and more advanced cases including P&T and the fully closed cycle. All options, assumed for deployment in the 21st century, are characterised by the same power capacity (60 GW) and electricity production (roughly 400 TWh/year). Using the INPRO methodology IAEA experts defined system features on the basis of the experience and estimates of six countries with strong programmes on fast reactor development (China, France, India, Japan, the Republic of Korea, and the

Russian Federation). The five cases considered correspond to “steady state” scenarios with the following characteristics (also summarised in Table 4.2):

1. PWR fleet with UOX fuel utilising an open fuel cycle (spent nuclear fuel sent to repository) – reference case.
2. PWR fleet, with spent UOX fuel reprocessing, vitrification of FPs and MAs, and Pu “mono”-recycling (spent MOX fuel sent to interim storage).
3. PWR fleet, with reprocessing of all spent UOX and MOX fuel, Pu recycling in MOX assemblies, and vitrification of FPs and MAs. At equilibrium, the fleet is composed of 74% of PWR loaded with UOX, and 26% loaded with MOX.
4. A mixed fleet with 45% of PWR, 55% of FRs recycling Pu and incinerating 90% of americium (Am) in transmutation targets. Neptunium (Np) and curium (Cm) are vitrified with FPs.
5. FR fleet recycling all MAs together with plutonium (fully closed cycle). Only FPs are vitrified.

Table 4.2 provides some selected results of the study in terms of the amount of spent fuel and resource consumption for each of the scenarios.

Table 4.2: Amount of spent nuclear fuel and uranium consumption in the FC strategies involving different degrees of recycling

	Pu + Am + Cm sent to waste (mass)*	SNF + HLW to final disposal (volume)*	Time for radiotoxicity to achieve equivalent of natural U ore (years)	Uranium consumption (mass/unit electricity production)*
1	100	100	300 000	100
2	67	31	n.a.	89
3	24	15	50 000	85
4	3	13	30 000	45
5	0.5	12	400	7

* Base = 100 for case 1: once through cycle.

Source: IAEA, 2010, summary of Section 4.5 with permission.

As the mass of Pu and MAs recycled increases, the waste volumes to be sent to the repository decrease dramatically (scenario 5 shows a ten-fold reduction in comparison to the reference case). This reduction is particularly noticeable in a fully closed cycle where Pu and MAs left in the waste are only small amounts attributable to reprocessing losses (scenario 5). Similarly, as more actinides are incinerated the radiological burden of waste packages (measured in terms of their radiotoxicity) decreases, reaching a minimum value for scenario 5, where only FPs are sent to waste. This has a direct impact on the time to achieve desired levels of radiotoxicity. Taking as reference the time to achieve a level of radiotoxicity equivalent to that of natural uranium ore, Table 4.2 shows how scenarios with full recycling could potentially shorten this period by three orders of magnitude, from a few hundred thousand years in the open fuel cycle to only a few centuries. Finally, by burning TRU isotopes (Pu and MAs), a much enhanced use of energy potential is obtained, leading to a lower consumption of uranium resources, with the greatest reduction of uranium requirements (~95%) theoretically achievable in scenario 5.

- Infrastructure

As noted before, introduction of Generation IV systems and new systems for actinide burning, whether through reactors or accelerator-driven technologies, will require significant investment in technologies, many of them new to the industry. International co-operation will maintain a key role in such development.

- Safety and proliferation resistance

Safety remains the overarching priority for all nuclear systems and technologies. Although for some of the advanced systems new approaches to reactor safety and to safety regulations are required, which are different from those adopted for the dominant LWR technology, the same safety standards must be maintained or exceeded. Excellence in safety and reliability is one of the objectives of Generation IV systems. Simplified designs are sought that are safe and that can further reduce the potential and consequences of severe accidents (including the likelihood and degree of reactor core damage), as well as the need for offsite emergency response. New technologies for advanced fuels are being explored that would result in major increases in safety margins and improved repository performance.

In terms of safeguards and proliferation resistance, making advanced systems and materials unattractive and difficult for diversion and use for weapons or acts of terrorism is the aim of several international programmes on advanced FCs, including GIF. For example, the more advanced reprocessing technologies under development in association with Generation IV avoid the separation of plutonium, thus easing proliferation concerns.

Moreover, international approaches and concepts are being developed, such as fuel banks, which can assure nuclear fuel supply and services, while limiting the spread of sensitive technologies like enrichment and reprocessing.

In summary, the closure or partial closure of the fuel cycle has large implications for infrastructure and requires political agreements because of its association with non-proliferation objectives and sensitive technologies, but its contribution to resource availability and waste would be a major enhancement in sustainability criteria related to the environment, safety and waste management. Implications for economics have yet to be demonstrated.

4.2. Trends in countries and global efforts for nuclear fuel cycle developments

Many of the world's nations believe that a greater use of nuclear energy will be required to achieve sustainable low emissions energy production and energy use while economically meeting the requirements of security of supply (energy independence) and growing demand. But the commitment to nuclear is not universal and challenges in establishing and maintaining a nuclear programme have resulted in different approaches in different countries:

- Countries actively and aggressively pursuing nuclear programmes – e.g. China, India, the Russian Federation.
- Countries with a mature nuclear programme and strong policy support – e.g. Finland, France, Japan, the Republic of Korea.
- Countries with a mature, stable but slowly evolving nuclear programme – e.g. Canada, the United States.
- Countries where policies have not favoured, or have had a negative impact in the development of nuclear programmes, or where there is not a clear policy – e.g. Belgium, Germany, Italy.

4.2.1. Countries with rapidly expanding nuclear programmes

China, India and the Russian Federation are implementing expansive programmes for nuclear power and are developing the fuel cycle in response. China and India are countries in great need of energy resources. Associated with the rapid growth comes the need for clear policies on all aspects of the fuel cycle.

As an example, China, as the largest developing country in the world, has made its strategic development goal for the coming 15 years to maintain a sustainable economic growth and improve its standard of living. By 2020, China's GDP is expected to be double that of 2000 and the demand for energy output will double that of 2000 accordingly. Estimates show that the annual consumption of primary energy in China will reach 3 billion tons of standard coal by 2020, with an installed power capacity of 900 GW. Most of mainland China's electricity is produced from fossil fuels (80% from coal, 2% from oil, 1% from gas in 2006) and hydropower (15%).

A series of policies and measures has been promulgated, including promoting hydropower development, speeding up nuclear power development, encouraging the development of new energy sources and laying equal stress on construction and efficiency. Nuclear power, as an important part of China's energy strategy, has been included into the national overall planning of power development. These policies provided favourable conditions for a thriving nuclear power development in China.

When China started to develop nuclear power, a closed fuel cycle strategy was also formulated and declared at an International Atomic Energy Agency conference in 1987. Now China is rapidly becoming self-sufficient in reactor design and construction, as well as in other aspects of the nuclear fuel cycle.

The following points have been set as key elements of China's nuclear energy policy:

- PWR will be the mainstream but not sole reactor type.
- Nuclear fuel assemblies are fabricated and supplied domestically.
- Domestic manufacturing of plant and equipment will be maximised, with self-reliance in design and project management.
- International co-operation is encouraged.

Key segments of the nuclear fuel cycle have progressed accordingly and as required by nuclear power construction.

Examples of the implementation of the policy intentions are detailed below:

- Identified uranium resources in China total almost 68 000 tU. This is not enough to cover increased demand due to planned expansion of nuclear generating capacities. China has therefore been investing in uranium resources in other countries to assure meeting their uranium demand.
- In terms of fuel, China manufactures both PWR and PHWR fuel, but currently imports fuel services as well, for example VVER fuel from Russian TVEL and enrichment services from Europe. First fuel for new PWRs (AP1000, EPR and VVER) will also be supplied by the vendors, but China intends to be self-sufficient in fuel services.
- The Chinese nuclear industries are now able to independently design and construct 300 MW and 600 MW PWR units, while 1 000 MW PWR units are being built in co-operation with international partners. While introducing advanced proven nuclear power technology from other countries China is actively promoting self-reliance of design and localisation of equipment manufacturing.

- CNNC has drafted a state regulation on civil spent fuel treatment as the basis for a long-term government programme. Spent fuel activities in China involve: at-reactor storage, away-from-reactor storage and reprocessing. A centralised used fuel storage facility has been built at Lanzhou Nuclear Fuel Complex, with an initial capacity of 550 tonnes, which could be doubled.
- China is taking responsible actions on the back end of fuel cycle (i.e. reprocessing, recycling and fast reactor development) within their expanding nuclear power programme:
 - Industrial-scale disposal of low- and intermediate-level wastes has been established at two sites: near Yumen in northwest Gansu province and at the Beilong repository in Guangdong province.
 - Separated high-level wastes will be vitrified, encapsulated and put into a geological repository some 500 metres deep. The site selection, which has been underway since 1986, focusing on three candidate locations, will be completed by 2020. An underground research laboratory will be built in 2015-20 and operate for 20 years. Disposal of high-level wastes into a national repository is anticipated from 2050.
- A pilot (50 t/yr) reprocessing plant using the PUREX process was opened in 2006 at Lanzhou Nuclear Fuel Complex. This is capable of expansion to 100 t/yr. The plant was commissioned in 2009 with hot tests successfully completed in December 2010. A large (800-1 000 t/yr) commercial reprocessing plant based on indigenous advanced technology is planned to follow and begin operation around 2020.
- Basic and applied studies on nuclear energy are increasing.
- In terms of advanced fuel cycles, China has a number of initiatives underway:
 - In 2010, 24 fuel bundles made from recycled (reprocessed) uranium have been loaded into one of their CANDU reactors in a demonstration campaign. This was the first time recycled uranium from light water reactors has been directly used in a thermal reactor.
 - The 65 MWt/20 MWe CEFR was started up in July 2010 and future plans are being developed for fast reactor expansion.
 - In October 2010, GDF Suez Belgian subsidiary Tractebel, with Belgonucléaire and the nuclear research centre SCK•CEN signed an agreement with CNNC to build a pilot MOX fuel fabrication plant in China.
 - In December 2008, the Chinese government (National Development and Reform Commission, the “Senior Ministry” in the Chinese cabinet) organised a meeting of experts and decided that China should start expanding R&D in the area of utilising thorium as nuclear fuel, with the allocation of additional funds.

Overall, there is strong policy support for nuclear and active involvement in almost all aspects of the nuclear fuel cycle. These are being driven by the need to support and effectively manage the rapid nuclear expansion, a feature which is also consistently found in the programmes of the Russian Federation and India.

4.2.2. Countries with a mature nuclear programme and ongoing support

France has been developing its nuclear industry as the major part of its energy policy since the 1970s. It has also been operating reprocessing and enrichment facilities over many decades and has evolved a mature industry with high efficiency, through long-term government support and a largely state-owned industry.

