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Trends towards Sustainability in the Nuclear Fuel Cycle

Executive Summary

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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 generally increased mining costs and challenging approval processes, in association with the depletion of secondary uranium resources, 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

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.
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.

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 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 emcompass 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.

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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.

OECD Nuclear Energy Agency
12, boulevard des Îles
92130 Issy-les-Moulineaux, France
Tel.: +33 (0)1 45 24 10 15
nea@oecd-nea.org **www.oecd-nea.org**

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