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Management of Recyclable Fissile and Fertile Materials

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NUCLEAR ENERGY AGENCY
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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full member. NEA membership today consists of 28 OECD member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

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FOREWORD

The main objective of the study on recyclable fissile and fertile materials, carried out under the auspices of the NEA Committee on Technical and Economic Studies on Nuclear Development and the Fuel Cycle (NDC), was to provide policy makers with an overview of key issues raised by the management of such materials. The study was carried out by a group of experts which collected and analysed data and information on inventories of recyclable materials and on technologies available or under development for their management.

The study focuses on policy and strategic issues, with emphasis on impacts of technology choices and timing of the development of alternative reactor types and fuel cycle schemes on the potential energetic value of recyclable materials.

The study's conclusions highlight the importance of recyclable fissile and fertile materials in view of future nuclear energy development, taking into account sustainable development goals. In addition, the analyses show that technical options are available or under development for the management – by means of recycling and/or disposal – of all material inventories.

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The availability of recyclable fissile and fertile materials that may provide new fuel for existing and future nuclear power plants is a key, nearly unique, characteristic of nuclear energy. The choice of management options for those materials is determined taking into account two major aspects: adequacy of processes and measures to ensure their safe, environmentally sound and economically viable handling, storage and/or reuse, and eventual disposal; and optimisation of their value in the overall energy context of a given country at the world level.

The present report, prepared by an *ad hoc* Group of Experts under the auspices of the Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC), aims at providing insights on the challenges raised and the opportunities offered by the management of recyclable fissile and fertile materials. While it contains some numerical data and technical information, it focuses mainly on policy issues of relevance for decision makers in governmental bodies and the industry.

The study includes an overview on the inventories of recyclable fissile and fertile materials available worldwide based on inputs from participants and estimates drawn by the Secretariat from a literature survey. It shows that the amount of materials potentially recyclable represents an energy content not to be overlooked. If all the challenges and barriers to the recycling of available materials would be overcome, these materials could provide fuel for a fleet of current generation light water reactors (LWR) with a total capacity of at least 100 GWe – roughly the US installed nuclear capacity – during nearly 40 years.

Recyclable materials include a variety of products, including depleted uranium from enrichment plants, uranium and plutonium issued from the reprocessing of spent fuel, plutonium and highly enriched uranium declared excess to national security by Russia and the United States, and stockpiles of thorium. The inventories of materials that are not being processed in nuclear fuel cycle facilities are stored in different physical and chemical forms on various sites. In all OECD countries, stringent regulations and norms are in place regarding the transport, storage and processing of those materials ensuring that their health and environmental impacts are as low as reasonably achievable.

A thorough review of management options available to store, re-use or dispose of recyclable materials demonstrates that a range of technically-, environmentally- and economically-viable solutions are in place or being developed for all materials. Extended interim storage is a relevant short- to medium-term option but it is not a long-term solution. All options will require eventually the disposal of ultimate radioactive waste but some alternatives reduce the volumes and radiotoxicity of ultimate waste more than others. Repository designs and sizes should be adapted to the options adopted.

The evaluation of options for the management of recyclable materials from a policy-making viewpoint should take into account their economic, environmental and social aspects in a comprehensive assessment carried out in the framework of sustainable development. A prerequisite to decision making in this field is to identify irreversible measures which would foreclose the choice of

other options at a later date. Generally, reversibility is a desirable characteristic as it keeps open the possibility of re-considering options in the future, taking advantage of technology progress and changes in the socio-economic landscape.

The energy content that may be recovered from recyclable fissile and fertile materials varies dramatically depending on the recycling options that will be chosen and the strategies adopted for their implementation. The fresh uranium consumption of nuclear energy systems of current generation could be reduced by 50% through reprocessing spent fuel followed by recycling of the retrieved uranium and plutonium rather than adopting the once-through fuel cycle. Advanced systems, in particular those based on fast neutron reactors, could multiply by more than 50 the energy produced per tonne of natural uranium and facilitate the recycling of minor actinides.

The driving factors when comparing options for the management of recyclable materials are mainly strategic, social and environmental. Issues such as security of energy supply, stewardship burden imposed on future generations and proliferation resistance have a much larger impact on the assessment of alternatives than variations in the fuel cycle cost which in any case represents today less than 20% of the total cost of electricity generated by nuclear power plants.

All the options that may be considered for the management of recyclable materials require specific infrastructures which might be difficult to implement, finance and operate at the national level, especially for countries having rather small nuclear energy programmes. International collaboration could provide solutions better optimised from a global viewpoint, reducing costs, improving effectiveness and enhancing proliferation resistance.

While a number of options for the management of recyclable materials are technically and industrially mature, R&D is required for the development of more advanced approaches and also for improving the performance of options already in place. Bilateral and multilateral collaborations could facilitate research in this domain and accelerate the design and implementation of globally effective options.

Chapter 1

INTRODUCTION

1.1 Background

After several decades of commercial operation of nuclear power plants for electricity generation, a significant amount of "by-products" containing fissile and/or fertile materials has been accumulated worldwide. In addition, some materials formerly used for military purposes have been declared excess to national security by the Russian Federation and the United States and may be used for civil applications of nuclear energy.

The possible utilisation of those products through their recycling was recognised early on. Consequently, extensive research and development activities have been carried out on the technical feasibility of recycling some fissile materials, in particular plutonium and minor actinides.

On the other hand, the disposal of radioactive materials, including those which may be recycled, has been investigated in most countries using nuclear energy, and repository concepts have been developed aiming at safe and reliable solutions ensuring adequate health and environmental protection.

Today, while recycling already is an industrial reality in some countries and for some materials, it is not widely implemented. When considering long-term scenarios of nuclear energy development, it is of high interest to evaluate the potential offered by recycling inventories and future arising of fissile and fertile materials in terms of economics and resource management, taking into account as well the social dimension of sustainable development.

The goals of sustainable development include maintaining natural resource assets. In this context, recycling is an obvious means to use more efficiently limited, non-renewable natural resources and thereby to enhance the sustainability of nuclear energy systems. Recycling fissile and/or fertile materials for improving the overall efficiency of the nuclear fuel cycle is of particular interest when contemplating a revival of nuclear energy programmes in the world, potentially leading to drastically increasing demand for nuclear fuel and radioactive waste repositories.

The present study on the management of recyclable fissile and fertile materials was undertaken under the umbrella of the Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC). It was carried out by an *ad hoc* Group of Experts from member countries; the International Atomic Energy Agency (IAEA) participated in the work, and provided data and information on non-OECD countries. The Group met four times between September 2005 and November 2006 to refine the scope of the study, collect and analyse data and finalise its report.

1.2 Objectives, scope and approach

The overall objective of the study was to investigate strategic issues related to the decision of whether or not to recycle fissile and fertile materials. The analysis covers to some extent scientific, technical and economic aspects of recycling but emphasis is placed on topics of relevance for policy makers. The analyses presented in this document were carried out by the Group of Experts in charge of the study and are based mainly on data and information provided by participants. In addition, findings and conclusions from previously published literature, including recent OECD/NEA and IAEA publications, were used whenever relevant.

The framework of sustainable development serves as a backdrop for evaluating benefits and drawbacks of different strategies for managing recyclable materials. Alternative options and strategies are examined with emphasis on investigating how recycling responds to the economic, social and environmental criteria.

It was recognised by the Group that country specific circumstances are driving factors in the choice of fuel cycle options and that ultimately national strategies will be determined by local factors. Therefore, the study aims at highlighting key issues raised by alternative options for the management of recyclable materials rather than at a comparative assessment of those options.

The study covers all fissile and fertile materials that may be recycled, including:

- spent fuel (from commercial power reactors);
- depleted uranium (from enrichment tails);
- uranium arising from reprocessed commercial power reactor fuel;
- ex-military materials declared excess to national security by the Russian Federation and the United States;
- plutonium arising from reprocessed commercial power reactor fuel; and
- thorium inventories.

The data provided by participating experts and compiled by the Secretariat were used as the basis for quantitative analysis of the amounts of recyclable materials available. The data provided by member countries to the NEA Secretariat for the Brown Book (NEA, 2006a) and Red Book (IAEA and NEA, 2006) were used whenever relevant and the IAEA provided data on non-member countries drawn from its data bases.

Beyond numerical data, national experts participating in the study also provided qualitative information on the situation in their respective countries including national policies regarding nuclear energy and fuel cycle options. This information gave some insights on the drivers of national policies.

1.3 The study in perspective

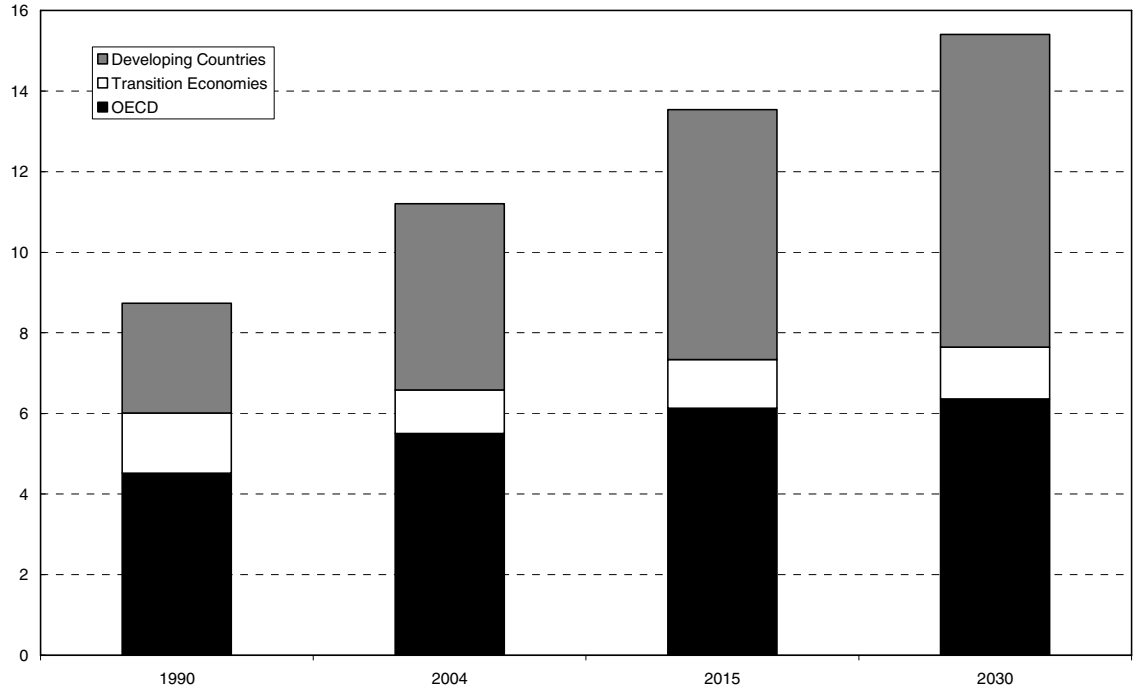
Investigating options for the management of recyclable materials seemed especially relevant in the present energy demand and supply situation and while the role of nuclear energy is being reconsidered in many countries. According to all recent international studies – see for example the *World Energy Outlook* of the International Energy Agency (IEA, 2006) – energy demand will continue to rise worldwide, although analysts call for even more emphasis on energy efficiency in policy making. On the supply side, nuclear energy attracts interest for security and environmental reasons.

In this context, adequate management of recyclable materials will become increasingly important. The volumes of such materials will grow automatically as more nuclear electricity is generated and their safe management will be essential in a sustainable development perspective. Furthermore, their energy content may become a key asset, as a complement to fresh natural resources, for secure supply of nuclear fuel in the long term.

Although in OECD countries energy demand growth is expected to be modest and economies in transition are projected to keep their demand below 1990 levels for several decades, rapid economic growth in developing countries will drive total requirements to ever increasing levels. In Asia and South America in particular, energy demand is expected to grow steadily as population increases and industrialisation proceeds.

The scenarios of the IEA *World Energy Outlook 2006* illustrate the type of energy demand developments expected by analysts. The reference scenario projects a 1.6% per year increase of total energy demand in the world up to 2030 and the alternative scenario, which postulates significant policy measures to limit demand, projects a 1.2% per year increase (see Figure 1.1).

Figure 1.1 Total primary energy demand in the world (Gtoe)
WEO 2006 alternative scenario



Security of energy supply is a concern for policy makers in particular in OECD countries with limited natural resources. Several production disruptions and threats on adequate delivery from key producers have created tensions in the world market followed by increases in the price of fossil fuels, in particular oil and gas. Also, the use of fossil fuels generates inevitably carbon dioxide, whose anthropogenic emissions are considered by most experts as responsible for global warming. As a consequence of those two concerns – security of supply and global climate change – many OECD countries are showing renewed interest in nuclear power as a source of secure, economic and non-polluting electrical energy.

When environmental impact is being considered, carbon dioxide emission is not the only indicator. It is necessary to take into account the quantity of fuel that is required by different types of electricity generating plants to produce a given amount of electricity, together with the quantities of greenhouse and other potentially polluting gases and solid waste arising. Many comprehensive studies have been published on comparative assessment of alternative options for electricity generation covering all aspects of environmental burdens; the ExternE reports (EC, 1995 and 1999) constitute an authoritative reference in the field.

A comparison limited to annual fuel consumptions, CO_2 emissions and ash arising for 1 000 MWe power plants operating at 80% load factor, i.e. generating 7 TWh per year, is shown in Table 1.1. It is based on typical average quantities for state-of-the-art plants. The data shown relate only to the combustion/utilisation of fuel at the generating plant site; they do not include quantities and emissions in any "pre-combustion" activities that take place off-site, e.g. mining and transport of the fuel.

The data shown have been suitably rounded and are presented as typical values to indicate the relative impact of generating electricity by using different fossil fuels as compared with the nuclear option. Fuel from different geographic sources have different characteristics and these dictate the specific quantity of fuel required and amount of carbon dioxide released and ash produced. In broad terms, a range of plus/minus 25% can be applied to the fossil fuel and uranium ore data shown in order to take into account global diversity in fuel sources.