In a similar way, Japan and the Republic of Korea developed nuclear power in response to a lack of indigenous energy sources. Security of supply was the key driver and this has been supported by successive governments. In addition, measures to combat global warming are urgently required and nuclear power is seen as an important element, together with renewable sources. At present, however, renewables are still considered to have issues of supply stability and economic feasibility. Therefore, the direction of energy policy in Japan and the Republic of Korea has been to utilise nuclear energy and diversify imports. Both countries announced goals to generate at least one-third of electricity from nuclear by 2030, with the Republic of Korea setting even higher targets.

By way of a governmental decision in 1974, France embraced nuclear energy as its main electricity generation technology. The parliamentary debate in 1999 reaffirmed the three main planks of French energy policy: security of supply, respect for the environment and proper attention to radioactive waste management and in 2005 a law established guidelines for energy policy and security, reinforcing the role of nuclear power. The importance of nuclear technologies to France in terms of economic strength and notably power supply is further underlined by the establishment of a top-level nuclear policy council (*Conseil politique nucléaire – CPN*) by presidential decree early in 2008.

With 74% of the total net electricity generated from 58 nuclear reactors in 2010, France claims a substantial level of energy independence and almost the lowest cost of electricity in Europe. The level of CO₂ emissions per capita from electricity generation is also extremely low, since over 90% of electricity is produced from nuclear or hydro, both low CO₂ emission sources.

From being a net electricity importer through most of the 1970s, France has become the world's largest net electricity exporter. Over the last decade France has exported up to 70 billion kWh of net electricity each year,¹ and is looking to continue exporting 65-70 TWh/yr, to increasingly take a strategic role as a provider of low-cost, low-carbon baseload power for the whole of Europe.

In Japan, the goals of research, development and utilisation of nuclear energy are all limited to peaceful purposes by the Atomic Energy Basic Law of Japan. Since 1956, approximately every five years the Atomic Energy Commission of Japan has determined long-term plans for research, development and utilisation of nuclear science and engineering. Nine long-term plans have been defined so far, with the last being formulated in 2000.

In October 2005, the commission determined a nuclear energy policy framework for the promotion, research, development and utilisation of nuclear science and engineering. Adopted by the government as the Framework for Nuclear Energy Policy, it entails the following basic targets:

- nuclear power to continue to provide at least approximately 30% to 40% of total electricity generation even after the year 2030;
- promote nuclear fuel cycle activities (domestic reprocessing to recover fissile material);
- commercialise fast breeder reactors.

Following the Fukushima Daiichi accident, the Japanese government announced a review of their energy policy with consideration to be given to increasing other non-nuclear forms of electricity. The outcome of this review was not known at the time of writing this report.

1. Principally to Germany, Italy and the United Kingdom, but also to Belgium, Spain and Switzerland.

In the Republic of Korea, a series of national plans have set out a path for nuclear. According to its current 5th Basic Plan of Electricity Supply and Demand (BPE), announced by the Ministry of Knowledge Economy in 2010, the Republic of Korea will aim for up to 49% of the country's total production of electricity and plans are being pursued to reach 59% by 2030. This will require investment of KRW 40 trillion up to 2025.

Fuel cycle initiatives

France and Japan have more developed fuel cycle activities than the Republic of Korea, reflecting the greater spread of their nuclear programmes and longer involvement in the industry. In particular, France is self-sufficient in most fuel cycle services, which are largely provided by AREVA NC. The Republic of Korea has agreed, for non-proliferation reasons, to abstain from development of enrichment and reprocessing; instead the government has pursued its involvement through international agreements.

Uranium mining, milling and conversion

Since France, Japan and the Republic of Korea do not have significant uranium resources, they import uranium for their nuclear power needs. Uranium is purchased from Australia, Canada and elsewhere, under long-term purchase contracts and other arrangements. In France, national needs for conversion are met by Comurhex Malvesi and Pierrelatte plants, with additional capacities available for export (about 40% of production is on fee basis or exported). These facilities also perform conversion of reprocessed uranium and deconversion of enrichment tails. Since 2007, AREVA NC has undertaken a new conversion project (Comurhex II) to expand and modernise existing facilities. First production from these new and refurbished facilities is expected in 2012 and will strengthen France's global position in the front end of the fuel cycle. In the Republic of Korea and Japan all the milling and conversion service to produce uranium fluoride (UF₆) from uranium ore are provided by overseas companies.

Enrichment and fuel fabrication

Enrichment services in France have been provided for 30 years by the Eurodif's 1978 Georges Besse I plant, near Tricastin. Its 10.8 million SWU capacity is sufficient to supply some 81 000 MWe of generating capacity, which is approximately one third more than France's total capacity. Being of the gas-diffusion type, however, the Eurodif enrichment plant is very energy intensive and has been by far the largest single electricity consumer in France. Having acquired a 50% stake in Urenco's Enrichment Technology Company, AREVA is using their current centrifuge technology to replace Eurodif plant with the new Georges Besse II enrichment plant at Tricastin. Georges Besse II was officially opened in December 2010 and commenced commercial operation in April 2011. When fully operational, the plant will have a nominal annual capacity of 7.5 million SWU (with potential for an increase to 11 million SWU) and will be composed of two units: the south unit whose construction started in 2007 and is expected to reach full capacity (4.3 million SWU/y) in 2015 and the second (north) unit whose construction began in 2009 and which will be fully operational in 2016 (with 3.2 million SWU/y capacity). There is potential to expand capacity to 11 million SWU/y, probably with a third unit. Enrichment will be up to 6% ²³⁵U, and reprocessed uranium will only be handled in the second, north unit.

About 7 300 tonnes of depleted uranium tails are produced annually, and are expected to total some 450 000 tonnes by 2040. Most depleted uranium is stored for future use in Generation IV fast reactors, with only 100-150 tU/y used for MOX fabrication.

AREVA runs several facilities in France and Belgium providing fuel fabrication services. Plans for significant upgrades of these plants form part of AREVA's strategy for strengthening its front end capabilities.

Japan Nuclear Fuel Ltd. started operation of a commercial plant with a capacity of 50 tSWU/y in 1992. The licensed capacity is 1 050 tSWU/y and it is planned to eventually reach 1 500 tSWU/y. Centrifuge technology is employed in the plant. However, most enrichment services are still imported from overseas companies.

Mitsubishi Nuclear Fuel Co., Ltd. has a reconversion capacity of 450 tU/y and provides 30% to 40% of the domestic demand of reconversion service in Japan. The rest of the service is provided by overseas companies.

Nearly 100% of the domestic demand of fuel fabrication of LWRs is provided by Mitsubishi Nuclear Fuel Co., Ltd. (PWR, capacity: 440 tU/y from 1972), GNF-J (BWR, capacity: 750 tU/y from 1970), Nuclear Fuel Industries, Ltd. (BWR, capacity: 250 tU/y, PWR capacity: 284 tU/y).

In the Republic of Korea all enrichment is also purchased overseas. Korea Nuclear Fuel Co., Ltd. (KNFC) has manufactured and supplied nuclear fuel for all domestic PWRs and CANDU reactors. To meet the increasing demand of nuclear fuel, KNFC completed the construction of new fuel manufacturing facilities at the end of 1997 in addition to the previous PWR fuel manufacturing facility. The annual production capacity becomes 550 tU for PWR fuel and 400 tU for PHWR fuel. With this expansion of the fuel production capacity, KNFC has established a firm basis and capability to export fuel.

Reprocessing

From the outset of its nuclear programme, France opted for the closed fuel cycle, involving reprocessing and recycling of used fuel. Reprocessing is undertaken a few years after discharge, to allow for some cooling. Spent fuel is reprocessed in the AREVA NC plant at La Hague, which has a capacity of 1 700 tU/y from its two facilities UP2 and UP3. To the end of 2009, about 27 000 tU of LWR fuel from France and other countries had been reprocessed at La Hague. Previously, gas-cooled reactor natural uranium fuel was also reprocessed at La Hague (approximately 5 000 tU) and at the UP1 plant at Marcoule (over 18 000 tU). This plant, specifically geared to treat such fuel was closed in 1997. In 2009 AREVA reprocessed 929 tU, mostly from EDF and it aims to increase its throughput to 1 500 tU/y by 2015 as discussed later.

The treatment extracts 99.9% of the plutonium and uranium for recycling, leaving 3% of the used fuel material as high-level wastes which are vitrified and stored *in situ* for later disposal. Currently the typical input is 3.7% enriched used fuel from PWR and BWR reactors with burn-up up to 45 GWd/t, which has undergone cooling for a period of four years.

In Japan, the reprocessing service is provided by Tokai Reprocessing Plant (TRP) and overseas reprocessing plants. Tokai Reprocessing Plant has a capacity of 0.7 tU/d and was the first reprocessing plant in Japan. It started operations in September 1977, reprocessing, since then, a total of about 1 140 tU of spent fuel, including MOX fuel from an advanced test reactor Fugen. About 7 140 tU of spent fuel arising from LWRs and a GCR was reprocessed in United Kingdom by BNFL and in France by COGEMA (AREVA) plants. Spent fuel shipments to Europe stopped in 1998 and the reprocessing in COGEMA was finished in 2005.

JNFL started the construction of the Rokkasho Reprocessing Plant (RRP), which has a reprocessing capacity of 800 tHM. Test operations using actual spent fuel have been carried out since 2006 and about 425 tU have been reprocessed in the plant. Commencement of the plant operations has, however, been delayed and the construction is expected to be completed in October 2012.

It should be noted that, within TRP and RRP processes the separated Pu solution is mixed with reprocessed U solution giving the MOX product, in order to decrease the attractiveness of separated plutonium.

As mentioned above, the Republic of Korea has no reprocessing facilities.

Fabrication of MOX and REPU fuels

In France, the plutonium extracted from reprocessing at La Hague is immediately shipped to the MELOX Plant near Marcoule for prompt fabrication of MOX fuel. MOX fuel is currently used in 20 of EDF's 900 MWe reactors and four more reactors are being licensed for its use. AREVA has the capacity to produce and market 150 t/year of MOX fuel at its Melox plant for French and foreign customers (though it is licensed for 195 t/y). In Europe 35 reactors have been loaded with MOX fuel and contracts for MOX fuel supply were signed in 2006 with Japanese utilities.

EDF's recycled uranium is converted at the COMURHEX plants in Pierrelatte, either into U_3O_8 for interim storage, or into UF_6 for re-enrichment there or at Seversk in Russia.² The re-enriched REPU UF_6 is then turned into UO_2 fuel at AREVA NP's FBFC Romans plant (capacity 150 tU/y) for use in the Cruas 900 MWe power reactors (since the mid-1980s). The main REPU inventory, however, constitutes a strategic resource, and EDF intends to increase its utilisation significantly.

In Japan, domestic MOX fuel fabrication technology has been developed since 1960s. Although the development was carried out for MOX fuel of advanced test reactors (ATRs) and FBRs, the technology can be applied to the LWR MOX fuel fabrication. JNFL is developing a plan to construct a MOX fuel fabrication plant (the J-MOX plant) at Rokkasho-mura, which will start operation in June 2015. The plant is the first commercial MOX plant in the country and will have a capacity of 130 tHM/y. Plutonium recovered in reprocessing plants overseas is fabricated as MOX fuel assemblies and transferred to Japan for the utilisation in LWRs.

Waste management

In France, waste management is being pursued under the 1991 Waste Management Act (updated 2006). ANDRA (Agence nationale pour la gestion des déchets radioactifs) was established under this act as the national radioactive waste management agency and reports directly to the government so that parliament could decide on the precise course of action.

In June 2006 France adopted the Nuclear Materials and Waste Management Programme Act, which notably covers national management policy, transparency and financing. In particular the act gives directions for the radioactive waste and spent fuel management and prescribes the establishment and the publication every three years of a national plan for the management of radioactive materials and waste, according to the law on nuclear transparency and security.

The act, valid for 15 years, is based on three main principles concerning radioactive waste and substances: the reduction of their quantity and toxicity, interim storage of radioactive substances and ultimate waste, and deep geological disposal. The act also reaffirms the principle of reprocessing used fuel and using recycled plutonium and uranium "in order to reduce the quantity and toxicity" of final wastes, and calls for construction of a sodium-cooled prototype fourth-generation reactor around 2020 to test transmutation of long-lived actinides. Deep geological disposal is formally defined as the reference solution for high-level and long-lived radioactive wastes, and target dates for licensing and opening the repository, are set respectively for 2015 and 2025. Wastes disposed of are to be retrievable. Research is ongoing mainly in the underground rock laboratory, in clay rock formations, at Bure, eastern France, but also in a second

2. About 500 tU/y of French REPU as UF_6 is sent to JSC Siberian Chemical Combine at Seversk for re-enrichment. The enrichment tails remain at Seversk, as the property of the enricher.

laboratory where granite host rocks are investigated. Further research is conducted on partitioning and transmutation, and long-term surface storage of wastes following conditioning.

In Japan, waste management is the responsibility of the waste generators. The Nuclear Waste Management Organization of Japan (NUMO) was created in October 2002 as an implementing body for disposal. In December 2002, NUMO started “Open Solicitation”, encouraging consideration by all municipalities to accept the investigation on the adequacy and suitability of their local area for the development of a deep HLW repository. Meanwhile, electric utilities and others have been building funds for the disposal of HLW. Repository operations are expected to start by about 2035 and will cost some JPY 3 000 billion.

The LLW from nuclear power plants in Japan, equivalent to about 600 000 tanks of 200 litres, was stored in the NPP sites at the end of March 2009. A disposal business has already been established for most of the LLW generated at nuclear power plants. This was packed into about 211 000 drums of 200 litres (as of October 2009) and buried by JNFL. As for the remaining part of the LLW, discussions are underway among concerned parties regarding treatment and disposal.

In the Republic of Korea, a site for low- and intermediate-waste was finally agreed with a host community after a long period of discussion and several failed attempts. However, the process used was well regarded, with deep engagement with the host community and a commendable commitment to longer-term investment in the community.

Spent fuel in the Republic of Korea is currently stored at the reactor sites pending construction of a centralised interim storage facility by 2016, which will eventually have a 20 000 tHM capacity. About 11 000 tHM was stored at the end of 2009, with total onsite pool capacity of 12 000 tHM (about half of both figures pertain to CANDU fuel at Wolsong). By comparison, about 6 000 tHM was stored at the end of 2002. Dry storage is used for CANDU fuel after 6 years of cooling. For the long term, deep geological disposal is envisaged.

The Korea Radioactive Waste Management Co., Ltd. (KRWM) was set up early in 2009 as an umbrella organisation to resolve the Republic of Korea’s waste management issues and waste disposition, and particularly to forge a national consensus on high-level radioactive wastes. Until then, Korea Hydro Nuclear Power Co., Ltd (KHNP) is responsible for managing all its radioactive wastes.

Progress towards sustainability

In France, reprocessing and recycling have been part of the French approach for waste management and strategic resource utilisation. Out of about 1 200 tonnes of used fuel discharged per year, EDF has been sending some 850 tonnes for immediate reprocessing, with the remainder of spent fuel being kept for deferred reprocessing to provide the plutonium required for the start-up of Generation IV reactors. From the 850 tonnes treated each year until 2009, some 8.5 tonnes of plutonium are recovered each year along with 810 tonnes of reprocessed uranium. Reprocessing and recycling practices are poised for a further increase, with the renewed agreement announced in late 2008 between AREVA and EDF. The agreement, valid until 2040, sets out an increase of used fuel sent by EDF for reprocessing, from 929 tonnes (in 2009) to 1 050 t/y from 2010, supporting AREVA’s intent to rump up La Hague reprocessing capacity to 1 500 t/y by 2015. The Melox plant will also increase its production of MOX fuel for EDF, from 100 tonnes in 2009 to 120 t/y.

R&D on the back-end of the fuel cycle is focused on several activities:

- further investigation on waste behaviour at storage or disposal;

- adaption and optimisation of current processes and recycling technologies to further reduce costs and wastes in the light of expected PWR fuel evolution, including higher burn-up, greater use of MOX fuel, etc;
- development of uranium and plutonium multi-recycling in fast reactors;
- further investigation of advanced waste management options (e.g. minor actinides partitioning and transmutation).

An important example of process improvement is the COEX process. Designed for Generation III recycling plants and based on co-extraction and co-precipitation of uranium and plutonium along with a pure uranium stream (eliminating any separation of pure plutonium), the COEX process is close to near-term industrial deployment. Different advanced waste management options include the selective separation of long-lived radionuclides and the joint extraction of actinides. One such technique for the selective separation of long-lived radionuclides focuses on Am and Cm separation from short-lived fission products, for their subsequent recycling in Generation IV fast neutron reactors with uranium as blanket fuel. This option is based on the optimisation of DIAMEX-SANEX processes and can also be implemented in combination with COEX. In the EXAm process americium undergoes selective separation to be recycled, while curium is conditioned with fission products. This process would be less beneficial in terms of radiotoxicity reduction but will allow handling material with much reduced thermal load. Joint extraction of actinides (the GANEX process) is directed towards the long-term R&D goal of actinide homogeneous recycling (i.e. minor actinides with U-Pu) in Generation IV fast neutron reactor driver fuel.

A major commitment of the French government towards Generation IV fuel cycles is the deployment of ASTRID, a 600 MWe prototype of a sodium fast reactor commercial series, envisaged for about 2050. In September 2010 the government confirmed its support, with EUR 651.6 million funding up to 2017, with a final decision on construction to be made in 2017. The programme includes development of the reactor as well as its associated fuel cycle facilities: a dedicated MOX fuel fabrication line, a pilot reprocessing plant for used fuel, as well as a workshop for the fabrication of fuel rods containing actinides for transmutation (Alfa rods), which is currently under investigation. With the involvement of national and foreign industrial companies, CEA is responsible for the realisation of the project, with plans to build the prototype at Marcoule. CEA has undertaken the design of the reactor core and fuel, while AREVA with EDF, Alstom and other companies will collaborate in the design of the nuclear steam supply system, the nuclear auxiliaries and the instrumentation and control system. Designed to meet the stringent criteria of the Generation IV International Forum in terms of safety, economy and resistance to proliferation, ASTRID will have high fuel burn-up, with potential for later consideration of minor actinides incorporation in the fuel elements, and the use of an intermediate sodium loop.

In the Republic of Korea and Japan, electric utilities are making efforts to diversify supply sources and regions and to efficiently combine different procurement methods to secure stable and economic supplies of uranium resources.

Japan's basic policy has been to effectively use plutonium and uranium obtained by reprocessing spent fuel. The government investigated several scenarios and adopted the approach that spent fuel should be reprocessed after being stored for an appropriate period of time. Reprocessing of spent fuel is to be conducted within the country with a view to securing the autonomy of nuclear fuel cycle activities. As mentioned above, construction of Rokkasho Reprocessing Plant has progressed and the commencement of operations is expected to be in October 2012. In June 2009, the Federation of Electric Power Companies showed that nine utilities would start the utilisation of Pu recovered from reprocessing as MOX fuel in 16 to 18 LWRs by 2015. Production of MOX fuel is expected to start in J-MOX of JNFL in 2015.

In the meantime, FBRs are being developed as a promising technical option. JAEA launched the Fast Reactor Cycle Technology Development project in co-operation with the Japanese electric utilities in 2006. The electric utilities present requirements for the development of fast reactor cycle technology and also provide funds for the conceptual study of commercial fast reactors. In 2007 Mitsubishi Heavy Industry was selected as a “core” enterprise for fast reactor development programme until beginning a basic design for FBR demonstration.

During this decade, various types of advanced reprocessing technologies have been studied in Japan. Some of these technologies include:

- an improved PUREX method to recover Pu in the presence of U, so that separated Pu cannot exist throughout the process;
- partial U recovery process by crystallisation after spent fuel dissolution and a co-recovery process of U-Pu-Np using a simplified PUREX method;
- employment of newly developed monoamide derivatives which have abilities to selectively separate and recover U and Pu without additional reductants;
- a FLUOREX method consisting of a partial U recovery process by fluoride volatile method and a U and Pu recovery process by the PUREX method;
- partial U recovery step by selective precipitation of U by NCP and a U and Pu recovery by NCP precipitation after Pu(IV) is oxidised to Pu(VI);
- a supercritical extraction method that uses supercritical CO₂ fluid containing TBP-HNO₃ complex to extract U, Pu and MAs directly from pulverised spent fuel.

With regards to partitioning and transmutation, using FR and ADS, there have been comprehensive studies and reviews conducted by the Atomic Energy Commission of Japan in 2008-2009. A separation process for transuranium elements and some fission products has been developed at JAEA using new innovative extractants such as TODGA and adsorbents to improve the partitioning process from the viewpoints of the economy and the reduction of secondary wastes. This work is ongoing.

The Korean government has not yet established a definite long-term management policy on whether to recycle or to permanently dispose of spent fuel. Instead, the Korea Atomic Energy Commission set the main goal for spent fuel interim storage, as a mid- and long-term expedient. Even though the Republic of Korea has not made a final decision on spent fuel management, several alternative studies on spent fuel management have been carried out over a long period. KAERI is the main body responsible for R&D, and the DUPIC programme (direct use of used PWR fuel in CANDUs) is one of KAERI's prominent R&D activities in this area.

However, for the current Korean nuclear programme and expansion plans to be sustainable, the volumes of waste must be drastically reduced. PWR spent fuel is currently stored *in situ* at the NPP sites in temporary storage pools, but despite extension of facilities and densification of racks, at the current rate of waste generation, saturation of interim storage capacity would be reached in the forthcoming years. Hence effort is being directed towards the development of pyroprocessing and closure of the fuel cycle through the introduction, in the longer term, of sodium fast reactors.