Table 1.1 Illustrative characteristics of nuclear and fossil-fuelled power plants (quantities for the generation of 7 TWh of electricity)

Fuel type	Quantity of fuel (tonnes)	CO_2 released (tonnes)	Ash produced (tonnes)
Hard coal	3 500 000	7 200 000	280 000
Oil	1 700 000	5 000 000	35 000
Natural gas	1 600 000	4 000 000	small
Uranium in PWR		0	very small
Ore	50 000		
U_3O_8	200		
Enriched U	30		

1.4 Nuclear fuel cycle and fossil fuels

The generation of electricity in thermal power plants requires a source of heat. Worldwide, the vast majority of these plants use fossil fuels, such as coal, natural gas or oil as the heat source. In the case of nuclear power plants, the heat is derived from the controlled fission of fissile materials, such as uranium and plutonium. The two types of plants have very different characteristics in terms of fuel/fuel cycle. The possibility to recycle spent fuel discharged from the power plant after its first use is unique to nuclear systems.

Nuclear and fossil fuels differ significantly regarding their preparation, use and environmental burdens. Regardless of which type of fossil fuel is used, its fuel cycle is of relatively short duration, measured in weeks or months. By contrast, the nuclear fuel cycle is of relatively long duration and involves a number of stages for the production of a fuel assembly suitable for use in the reactor. These front-end stages take about two to three years.

The vast majority of nuclear power plants currently in operation around the world use uranium fuel which has been processed to increase its content of ^{235}U atoms. Before this enrichment process takes place, uranium ore is mined and concentrated in the source country prior to shipment of the concentrate (uranium oxide, U_3O_8) to a plant where it is converted and enriched. After enrichment the uranium is fabricated into a fuel assembly. Each assembly spends about three to four years in the reactor steadily providing heat, before it has to be removed and replaced with fresh fuel.

When a fossil fuel is burned, its usable energy content is totally consumed; all that remains is waste material. On the other hand, on its removal from the reactor the "spent" nuclear fuel contains materials recyclable to produce more energy and only a very small amount, a few percent, of this spent fuel is truly waste material. The vast majority of it, more than 90%, is unused uranium together with a small amount, a few percent, of a man-made nuclear fuel, plutonium.

Another key difference between fossil and nuclear fuel is their respective economics. Whilst the capital investment and construction time for a nuclear power plant is greater than for a fossil-fired plant, the nuclear fuel cost is a much smaller component of the total cost of generating a unit of electricity. In broad terms, the cost of fossil fuel accounts for some 40 to 80% of the total generating cost, whereas the cost of nuclear fuel accounts for less than 20% of the total for nuclear unit in operation today. Against a background of volatile and rapidly increasing fossil fuel prices, this gives the nuclear option a strategic, long-term advantage.

When fossil fuels are burned there is an instantaneous release of heat accompanied by the production of a number of gases of which the most potentially damaging for the environment are carbon dioxide, a greenhouse gas, and sulphur dioxide and nitrogen oxides, sources of acid rain and smog. Small quantities of these gases are trapped by pollution control devices but most of them are discharged into the atmosphere, usually via a tall stack.

The combustion process also gives rise to solid waste in the form of ash residues, some of which are removed from the gaseous discharge but the bulk of which fall to the base of the boiler from where they must be removed. Coal produces by far the largest amount of ash, which are slightly radioactive; oil relatively less and gas by far the smallest amount. A limited quantity of this ash is recycled into building materials; but most of it has to be disposed into the ground as waste.

Nuclear fuel, on the other hand, has to be cared for beyond its stay in the reactor. Spent nuclear fuel can be processed to recover the re-usable materials that it contains or it can be stored during the time needed for its cooling and disposed of eventually after adequate conditioning. The existence of two options offers policy makers opportunities to design and implement the alternative best adapted to their specific context and goals.

If recycling is chosen, the fissile material must be separated from the small amount of waste it contains. Chemical processes have been developed and perfected over the past 50 years to allow this to be done. The generic term "reprocessing" has been given to these processes. When reprocessing is undertaken in the short term, the fuel cycle is usually referred to as closed. Reprocessing allows the predominant quantities of uranium and plutonium to be recovered and made available for recycle; the small quantity of highly radioactive waste material can be treated, stored and eventually, safely disposed.

If recycling is not the chosen option, spent fuel can be safely stored for prolonged periods before eventual disposal. A number of different engineering options have been developed to enable spent fuel to be suitably packaged before its final disposal in adequate repositories such as stable, geologic formations. This option for spent fuel management is termed the open fuel cycle. The ability to safely

store spent fuel for prolonged periods maintains the option to move from an open fuel cycle to a closed one at some future time. It is only at the point of disposing the packaged, spent fuel without intent/feasibility to retrieve it that the option is foreclosed.

In addition to capabilities for recycling fissile materials, some nuclear reactor designs are available that can transform fertile atoms into useful, fissile ones which can then be used in the generation of electricity. For example, neutron irradiation of ^{238}U will produce ^{239}Pu; and ^{233}U can be produced by irradiating ^{232}Th. Fast neutron reactors already operated in several countries and thorium reactors which exist at the concept level are examples of systems capable of breeding.

The ability to recycle fissile material through the nuclear fuel cycle and the ability to breed nuclear fuel by a suitable choice of reactor design are two unique and crucially important features of nuclear power when consideration is being given to the long-term potential of energy systems from a strategic perspective and to sustainable development objectives.

While recognising the potential advantages of recycling, policy makers are sensitive to issues raised by reprocessing and in particular by the separation of plutonium. Therefore, a number of technical and strategic options have been considered recently in various countries and at the international level. These include advanced reprocessing technologies avoiding the separation of plutonium as well as the implementation of international agreements and/or facilities to ensure security of nuclear fuel supply while avoiding the implementation of a large number of reprocessing facilities worldwide.

1.5 Other relevant studies

The NEA has published a number of studies, referred to in the body of the present report, related to the management of recyclable fissile and fertile materials. In particular, extensive NEA work has been devoted to plutonium management and, to a lesser extent, to the management of reprocessed and depleted uranium. Two publications on trends in the fuel cycle (NEA, 2002) and on advanced fuel cycles and waste management (NEA, 2006) investigated alternative fuel cycle options, including closed fuel cycle schemes involving the recycling of fissile materials, mainly plutonium and minor actinides, in a sustainable development perspective. They provide comprehensive information on material flows for a wide range of fuel cycle schemes. Also, they offer indicators that may be used to assess alternative schemes through multi-criteria analysis taking into account the three dimensions of sustainable development.

The IAEA has an extensive programme of work covering many aspects of management of recyclable fissile materials. The bibliography provided at the end of this chapter covers only the most recent documents issued by the IAEA on topics closely related to those issues. More information on the IAEA activities in the field may be found on its web site (http://www.iaea.org/).

In France, after the presentation and discussion of the conclusions of the 1991 Law on long-lived nuclear waste management, a new Law was voted in June 2006 which gives orientations and steps for the future. This Law indicates that studies on partitioning and transmutation have to be continued in close coordination with the development of Generation IV nuclear systems. A fast reactor prototype is planned to be built before 2020. Short-term R&D will be focused on the preparation of a feasibility assessment due to be released in 2012.

Japan has a very active programme of work in the field of recycling. In March 2006, the Japan Atomic Energy Agency (JAEA) reported on the result of a feasibility study on commercialised fast reactor cycle systems. The Ministry of Education, Culture, Science and Technology (MEXT) has

evaluated JAEA report and proposed guidelines for the development of a fast reactor (FR) and fuel cycle system in Japan. The Japan Atomic Energy Commission is reviewing MEXT proposal and will take a decision on Japanese fast reactor and fuel cycle development guideline. Developers, including JAEA, will continue working on new fast reactor and fuel cycle technologies and propose a conceptual system by 2015.

1.6 Overview of the report

The present report includes four chapters and four appendices. Chapter 1 introduces the report, provides background information on its objectives, scope and the approach adopted by the Group in charge of the study. It includes also a short overview on the nuclear fuel cycle in perspective, i.e., as compared with alternative electricity generation sources. Finally, Chapter 1 provides a selected survey of other studies recently published on the management of recyclable fissile and fertile materials.

Chapter 2 reviews the sources of recyclable materials and provides an inventory of those materials based on information supplied by members of the Group complemented by a literature survey and Secretariat estimates. It investigates issues raised by the management of each category of recyclable materials including radiation protection, reactor physics, fuel cycle characteristics and waste management.

Chapter 3 examines the two main management options, noting that long-term storage is only an interim solution, and provides some insights on the strategies that may be implemented for optimising the exploitation of the energy content of recyclable materials and minimising the burdens, including waste arising, from nuclear energy systems.

Chapter 4 summarises the various aspects of management options on the basis of key indicators related to the three dimensions of sustainable development, i.e., environment, social and economics.

Chapter 5 draws findings and conclusions from the study and provides some recommendations that policy makers from governmental bodies and the industry may consider when assessing alternative options for the management of recyclable fissile and fertile materials.

Appendix A gives the list of members of the ad hoc Expert Group who participated in the meetings and/or contributed to the study by providing input data and assisting the Secretariat in drafting the report.

Appendix B is a compilation of numerical data collected for the purpose of the study. It provides an overview on the inventory of fissile materials available in OECD and some non-OECD countries based on data provided by members of the Group complemented by literature survey and Secretariat estimates.

Appendix C provides illustrative projections of nuclear electricity generation and associated uranium demand, and examines supply-demand issues taking into account alternative options for the management of recyclable materials.

Appendix D summarises the experience and viewpoint of a utility on recycling plutonium and reprocessed uranium in a pressurised water reactor.

Appendix E is a comprehensive review of environmental aspects of nuclear energy systems, covering waste streams and effluents, based on extensive literature survey. It includes a broad list of

references and may serve as a backdrop to assess alternative options for the management of recyclable fissile and fertile materials in a broad perspective.

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Chapter 2

INVENTORIES, MANAGEMENT ISSUES AND TRENDS

2.1 Sources of recyclable materials

2.1.1 Materials issued from civil nuclear power plants

The earliest civil nuclear power plants developed in Europe used natural uranium fuel. This fuel required no enrichment of the ^{235}U content and hence no uranium enrichment tails material was produced. However, the fuel could be irradiated to only relatively low levels in the reactor. After discharge, the fuel was promptly reprocessed to separate and recover the unused fissile materials in the form of uranium oxide and plutonium oxide. These materials were highly purified and contained virtually no fission product contamination. Due to low fuel irradiation levels, the uranium and plutonium were of very good fissile quality.

In the United States, civil nuclear power plants using enriched uranium fuel were developed early on, which gave rise to uranium enrichment tails material from the front-end of the fuel cycle. The reprocessing option was abandoned in the late 70s and potentially recoverable fissile materials remained stored in the irradiated fuel.

Early Russian (former Soviet Union) civil nuclear power plant designs used both natural uranium and enriched uranium fuels, thus giving rise to enrichment tails material and recovered uranium and plutonium from reprocessing.

Other countries, notably Canada, developed a nuclear power plant design which, although it used natural uranium fuel, was capable of achieving higher fuel irradiation levels before the fuel had to be discharged from the reactor. Fuel reprocessing was not undertaken, so the fuel did not give rise to any recovered fissile materials at either the front-end or the back-end of the fuel cycle.

As the utilisation of nuclear energy expanded around the world, nuclear power plant designs became focussed more and more on the use of enriched uranium fuel that was capable of high irradiation levels. This gave rise to relatively greater amounts of uranium enrichment tails material at the front-end; on the other hand, the majority of the discharged fuel has not been subject to reprocessing so its unused fissile content remains stored in the irradiated fuel.

The sources of the fissile materials that exist in the civil nuclear fuel cycle and that could be potentially recycled may be summarised as follows:

- uranium enrichment tails material with ^{235}U content of less than 0.7%, typically in the range 0.2 to 0.4%;
- uranium from irradiated fuel reprocessing, commonly referred to as RepU, with ^{235}U content typically in the range 0.4 to 0.8%;

- plutonium from reprocessing irradiated fuel; and
- unused fissile content of irradiated fuel held in storage but recoverable by reprocessing.

Although it is not fissile itself, if the element thorium is irradiated in a neutron flux some of its atoms become ^{233}U which is fissile. This transmutation is analogous to that which occurs when ^{238}U is irradiated to form ^{239}Pu. For completeness, extracted thorium inventories are included in this report as a fertile material that could be utilised as a nuclear fuel in the future.

Thorium occurs naturally in the earth's crust. Natural thorium is made up of virtually 100% ^{232}Th atoms. Monazite sands, containing up to 5-10% thorium, have been found on beaches in Australia, Brazil, Egypt and India and other thorium deposits have been found in the United States. Monazite sands are processed to recover the rare earths, titanium and zirconium; the thorium content usually being left in the process residues (NEA, 2002a). Worldwide exploration efforts to identify thorium ore bodies have been low so far but geologic analyses lead to think that thorium is as abundant as tin, and about three times more abundant than uranium.

2.1.2 Ex-military materials

The development of nuclear weapons preceded the exploitation of nuclear power for peaceful purposes. Earliest weapons were made from highly enriched uranium (HEU) with ^{235}U content higher than 93%. These were followed by weapons based on plutonium, almost all of which was ^{239}Pu. In order to obtain these materials it was necessary to either:

- enrich large quantities of natural uranium feed material, giving rise to large quantities of enrichment tails; or
- reprocess lowly irradiated uranium to separate and recover its plutonium content and, incidentally, its unused uranium content.

These processes gave rise to large stocks of potentially recyclable uranium in the form of enrichment tails and RepU.

Most recently, Russia and the United States have declared a large quantity of weapon-grade material, in the form of highly enriched uranium and plutonium, to be surplus to national security requirements and potentially available for recycling for peaceful purposes through civil nuclear power plants.

2.2 Inventory and energy content of recyclable materials

In 2006 there were some 435 commercial nuclear power plants in operation around the world. Annually, they generate over 2 500 TWh of electricity and require the equivalent of about 70 000 tonnes of natural uranium fuel.

Based on country specific returns and authoritative data, a detailed inventory of the stocks of recyclable materials accumulated at the end of year 2005 is presented in Appendix B. Table 2.1 summarises the information regarding separated materials with suitably rounded numbers. Spent fuel inventories are discussed separately below because their eventual re-use would require an additional reprocessing step prior to their recycling.

The present global stockpile of separated fissile materials shown in Table 2.1 represents in total almost 4 000 reactor-years worth of fuel with existing reactor technology. Put another way, recycling the entire inventory of existing, separated material through currently operating commercial nuclear power plants would provide an additional supply equivalent to some 10 years of present consumption. In comparison with the 85 years corresponding to identified resources of natural uranium (NEA and IAEA, 2006); this is by no means trivial, although it does not represent a dramatic increase in nuclear fuel supplies.