4.2.3. Countries with mature but slowly evolving nuclear programmes

The United States were a pioneer in the early development of nuclear power, beginning in 1951 with the first electricity ever produced by nuclear power in the Experimental Breeder Reactor-I in Idaho. Westinghouse designed the first commercial PWR of 250 MWe capacity, Yankee Rowe, which started up in 1960 and operated to 1992. Meanwhile BWR design was developed by the Argonne National Laboratory and the first

commercial plant, Dresden 1 (250 MWe) designed by General Electric, was started up in 1960.

The United States also pioneered the development of nuclear fuel reprocessing methods, originally as part of its weapons programme, with the PUREX process. Nuclear power saw a rapid growth in the United States until 1979, when the Three Mile Island #2 reactor experienced a partial core meltdown, followed by the 1986 accident at the Chernobyl nuclear power plant in Ukraine. Declining public support for nuclear power, combined with construction cost overruns and delays in licensing plants, resulted in no new nuclear builds in the United States for three decades. With concern over climate change and building on a very strong safety record for the past 30 years, nuclear power has regained public confidence in the United States and is poised for new growth, but is now competing against large discoveries of shale gas.

The United States currently practise a once-through fuel cycle, with plans to directly dispose of the used fuel in a geological repository. Until 2010, the Yucca Mountain site in Nevada was the proposed site for the repository and was being reviewed for a licence by the NRC. The Obama administration moved towards terminating the Yucca Mountain project and appointed a “Blue Ribbon Commission” to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle and make recommendations for a new plan to address related issues. At the present time, used fuel from nuclear reactors is stored at the reactor sites in wet and dry storage. If the Yucca Mountain repository project is terminated, used fuel will likely be stored at either reactor sites, regional or centralised storage locations for at least the next 20-30 years. The United States currently have about 60 000 Mt of spent fuel in inventory and generates spent fuel at a rate of about 2 200 Mt/y.

The United States have had little success in implementing commercial reprocessing but government policy in the United States has supported research into new reprocessing methods since the early 2000s. Currently, the debate on whether to recycle spent fuel or not has been centered on the themes of economics, availability of uranium and non-proliferation. The United States will likely maintain the once-through fuel cycle for the next few decades, while research on new fuel recycle methods continues.

At the front end of the fuel cycle, the United States have seen a substantial increase in enrichment capacity with three new enrichment plants expected to begin operation before 2020 (Urenco USA, Eunice, New Mexico; AREVA, Eagle Rock Enrichment Facility; USEC’s American Centrifuge Plant in Piketon, Ohio).

Overall then, the United States have maintained infrastructure and capabilities for the past decade with substantial increase in the amount of enrichment capability. The United States should see the first new builds in reactors in the very near future, but remains decades away from a solution to the long-term management of spent nuclear fuel.

In regard to the sustainability measures, the role of government has not been influential in improvements in the sustainability measures discussed in this report. Policy positions have been changeable and therefore uncertain. Industry efforts in centrifuge technology and power utilities improved operational performance have been the main contributors to improved sustainability. Investment in R&D has been maintained but, at this stage, has not led to progress in waste disposal or in closing the fuel cycle.

4.2.4. Countries where policies have not favoured, or have had a negative impact in the development of nuclear programmes

Germany commissioned its first reactor in 1975. After an initial phase of significant growth in nuclear, the replacement of the Christian Democrat government by the Social Democrat and the Green Party coalition in 1998 brought about a radical change in the

direction of nuclear policy of the country. The defeated government was the strong supporter of nuclear technology whereas the new government held the opposite view. During this time, Germany adopted the nuclear phase-out policy, enforcing a specific time frame to wind down the nuclear energy programme and to phase out civil usage of nuclear energy by 2020. The National Energy Policy (2010) deals with this aspect. More recently, the present government, after initially agreeing to an extension of the lifetimes of the existing German nuclear power plants from 12-17 years, has decided to phase out nuclear power by 2020. Germany has introduced significant incentives for renewables, so that nuclear reactors are now being used in a load following mode.

German research and development is now focused on the safety of LWR operations as well as studies to reduce waste burden on the final repository, including P&T. Such activities are partly developed in the framework of European Commission projects.

German policies have been determining in the changes in the German nuclear industry, which is now in a closure phase. This seems to have been consolidated by the events in Fukushima Daiichi. In a related manner, German attempts to locate a site for final disposal of HLW have stalled, as public acceptance has moved against the original proposals to site facilities in Gorleben.

Belgium was very quickly active on the nuclear scene in Europe, both with its research and nuclear power plants. It established 3 test Belgian Reactors (BR1, 2 and 3) with BR2 still in operation today, and other experimental facilities such as Thetis and VENUS.

Based on the experience gained in operating these test reactors Belgium embarked on a nuclear power programme, with seven nuclear power plants that became commercially available between 1975 and 1985. Ongoing operations of all such reactors provide about 54% of Belgium's total produced electricity. In the past there have been campaigns with partially loaded MOX cores in two of the reactors, in line with the 1993 parliament resolution which approved recycling of plutonium recovered from spent fuel. However, since the moratorium on reprocessing issued in 1999, this has ended and the last MOX fuel elements were loaded in 2006.

Belgium has been actively involved in scientific and technological developments at the international level, including partitioning and transmutation and innovative nuclear reactors with fast neutron spectra, building synergies with the lead fast reactor concept of the Generation IV International Forum and the European Commission. Such work is intended to be continued with the proposed MYRRHA project, which has evolved to a design using a 100 MWth installation, able to work in sub-critical and critical mode.

Aside from fuel fabrication, Belgium does not cover other parts of the front of the nuclear fuel cycle. Belgium holds no uranium deposits that can be mined economically, but in the past it produced some uranium from phosphates imported from Morocco.

Belgium has gained substantial experience in nuclear fuel fabrication, through the operation of its two plants: FBFC and Belgonucléaire. FBFC, now owned by AREVA NP, has a production capacity of 500 tonnes of uranium per year for PWR and BWR fuel fabrication, with an additional production line to assembly MOX fuel. Belgonucléaire operated a MOX fuel fabrication plant between 1986 and 2006. The company has produced, over its lifetime, about 650 tonnes of MOX fuel for nuclear power plants in Belgium, France, Germany, Japan and Switzerland.

With respect to strategies for the back end of the fuel cycle, Belgium initially followed the reprocessing-recycling route, with a number of reprocessing contracts conducted between Synatom and Cogema from the mid-1970s to the late-1980s. Since the parliamentary debate on the suitability of reprocessing in 1993, the reprocessing and direct disposal options were to be treated on an equal footing. In 1998, the Belgian government decided that no reprocessing contract may be concluded without its formal

agreement. Since then, spent fuel from both nuclear power plant sites has been stored on site, using dry storage at the Doel and a wet storage pond at the Tihange site.

Vitrified waste produced at La Hague as a result of the reprocessing contracts was returned to Belgium between 2000 and 2007 and is temporarily stored at Belgoprocess. As stated in the multilateral convention signed in 2008, through the repatriation of the last consignment of vitrified HLW, Synatom has fulfilled all its obligations.

Based on the public enquiry which ended in September 2010, NIRAS/ONDRAF was expected to submit a waste management plan to government in 2011 to obtain a decision on the long-term management of long-lived medium and HLW. In 2008 a state-of-the-art report has been written and preparation made for a societal consultation. In the meantime, research and safety activities are continuing in the field of geological disposal for long-lived and HLW, supported by an underground laboratory (200 meters below surface) at SCK•CEN and operated in collaboration between SCK•CEN and NIRAS/ONDRAF. The aim is to present by 2013 a first safety and feasibility case to the safety authorities.

At present, a project is running for near surface disposal of short-lived low and intermediate-level waste. Detailed design and safety studies are under peer review in view of an application for construction and operation license in 2011. The selected site, Dessel, is also partner in the integrated project, so that measures to promote the economic and social development of the region can be considered.

Due to a series of governmental decisions, the future for nuclear power generation in Belgium is at this moment quite uncertain. A law for the gradual phase out of nuclear energy production was approved in 2003 for the shut-down of NPPs after 40 years of operation. This would entail the shut-down of the first 3 reactors in 2016, with a loss of nearly 1 800 MWe production capacity. The other units would need to close in 2026. In 2008, however, a new expert body, the GEMIX group, was established by the Belgian government. This group was to study the ideal energy mix for Belgium with a look at multiple nuclear scenarios and a focus on security of supply, competitiveness and protection of the environment and climate. The final report issued by the GEMIX in late 2009 concluded that without the three oldest nuclear power plants, Belgium will face a severe energy shortage by the end of 2015. Based on this, the Belgian government decided to reconsider the 2003 phase-out law and to prolong the operational lifetime of the three oldest nuclear power reactors by 10 extra years. Due to the political crisis at the time, however, the parliament never confirmed the government decision, and thus the original phase-out law still remains in place.

Hence both Germany and Belgium have issued policies to phase out nuclear, although the implementation has varied. In this environment, progress with closure of the nuclear fuel cycle or nuclear expansion has not been possible.

4.2.5. Global efforts

Aside from national initiatives, which have varied significantly as a result of the national policies in nuclear expansion, other international initiatives have been established, such as the GIF, INPRO and IFNEC. Selected examples are summarised below to illustrate progress towards sustainability including unique approaches and setbacks.

- **The Global Nuclear Energy Partnership (GNEP) and International Framework of Nuclear Energy Cooperation (IFNEC):** GNEP began as a United States proposal in 2006 as an international partnership to promote the use of nuclear power and close the nuclear fuel cycle in a way that reduces nuclear waste and the risk of nuclear proliferation. As a part of the initiative ways were considered on how to provide assurance of nuclear fuel supply to all countries without increasing the risk of proliferation. GNEP eventually evolved into a new initiative referred to as the IFNEC. This international framework provides a forum for co-operation among participating states to explore mutually beneficial approaches to ensure the use of

nuclear energy for peaceful purposes, in a manner that is efficient and that meets the highest standards of safety, security and non-proliferation.

- **Global Nuclear Infrastructure Initiative:** This programme, launched in 2006 and sometimes referred to as the Russian Initiative envisages the development of international centres for nuclear fuel service as joint ventures financed by several countries. Such international centres would be aimed at the provision of enrichment and recycling/ reprocessing services, or/and storage of fuel as well as related R&D and training of personnel. The aim is also to minimise the proliferation threat.
- **Nuclear Threat Initiative (NTI):** NTI was founded in 2001 as a result of concerns that the threat from nuclear weapons has fallen from the public views after the end of the Cold War. It was initiated by former US Senator Sam Nunn to engage private organisations in helping strengthening global security by reducing the risk of spread of nuclear, biological and chemical weapons. One of the aims of the NTI is the development of nuclear fuel banks providing assurance of nuclear fuel supply to all countries, eliminating the need for them to have individual fuel enrichment facilities at a national level.
- **The European Strategic Energy Technology Plan (SET-Plan):** The SET-Plan is the EU's response to the challenge of accelerating the development of low-carbon technologies, leading to their widespread market take-up. It proposes joint strategic planning and sets out a vision of a European Union holding the world leadership in a diverse portfolio of clean, efficient and low-carbon energy technologies as a motor for prosperity and a key contributor to growth and jobs, with nuclear fission representing a key contribution. Within the SET-Plan framework the European Sustainable Nuclear Industrial Initiative has been launched to demonstrate the long-term sustainability of nuclear energy. This is piloted by members of **the Sustainable Nuclear Energy Technology Platform (SNETP)**, a parallel European programme which now focuses the European research on nuclear systems. SNETP objectives are set out in the SNETP Vision Report (SNETP, 2007) and its broad aims, largely common with those of GIF, are:
 - achieving sustainable energy production;
 - achieving significant progress in economic performance;
 - improving the efficiency in the utilisation of natural resources;
 - cogenerating electricity and process heat;
 - continuously improving safety levels;
 - minimising waste and resistance to proliferation.