Table 2.1 Inventory of separated recyclable fissile materials at the end of the year 2005

Supply source	Quantity (tHM)	Nat. U equivalent (10^3 tU)	Potential supply reactor-years*
Ex-military HEU	230**	70	420
Ex-military Pu	70	15	90
Pu	320	60	380
RepU	45 000	50	300
Enrichment tails	1 600 000	450	2 650

* based on a 1 000 MWe LWR operating at an 80% load factor.

** Remaining inventories, taking into account the quantities already down-blended and re-used (see section 2.4.2).

Of the materials shown in Table 2.1, the recycling of enrichment tails[1] offers by far the greatest potential. However, most of this tails material is either owned by the enrichment companies, or, in the case of tails material from weapons production, is owned by a national government. Utilities have little or no direct control over the recycling of this material. Furthermore, the capacity, and technology, of enrichment plants currently in operation are not adapted to a massive re-enrichment of tails.

Table 2.1 does not include the very large amount of potentially recyclable material that is contained in spent fuel which is currently being held in storage. To date, a total of about 280 000 tonnes of spent fuel has been discharged from commercial nuclear power plants around the world. Of this, about 80 000 tonnes have been reprocessed, leaving about 200 000 tonnes in storage, the vast majority of which is LWR fuel. In addition, spent fuel is presently arising at a rate of about 10 000 tonnes per annum, increasing the size of the existing stockpile.

The 200 000 tonnes of spent fuel inventory contains potentially re-useable fissile material including plutonium, uranium and minor actinides. Some 1 700 tonnes of plutonium and about 190 000 tonnes of natural uranium equivalent could be recycled with current reactor and fuel cycle technology. If spent fuel inventories were to be reprocessed, the recovered fissile material would provide sufficient fuel to operate all the nuclear power plants in service worldwide at the beginning of 2006 during seven and a half years.

However, the commercial reprocessing plants that are currently in operation or planned have a total production capability of no more than 4 000 tonnes of LWR spent fuel per year and their actual capacity is even lower. It is clear, therefore, that a massive increase in reprocessing capacity would

1. More information on depleted uranium inventories may be found in a previous NEA publication (NEA, 2001).

need to be built if any sizeable portion of the current spent fuel stockpiles were to be reprocessed instead of being disposed directly to the final repository, as is intended under present plans.

Although recyclable fissile material recovered by reprocessing is able to be recycled in existing LWR designs, this may not represent the optimum usage of such material. For example, the plutonium contained in spent fuel stockpiles could be used to start-up fast breeder reactors, with the aim of moving towards the realisation of a sustainable global energy strategy.

In broad terms, a 1 400 MWe fast reactor will require between 10 and 12 tonnes of plutonium for its initial fuel load and first two reloads. After the second reload, or after about two years of full-power operation, the plutonium recovered by reprocessing the fuel downloaded from the fast reactor would allow the system to become self sustaining.

Thus the 1 700 tonnes of plutonium contained in the present stockpile of spent LWR fuel would allow the prompt start-up of some 150 fast reactors of 1 400 MWe installed capacity each. However, the rate at which fast reactors could be introduced to substitute for retiring LWRs would depend on the installed capacity of reprocessing plants capable of extracting the plutonium from the spent LWR fuel stocks (NEA, 1997).

The deployment of advanced reactor designs and fuel cycles based on prompt recycling could increase drastically the lifetime of natural resources of nuclear fuel. Widespread deployment of fast breeder reactors supported by fuel recycling plants would achieve at least a fifty-fold increase in the worth of the presently identified natural uranium resources, extending the lifetime of presently known resources to 4 000 years at least.

A single recycle of current stocks of separated fissile material through present LWRs does not foreclose the option for further recycle through fast reactors at a later time. A single recycling in LWR can be implemented as a transition to future recycling in fast reactors and would reduce the total required reprocessing capacity.

Furthermore, recycling now can offer an individual utility an assured, long term source of fuel over a substantial part of the generating plant lifetime. For example, at the KKG nuclear power plant at Gosgen in Switzerland, the recycle of material made available by reprocessing has provided an assured supply of fuel that will satisfy future demand over the remaining lifetime of the plant (see Appendix D for more detail).

2.3 Recycling and waste management

Besides retrieving the energy content of recyclable materials, another potential benefit of neutron irradiation is the ability to reduce the radiotoxic potential of the waste products that are present in spent fuel (see Figure 3.3). Although the amount of radioactive waste material is extremely small as compared with waste quantities arising from other industrial processes, the public is concerned about the possible risk posed by this waste because it will remain radioactive for many thousands of years.

In the past, strategic and policy issues have driven the choice for or against reprocessing and the recycling of fissile materials. Such issues will continue to play a major role in the development and deployment of advanced fuel cycles, such as multiple recycling schemes with partitioning and transmutation of minor actinides. An increasingly important factor, in addition to enhanced uranium resource management, is the reduction of radioactive waste volumes and toxicity achieved by reprocessing and recycling, and the associated benefits in a sustainable development perspective.

At present, without fast breeder reactors, recycling of plutonium extracted from spent LWR fuel can be implemented only through the use of mixed uranium-plutonium (MOX) fuel for LWRs. Recycling of plutonium in LWR-MOX reduces the radiotoxicity of residual spent fuel if spent MOX fuel is disposed of after one use, i.e. not recycled. Multiple reprocessing and recycling can reduce waste radiotoxicity by a factor of three to ten. Theoretically, separating the plutonium and uranium from the fission products and minor actinides several times could lead to a decrease in the long-term radiotoxicity of waste to be disposed of by a factor of 10. However, this reduction can be obtained only after many decades and if process losses are very small.

Current reprocessing practices already contribute significantly to reducing the volumes of radioactive waste. Whilst each tonne of spent fuel represents around 1.5 m^3 of high-level waste (HLW), less than half of a cubic metre, including 0.115 m^3 of vitrified HLW and 0.35 m^3 of intermediate-level waste (ILW), remains after reprocessing, and further compacting can be achieved before disposal (NEA, 2002a). However, irrespective of the fuel cycle option chosen, the need for a final repository of radioactive waste remains.

2.4 Management opportunities and challenges

2.4.1 Enrichment tails

Tails from previous enrichment operations are readily available in storage facilities and represent by far the greatest potential for fissile material recycling. Based on an estimate that 1.5 million tU of tails material is held in storage, and assuming an average assay of 0.3% ^{235}U, this material could be enriched to yield about 420 000 tonnes of natural uranium equivalent by the use of around 460 million units of separative work (SWU). A second round of enrichment, using tails from the first round, which would have an assay of about 0.14%, would yield a further 130 000 tonnes of natural uranium equivalent. This second round would require the expenditure of a further 590 million SWU.

Currently, the installed capacity of operational uranium enrichment plants totals about 49 million SWU per annum worldwide. Approximately 55% of these plants use centrifuge technology; the remainder use gaseous diffusion technology (NEA, 2002a; IAEA, 2006). A further two plants using centrifuge technology and having a combined capacity of about 10 million SWU per annum are under construction.

For a given amount of separative work, the electrical energy requirement of a centrifuge plant is only some 5%-10% of that required by a plant based on gaseous diffusion technology. Almost all of the enrichment plants have been in operation for a prolonged period and, in financial terms, they have been heavily depreciated. Thus, the cheapest operating costs are associated with the centrifuge plants, and economically, these would be the most favoured for the recycle of tails. Technically, centrifuge plants also possess superior features in that far smaller quantities of uranium hexafluoride can be fed into the process as a discrete campaign.

The present demand for enrichment capacity to satisfy the fuel requirements of nuclear power plants in operation worldwide stands at 37 million WU/y. This figure may be on the low side due to the current effect of HEU down blending. However, based on this figure, enrichment capacity in excess of requirements currently amounts to about 12 million SWU/y. If this surplus capacity were to be deployed on the first round of enriching current stocks of tails material, then the quantity of natural uranium equivalent that could be produced per annum would be about 11 000 tonnes corresponding to some 15% of the world's current demand. At this rate, it would take almost 40 years for the present tails stockpile to undergo this first round of re-enrichment. Noting that there is a further

10 million SWU/y of new capacity under construction, then the above production rate could be increased and the timescale reduced if none of the presently operating plants were retired.

Meanwhile, at present production rates around 60 000 tonnes of tails material will arise each year and this should also be taken into account when evaluating the potential worth of the global stockpile. These future tails will arise from civil operations and their ownership will rest with either the utility or the enrichment company depending on contractual terms. To date, utilities have favoured transferring ownership of tails material to the enrichment companies. At current production rates it will take only 25 years to create a further stockpile equal in size to the present one.

As a broad economic guide, the break-even point for recycling tails material is reached when the price of one SWU equals the price of one kg of uranium ore (U_3O_8) plus the price of converting it to UF_6. This assumes that the cost of storing the tails is negligibly small. Based on previous NEA studies on uranium and fuel cycle component prices (NEA, 2002a and 1994) the price of uranium would have to be at the upper bound and the price of enrichment at the lower bound for the recycle of tails material to be justified purely on economic considerations.

It should be noted that the great majority of the current tails stockpile is the result of military enrichment operations and its ownership remains under government control. The remainder of the stockpile is due to civil operations where the ownership of tails is often transferred to the enrichment company as part of the contractual terms. Under these circumstances, the decision to use spare enrichment capacity to re-enrich tails may be taken on other than strictly economic grounds since marginal cost arguments come into play.

To be chemically suitable for the enrichment process, purified uranium oxide must be converted to the gaseous form, uranium hexafluoride. Whilst the costs associated with this conversion process are modest – some 10 to 15% of the uranium purchase price – it is, nevertheless, an important factor in the economic appraisal of tails recycle.

From an economic viewpoint, it is fortunate that the vast majority, almost 90%, of existing tails are still contained in steel cylinders in the uranium hexafluoride form. The cylinders are initially filled with hot, liquid UF_6. They are allowed to cool over several days. During this period nearly all the UF_6 contracts to a solid state, occupying about 60% of the cylinder volume. The remaining space is filled with UF_6 gas at below atmospheric pressure. UF_6 combines with the iron on internal surfaces to form a protective layer of iron fluoride, thus inhibiting internal corrosion. External corrosion may occur, leading to a breach in the cylinder wall. Experience has shown this to be an extremely rare occurrence. However, because the gas in the cylinder is below atmospheric pressure, if a breach does occur then moist air is drawn into the cylinder until the pressure is equalised. This moist air reacts with the UF_6 content and any exposed iron, resulting in the formation of a dense plug of solid uranium and iron compounds and the very slow production and possible escape of hydrogen fluoride gas.

The safety of storing large quantities of UF_6 tails has to be kept under review, the integrity of the containers being of crucial importance. In some countries, notably France, it is common practice to reconvert the tails UF_6 to a stable, solid uranium oxide form (U_3O_8). In the United States, the DOE is constructing two UF_6 to U_3O_8 conversion plants with the intention of converting to solid form the UF_6 tails material currently held in about 58 000 cylinders; this conversion is planned to start by 2020.

Action to reconvert tails to a solid form reduces the potential chemical hazard but adversely affects the economics of re-enrichment. The longer the decision to re-enrich tails is deferred, the greater the likelihood that safety considerations will force action to convert the UF_6 to a more stable solid form and hence weaken the economic advantage.

Although stocks of tails material represent a major reserve of uranium, only limited recycle has taken place so far. It requires the availability of surplus capacity in centrifuge type enrichment plants plus low operating costs to make the procedure commercially attractive. Over the past 7 years, almost all the re-enrichment of tails material has taken place in plants in the Russian Federation with the resulting natural equivalent uranium being delivered to countries within the European Union at a rate up to 1 200 tU per year, or about 7% of the annual EU nuclear fuel requirement (NEA and IAEA, 2006). Most recently, deliveries have been reduced to about a half this value. In addition, tails material has been re-enriched in the Russian Federation to produce blend stock, at about 1.5% ^{235}U assay, for use in blending down ex-military HEU to low enriched uranium (LEU).

In the United States, the DOE and the Bonneville Power Administration have initiated a pilot project to re-enrich 8 500 tonnes of the DOE tails inventory (at greater than 0.4% ^{235}U). The pilot project is anticipated to produce, over a two-year period, a maximum of 1 900 tonnes of natural uranium equivalent for use by the Columbia Generating Station between 2009 and 2017.

2.4.2 Ex-military highly enriched uranium

The recycling of ex-military HEU offers an opportunity to demonstrate concretely the move to transform "swords into ploughshares". The agreements signed in 1993 between the United States and the Russian Federation pave the way for this recycling but its implementation raises a number of technical, economic, safety and security issues.

To date, about 50% of the 500 tonnes of Russian HEU that was committed to peaceful recycle has been blended down in the Russian Federation and transported to the United States, where it is being sold by the USEC to civil nuclear power plant operators. So far, fuel made from this material has been loaded into more than 90 US power plants in 31 states. The remaining Russian HEU stockpile committed to civil use amounts to 250 tonnes (see Appendix B).

By the end of 2005, almost half of the 150 tonnes of HEU that the United States declared excess to national security and committed to civil use in nuclear power plants had been converted prior to blending down. At the beginning of 2005, some of the blended material was fabricated into LWR fuel and delivered to TVA's Browns Ferry power plant. The HEU was blended down by Nuclear Fuel Services at Erwin, Tennessee. In addition, over 100 tU at 4.95% ^{235}U assay had been produced by blending operations at the DOE's Savannah River site (Nuclear Fuel, 31 January 2005). The remaining amount of ex-military HEU committed to use in nuclear power plants was around 70 tonnes at the end of 2005 (see Appendix B).

Although in November 2005 the US DOE announced that an additional 200 tHEU would be permanently removed from weapons' usage, most of this material will be devoted to marine propulsion and space or research reactors. Less than 20 tonnes will be down-blended to LEU for use in civil power reactors. The LEU for civil power plant use will be made available gradually over the next 25 years (NEA and IAEA, 2006).

Blending down ex-military HEU to ^{235}U assay levels that are suitable for use in LWR fuels represents the next important recycle option. Military HEU is held in metallic form which needs conversion into uranium oxide before it can be blended down to the low enrichment levels (<5% ^{235}U) that match the design and are required for the chemical treatment and blending down operations. Also, ex-military HEU which has an enrichment level of up to or greater than 93% ^{235}U cannot be handled in current nuclear fuel cycle facilities and requires plants specially designed and licensed to address criticality safety aspects and to comply with physical protection and safeguards requirements.

It is likely that the chemical treatment and blending of HEU will be restricted to plants in the Russian Federation and the United States because of the sensitivity surrounding the type and source of this material. However, once the HEU has been blended down to low enrichment uranium levels, there is no reason why it could not be sold to other countries, although some of them may have political or public acceptance concerns about purchasing civil nuclear fuel with ex-military origins. Indeed, LEU derived from down blending Russian HEU has been shipped already to the United States and, in much lesser quantities, to countries in the European Union.

The remaining ex-military HEU committed to civil use in nuclear power plants, estimated to 230 tonnes (see Appendix B and Table 2.1), could fuel the world fleet during around one year. However, it is expected that the use of this material will take place over a long period of time because the United States is eager to avoid disturbing the uranium and enrichment markets by commercialising LEU derived from ex-military HEU.

2.4.3 Ex-military plutonium

In addition to the recycle of ex-military HEU, surplus weapon-grade plutonium has been committed to use as fuel in civil nuclear power plants. Towards the end of the year 2000, the United States and the Russian Federation concluded a surplus plutonium disposition agreement. Under this agreement, each country will dispose of 34 tonnes of weapon-grade plutonium by the year 2020. This plutonium will be mixed with uranium to form mixed oxide (MOX) fuel suitable for use in existing civil power plants, mainly LWRs.

The development of MOX fuel fabrication facilities is underway in both countries. In the United States, the planned MOX fabrication plant will be located at the US DOE's Savannah River site. It is expected to begin production in 2015 with the fuel destined for use in four specially licensed civil power plants. Lead fuel assemblies have already been loaded to confirm acceptable fuel performance. The MOX fuel that will result from the use of almost 70 tonnes of surplus weapon grade plutonium will displace some 14 000 to 16 000 tonnes of natural uranium over the programme lifetime.

2.4.4 Uranium from reprocessing

Of all the options for the recycle of fissile material, the reuse of uranium and plutonium from reprocessing is the most mature and offers the greatest amount of industrial experience. Although the recycle of current RepU and plutonium stocks offers only a modest potential in energy worth terms, about 70 000 tonnes of natural uranium equivalent or one year of current world demand, the demonstration of recycling feasibility at the industrial and commercial scale is important for future developments. Commercial scale plants have been operating in a competitive market during the past decades. There is geographical diversity in the location of these plants and diversity also exists in the technical basis of the processes that they employ.

Worldwide, the reprocessing of irradiated oxide fuels, mainly from LWR but also from the advanced gas-cooled reactors (AGR) in the United Kingdom, has produced some 45 000 tonnes of RepU in the form of uranium oxide. The recycle of fissile materials recovered by reprocessing fast reactor fuel has been successfully demonstrated also on an industrial scale in several countries. Only limited quantities of this material have been recycled by re-enrichment through plants based on gas-centrifuge technology and located in Russia and the Netherlands. Although the practicalities of recycle have been demonstrated, new, much larger capacity plants would have to be built to allow the recovered uranium oxide to be converted to UF_6 prior to re-enrichment.

Significant amounts of uranium from reprocessing have been recycled already in several countries. In the United Kingdom, over 15 000 tonnes of RepU from Magnox fuel reprocessing was converted and re-enriched to AGR fuel levels during the final operating years of the Capenhurst gaseous diffusion plant in the 1980s. This source of fuel formed the bulk of the initial cores of many of the AGR power stations and good operating experience was obtained. In Belgium, the Doel-1 reactor has operated for a number of years exclusively with fuel derived from re-enriching RepU. In India, 250 tonnes RepU has been recycled into PHWRs. In Sweden, 136 tonnes of RepU has been recycled into LWRs during the years 2000-2001.

The use of RepU as blend stock when down blending either HEU or MEU (medium enriched uranium) has proved to be an extremely effective and efficient use of this material. Since the year 2000, the Swiss utility, KKG, has regularly loaded fuel produced by this route (see Appendix D for more detail). Using RepU in this way overcomes the technical constraints associated with the presence of ^{236}U.

It is likely that the future of RepU recycle will be influenced by both economic and strategic considerations. From the natural resource management viewpoint, the use of RepU eliminates the need for some natural uranium ore with its attendant mining and milling waste materials. This could be an important feature in a sustainable development context. The current stocks of RepU are modest but future operation of various commercial reprocessing plants around the world could supply up to 4 000 tonnes of RepU per annum with a ^{235}U assay of between 0.4% and 0.8%. This is equivalent to between 5% and 10% of the current uranium demand in the world and represents the output of a major uranium mine.

2.4.5 Plutonium from reprocessing

Extensive experience has already been gained with the fabrication and use of MOX fuel in nuclear power plants, particularly in Europe. MOX fuel fabrication facilities with an annual production capacity of about 230 t of LWR fuel already exist in Europe. These facilities were developed to enable the recycle of plutonium recovered from reprocessing.

At the end of 2005, there were a total of 39 LWRs licensed to use MOX fuel. It is estimated that to date nearly 2 000 tonnes of MOX fuel has been fabricated and loaded into these reactors. As an approximate guide, the current recycle of 1 tPu produces about 25 tonnes of MOX fuel suitable for use in an existing LWR power station and is equivalent to displacing almost 200 tonnes of natural uranium. It is estimated that the inventory of plutonium recovered from reprocessing currently lies in the range 200 to 250 tonnes and its use in MOX fuel would displace the need for between 40 000 and 50 000 tonnes of natural uranium.

Because the currently operating LWRs were not designed specifically to use MOX fuel, reactor physics constraints have limited the amount of this fuel that can be present in their cores at any one time to less than 50% of the whole core loading. New LWR designs incorporate features that allow operation with 100% core loading of MOX fuel. Extensive modelling and safety studies have shown that there is no fundamental problem associated with the use of MOX fuel in current or future designs of LWR (NEA, 1995, 2002b and 2003).

In addition to the current reactor design constraints, the total capacity of operational MOX fuel fabrication plants – at present about 230 tHM/y – is limiting the use of such fuel. A new MOX fuel plant, with a 130 tHM/y capacity, is planned to come on stream in Japan in 2012 and, in the shorter term, plans exist to increase the capacity of the French MOX plant by 50 tHM/y. On the other hand,

production constraints continue to limit the capacity of the British plant and the shutdown of the Belgian plant will take place shortly. Therefore, if more LWR operators would opt for reprocessing and the recycling of plutonium, MOX production capacity could become insufficient.

Depending upon the planned fuel irradiation level in the reactor, MOX fuel plants incorporate some 50 to 70 kg of plutonium into each tonne of MOX fuel produced (NEA, 1989). The currently operating MOX plants worldwide are capable of incorporating about 15 tPu/y into fuel; this will rise up to 20 to 25 tPu/y within the next decade. The current stock of civil plutonium is estimated to be between 200 and 250 tPu, so current and planned MOX fabrication plants would take at least 15 years to convert this quantity into MOX fuel for LWR use.

In addition to the present civil stockpile, if current reprocessing plants operated at full capacity they could produce annually between 30 and 40 tonnes of plutonium. This plutonium must be recycled very soon after reprocessing to avoid the build up of americium. Therefore, MOX fuel fabrication plant capacities should be sized according to reprocessing outputs and MOX reactor licences should be planned accordingly.

Technically, plutonium can be stored for a very long time but, like for other materials, extended storage is not a final solution and eventually a decision on its use has to be taken. As with the storage of tails material, long term safety concerns will demand that consideration be given to converting the PuO_2 into a more acceptable form. Developments to date have shown that PuO_2 can be incorporated into a ceramic or vitrified form suitable for long term storage and geological disposal.

Currently, MOX fuel fabrication for LWR use is mainly based on the MIMAS process (in Belgium and France) or the “Short Binderless Route” (in the United Kingdom). In the MIMAS process, plutonium oxide from the reprocessing plant is first micronised with a small amount of uranium oxide, in the proportion 70:30, before further dilution with uranium oxide takes place mechanically. The resulting mix is then pelletised and sintered. In the “Short Binderless Route” the plutonium oxide is micronised with all the required uranium oxide in a single process step, before the resulting mix is pelletised and sintered.

In Japan and in the Russian Federation, development work has focussed on avoiding the production of separated plutonium oxide, considering that this approach is more proliferation resistant. The Japanese work is based on mixing the plutonium nitrate solution stream with uranium nitrate. The 50:50 mix is heated using a microwave heating technology resulting in de-nitration and the production of MOX powder.

In the Russian Federation two types of MOX production technology have been developed. The first is relying on ammonia-based co-precipitation of the plutonium and uranium streams followed by MOX powder production and pelletisation. The second is based on pyro-electrolytic conversion of spent fuel which results in the deposition of a mix of plutonium and uranium oxides on the cathode. This deposit is then crushed, sieved and vibro-compacted to form the fuel content of fast reactor pins. This type of fuel is currently undergoing irradiation testing in the BOR-60 and BN-600 fast reactors.

In France, two advanced schemes are under development: COEX which separates together uranium and plutonium to fabricate MOX fuel based on co-conversion in an integrated facility; and GANEX which co-extracts all actinides from the spent fuels and which allows to recycle together uranium, plutonium and minor actinides. It is planned to implement some laboratories or workshops for experimental demonstration of generation IV nuclear systems using those technologies before 2012.

If multiple recycling of fuel is to be held open as an option, then attention needs to be paid to the solubility of the irradiated MOX fuel pellets during subsequent reprocessing operations. The higher heat output of spent MOX fuel also needs to be noted and taken into account in plant designs, particularly if the disposal of this type of fuel is intended without further reprocessing. At present, only single recycle through LWRs is planned, followed by storage of the spent MOX fuel pending further reprocessing and recycle through advanced reactor designs.

The continuing move towards achieving higher irradiation levels before enriched uranium fuel needs to be discharged from the reactor has implications for the quality of the plutonium content. The higher the discharge level, the higher is the amount of minor actinides that are present and the greater is the relative proportion of plutonium isotopes above mass number 239. This has implications for the design of future MOX fabrication plants. Greater shielding will be required and the criticality safety case will have to cover plutonium content of MOX fuel above the current limit of around 12%.

The present trend of using separated plutonium from civil or ex-military sources in LWR MOX fuel corresponds to the current industrial development of reactor and fuel cycle technologies. It provides useful energy in the short term and may be seen as a method of safeguarding the plutonium's huge energy potential by locking it away in a highly radioactive matrix (irradiated MOX fuel) until the time comes for its full potential to be realised through fast neutron reactors.

The use of plutonium raises concerns in civil society and therefore is considered with caution by policy makers. The perceived threats of separated plutonium, real or not, lead to very stringent security and safeguard requirements that have to be undertaken whenever this material is processed, transported and used. On the other hand, the energy content of plutonium, especially if it were to be used in fast breeder reactors, could be a considerable asset from a sustainable development perspective.

If a decision were to be made to give up this potential, then a number of technical options exist to achieve the final disposal or destruction of plutonium. From a waste disposal aspect, the presence of long-lived actinides in the high level waste that arises from reprocessing operations raises concerns and may be prevented by regulations in some countries. Technical options exist for destroying these actinides but they come at a price and their implementation would depend on the development of new reactor and/or accelerator driven systems (see NEA, 1999, 2002c, 2002d and 2006 for more information on these advanced fuel cycle schemes).

2.4.6 Thorium

When ^{232}Th is irradiated with neutrons it becomes ^{233}Th, which decays rapidly to become ^{233}Pa and then ^{233}U which is fissile and possesses nuclear physics properties superior to ^{235}U. This transmutation process is very similar to the production of ^{239}Pu by the neutron irradiation of ^{238}U atoms. Naturally occurring thorium does not contain any fissile atoms; it is a fertile material that can be used to breed fissile ^{233}U providing it is mixed with fissile material, such as uranium or plutonium, and placed in a nuclear reactor. Therefore, self-sustaining thorium fuel cycles would have to include a reprocessing stage in order to recover the ^{233}U and the other unused fissile content of the irradiated fuel. Reprocessing techniques that have been considered for thorium based fuels include the use of highly corrosive chemicals and they remain to be proven on an industrial scale.

Only limited experience has been gained in using thorium oxide fuel in power reactors. Initially, this was mostly confined to early developments of reactor designs in the United States, but more recently India has shown an increasing interest in the thorium fuel cycle because the country has large

domestic thorium resources. Experience has shown that thorium based fuels have good thermal conductivity and fission-gas retention properties.

However the thorium that would be recovered by reprocessing would contain a strong gamma-emitter, ^{228}Th, and the recovered ^{233}U would be accompanied by ^{232}U, whose daughters also emit hard gamma radiation. The presence of these isotopes poses a radiological design challenge and they are likely to impose some health physics constraints during the re-fabrication and handling of the fuel prior to its return to the reactor core. As shown in Table 2.2, the radiation levels doses at the fabrication and reprocessing steps are dramatically higher for thorium cycles than for the LWR MOX cycle, by four orders of magnitude for the U/Th/U and Th/U cycles. It means that those cycles would require dedicated plants specifically designed to ensure adequate radiation protection.

Table 2.2 Irradiation levels (n+γ) in thorium fuel cycles as compared with MOX in LWRs

	Fabrication step (no impurities)	**Spent fuel processing step**
MOX (U,Pu) in LWRs	1	1
Th/Pu	2	5
U/Th/Pu	2	30 400 ($\gamma >> n$)
Th/U	1	13 100 ($\gamma >> n$)

In the United States, interest in the Th/U fuel cycle has been recently revived with the Radkowski thorium reactor (RTR) concept (Radkowski *et al.*, 1998) and studies pursued at the former INEEL for LWRs (Herring *et al.*, 2006; NEA, 2002a), both based on a once-through fuel cycle. Any major move towards the thorium fuel cycle would almost certainly involve new reactor designs and would also require the development of dedicated fuel cycle plants. Wide-scale deployment of nuclear power plants based on the thorium fuel cycle can be viewed as a viable option only in the longer term, on a 50 year timescale, due to the low maturity of fuel cycle technologies, especially for reprocessing, as compared with the uranium cycle.

2.5 Impact of fuel cycle trends on recycling uranium and plutonium

Over the past three decades, reactor and fuel designs have progressively evolved with the aim of optimising fuel utilisation in the core. Optimisation of the fuel/moderator distribution, reduction of parasitic absorption and reduction of radial and axial neutron leakage have been the main objectives. These developments have resulted in a total saving of more than 25% in natural uranium requirements per unit of electricity produced, as well as in significantly reducing fuel cycle costs (NEA, 2002a). However, the resulting progressive increase in the irradiation level of the fuel before it is discharged from the reactor has implications for the quality of the fissile material content of that fuel.