Overall, then, only incremental changes or improvements towards sustainability have been achieved through global efforts during the last ten years. It is significant however that the global perspective has become more dominant as the complexities and challenges of sustainability are better understood.

4.3. Comments on policies

This section focuses on reviewing the influence of policy settings (national and global) on the uptake of nuclear technology for power generation and in particular on the uptake of specific nuclear technology relevant to sustainability. The issue of technology uptake is a complex one and technologies are not developed or adopted on their own accord, but as a result of government policy (including national security, energy and legal, regulatory and institutional frameworks), taking into account public attitudes, energy needs, investor confidence and technology developments.

The motivation for different countries to adopt elements of the nuclear fuel cycle has changed over the last 40 years. Countries that had been early developers of a fuel cycle approach to nuclear were generally weapons states, which required both reprocessing and enrichment, as well as operation of nuclear power plants. Civil nuclear technology flowed from the US Atoms for Peace initiative and began to be adopted globally after the Second World War. These countries are now mature nuclear countries, where the technologies have been adopted or transferred to the civil nuclear power area. They include France, the Russian Federation, the United Kingdom and the United States, although subsequent policies in the United States suspended use of reprocessing and progress on waste management has seen many setbacks. Later weapon states have also introduced reprocessing and enrichment into their nuclear programmes, including China and India. With the strengthening of the international safeguards and non-proliferation regimes, the adoption of these more sensitive parts of the fuel cycle has decreased or stopped and a number of international initiatives are focused on promoting alternatives to the need for individual countries to adopt the full fuel cycle.

Since that early phase, world events have influenced the rate of uptake or otherwise of nuclear technology (e.g. oil shocks of 1973 and 1979) and focused many countries on enhancing their security of supply. This was particularly true in France, Japan, the Republic of Korea and the United States. However, following Three Mile Island and Chernobyl, there was stagnation in such expansion, especially in Western countries and the majority of nuclear expansion moved to the East. For example, in Italy the Chernobyl accident resulted in the 1987 referendum, which led to a policy to phase out its reactors.

More recently the motivations for developing nuclear programmes have been driven by a combination of energy needs, enhancing security of supply at a competitive cost and actions to mitigate the effects of climate change. This is the case in China, India and the Republic of Korea as well as in a number of developing countries. For these latter countries, the focus has been on nuclear power plant development and not directly on the other parts of the fuel cycle.

4.3.1. Environmental sustainability and energy security

Until the late 1990s, the role of sustainable development concentrated mainly on the environment. By the end of 1990 the focus began to shift to energy policy settings. During this period significant concerns over exhaustion of national resources and heavy reliance on energy imports highlighted the energy security issues inherent in any response to climate change and sustainability. Many countries, particularly the EU members, began to include fuel diversification into their sustainable development blueprints to achieve energy security.

The promotion of nuclear energy for GHG reduction reasons brought nuclear into the environmental arena and into discussions over low-carbon futures and climate change abatement. Despite the positive contribution that nuclear is making, however, nuclear has not been accepted into any of the climate change mechanisms, such as the clean development mechanism of the Kyoto Protocol. This has been linked to the potential for proliferation of parts of the fuel cycle and the continuing concern among policy-makers over the lack of a final solution for radioactive waste management. However, many countries have made moves to encourage low-carbon technologies, the most notable being the European Emissions Trading System, with similar discussions occurring in other countries. In the United Kingdom, electricity market reforms are being introduced to allow long-term contracts for low-carbon technologies, such as nuclear; these proposed reforms include introducing a floor for the carbon price and a proposal for contracts for difference for electricity prices. Both provide greater support and certainty to the price of electricity, encouraging investment in low-carbon electricity generation. These are energy market policy changes that will enhance the prospects for nuclear development.

Generally, policy discussions over nuclear energy in many countries are now focusing on:

- energy and climate change drivers that promote nuclear power as part of a diverse energy mix;
- the adequacy of the regulatory regimes to ensure non-proliferation, security and safety; and
- challenges to growth such as radioactive waste and spent fuel management and public acceptance.

In Chapter 2, the drivers for nuclear were examined and these remain the essential reasons for interest in nuclear power. The challenges to nuclear power expansion are related to the sustainability elements defined in this report. Section 4.1 provided a brief outline of the overall sustainability conclusions from a technology perspective, while Section 4.2 outlined how different countries are implementing policies that favour, or not, the growth of nuclear power. The issues related to regulatory and waste management aspects are discussed in the following sections.

4.3.2. Safety, security and non-proliferation regimes

Safety

Internationally conventions and standards have become a key aspect in the enhancement of the legal and regulatory frameworks for nuclear power. These are mainly developed under the auspices of the IAEA, but also through other international bodies. They are promulgated as conventions (ratified by member states), standards (adopted by member states in national legislations) and guidance documents (for use by relevant nuclear organisations). This occurs in the safety, security and safeguards areas, as well as with third party liability regimes, which are currently centred on international conventions, adopted by groups of countries.

Safety is one of the high level, high priority imperatives that need to be considered in policy. The ongoing focus on safety and safety culture over the last decade is well demonstrated through ongoing national, international and industry initiatives. Regulatory functions have been heightened and the general trend has been to continuously promote and legally strengthen the autonomy and independence of regulatory bodies in each of NEA countries. Harmonisation on regulatory approaches has seen considerable impetus, for instance, with the development of the Multinational Design Evaluation Programme (MDEP)³ and the establishment of the European Nuclear Safety Regulator Group (ENSREG).⁴

The IAEA statutory basis includes two specific mandates under its safety and security pillar – the promulgation of authoritative guidance on how to best assure the safety (and security) of peaceful nuclear technologies and the application of this guidance worldwide. These mandates have been brought to fruition through the development of international agreements and safety standards and through the conduct of assistance missions and reviews.

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3. A multinational initiative taken by national safety authorities to develop innovative approaches and leverage resources and knowledge of national regulatory authorities tasked with the review of new reactor designs.
 4. ENSREG aims at the development of a common understanding among European nuclear safety regulators on the safety of nuclear installations and spent fuel and radioactive waste management.

Increased safety worldwide can also be achieved through the development and adoption of legally binding safety instruments. Since 1986 four conventions were ratified in the areas of nuclear safety, emergency response and radioactive waste management:

1. *Convention on Early Notification of a Nuclear Accident* establishes a notification system for nuclear accidents that have the potential for international transboundary release that could be of radiological safety significance for another state.
2. *Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency* sets out an international framework for co-operation among parties and with the IAEA to facilitate prompt assistance and support in the event of nuclear accidents or radiological emergencies.
3. *Convention on Nuclear Safety* to legally commit contracting parties operating land-based nuclear power plants to maintain a high level of safety by setting international benchmarks to which states would subscribe.
4. *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management* is the first legally binding international treaty on safety in these areas. It represents a commitment by participating states to achieve and maintain a consistently high level of safety in the management of spent fuel and of radioactive waste as part of the global safety regime for ensuring the proper protection of people and the environment.

At the European level, the 27 member states of the European Union have adopted legally binding EU-legislation, based on the treaty establishing the European Atomic Energy Community (Euratom Treaty) in order to harmonise safety standards within the EU in the areas of nuclear safety and radioactive waste management:

1. *Council Directive 2009/71/EURATOM of 25 June 2009 establishing a community framework for the nuclear safety of nuclear installations* is based on the Convention on Nuclear Safety and aims, inter alia, to ensure that member states shall provide for appropriate national arrangements for a high level of nuclear safety to protect workers and the general public against the dangers arising from ionising radiations from nuclear installations.
2. *Council Directive 2011/70/EURATOM of 19 July 2011 establishing a community framework for the responsible and safe management of spent fuel and radioactive waste* which aims to ensure that EU member states provide for appropriate national arrangements for a high level of safety in spent fuel and radioactive waste management to protect workers and the general public against the dangers arising from ionising radiation.

Instruments in the field of nuclear third party liability were developed before the Chernobyl disaster and over the years, since the 1960s, they have become more comprehensive. Under the auspices of the OECD Nuclear Energy Agency, some of its member countries have established the so-called Paris/Brussels regime, including the Paris Convention on Nuclear Third Party Liability, the Brussels Supplementary Convention on Nuclear Third Party Liability and the 2004 Protocols to amend these conventions (not yet in force). Under the auspices of the IAEA, some of its member states have established the so-called Vienna regime (including the Vienna Convention on Civil Liability for Nuclear Damage and the Protocol to amend it), as well as the Convention on Supplementary Compensation for Nuclear Damage (not yet in force). As a bridge between the Paris/Brussels regime and the Vienna regime and in order to extend the privileges of countries party to the Paris Convention to countries party to the Vienna Convention (and vice versa), the Joint Protocol Relating to the Application of the Vienna Convention and the Paris Convention (referred to as the Joint Protocol) has also been adopted in 1988.

Fukushima Daiichi

The Fukushima Daiichi events of March 2011 are expected to re-enforce the focus on safety and safety culture in the nuclear industry globally, and to result in increased focus on accident response.

As in the cases of Three-Mile Island and Chernobyl, time will tell how attitudes formed during the Fukushima Daiichi crisis affect government policy decisions going forward. These attitudes may be positively shaped by the activities currently underway to strengthen safety standards and international co-operation. Concerns about nuclear safety may continue to be balanced by ongoing concerns related to climate change and global warming.

Safeguards

In terms of safeguards, until the turn of the 21st century, international non-proliferation measures meant almost exclusively the verification of nuclear material inventories at declared nuclear facilities. Following the first Gulf War and the discovery of Iraq's clandestine nuclear programme that had escaped these traditional safeguards measures of the IAEA, steps were taken to broaden the focus to complete fuel cycle and infrastructure assessments (the "Additional Protocol") and ultimately a comprehensive state-level focus ("Integrated Safeguards").