2.5.1 Uranium

Natural uranium is made up of three isotopes: ^{238}U (99.28%); ^{235}U (0.71%); and a trace of ^{234}U (0.01%). After irradiation in a nuclear power plant the uranium contained in the spent fuel also

includes ^{232}U and ^{236}U. The amount of ^{232}U is extremely small (less than one part per million) but the ^{236}U content approaches 0.5%. If the spent fuel is reprocessed the uranium stream also contains some decay products of which ^{208}Tl is important as it emits penetrating radiation. The ^{208}Tl content of reprocessed uranium reaches its peak after 10 years, thereafter decaying away to insignificant levels after a further 10-15 years. The typical composition of RepU derived from spent LWR fuel is: ^{232}U 0.1-0.3ppm; ^{234}U 0.01-0.03%; ^{235}U 0.5-1.0%; ^{236}U 0.4-0.7%; with ^{238}U as the balance.

From the radiological viewpoint, most of the uranium isotopes contained in RepU, which have very long half-lives and emit alpha radiation, pose very similar demands to those associated with the handling of natural uranium. Their chemical toxicity far outweighs the radiological hazard. However, the presence of ^{208}Tl imposes specific radiological protection during the handling, storage, re-enrichment and re-fabrication processes. To date, only two centrifuge enrichment plants have been used for the re-enrichment of RepU, one in the Russian Federation, the other in the Netherlands. Eight fuel fabrication plants are or have been licensed to re-fabricate fuel made from RepU.

Uranium 236 is a neutron absorber in the reactor core and some allowance must be made for its negative reactivity effect when RepU is used in the manufacture of new fuel. Compared with natural uranium feed, about 1.5% more RepU needs to be fed to the enrichment process, which in itself requires about 2.5% more separative work units to be expended to produce the same reactor worth of fuel (NEA, 1986).

Techniques have been developed and industrially deployed in the Russian Federation for blending RepU with HEU or with MEU that has been derived by reprocessing propulsion reactor, fast breeder reactor or research reactor fuel with VVER fuel. This technique overcomes the drawbacks associated with the re-enrichment of RepU (Bairiot *et al.*, 2005).

In addition to the presence of ^{236}U, RepU also contains small quantities of ^{232}U and ^{234}U; the daughter products of which emit strong gamma radiation. The recycling of large quantities of RepU could result in the need for greater radiological controls to be applied at the conversion, re-enrichment and fuel re-fabrication stages of the process. These, in turn, could involve the imposition of a price premium when dealing with RepU compared with natural uranium. The economic worth of RepU has been considered in some detail in a previous study on nuclear fuel cycle costs conducted by the NEA (NEA, 1994) which suggested that the monetary value of RepU was likely to lie in the range of 50-80% of the value of natural uranium when full allowances were made for the effects of ^{232}U, ^{234}U and ^{236}U and daughter products.

2.5.2 Plutonium

Plutonium is produced in any nuclear reactor that has uranium in its core. This is particularly so for all the presently operating nuclear power plants around the world, where the LWR design is predominant. Although these reactors use low enriched uranium fuel and the bulk of the heat produced comes from the fission of ^{235}U, a significant amount is also produced by the fission of plutonium isotopes that arise as the uranium fuel is progressively used. ^{239}Pu is the predominant isotope; it is produced by neutron capture in ^{238}U. If the fuel remains in the reactor for prolonged periods, as is now common practice, then capture in ^{239}Pu leads to the production of ^{240}Pu and subsequent captures produce the higher isotopes such as ^{241}Pu and ^{242}Pu. In addition, very small quantities of ^{236}Pu and ^{238}Pu are produced.

The exact composition of the plutonium isotopes in discharged LWR fuel depends on the isotopic composition of the initial uranium fuel, the time the fuel spent in the reactor, and the flux and energy

distribution of the neutrons in core. Detailed information on this topic is given in a previous OECD study on plutonium (NEA, 1989). As an approximate guide, using suitably rounded numbers, the plutonium isotopic composition of spent PWR fuel on discharge from the reactor is: 53% ^{239}Pu; 25% ^{240}Pu; 15% ^{241}Pu; 5% ^{242}Pu; and 2% ^{238}Pu.

By comparison, the isotopic composition of the plutonium contained in fuel discharged from reactors that use natural uranium fuel such as gas graphite Magnox or PHWR Candu reactors is: 65% ^{239}Pu; 25% ^{240}Pu; 5% ^{241}Pu; 1% ^{242}Pu; and negligible amount of ^{238}Pu.

Plutonium isotopes are radioactive and decay primarily by emitting an alpha particle together with some X-rays and/or gamma radiation. They have greatly differing half-lives ranging from about 15 years in the case of ^{241}Pu up to 400 000 years for ^{242}Pu. ^{239}Pu has a half-life of 24 000 years. Unlike the other plutonium isotopes, ^{241}Pu decays by emitting a beta particle to form ^{241}Am with a half-life of 430 years that in turn decays by emitting an alpha particle plus penetrating radiation in the form of X-rays and gamma radiation.

Plutonium is a very radio-toxic substance if it is taken into the body by inhalation, ingestion or injection. Radiological protection measures revolve around the safe containment of the material using high integrity glove boxes and filtered ventilation systems. However, the emission of X-rays and gamma radiation, particularly by ^{238}Pu and ^{241}Am, and also neutrons, poses an external radiation hazard. Radiation shielding, in addition to that provided by the glove-box materials, is required in some stages of the processing chain. The decay heat associated with plutonium is a further factor that requires consideration when this material is handled and stored. However, plutonium is far from being a uniquely hazardous material. Rather, it is one amongst many toxic materials that have to be handled with due caution to minimise the associated but well-understood risks.

Atoms of plutonium undergo fission when bombarded by neutrons over a wide energy range from “thermal” to “fast”. Atoms with odd mass numbers (239, 241) undergo fission much more readily than those with even mass numbers (238, 240 and 242). This is particularly true in LWRs where mainly “thermal” neutrons are involved. Indeed, in this instance, the even numbered plutonium isotopes plus ^{241}Am actually act as neutron poisons and this needs to be taken into account when calculating the required reactivity worth of MOX fuel for use in LWRs. In the case of fast reactors, all the plutonium isotopes are fissionable. This is why fast reactors are a better option than thermal reactors (e.g. LWRs) for an efficient use of plutonium, although but ^{241}Am still acts as a neutron poison.

However, the recycling of plutonium once in existing LWRs offers the opportunity to increase the energy produced by the original uranium feed by up to 20-30%. It has been successfully demonstrated on an industrial scale and its use is currently being expanded. Plutonium derived from reprocessing gas graphite reactor fuel, or PHWR/Candu reactor fuel, if that were to be undertaken, offers superior characteristics for recycling as MOX through LWRs.

With current technology, when irradiated fuel is reprocessed, all of the constituent parts get separated into three streams: uranium; plutonium; and fission products and other actinides. The uranium and the plutonium streams go through further purification processes so that the resulting oxide material is extremely pure. In the case of plutonium, some fairly short-lived isotopes are present and radioactive decay leads to changes in the isotopic composition of plutonium during its subsequent storage period. The decay of ^{241}Pu into ^{241}Am is of particular importance for further use of the plutonium.

If plutonium derived by reprocessing LWR fuel were to be stored for a 15 year period, the valuable, highly fissionable ^{241}Pu content would reduce through decay from 15% to 5%, whilst the

detrimental ^{241}Am content would rise to around 10%. Thus, the longer separated plutonium is stored, the greater is the reduction in its fissile worth and the greater are the radiological demands when the plutonium, including ^{241}Am, is eventually fabricated into MOX fuel for use in either LWRs or fast reactors.

The economic worth of plutonium is a complex subject, highly dependent on the reactor system into which it may be deployed. Clearly, far greater radiological precautions have to be taken in storing, transporting, handling and fabricating plutonium-based fuel than is the case for uranium-based fuel. These precautions, together with the stringent plutonium accountancy requirements that are necessary to satisfy international safeguards and criticality safety standards, make the costs of fabricating MOX fuel much higher than those of fabricating uranium fuel.

Detailed discussions of costs for the various stages of the MOX fuel cycle may be found in earlier NEA publications (NEA, 1989 and 1994). In the latter, the value of plutonium recovered by fuel reprocessing was calculated by the so-called "indifference method" described briefly below. In the light of the developments that occurred recently in the field of fuel and fuel cycle technologies as well as uranium prices, it would be highly relevant to update those economic studies.

If the cost of producing one PWR fuel assembly by the MOX route is compared with the cost of an equivalent assembly produced by the low enriched uranium route, then at the economic break-even point a value can be obtained for the plutonium content of the MOX assembly. This approach produced a value of USD 5 per g of fissile Pu when the price of uranium was USD 70/kgU.

In obtaining a value of plutonium by the "indifference method" in the 1994 study, the significant cost of storing plutonium was not taken into account. This could be seen as a shortcoming as these storage costs are significant. When these costs are taken into account along with the reduction in fissile worth that takes place during storage, there is an enhanced economic and technical attraction for recycling plutonium as soon as possible after separation in the reprocessing plant.

Despite this, there are considerable quantities of separated plutonium that have been held in storage for prolonged periods, in the United Kingdom in particular but also in other countries. In the case of the United Kingdom, for technical and economic reasons, the early recycle of plutonium derived from Magnox fuel reprocessing into MOX fuel for the AGR power stations did not carry a compelling argument. Now, following privatisation of part of the nuclear power industry in the country, the transfer of legal ownership of the plutonium would also come into play.

The social aspect is important also in policy making regarding plutonium use. Civil society is concerned by a number of issues raised by plutonium utilisation, including security, physical protection and international safeguard requirements. The need to address those concerns is a challenge for the nuclear industry and for governments wishing to develop national and/or international solutions for the implementation of efficient plutonium recycling strategies.

In spite of the political and social barriers to the establishment of a plutonium market, progress and success with the introduction of ex-military plutonium into the civil nuclear fuel cycle may offer an opportunity for broader acceptance of recycling. Furthermore, the concept of sustainable development, which is increasingly referred to by policy makers, fosters the attractiveness of recycling options which enhance efficient use of finite natural resources. A nuclear energy policy embracing sustainable development should promote and encourage the implementation of closed fuel cycles.

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Chapter 3

MANAGEMENT OPTIONS

3.1 Introduction

In order to manage fissile and fertile materials arising at various steps of the fuel cycle, or made available for civil uses, three main options are at the disposal of operators of nuclear facilities and decision makers: final disposal, long-term storage, and recycling. However, depending on the national policy and/or on the technology and infrastructure available in the country, the implementation of some options may not be feasible in a given context. For example, recycling is not an option in countries where reprocessing is prevented by law. Also, it should be noted that long-term storage is only an interim solution; decision makers choosing this approach will have to opt eventually for final disposal or recycling.

Fissile and fertile materials potentially recyclable include two categories of products: separated uranium, plutonium and thorium; and spent fuel. The latter needs reprocessing before it can be recycled while separated materials are more readily available for further use, although in some cases, e.g., HEU, some pre-processing is required also. The inventory of recyclable materials is presented in section 2.2. Technical and strategic issues raised by management of those materials differ according to their types and physical or chemical status. This chapter examines the two long-term options, i.e., final disposal and recycling, from the technical and strategic view points.

3.2 Disposal

The implementation of the final disposal option implies that the materials being managed this way are considered as waste, at least temporarily. It is envisaged mainly for spent fuel but may be implemented also for separated fissile or fertile materials. This option limits drastically the amount of energy extracted from natural resources. If it were to be adopted worldwide in a scenario of continued reliance on nuclear energy, uranium supply may become a concern before the middle of the century taking into account presently known resources.

Long-term interim storage and retrievable disposal offer, on the other hand, the opportunity to revisit the decision eventually and retrieve the materials in storage for further uses. Also, more recoverable uranium resources may be identified through enhanced exploration efforts triggered by increased demand and higher market prices.

At present, as there is no repository in operation for the disposal of high-level waste including spent fuel, non-reprocessed spent fuel has to be stored until a disposal facility is available. Irradiated fuel discharged from nuclear power reactors is usually stored initially in water filled ponds at the reactor site to allow time for decay of the high radioactivity present when the fuel is downloaded from the reactor. The water conducts the decay heat away from the spent fuel and also acts as a shield to the intense gamma radiation emanating from freshly discharged fuel.

Three main options are available for interim storage of spent fuel after its cooling in on-reactor-site ponds: wet pond, dry cask and dry vault. The technologies used are mature, reliable and safe. For all options, the operator has to provide evidence that any potential degradation of the fuel as a function of time, temperature, radiation, oxygen or change of environment should not compromise the possibility to retrieve and process the fuel. Additionally, the records and other associated documentation for the fuel and the storage system need to be maintained and useable at the end of the storage period. Information related to the history of the fuel and how it has been stored is likely to be required in order to determine its suitability for onward processing, as well as compliance with future transport regulations.

The three methods are used in different countries (see Table 3.1) and some countries use more than one option. Wet storage is more widespread today but dry storage technology in vaults or casks has matured progressively and is considered by an increasing number of countries and utilities for the future.

Table 3.1 Interim spent fuel storage options used in various countries

Option	Countries where it is used
Wet pond	Belgium, Finland, France, Germany, Japan, Sweden, United Kingdom, United States
Dry cask	Belgium, Canada, Germany, Japan, Russia, Switzerland, United States
Dry vault	Hungary, United Kingdom

Wet storage of spent fuel in water-filled ponds is commonly applied – more than 90% of the spent fuel in storage in the world today is stored in ponds – and some spent fuel has been stored in ponds for many decades. No substantial problems have been encountered for oxide fuels, but pond storage is known to be more problematic for metallic fuel.

The advantages of wet storage technology include shielding, cooling efficiency and ease of fuel inspection. Spent fuel assemblies are typically placed in racks in ponds made of lined concrete. Key safety issues in wet pond storage include: prevention of any accidental nuclear chain reaction through mechanisms ensuring sufficient spacing and neutron absorption; maintaining a water level adequate to cover the fuel. The disadvantages of wet pond storage include high maintenance requirements to keep cooling capabilities adequate to avoid significant fuel alteration and to make water chemistry adjustments, such as by boron addition, ion exchange purification, filtration, and wall examination for leaks.