Many advances in safeguards, such as unattended and remote monitoring, are policy-driven or economics-driven concepts with technology-dependent applications. Some progress in safeguards technology will be driven by technology alone, such as the requirement to verify fresh fuel with significantly different radiation signatures in closed fuel cycle systems than inspection regimes have been accustomed to distinguishing between in the past. Similarly, the safeguarding of thorium fuel cycles will require an ability to verify non-fissile thorium fresh fuel and spent fuel, bearing quite different uranium isotopes (^{233}U and ^{232}U), and associated decay chains. Finally, although bulk and quasi-bulk fuel management (e.g. molten salt, pebble bed) will require significant changes in reactor safeguards instrumentation and approach in order to provide an adequate level of material accountancy, safeguards may be simpler overall due to the low fissile content of fuels to be controlled.

By far, it is expected that the more significant area of improvement in new nuclear energy systems will be that of "safeguardability" – the degree to which a technology facilitates safeguards, thus affecting both efficiency and ultimately effectiveness of the safeguards approach. In this respect, most advances will be made in the areas of plant layout and fuel cycle. It is expected that any advanced system will incorporate the lessons of past generations of reactor technology safeguards, which focus in large part on the path of fuel movement and storage of fuel within the plant.

Along with these recent advances in non-proliferation concepts, there have been parallel developments in the approach to physical protection. Once again global events intervened to energise the process; in this case the events of 11 September 2001 that highlighted unforeseen vulnerabilities in societal infrastructure. As with non-proliferation, the IAEA and the nuclear design community have directed increased attention to the inherent characteristics of nuclear facilities, along with obvious increases in traditional protective measures.

Again the focus tends to be on fuel material, movement and storage and plant layout, with a view to either minimising the attractiveness of targets, or the implications of targets being attacked. Increased attention has been directed to non-traditional targets as well, such as cyber-attacks, information theft and insider collaboration.

Finally, these advances in concepts and approaches for both non-proliferation and physical protection have required a corresponding development of methodologies for assessment and analysis. These methodologies have a diverse user community, from

policy-makers to design engineers; and so they must be flexible as well as efficient and effective. Two notable contributors of tools for this purpose are the INPRO project of the IAEA and the PR&PP Working Group of the GIF. For non-proliferation as well as physical protection, these two methodologies have been shown to work in harmony together, with INPRO providing a comprehensive assessment checklist and PR&PP providing a comprehensive evaluation methodology that satisfies some of INPRO's requirements.

4.3.3. Radioactive waste and spent fuel management

Disposal of spent fuel and high-level waste

The emplacement of spent fuel and high-level waste in geological repositories has been retained as the favoured disposal policy option in the past decade by most NEA countries. The different actions undertaken in the 1990s to improve public acceptance of this strategy resulted in a more positive response of the different stakeholders during this past decade thus enabling progress in decision-making. Early in 2001, the Finnish parliament endorsed a decision in principle by the government stating conformity with the proposed designation of Eurojoki as the site where a geological repository for spent fuel would be built. The Swedish waste management agency SKB announced in July 2009 that an application for a construction licence will be prepared for a repository in Forsmark, after a positive declaration by the municipality of Östhammar. In both cases the repository is expected to become operational by approximately 2020 (NEA, 2008).

Since 2001 more countries have officially confirmed underground disposal as their preferred management option, with decisions usually adopted by means of legally binding provisions or government policy statements. This was the case of Canada, France, Japan, Switzerland and the United Kingdom. Backed by such legal measures, the process for site designation has already been launched in all of these countries, integrating technical and stakeholders' demands. In France an underground laboratory near Bure is currently operating in a highly confining callovo-Oxfordian argillite environment, in view of the forthcoming implementation of a geological repository for HLW & ILW-LL in the area. A zone of 30 km² has been approved for the location of the future underground disposal facility; a licence application for the construction of the geological repository is expected by the end of 2014, also implementing reversibility conditions as defined by law. The success of these programmes, in conjunction with the potential start and re-start of those in Belgium and Germany respectively, would see three national repositories become operational between 2020 and 2025 (in Finland, France and Sweden), followed by a few more by 2040 (see also NEA, 2008).

A setback has been experienced in the United States, where, in 2002, following the procedure defined in the Nuclear Waste Policy Act, the US congress designated the Yucca Mountain as the site for a national repository. In 2009, however, the new government decided not to pursue the programme, announcing the unsuitability of the site to become a deep geological repository. Accordingly, the licence application to the regulatory body (the NRC) has been withdrawn and a dedicated commission has been established to provide recommendations for developing alternative, safe and long-term solutions for the management of spent nuclear fuel and nuclear waste in the United States.

In many countries legal and institutional frameworks on SNF and radioactive waste management have been further strengthened. Progress has been achieved through the creation or restructuring of new separate agencies in charge of managing spent fuel and radioactive waste during the end of the 1990s and the early 2000s.⁵

5. For example, Nuclear Waste Management Organization (NWMO) in Canada, PURAM in Hungary, NUMO in Japan and the Radioactive Waste Management Directorate (RWMD) established by the Nuclear Decommissioning Authority in the United Kingdom.

Besides the progress in the implementation of domestic geological repositories, the concept of regional and international repositories for SNF and HLW has also taken particular significance in recent years. Some countries with small nuclear programmes see it as a practical economic and technical solution. Although facing great challenges from the point of view of politics and public opinion, international repositories will continue to be an attractive way for the final management of waste in small countries.

In the international scene, the entry into force of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management in 2001 brought a new important tool to direct common efforts for those countries that have ratified the text, working as a driver and a platform for the validation and harmonisation of practices and policies (e.g. through international peer reviews).

Reprocessing of spent fuel

Traditionally, there has been a clear divide among countries that have adopted a national reprocessing policy and those who have not. Reprocessing policies have been sustained in France, Germany, Japan, and the United Kingdom and, among non-NEA countries, India and the Russian Federation. Historically Belgium, the Netherlands and Switzerland had also significant amounts of their spent fuel reprocessed. On the other hand, Canada, Finland, Spain and Sweden were countries where either an early decision was made not to reprocess or where reprocessing policies were abandoned early on.

The decision to put an end to reprocessing taken in 1999 by the German government and legally adopted in 2002 through the amended of the Atomic Energy Act (BMU, 2008) had a profound impact on some central European countries like Belgium, the Netherlands and Switzerland, whose existing policies were put at stake. While in the case of Belgium this resulted in a confirmation of a previously adopted moratorium, policy in the Netherlands did not change and the issue in Switzerland was solved by means of a provision in the Nuclear Act of 2003 stating that shipment of spent fuel for reprocessing abroad would not be allowed for a period of ten years starting July 2006 (HSK, 2008).

In Scandinavian countries (Finland and Sweden) policies for spent fuel management have consistently been oriented to direct disposal of spent fuel in underground repositories. Similarly, Spanish policies maintained a position against reprocessing as well, although some former commitments from standing contracts were fulfilled.

The United States decided to abandon the reprocessing policy in the late 1970s, although a large national industry for reprocessing was kept and R&D in the area continued, focusing in particular on advanced technologies for the separation of transuranics. A recent report by the Boston Consulting Group (BCG, 2006), based on proprietary information from AREVA, concluded that recycling spent fuel in the United States using the COEX™ aqueous process would be economically competitive with direct disposal (Kok, 2009). It is recognised that advanced options for reactor/closed fuel cycle such as partitioning and reprocessing of irradiated fuel may enhance waste management and public acceptance and, as such, they should not be foreclosed (MIT, 2011).

Countries holding commercial reprocessing facilities (France, the United Kingdom) or intending to move from pilot to commercial plants (Japan) have kept sustaining reprocessing. In particular, in France⁶ the use of recycled material has recently seen a sharp increase, with 22 NPPs licensed to use MOX (with 21 currently using it) and 4 NPPs licensed to use REPU. In 2010 the contribution to nuclear generation coming from recycled products in France amounted to approximately 17% (WNA, 2011). In addition,

6. The French law establishes that the national plan for the management of radioactive materials and waste has to comply with the guideline according to which: "Reduction of the quantity and toxicity of radioactive waste is sought in particular by treating spent fuel and by treating and conditioning radioactive waste".

used MOX and REPU fuels are currently stored pending reprocessing and use of the plutonium in Generation IV fast reactors though other possible options for second recycle or use of the second generation Pu in LWRs are being considered.

A number of countries have been holding from developing firm strategies and have not formulated a final policy disposal. While this approach enables countries to take advantage of progress in advanced technologies and options, it represents only an interim stance and cannot be considered a final solution. In the meantime, due consideration must be given to the potential impact that prolonged storage times could have on the interim storage facilities and their design as well as the integrity of spent fuel or separated Pu stored.

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5. Conclusions and recommendations

Trends in the nuclear fuel cycle during the past ten years, the next ten years and for the longer-term future were assessed in this report with a specific focus on consideration of sustainability dimensions. In doing so, a review was made of the technical trends towards sustainability and the global efforts that relate to the fuel cycle, with a particular focus on national strategies and policies and their effects on sustainability. Seven key areas were addressed for a qualitative assessment of sustainability impacts:

- environment;
- resource utilisation;
- waste management;
- infrastructure;
- proliferation resistance and physical protection;
- safety;
- economics.

There is currently no consensus on quantitative methodologies and tools to assess progress towards sustainability and proposed methods are very data intensive, which leads to divergence of opinions. There would be value in having a more quantitative but easily applicable method.

Recommendation 1

Work should continue towards developing a single set of simple and universally agreed upon indicators that can be used to assess the sustainability aspects of the nuclear fuel cycle.

Overall, while progress has occurred across the fuel cycle, the enhancement of sustainability *per se* has not been a major driver of policy or technology changes over the past decade and this is not expected to change significantly in the near future. Government initiatives to specifically foster sustainability have been very limited.

Unsurprisingly, national development and uptake of technologies are influenced by complex and interconnected factors, including overall energy and environmental policies, public and political attitudes, investor confidence and technological maturity, as well as the effects of global events (e.g. oil shocks of 1970s or the accidents in Three Mile Island, Chernobyl and Fukushima). Thus government policies on the nuclear fuel cycle have to be seen in the wider context of these and other factors, such as the growth of energy demand, the enhancement of security of supply including, for many countries, reducing heavy reliance on energy imports, together with aspirations to mitigate the effects of climate change.

From the review of national situations undertaken in Chapter 4, it transpires that the major strategic considerations that have shaped and are likely to continue driving energy policies are:

- availability of energy resources and security of supply;

- environmental concerns, including the need to minimise GHG (CO₂) emissions;
- economic competitiveness; and
- public acceptability and growth in awareness of the benefits of nuclear as part of a diversified energy mix.

In this wider context, nuclear technology presents a number of attractive features able to address the above geopolitical issues that influence country policies:

- A mature technology which does not require new technological breakthroughs.
- Generation of very low quantities of GHG emissions and therefore a way to limit climate change.
- Less potential for disruption as its fuel is produced by a diverse range of countries and can be stored in a relatively straightforward manner given its very high energy density.
- Enhanced indices of security of supply, notably due to the abundance and geographical spread of uranium and the very limited impact that U price and its possible changes and volatility have in the electricity produced. This latter feature makes nuclear power a quasi-indigenous source of electricity.
- No intermittency and unpredictability (which affect wind and solar energy and need the development of energy storage or back-up systems).
- Economic competitiveness with other energy sources, especially if carbon pricing is considered and financing costs are controlled.