The chemistry of the pond needs to be controlled in order to minimise any potential corrosion of the fuel cladding, thereby maintaining the integrity of the fuel. Often, the fuel is stored in containers for corrosion prevention and ease of handling. The ponds need to be closely monitored for leakage, and radioactivity in the water is kept as low as reasonably achievable. As cladding is a primary barrier for containment, inhibiting corrosion of it in ponds is an important factor, thereby impacting on the technical complexity of pond storage, i.e. pond chemistry and its associated control. Wet storage of zirconium alloy clad fuel, such as PWR fuel, is not generally a cause for concern even in poor pool chemistry conditions, and although stainless steel clad LWR fuels usually have significantly higher cladding corrosion rates, cladding corrosion is not considered a time limiting factor for storage up to 100 years.

The worldwide trend, however, is towards more robust dry storage methods. Transitioning from wet to dry conditions is an issue encountered by countries such as the United States and Germany,

where spent fuel has been transferred into interim dry stores. There are two main drying processes in use currently: vacuum drying is utilised by Canada, Germany, Spain and the United States; and hot-gas drying is used by Canada, Hungary and the Republic of Korea. Vacuum drying lowers the cover gas system pressure below the vapour pressure of the water at the drying temperature for a specified period of time, and may require long drying times or more sophisticated methods where there are large amounts of residual water or "cold" fuel. The hot-gas drying technique uniformly heats the fuel assembly (usually 90 to 150°C) using a flow of hot gas to evaporate the water.

Dry vault storage is implemented typically in a large concrete building with an exterior structure serving as a radiation barrier and an interior that has large numbers of cavities suitable for spent fuel storage units. Heat is removed in vault systems by either forced or natural air convection. Where it is judged necessary, the ventilation-air temperature, humidity and chloride content are controlled to ensure that storage conditions are optimised to maintain the integrity of the fuel assembly. The fuel is often stored in sealed metal storage tubes or storage cylinders, which may hold one or more fuel assemblies; these provide containment of the radioactive material in the spent fuel.

Dry vault stores will be operated at higher temperatures than wet stores, but have a larger heat-handling capacity than casks. However, cooling prior to loading into a vault is required: an LWR spent fuel assembly (approximately 45 GWd/t burn-up) may require about 3 years pre-cooling. These higher temperatures also require close attention to cladding corrosion mechanisms and to thermal creep. Higher burn-ups may constrain use of vaults due to heat loading.

While the up-front cost of establishing a vault is substantial, the cost of building a larger vault to expand its capacity is marginal. Given this economy of scale, for storage of very large quantities of spent fuel at a single facility, the unit cost of vaults tends to be somewhat lower than the cost of other dry storage approaches.

In a dry cask storage system, a flat concrete pad is provided either outdoors or within a building and large casks that contain the spent fuel can be added as needed to store the amount of fuel required. The casks provide both shielding and containment. The initial cost of establishing the facility is small, and the operating costs once the fuel is loaded are also small, but the capital cost of the casks themselves is significant; as each cask costs roughly the same amount as previous casks, there are few economies of scale in storing more fuel. A wide variety of specific cask designs are available from several manufacturers, including both metal and concrete casks (the latter typically having metal inner liners). Originally casks were designed only for storage (often referred to as "single purpose" casks). More recently, some cask designs have been licensed for both storage and transport ("dual purpose"), and design work continues on casks intended to serve for storage, transport, and permanent disposal ("multi-purpose").

The VSC-24 concrete cask in use in the US is 5.6 m high by 3.5 m diameter, weighing 132 tonnes when full and has a spent fuel capacity of 17 tonnes. Most metal casks are sealed and therefore unventilated, meaning that cooling is by direct radiation to the cask inner surface, conduction through the cask wall and air convection of outer surfaces, and not by inner air convection. Metal casks have higher heat conductivities than concrete casks. Casks store fuel at higher temperatures than vaults due to less efficient cooling of the containers, especially if they are constructed from steel-reinforced concrete rather than ductile iron. Maximum permissible cladding temperatures for casks to maintain containment can range from less than 250°C up to 364°C, where the higher temperatures are associated with concrete casks. As a consequence of poor cooling of fuel in casks, longer periods of cooling are required before material can be loaded, e.g. a high-burn-up LWR spent fuel (approximately 45 GWd/t) may require about 10 years of pre-cooling.

All disposal techniques require a defence in depth or multi-barrier approach to containment of the radioactive waste. Before spent fuel is consigned to a disposal facility, it is necessary to package the fuel to facilitate its handling and emplacement in the facility. The packaging also ensures that the fuel is stored in the best environment to limit degradation and spread of radioactivity. However, it is common for geological repository models to take limited credit for the package containment during the repository lifetime. Package integrity may be more important if retrieval it is part of the disposal policy.

While no spent fuel has been packaged for final disposal as yet, plans for spent fuel packaging for disposal are in development. Where existing or developing approaches for ILW, LLW and other HLW are identified, they will be considered for suitability against a spent fuel application. Approaches that have been considered internationally for packaging of spent fuel prior to disposal include: encapsulation in cement, glass, phosphate ceramic, molten metal, organic polymer, inorganic polymer or synthetic zeolite, bitumen or Synroc (i.e., hot isostatic pressing), copper over-pack, glass ceramics, and high-temperature incineration and melting.

There is a general consensus in OECD member countries that geological disposal of spent fuel and high-level waste offers a reliable and safe option for present and future generations. Deep geological disposal involves the use of the so-called "*multi-barrier system*", where combinations of engineered and man-made barriers (e.g. canisters, backfilling materials) are incorporated into the repository design, intended to prevent any water within the rock gaining access to the waste for thousands of years, and conversely restricting the transport of radio-nuclides into the environment during the time cooling and radioactive decay of the waste occurs. Repositories would be accessed by either shafts or inclined tunnels, which would be closed and sealed when all the waste had been emplaced. Construction and filling of a repository is expected to take several decades, perhaps longer in countries with large quantities of long-lived waste.

The waste would be packaged in suitable containers (stainless steel, copper alloy); these would be placed in short vertical boreholes drilled down from the repository tunnel floor or placed horizontally on the floor. The tunnel would eventually be backfilled. In each case, the waste would be surrounded by clay, bentonite or crushed rock.

Emplacement would take place at depths ranging from 250-1 500 metres, depending on the concept adopted and the host rock. Excavation of a deep underground repository using standard mining or civil engineering technology is likely to be limited to accessible locations (e.g. under land or near-shore). Salt, clay, granite and volcanic tuff are among the rock types that are currently proposed for use in different countries because of the low groundwater flows through them.

In the original geological disposal concepts, it was envisaged that the repositories would be backfilled and sealed as soon as possible, after waste emplacement. Several countries are now adopting so-called "*staged disposal concepts*" where the decision to finally close and seal the repository will not be taken until many years into the future. During the time when the repository is open it would be monitored and the waste would be in a state where it would be possible to retrieve it fairly easily, should it prove necessary to do so. This allows confidence to be gained in the disposal method, and allows decisions regarding final design and closure to be made in the light of experience gained during the life of a repository, rather than committing to a particular course of action right from the start. Until a repository is sealed there is more risk than after sealing to the workers and the public because of the risk of fires, floods and other natural disasters. Safety cases have been made in various countries. In most recent instances these cases have been subjected to international peer review by the radioactive waste management community and found to be sound.

In the short term, the sooner the repository is closed after waste emplacement the lower the cost. However, the longer term costs are dependant on the monitoring regimes and contingency fund. In principle the contingency fund should be sufficient to cover retrieval of all the nuclear material. One of the reasons that deep geological disposal is a popular nuclear management option is that it places no responsibilities on future generations and is highly stable to adverse socio-political changes. However, these advantages only exist when the repository has been closed. On the other hand, a repository that remains open for a number of years has advantages; it is relatively easy and cheap to retrieve the fuel should there be an accident or a need to use the spent fuel as a resource for recycle. For example, at present, the US intends to keep the repository open for at least 50 years for ventilation to keep the temperature low. The repository then will be sealed. At present that does not include backfill of the emplacement drifts, which may be needed to prevent rock fall from damaging the containers or to provide a barrier against water ingress.

3.3 Recycling

The main goals of recycling are better utilisation of the energy content of natural resources and reduction of the volumes and toxicity of waste. Recycling the fissile and fertile materials available worldwide could provide a significant amount of energy in the coming decades. Appendix C on nuclear development scenarios and associated uranium requirements illustrates the range of demands that industry may have to face in a few decades. Furthermore, recycling fissile and fertile materials reduces the amount of plutonium and minor actinides to be disposed of eventually and thereby the long-term stewardship of radioactive waste.

The efficiency of recycling depends on the nuclear energy systems used and on the timing of their deployment. The reactors in operation today will remain in service up to 2020-2050 and will be renewed by reactors that will remain in service up to the end of the century. The performance of the next generation of reactors will have a drastic influence on the efficiency of recycling.

3.3.1 Physical aspects of material recycling

The effectiveness of recycling depends on the performance of the system adopted in terms of waste volume and radiotoxicity reduction and energy produced.

Table 3.2 One group neutron cross-section

Isotope	Thermal spectrum			Fast spectrum		
	σ_f	σ_c	$\alpha = \sigma_c/\sigma_f$	σ_f	σ_c	$\alpha = \sigma_c/\sigma_f$
^{235}U	38,80	8,70	0,22	1,98	0,57	0,29
^{238}U	0,103	0,86	8,30	0,04	0,30	7,50
^{239}Pu	102,00	58,70	**0,58**	1,86	0,56	**0,30**
^{240}Pu	0,53	210,20	**396,60**	0,36	0,57	**1,60**
^{241}Pu	102,20	40,90	**0,40**	2,49	0,47	**0,19**
^{242}Pu	0,44	28,80	65,50	0,24	0,44	1,80
^{237}Np	0,52	33,00	63	0,32	1,70	5,30
^{241}Am	1,10	110,00	100,00	0,27	2,00	7,40
^{243}Am	0,44	49,00	111,00	0,21	1,80	8,60
^{244}Cm	1,00	16,00	16,00	0,42	0,60	1,40
^{245}Cm	116,00	17,00	0,15	5,10	0,90	0,18

The reactivity balance is in favour of recycling in a fast neutron spectrum because the ratios of capture versus fission cross-section are lower in a fast spectrum for all plutonium isotopes (see Table 3.2, drawn from Varaine *et al.*, 2005). Also, minor actinide transmutation, leading to residues with shorter life and less radiotoxic, is more efficient in a fast neutron spectrum.

The evaluation of the cross-sections alone is not sufficient to assess global efficiency of transmutation through recycling. In addition, it is necessary to consider the neutron potential and to quantify the number of neutrons available for the transmutation or breeding process. This D-value approach (Salvatores *et al.*, 1996 and 1997) allows to asses the capability to operate at critical conditions and to produce the excess of neutrons needed for transmutation. It is based on the probabilistic approach applied to the cores at equilibrium. Table 3.3 shows that the fast spectrum provides a positive neutron balance for minor actinides and plutonium thus making transmutation possible for those isotopes.

Table 3.3 D-values for minor actinides in thermal and fast neutron spectra

Isotope/element	Thermal spectrum	Fast spectrum
Minor actinides	-1.2	+0.4
Pu + minor actinides	-0.2	+0.9
Long-lived fission product (LLFP) elements	-2.3	-2.2
LLFP isotopes only	-0.6	-0.6

The reactor physic analysis indicates that the fast neutron spectrum is suitable for a large recycling of all materials contrary to the thermal neutron spectrum which implies constraints on reactivity coefficients and fissile requirements that limit its material recycling capabilities.

3.3.2 Assessing recycling options

The full assessment of recycling options requires an analysis of the physics characteristics of the reactor, in order to evaluate the most efficient way to use and recycle materials for saving resources or for transmutation, and a review of the entire nuclear system, including its fuel cycle.

Fissile and fertile materials – uranium and plutonium – may be recycled either in light water reactors or in fast reactors. For the transmutation of minor actinides, two options are possible: homogeneous and heterogeneous recycling. In the homogeneous recycling option, uranium, plutonium and minor actinides are processed together. In the heterogeneous recycling option, uranium and plutonium (neptunium) are processed separately from the minor actinides – americium, curium (neptunium) – which are transmuted in specific fuels or targets.

Recognising that a fast neutron spectrum is more efficient for transmutation and imposes fewer constraints, it is not envisaged to recycle minor actinides in light water reactors or other thermal neutron spectrum reactors. If this option was to be considered, it would have dramatic impacts on fuel cycle characteristic requirements.

In light water reactors with thermal neutron spectrum, the main materials that can be recycled are uranium and plutonium. The resource savings can be estimated as follows for reactors of the present generation:

- 5% by extending the burn-up and fraction loading;
- 20% by reducing the uranium 235 content in depleted uranium;

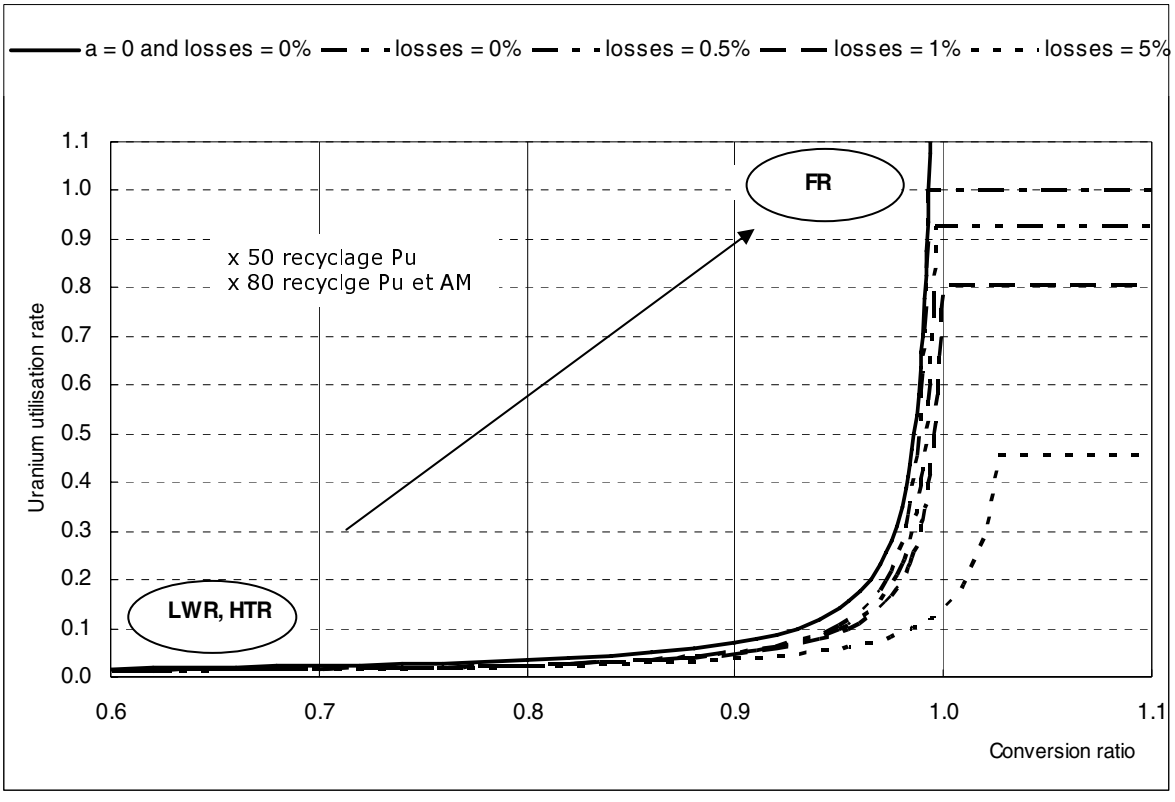
- 20% by recycling the irradiated uranium and plutonium;
- 5 to 10% by improving the reactor performance (heavy reflector, thermal efficiency, etc.); and
- 5 to 10% by improving the conversion ratio in the reactor.

Thus, recycling uranium and plutonium in current-generation light water reactors can reduce uranium consumption by 50% maximum as compared to present once-through cycle. Other means of reducing uranium consumption in current generation of reactors include higher thermal efficiency and availability factors as well as higher fuel burn-up.

On the other hand, recycling of fissile and fertile materials in fast neutron reactors allows the use of all materials available and breeding *in situ*, the fission products being removed after irradiation. As around 10 to 15 tonnes of plutonium are required per GWe of fast reactor installed capacity, the plutonium produced by a light water reactor during its lifetime is sufficient to start a fast reactor of the same capacity. Furthermore, the uranium arising from the reprocessing of spent fuel from a light water reactor is sufficient to operate a fast reactor of the same capacity during several thousands of years.

Based on the existing availability of plutonium and highly enriched uranium, it would be possible to install 150 GWe of fast neutron reactors and to continue producing electricity for more than five centuries, replacing the breeder reactors by other breeder reactors at the end of their lifetime, without need for additional fresh uranium. However, the implementation of this option will be feasible only if and when a technically-mature, economically-competitive fast neutron system will become available.

Figure 3.1 Resource utilisation efficiency as a function of conversion ratio

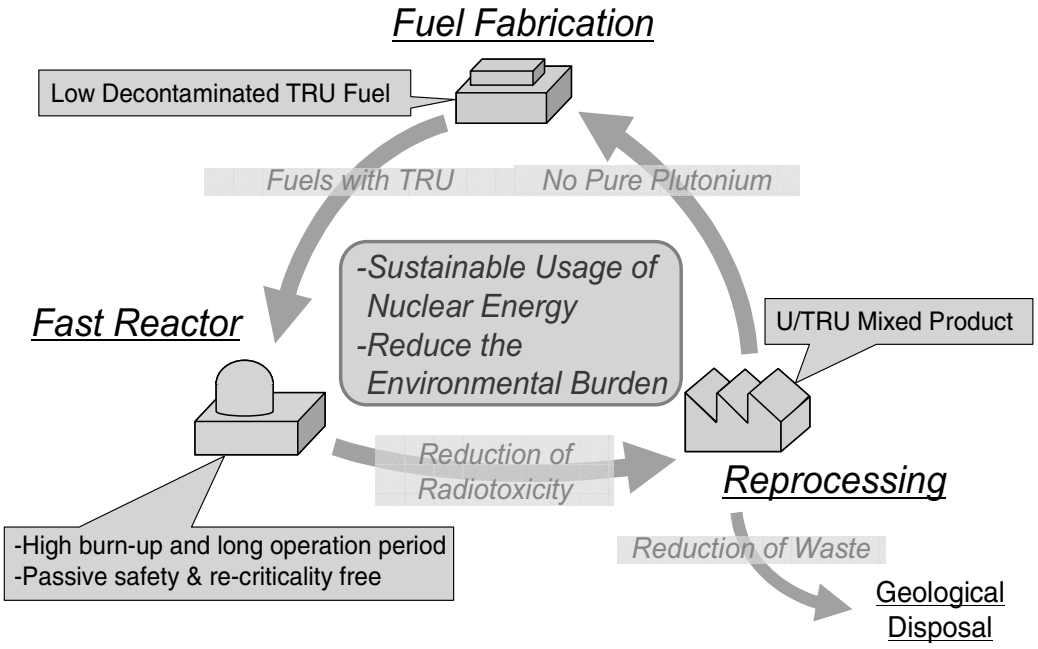


The introduction of fast reactors allows increasing significantly the energy content extracted from natural uranium as compared with light water reactors operated once through as shown in Figure 3.1. The multiplying factor obtained depends on many factors including the conversion ratio of the fast neutron reactors, their rate of introduction and the losses in the fuel cycle processes. The figure illustrates dependency on the ^{235}U level in depleted uranium (a = 0% or 0.3%) and losses during reprocessing and recycling (0%, 0.5%, 1% and 5%).

3.3.3 Recycling strategies

The ultimate goal of a fully-closed cycle option is the recycling of transuranic elements which is better achieved by fast neutron reactor systems. Figure 3.2 illustrates a closed cycle concept with FR.

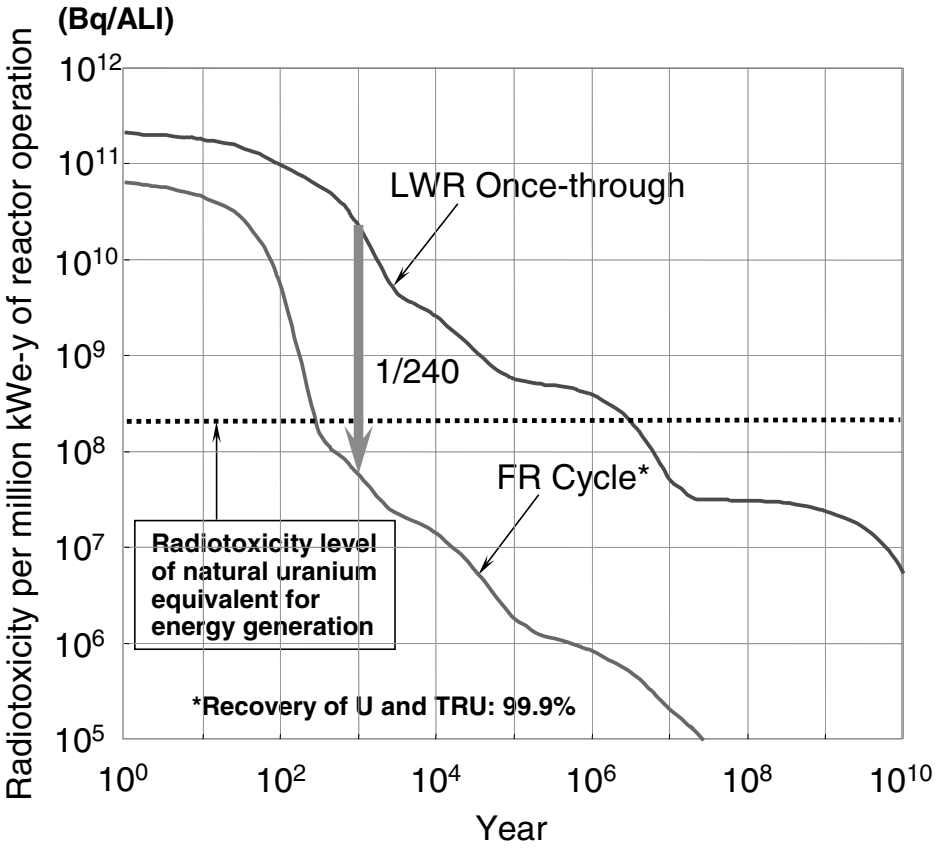
Figure 3.2 Closed fuel cycle



The main advantages of the FR option are a drastic reduction of cumulative uranium demand and of the volumes and radiotoxicity of high-level waste to be disposed of eventually. Therefore, the FR cycle system may greatly contribute to national security of energy supply and enhance the sustainability of nuclear energy systems.

Figure 3.3 shows a comparison of the long-term radiotoxicity of HLW from the FR and the LWR once-through cycle schemes; the dotted line on the graph indicates the radiotoxicity level of the amount of natural uranium needed to fuel a 1 GWe LWR during one year. After 1 000 years of storage/disposal the radiotoxicity level of waste in the FR cycle scheme is approximately 1/240 of that in the LWR once-through scheme.

Figure 3.3 Radiotoxicity of HLW for LWR once-through and FR fuel cycle options



Starting from the present situation, the recycling strategy may be implemented in 3 main successive steps to reach the ultimate goal of fully closed cycle: recycling in thermal reactors; transition from thermal to fast neutron spectra; full implementation of fast neutron systems.

In the first step, which could last for a couple of decades until successful development of the fast reactor cycle technology, plutonium would be recycled in light water reactors. The continued use of the LWR once-through scheme would increase of the cumulative natural uranium demand and spent fuel accumulation. Full recycling of transuranic elements with the fast reactor system may result in a small increase in the amount of spent fuel and vitrified high-level waste.

For the implementation of this first step the existing industrial infrastructure, including reprocessing and MOX fuel fabrication plants, is a driving factor in decision making. In a country where those industrial facilities are not in place, the development and construction costs of these plants would be very high but this challenge could be alleviated by international collaboration for the implementation of the necessary facilities.

The second step would be a transition period from light water reactor systems to fast reactor systems. The replacement of light water reactors reaching the end of their lifetime by fast reactors would start when fast reactors would become competitive with light water reactors. The rate of introduction of fast reactors would be driven by the obsolescence rate of light water reactors and by plutonium availability. When contemplating the development of this step, policy makers should be

aware of the need to adapt LWR fuel reprocessing capacity to the plutonium requirements for fuelling fast reactors; furthermore, the conversion ratio of the fast reactors is an essential parameter for the maximum rate of introduction of this reactor type. Another important issue that may be tackled at this step is the recycling of minor actinides contained in the accumulated inventory of LWR spent fuel. Although it might increase slightly the fuel cycle cost, the recycling of minor actinides in fast reactors is effective to reduce the environmental impact of HLW.

The third step would be the recycling of transuranic elements in fast reactors, aiming at the objectives of secure energy supply, effective use of nuclear fuel resources and implementation of more environmentally friendly and sustainable nuclear energy systems. At this step, the establishment of a global infrastructure including advanced reactors and fuel cycle facilities would be needed. Collocation of reactors and fuel cycle facilities, in particular reprocessing plants and international collaboration for the secure supply of fuel cycle services could be considered.

3.3.4 Impacts of recycling on material flows and fuel cycle parameters

Table 3.4 summarises indicatives values of material and fuel cycle service flows for different fuel cycle options drawn from previous national and international studies.

Table 3.4 Material and service flows per GWe x year for illustrative fuel cycles

Fuel cycle	Natural U (tU)	Enrichment (MSWU)	Fabrication/ reprocessing (tHM)	HLW (tHM)	Fissile material inventory (tHM/GWe)
PWR O/T	140	0.1	14	14	3.5
PWR MOX[1]	120	0.09	14	0.06	4.5
FR (Pu)	0	0	5.6	0.03	10
FR (Pu + MA)	0	0	5.6	0.001	10

1. Fuel containing 90% UOX and 10% MOX.

In addition, Table 3.5 shows the impact – multiplicative factor as compared to the MOX fuel with 12% of initial Pu content – of minor actinide presence on the physical scale of interest of objects to be manufactured. These results are the basic data from technical feasibility studies.

Table 3.5 Main fuel cycle parameters as compared to standard MOX LWR

Parameters	FR sub assembly (Pu + MA)	MIX sub assembly (Pu + MA)	Target sub assembly (Am + Cm)
γ α source	1.5	3	9
Neutron source	30	200	100
Heat source	0.5	3	1.7
Annual flux (tonnes)	340	820	1.6

3.4 Concluding comments

Several options and technologies are available for managing fissile and fertile materials. Decision makers may select recycling, long-term interim storage or disposal depending on the overall socio-economic context prevailing in their country, its energy policy and its industrial, nuclear energy related, infrastructure. Recognising the long-term implications of any choice, it is important to take into account in a holistic assessment economic, social and environmental issues in the selection of the

management option adopted. Furthermore, the implementation of the selected option should reflect in a responsible, stepwise approach the integration of short-term and long-term perspectives.

The disposal option provides a definitive solution, although in most OECD countries it is expected that materials disposed of may be retrieved eventually. Although no repository for civil HLW is in service yet, many countries are at an advanced stage of design and implementation of such a repository. There is a consensus among experts that the disposal of all fissile and fertile materials considered as waste can be achieved safely, ensuring their isolation from the biosphere during the period needed to prevent any significant impact on men or the environment.

The recycling strategy presents the advantages of reducing the volumes and radiotoxicity of waste while saving natural resources. There is extensive industrial experience on treatment and recycling of fissile and fertile materials. In some countries the fuel cycle industry has been managing recyclable materials for more than two decades. Other countries are considering with a renewed interest the recycling option for environmental and security of supply reasons.

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Chapter 4

INDICATORS FOR ASSESSING MANAGEMENT OPTIONS

4.1. Background

The nuclear power plant fleet and the associated fuel cycle facilities in operation worldwide are the result of fifty years of development during which nuclear technologies have reached industrial maturity and nuclear energy has become a reliable part of the electricity supply system. Most of this development has concentrated on the LWR concept and its associated fuel cycle for various historic and strategic reasons. Although the LWRs are relatively inefficient in their utilisation of fissile uranium, they are attractive in that their total fissile inventory per unit of power is small and they produce attractive quantities of plutonium suitable for use in future advanced reactors.