Increasing recognition of the potential contribution nuclear could have in the generation of low-carbon energy needed for a global development has recently led some countries to amend their national energy schemes and undertake new build projects. Of course, nuclear development faces a number of technical, financial and political hurdles, which would need to be overcome for the forecast growth to be achieved (IEA/NEA, 2010).

The Fukushima Daiichi events of 2011 March are expected to re-enforce the emphasis on safety and safety culture in the nuclear industry globally and to increase the focus on emergency response. It is expected that some governments will reassess and strengthen safety standards and international co-operation. For example, a number of activities are currently underway in response to the Fukushima Daiichi events sponsored by the IAEA, NEA, WANO, INPO and global regulators including WENRA and the US NRC.

5.1. Evolutionary trends

For countries with nuclear programmes, the motivations to adopt and develop elements of the nuclear fuel cycle have been different and have changed over the years. In countries with established nuclear programmes, trends have been, in general, towards a gradual evolution of technologies with important national research into advanced FC processes by those owning full FC infrastructures. Some countries with fast growing economies have recently embarked on aggressive new build programmes with the uptake or expansion of reactor technologies, some also initiating research into FC technologies as a way of dealing with the increasing volumes of spent fuel. With the strengthening of the international safeguards and non-proliferation regimes, the adoption of more sensitive parts of the fuel cycle such as enrichment and reprocessing has however been limited or stopped in other nuclear countries. In these cases the focus has been towards nuclear power plant development, mainly in the framework of international programmes, and not directly on the other parts of the fuel cycle.

Although major breakthroughs in technology have not occurred in the recent past and are not expected in the near future, the nuclear sector has seen a continuous evolution, driven mostly by the industry, with incremental changes in mainstream reactors and FC technologies aimed at their optimisation.

5.1.1. Front end of the fuel cycle

Timely availability of natural uranium is increasingly playing an important role in terms of security of supply for utilities and governments, as exemplified by the increasingly longer-term supply contracts and the build-up of strategic stockpiles in order to hedge against the rising prices of natural uranium.

Given the declining secondary resources, the emphasis has essentially turned to the need to increase primary resource capacity through new mining projects, or the expansion of existing capacity, in order to keep up with worldwide uranium demand. This, however, requires significant investments.

With the large number of new reactors in non-NEA countries, and given the prevalent ongoing use of a once-through fuel cycle, it is envisioned that non-OECD country demand for uranium resources will impact NEA countries during the next decade and certainly during the following decades. Further rises in the price of uranium are expected along with an increase in price volatility, which will influence fuel cycle decisions in NEA countries. It is notable that large reactor constructors are securing their supplies of uranium through moving into uranium mining.

Production capacity is expected to be adequate to meet the demand in the near term, even for high growth scenarios. However, this would require that existing and committed plans of capacity expansion are achieved in a timely manner. Even with favourable market conditions, this will be a challenge for the industry, due to the scarcity of resources in the ongoing financial crisis, but principally because of the considerable time that it takes to develop a uranium mine in most jurisdictions and the challenge of keeping mine production at or near production capacity.

Recommendation 2

To support nuclear development, governments would need to:

- a) ensure that the necessary approval processes are as efficient as possible;
- b) ensure that there is a longer-term plan for assuring resource sustainability, given the long timescales of nuclear power plant operations;
- c) encourage efforts and technological investment to develop uranium from conventional and unconventional sources.

Overall in uranium mining, the sustainability trends are slightly positive, especially in relation to development of *in situ* leaching in uranium mining and promulgation of best practices, with improved environmental performance and reduced occupational radiation exposures.

The generally stronger uranium market has spurred the development of production capability and exploration activities, which in turn, have resulted in an increased resource base. This expansion phase has encouraged newer, less established mining companies and producer nations to enter the market. This may pose some challenges, as new entrants may not be as aware of current international standards and optimal methods; hence the adoption and promulgation of best practices are of particular importance.

Recommendation 3

Governments and industry should work together to ensure that best mining practices are adopted by all players, especially new entrants to the market and developing countries with less established regulatory systems.

With regard to conversion and enrichment, capacity seems adequate if the trend towards replacement of gaseous diffusion by centrifuges continues at the current rate and will be enhanced if laser enrichment achieves commercial implementation. However, the latter is not expected to contribute significantly in the next decade.

5.1.2. Reactor operations

LWRs employing the once-through fuel cycle have remained and will remain, in the near term, the predominant reactor type worldwide, with prospective programmes of new build mostly based on LWR technology.

Partial recycle, through the use of REPU and MOX fuels has not increased significantly, held back essentially by political decisions and partly by limited fabrication capacity and issues of commercial competitiveness, as not all back-end benefits relating to waste management and fuel cycle flexibility are internalised by some utilities. However, expansion is expected and has been already registered in recent years (in France in particular, but also in other countries like Japan), with benefits in resource utilisation and waste management. Fast growing countries, relying on nuclear energy, such as China and India, have adopted reprocessing and recycling options.

Positive trends in the last decade include: the optimisation of fuel assembly designs and behaviour, the gradual increase of load factors and power upratings, the adoption of higher burn-ups and longer fuel cycles as well as system life extension in reactor operations. Changes in these areas are expected to continue in the next decades. Whereas most of these changes have been motivated by the industrial drive to enhance efficiency, reliability and ultimately the economics of systems and facilities, in many cases they have also benefitted, to a different extent, sustainability aspects such as safety, environment, resource utilisation and waste management. Some of these changes have also posed new challenges; for instance those associated with increasing burn-up, including the potential impending requirements to re-license some enrichment plants (due to criticality constraints from higher initial fuel enrichment); or its back-end implications, as increased transuranic fission and activation product inventories are generated in spent fuel from higher burn-ups along with increased decay heat and neutron sources.

While the main driver to higher burn-ups has been the economics of NPP operations, this can be undermined by the complex and interdependent impacts that this practice has on the back end of the fuel cycle. Consequent changes in conditions of systems for storage, transport, conditioning and reprocessing of the fuel will modify and complicate the operational requirements of these processes, increasing their costs.

Recommendation 4

A holistic view of the overall economy of the fuel cycle (including long-term waste management) should be developed, which carefully assesses the respective advantages and disadvantages.

More generally, as established LWR systems and fuel cycle facilities will continue to dominate up to the latter part of the century, with some prospective alternative uses such as small and medium reactors and high conversion thermal reactors, further research towards their improvement will be important to further enhance resource utilisation and waste management, while addressing some of the challenges emerging from recent trends.

The next few decades will also see the introduction of Generation III/III+ reactors and the phasing out of all but the newer Generation II designs. This, in itself, adds significantly to the enhancement of the sustainability elements in safety, economy and environmental protection, as these newer designs have derived benefit from lessons learnt in previous generations. However, it depends greatly on conducive market conditions favouring low-carbon technologies and means to ensure that nuclear construction risks are not perceived by investments as disproportionately high.

Recommendation 5

For those countries wishing to pursue nuclear development, government fiscal policy must support energy policy so that industry can better manage risk, particularly as it relates to the implementation of new technology characterised by long lead times. Market incentives could also be implemented to encourage investment in other low-carbon technologies such as nuclear power.

5.1.3. Back end of the fuel cycle

Reprocessing capacity is currently limited to five countries. Evolutionary changes have occurred with this technology, including improvements towards greater efficiency, reduction of the level of discharges to the environment, provision of higher flexibility and enhancements in the ultimate vitrified waste. Commercially there have been no major technology changes, but over the past decade extensive research and development has been performed on the continuous improvement of current PUREX plants, as well as advanced separation methods, driven, for instance, by the interest in moving to technologies that do not separate solely plutonium. Advances in this area will be linked to the introduction of Generation IV reactors and advanced fuel cycles.

Disposal of spent fuel and high-level waste remains an important issue, as no repositories exist yet.¹ More governments have accepted that deep geological repository is the appropriate approach. Although a high profile setback (Yucca Mountain) has occurred, some positive progress has been made in several countries (Canada, Finland, France, Sweden, Switzerland and the United Kingdom) with advancements in technologies benefitting from the experience acquired in underground laboratories. Although at this stage there is no clear consensus on their application and different countries adopt different approaches, the concepts of retrievability and reversibility have received significant attention, motivated by the ability to benefit from future scientific and technical progress, the potential economic valuation of the waste and entrusted freedom of decision to future generations.

Good progress has been achieved during the last decade in relation to the involvement of stakeholders in decision-making and in the reinforcement of legal and institutional frameworks for spent fuel and radioactive waste management. This needs to continue if there is to be credibility in the claims about progress towards sustainability.

1. While HLW represents the main challenge for the future of radioactive waste management, policies also need to take into account the other categories of radioactive waste, establishing appropriate long-term management solutions. The technology for the treatment, storage and disposal of VLLW, LLW and ILW is well developed and disposal facilities operate in most countries.

Recommendation 6

Progress towards implementation of deep geological repositories must remain a high priority as it is crucial for the future sustainability of nuclear energy, regardless of the fuel cycle strategies adopted.

Extended operational periods of interim storage facilities may be needed pending implementation of permanent repositories. Knowledge of the longer-term integrity and retrievability of SNF and the mechanisms that may degrade the fuel and fuel structure in the different storage systems will be crucial. High confidence in the integrity of SNF during longer-term storage, adequate for transportation and possibly reprocessing are important considerations for informed fuel cycle decisions (MIT, 2011).

Recommendation 7

Research on spent fuel interim storage should continue, including comprehensive studies on degradation mechanisms as well as regular inspections of spent fuel (in particular that having been subjected to high burn-up).

Recommendation 8

Research, development and demonstration (RD&D) will still need to be carried out and in many instances further enhanced, in order to optimise solutions and to move from results obtained in laboratories and pilot facilities to industrial-scale implementation in waste repositories.

Further challenges include:

- Licensing. Regulatory activity and capabilities to license repositories will require new developments both on the side of regulators as well as on that of implementers of radioactive waste management.
- Stakeholder confidence. Public acceptance of waste management activities and especially of HLW and SNF disposal will continue to be crucial.
- Knowledge retention through the long periods of time involved in repository development will be a further challenge.

The concept of regional and transnational repositories has also been discussed, in recent years, with particular significance especially for many small and populated countries, where it would be neither economical nor environmentally possible to site deep geological repositories.

5.2. Advanced fuel cycles

As projections have not indicated immediate constraints from shortage of resources, there has been little incentive to significant investment in advanced fuel cycles (including the thorium cycle) and/or in closing the fuel cycle.

However, it has become clear that step changes in sustainability are linked to the deployment of advanced fuel cycle technologies. The development and uptake of such advanced options cannot be driven purely by market forces, being primarily determined by national energy policy considerations and strategic choices, which today are not defined or internationally consistent. Opportunities for industry to promote the sustainability agenda are limited.

The commercial deployment of Generation IV nuclear reactors is an important step in this respect. These reactors are being developed with the objective of enhancing the safety, economics, sustainability, proliferation resistance and physical protection of future nuclear systems (GIF, 2002). They also hold the promise of opening nuclear

applications beyond today's electricity production (e.g. for process heat and hydrogen production), which could significantly expand the role that nuclear energy could play in the future (NEA, 2002 and 2009). Several such reactors are based on fast neutron spectra and can be operated in closed fuel cycles. Full closure of the fuel cycle through the introduction of fast breeder reactors and their fully integrated cycles, would greatly decrease the requirement for fresh uranium, prolonging the lifetime of its resources, whilst offering waste minimisation advantages. However, even in countries with well developed nuclear energy infrastructure and industry, it is expected that the transition from thermal to fast neutron (i.e. some Generation IV) systems will require significant efforts of adaptation and the commissioning of new facilities. The infrastructures to be reviewed and eventually adapted include laboratories and other research equipment, legal and regulatory frameworks, as well as human resources (NEA, 2009).

Education, training and knowledge management 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 or the nuclear renaissance and transitioning from thermal to fast neutron systems.

Recommendation 9

Governments will need to ensure that adequate regulatory frameworks and associated resources (both infrastructure and human) are available in those countries wishing to implement the transition to fast neutron systems.

Accurate analysis of the opportunities and challenges raised by the thermal-to-fast-neutron transition period is needed (in the policy arena) to support sound decision-making. For example, the management of recyclable fissile and fertile materials requires infrastructure and facilities that are unlikely to be technically and economically viable in all countries where nuclear power plants are or will be operated. The implementation of multinational, regional and/or international facilities could provide a broader range of options to all countries including those with small- or medium-sized nuclear power programmes that could result in optimised options from a global viewpoint. Key issues such as safety, proliferation resistance and physical protection may be addressed more effectively through international co-operation, including international agreements on regulatory frameworks (NEA, 2007 and 2002).

The adoption of fast reactors and accelerator-driven systems as burners can specifically target advanced waste management solutions, pursuing the sustainability objective of reducing the mass and radioactivity of wastes going to final disposal.

Used in symbiotic configurations with LWRs, advanced systems can offer innovative waste management options; for instance, "double strata" schemes concentrate hazardous highly radioactive radionuclides (Pu and MAs) in a separate part of the fuel cycle where these radioisotopes can be burnt through multi-recycling and therefore removed from the ultimate waste.

Over the past decade numerous countries have devoted extensive effort to the research and development of advanced separation methods. However, to accelerate progress, co-ordinated research into advanced reprocessing methods, including the achievement of full scale processes, will become more critical.

Partly driven by the interest in moving towards technologies that do not extract pure plutonium, enhancing the proliferation resistance of reprocessing, research in this area has also been aimed at the development of advanced processing techniques for the separation (partitioning) of MAs (but possibly some FPs too).

P&T allows the selective separation of these radioisotopes and their subsequent transformation into shorter-lived elements by fissioning or neutron capture (in FRs or ADS), holding the promise to reduce substantially the long-term radiotoxicity, heat and volume of waste.

It should be noted, however, that the incorporation of heavy MA inventories in fuels and targets will involve the handling of materials with very high activity levels, requiring new handling techniques and enhanced radioprotection measures.

In general, substantial R&D is still required to advance Generation IV systems, advanced fuels, fuel separation methods and transmutation technologies, together with waste management issues linked to new systems, such as new conditioning processes, characterisation and optimisation of waste streams from new FCs, etc. This calls for continued international co-operation, through programmes like GIF and INPRO that have become increasingly important in pooling R&D efforts towards common goals, but also for the support and involvement of governments in trying to secure the technological knowledge for new nuclear applications.

Recommendation 10

International co-operation on advanced reactors and separation technologies should be further promoted as the most effective way of closing the fuel cycle and reducing long-lived radioactive waste inventories.

Recommendation 11

Research on advanced fuel cycles should seek integrated holistic approaches, encompassing assessments of system-wide technologies from advanced fuel development through to recycling (separation) and waste forms.

Thorium FC

Depending on the price of uranium as well as recycling and back-end costs, the adoption of a thorium fuel cycle could reach commercial viability. However, so far the technology has not offered sufficient incentives to easily penetrate the market.

The successful large-scale reactor technology demonstration efforts conducted in the past suggest that there should not be insurmountable technical obstacles preventing the use of Th fuel and its fuel cycle in the existing and evolutionary LWRs. However, reprocessing and refabricating of UTh-fuels call for significant research and development efforts, including the implementation of remote fuel fabrication capabilities and adequate radiation protection and non-proliferation measures and the industrial infrastructure. Research, design and licensing data are not in place to warrant a deployment of thorium fuels in current reactors in the short term.

Options for the use of thorium-based fuels in closed fuel cycles in light or heavy water reactors alone or in symbiotic generating fleets with fast reactors are more appealing in terms of resource utilisation. The Generation IV International Forum considers molten salt reactors operating with a uranium-thorium fuel cycle as a potential long-term alternative to uranium-plutonium fuelled fast neutron reactors. However, advanced applications of thorium with full recycle of ^{233}U are only achievable in the long-term, as they still require considerable research efforts and technological developments, as well as feasibility and economic studies to prove their commercial viability.

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Annex 2. Acronyms

ABWR	Advanced boiling water reactor
ACR	Advanced CANDU reactor
ADS	Accelerator-driven system
AECL	Atomic Energy of Canada Ltd.
AGR	Advanced gas reactor
AHWR	Advanced heavy water reactor
APWR	Advanced pressurised water reactor
ATR	Advanced test reactor
BWR	Boiling water reactor
CEFR	China experimental fast reactor
CNNC	China National Nuclear Corporation
EEA	European Environment Agency
EISD	Energy Indicators for Sustainable Development
EPR	European pressurised reactor
ESBWR	Economic simplified boiling water reactor
EU	European Union
Euratom	European Atomic Energy Community
EW	Exempt waste
FBR	Fast breeder reactor
FOAK	First-of-a-kind
FP	Fission product
FR	Fast reactor
GCR	Gas-cooled reactor
GFR	Gas-cooled fast reactor
GHG	Greenhouse gas
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership
HDI	Human development index
HEU	Highly enriched uranium
HLW	High-level waste
HM	Heavy metal
HM-MOX	High moderation MOX
HTR	High-temperature reactor
HWR	Heavy water reactor

IA	Impact assessment
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IFNEC	International Framework for Nuclear Energy Co-operation
ILW	Intermediate-level waste
INPO	Institute of Nuclear Power Operations
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
IPCC	Intergovernmental Panel on Climate Change
ISL	<i>In situ</i> leaching
JAEA	Japan Atomic Energy Agency
JNFL	Japan Nuclear Fuel Limited
KAERI	Korea Atomic Energy Research Institute
KHNP	Korea Hydro Nuclear Power Co., Ltd.
KNFC	Korea Nuclear Fuel Co., Ltd.
KRWM	Korea Radioactive Waste Management Co., Ltd.
LCA	Life cycle analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LEU	Low-enriched uranium
LFR	Lead-cooled fast reactor
LILW	Low- and intermediate-level waste
LLW-SL	Low-level waste, with short-lived radionuclides
LWGR	Light water-cooled graphite-moderated reactor
LWR	Light water reactor
MA	Minor actinide
MCA	Multi-criteria analysis
MDEP	Multinational Design Evaluation Programme
MHI	Mitsubishi Heavy Industries
MSR	Molten salt reactor
MOX	Mixed oxide
NDC	Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle
NEA	Nuclear Energy Agency
NFC	Nuclear fuel cycle
NGNP	Next generation nuclear plant
NPP	Nuclear power plant
NRC	Nuclear Regulatory Commission (United States)
NTI	Nuclear Threat Initiative
NUE	Natural uranium equivalent

NULIFE	Nuclear plant life prediction
NUMO	Nuclear Waste Management Organization of Japan
OECD	Organisation for Economic Co-operation and Development
P&T	Partitioning and transmutation
PBMR	Pebble bed modular reactor
PCI	Pellet-cladding interaction
PFBR	Prototype fast breeder reactor
PHWR	Pressurised heavy water reactor
PP	Physical protection
PR	Proliferation resistance
PR&PP	Proliferation resistance and physical protection
PUREX	Plutonium and uranium extraction
PWR	Pressurised water reactor
R&D	Research and development
RAR	Reasonably assured resources
RD&D	Research and development and deployment
REPU	Reprocessed uranium
RMWR	Reduced moderation water reactor
RRP	Rokkasho Reprocessing Plant
RPV	Reactor pressure vessel
RRZs	Restricted release zones
SCWR	Supercritical-water-cooled reactor
SEA	Strategic environmental assessment
SET-Plan	European Strategic Energy Technology Plan
SFR	Sodium-cooled fast reactor
SNETP	Sustainable Nuclear Energy Technology Platform
SNF	Spent nuclear fuel
SMR	Small and medium reactor
TBP	Tri- <i>n</i> -butyl phosphate
TMI	Three Mile Island
TPES	Total primary energy supply
TRP	Tokai Reprocessing Plant
TRU	Transuranium
UN	United Nations
UNDES	United Nations Department of Economic and Social Affairs
UOX	Uranium oxide
UREX	Uranium extraction
USEC	United States Enrichment Corporation
VHLW	Vitrified high-level waste

VHTR	Very high-temperature reactor
VLLW	Very low-level waste
VVER	Vodo-Vodianoy Energetichesky Reactor (water-cooled, water-moderated power reactor)
WNA	World Nuclear Association

Units

billion	1 000 million
G	Giga = 10^9
k	kilo = 10^3
M	Mega = 10^6
m	milli = 10^{-3}
T	Tera = 10^{12}
GWe	gigawatt electric
GWth	gigawatt thermal
GWd/t	gigawatt-days per tonne
kWh	kilowatt-hour
Mtoe	million tonnes of oil equivalent
ppb	parts per billion
SWU	separative work unit
tHM	tonnes of heavy metal
toe	tonnes of oil equivalent
tU	tonne of uranium
/y	per year

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Trends towards Sustainability in the Nuclear Fuel Cycle

Interest in expanding nuclear power to cope with rising demand for energy and potential climate change places increased attention on the nuclear fuel cycle and whether significant moves are being taken towards ensuring sustainability over the long term. Future nuclear power programme decisions will be increasingly based on strategic considerations involving the complete nuclear fuel cycle, as illustrated by the international joint projects for Generation IV reactors. Currently, 90% of installed reactors worldwide operate on a once-through nuclear fuel cycle using uranium-oxide fuel. While closing the fuel cycle has been a general aim for several decades, progress towards that goal has been slow. This report reviews developments in the fuel cycle over the past ten years, potential developments over the next decade and the outlook for the longer term. It analyses technological developments and government actions (both nationally and internationally) related to the fuel cycle, and examines these within a set of sustainability parameters in order to identify trends and to make recommendations for further actions.