At the start of nuclear power development little attention was given to the back-end of the fuel cycle and there was little or no public concern about the management of the radioactive waste. Although the advantages of recycling and breeding were identified early on, interest in fast reactors receded as increasing resources of uranium were discovered. In many countries the once-through/open fuel cycle option was adopted with the spent fuel placed in long-term storage facilities, awaiting eventual final disposal. A very small number of countries developed reprocessing facilities and offered services on the international market, and some countries opted for the closed fuel cycle, including reprocessing and recycling of part of the recovered fissile materials, essentially plutonium.

The reprocessing plants used technology whereby the unused uranium and the plutonium content of the spent fuel were separated from the fission product waste stream which included the minor actinides. A process to vitrify this waste was then developed which was compatible with geologic disposal requirements, the ultimate goal being to dispose of HLW in deep geological repositories.

At present, large quantities of spent fuel, some stocks of separated plutonium and a growing amount of vitrified waste adequate for final geologic disposal after a few decades of cooling are held in different interim storage facilities. In the absence of operational repository for either the spent fuel or the high-level vitrified waste, final disposal of these materials has become an issue raising policy maker and public concerns.

There is a growing consensus that geologic disposal is an appropriate method of safely disposing long-lived, heat emitting radioactive waste. However, difficulties encountered in siting, constructing and licensing the necessary repositories against a background of public opposition have led to delays in implementing this disposal strategy. Simultaneously, long-term storage of materials containing radioactivity and potentially sensitive nuclides raises issues in connection with physical protection and proliferation resistance.

Regarding future development of nuclear energy, there is an increasing awareness, although not a general consensus in OECD countries, that it is a relevant option to address climate change issues, as a nearly carbon-free source of energy, and to ensure diversity and security of supply in a long-term

perspective. However, to play an increasing role in satisfying world energy demands, nuclear energy has to respond to social concerns expressed by civil society and shared by policy makers.

In a sustainable development perspective, the key, long-term drivers for technology and option choices in the nuclear energy field include:

- preservation and optimum use of natural resources like uranium;
- minimisation of radioactive waste volumes and radiotoxicity in order to reduce the number and dimensions of needed repositories;
- maintaining high level of safety and reliability;
- addressing physical protection and proliferation resistance concerns; and
- ensuring competitiveness with alternatives.

With these objectives in mind, energy policy makers will have to decide on the most suitable route forward for nuclear power taking into account current fuel cycle constraints imposed by national policies and practices.

The nuclear industry has been working to develop advanced reactor designs with higher efficiency in fuel utilisation, including some possessing the ability to breed their own fuel, while enhancing inherent safety features. Designs of plants to support the operation of these reactors using a closed fuel cycle with prompt fuel recycling are also available. These reactor and fuel cycle plant designs are based on fifty years experience of operating industrial scale facilities. They represent a modest extension of this mature and proven technology and, in a number of cases, they are based on the design and operation of prototype plants at an industrial scale.

A series of workshops organised by the NEA offered experts in the field opportunities to present and discuss advanced reactor and fuel cycle technologies and innovative fuels (see NEA 1999 and 2002a). Several studies on advanced fuel cycles aiming at enhanced management of fissile and fertile materials have been published by NEA, other international organisations and national institutes. The study on accelerator driven systems and fast reactors (NEA, 2002b) undertaken under the NDC auspices focused on comparative analyses of those two options from a sustainability viewpoint. This published literature provides insights on different design options and their relative merits in meeting the key long term drivers set out above.

Whilst current LWR designs and fuel cycle plants are capable of satisfying electricity generating requirements in the short term, they do not make the best use of current fuel resources in the longer term. If nuclear energy is to play a continuing and increasing role in supply mix, there must be a planned transition from current designs to the advanced designs. This transition will have to take place over a number of decades and will, for a long period of time involve the operation of a mix of current and advanced designs of plant.

Plutonium recycling through existing LWRs is already an industrial reality in a number of European countries and will commence soon in Japan. Utilities in Belgium, France, Germany and Switzerland have the greatest amount of experience. The KKG utility in Switzerland has particularly good, long term experience of recycling plutonium and RepU. Appendix D sets out this experience in greater detail and draws attention to factors that need careful consideration in adopting a recycling strategy. It demonstrates that, in the shorter term, recycling can offer a utility an assured and economically affordable supply of fuel to sustain the operation of a nuclear power plant over a large part of its lifetime, without jeopardising the possibility for further recycle in later, advanced reactors.

4.2 Security of supply

Security of energy supply is based, at the global level, on efficient management of identified resources. For non-renewable energy sources, the ratio between known resources, or reserves, and annual demand, expressed in years of current consumption provides an indicator of the longevity of those resources. Obviously, resources and demand are evolving in time with technology progress, prices, and many other technical and economic parameters. Therefore, the actual lifetime of non-renewable resources is not known with certainty. Indeed, a review of time series of statistical data on oil, gas and uranium resources highlights that the number of years of consumption represented by known resources or reserves remains fairly constant over time irrespective of the annual levels of production.

For oil, the ratio of known, economically viable resources to current annual production is about 40, while for natural gas it is about 65 and coal reserves are adequate for over 150 years of current production (BP, 2006). For the types of nuclear power plants in current operation, known uranium reserves are sufficient for at least 85 years of current production, or up to 270 years if all conventional resources are included (NEA and IAEA, 2006). This places nuclear energy in a good position as far as security of supply is concerned.

However, recycling fissile and fertile materials offers opportunities to prolong the lifetime of known uranium resources retrievable at reasonably low costs. Breeder reactors, depending on their rate of introduction, on their conversion ratios and on the efficiency and losses of recycling processes, could multiply the lifetime of uranium resources by a factor of 50 or much more.

Thus, the deployment of fast breeder reactors supported by fuel recycling plants carries with it an enormous potential for assuring the sufficiency of fuel for electricity generating purposes for millennia, without emitting any significant quantity of greenhouse gas and its adverse effect on global climate change.

4.3 Infrastructure and human resource requirements

During a great part of the 21st century, it will be necessary to operate a fleet of light water and, likely, fast breeder reactors. The current reprocessing plants (e.g., La Hague and THORP) designed for the treatment of LWR spent fuel (UOX, MOX) should be technically capable of operation up to the year 2040. Well ahead of that milestone (notwithstanding the commissioning of Rokkasho-Mura in Japan), there could be a need for new reprocessing capacities in several countries such as the United States and China. In these third-generation reprocessing plants the plutonium and uranium content of the spent fuel will be co-separated from the small quantity of waste material. The separation of the plutonium and uranium as discrete entities, as occurs in the current reprocessing plants, will be avoided to overcome proliferation concerns. In order to ensure an adequate transition from current to advanced nuclear systems, it will be necessary to build and operate these new reprocessing plants in conjunction with the present ones.

Beyond 2040-2050, it may be desirable to recycle plutonium, uranium and also the minor actinides. This will be possible in fourth generation processing and fabrication plants which will be designed to process both LWR and FR spent fuels, with new fuel fabrication as an integral part of the process and with advanced safeguarding features.

When considering the details of the infrastructure requirements, it is necessary to plan the reactor types and their supporting fuel cycle facilities as a coherent system approach. Several recent initiatives

promoted by the IAEA (IAEA, 2005), the United States (see Global Nuclear Energy Partnership/ GNEP, www.gnep.energy.gov), Russia and other countries propose a worldwide cooperation on fuel cycle service supply. Such endeavours may involve multinational facilities operated by consortia that could provide fuel cycle services to countries willing to forego their own enrichment and reprocessing plants.

In addition to infrastructure requirements, it is becoming apparent that insufficient personnel exist who have been trained in the scientific and engineering subjects required and who have experience of working in the nuclear industry. A comprehensive educational and training programme will have to be put in place ahead of any expansion of the use of nuclear power worldwide.

4.4 Social aspects

As far as the general public is concerned, there is and will be for the foreseeable future a certain stigma associated with nuclear power and the resulting nuclear waste. Nuclear waste already exists, issued from the operation of power plants and fuel cycle facilities over the past fifty years and it will have to be managed regardless of which option – recycling or direct disposal of spent fuel – is followed in the future. Public acceptance of facilities to either prepare and/or utilise recyclable nuclear materials will not be easy to obtain.

Communication with civil society and dialogue with all stakeholders will be essential to foster public understanding of options to be adopted for the back-end of the fuel cycle. The transparency of Governments and operators on nuclear energy issues will play a key role in achieving social acceptance. Dissemination of information is a prerequisite but building trust is needed eventually to ensure that the options to be implemented are endorsed by society.

Although it contributes to the reduction of nuclear weapons, the transfer of plutonium and highly enriched uranium from weapons programmes to civil uses of nuclear energy could raise ethical issues. One example of such sensitivities is given by some countries where governmental assurances that material supplied by the civil nuclear industry has no connection to weapons programmes are required by society. The ethical issue is associated with concerns in civil society arising from the use in commercial power plants of materials issued from a military programme which is not accepted in the first place.

The long timescales involved in recycling mean that public acceptance of the use once and dispose route may be easier to achieve given that it is always easier to accept and agree short-term solutions. Managing the social aspects of a recycling project that will span many generations will inevitably be much more difficult. The promise of increasing the employment prospects could help encourage social acceptance but public involvement through consultation and the availability of well-documented and balanced information on the associated risks would encourage a wider positive reaction.

Finally, there remains the matter of the disposal of the ultimate radioactive waste materials that already exist and those that will be produced in the future. Multinational facilities for radioactive waste disposal have been discussed since the early 70s and are coming back on the agenda of policy makers at the highest levels. Economics and resource management efficiency clearly call for international collaboration in this domain but ethical considerations favour the current approach where each country assumes responsibility for its waste up to final disposal on its own territory.

Civil society involvement will be a key factor in selecting the options corresponding to social preferences as well economic and environmental criteria optimisation. It is necessary to inform the public of the scientific facts and allow time for full consultation and debate to take place, before any rational decisions are able to be taken. As with personnel training, action needs to be started now.

4.5 Environmental impact

In order to assist the public debate, information is given in Appendix E on the environmental impact of using fossil and nuclear fuels for the generation of electricity. It presents a methodology for assessing the environmental impact of the entire fuel cycle and illustrates its application by reference to the operation of the fuel cycle plants that are required to sustain the operation of nuclear power plants. It also advocates that similar, rigorous assessments should be made for the fossil fuel cycle alternatives in order to arrive at a complete and balanced view on future energy strategy.

There are many similar national and international studies available in the published literature. On the nuclear fuel cycle in particular, a recent report OECD Expert Group proposed criteria for assessing sustainability in (NEA, 2002c). The report also provides extensive references to other studies and their findings.

From the public perspective, the management and safe disposal of radioactive waste is of paramount importance. The presence of very long-lived isotopes in the waste raises particular concerns because potentially it may affect future generations. The fact that radioactivity will decay in time making those waste innocuous eventually, as opposed to a large number of toxic chemical wastes that will remain toxic for ever, has little or no effect in assuaging public concern.

As a consequence, the advanced fuel cycles that have been developed are aimed at addressing many of the perceived problems associated with the long-term radiotoxicity of high level waste. For the HLW that arises from spent fuel reprocessing, the long term radiotoxicity is due to the presence of the minor actinides (neptunium, americium, curium, etc.) in the waste, the unused uranium and plutonium having been separately recovered for reuse. In the case of direct disposal of spent fuel, the long term radiotoxicity is increased by the additional presence of uranium and plutonium.

From a technical viewpoint, it is the heat emitted by the HLW that is one of the most important factors in designing a geological repository for its safe disposal. The major contributors to the heat load of HLW are not the long lived isotopes but rather the fission products that decay over the short to medium term (up to 100-200 years). Reducing the amount of actinides to be disposed reduces the technical challenge and helps in easing the perceived problem from the public point of view.

Advanced fuel cycles and fast neutron reactors can reduce the actinide content of high level waste to be eventually disposed of in repositories. In the meantime, the single recycle of plutonium as MOX fuel in a currently operating LWR has a beneficial effect in reducing the total amount of long-lived radiotoxicity that will require disposal and preparing the introduction of fast neutron reactors.

Overcoming the heat load difficulties will require the reprocessing technology to be changed and the adoption of advanced separation techniques to remove the troublesome fission product wastes, particularly caesium and strontium. These products would be stored to allow natural radioactive decay to reduce their heat load and ease the technical task of disposal.

A wide range of advanced fuel cycles are under development. A limited number of schemes, representative of the much greater number being studied, were considered by an OECD Expert Group

and the outcome from their assessments are summarised in a recent publication (NEA, 2006). Strategic choices will be based on the priorities of policy makers. They will be influenced by country specific criteria such as characteristics of available waste repositories, access to uranium and other fissile material resources, size of the domestic nuclear power programme, and social and economic considerations.

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Chapter 5

FINDINGS AND CONCLUSIONS

5.1 Main findings

Recyclable fissile materials available worldwide include: spent fuel from various reactor types – with a large majority being LWRs – containing plutonium, uranium and minor actinides; depleted uranium; reprocessed uranium; separated plutonium; highly enriched uranium; and thorium. The inventories of recyclable materials are significant, amounting to an estimated total weight exceeding 2 million tonnes.

A wide range of safe, technically- and economically-viable strategies are available to manage recyclable fissile and fertile materials, including direct disposal, long-term interim storage and various recycling options. Extended interim storage, however, does not provide a long-term solution and will have to be followed eventually by final disposal or recycling.

All strategies to manage recyclable materials require the implementation of stringent measures to ensure adequate levels of safety, radiation protection, proliferation resistance and physical protection. The legal and regulatory regimes in place in OECD countries provide a robust framework in this regard. Indeed, in all OECD countries, inventories of recyclable fissile and fertile materials are managed according to safety and radiation protection norms and standards which ensure that their impacts on human health and the environment are as low as reasonably achievable.

There is no single option for the management of recyclable materials that is optimal in all cases. The best strategy in a given context depends on a large number of factors including the specific situation of the owners of the materials, the national energy policy of the country concerned, the size and characteristics of the nuclear fleet considered for eventual recycling, the availability of a repository, the nuclear industry infrastructure available and the national regulatory framework.

There is significant industrial experience in several countries on recycling some fissile materials, mainly plutonium. Although no repository for high level waste, including spent fuel, has been put into service yet, experts are confident that the disposal of all recyclable fissile and fertile materials can be implemented in a safe and reliable manner. Research and development programmes undertaken in many countries aim at enhancing the technological performance, safety and economics of disposal and recycling options for the management of recyclable fissile and fertile materials.

Timely disposal of recyclable materials avoids long-term storage burdens and costs, and eliminates future financial liabilities associated with it. However, final disposal may foreclose other choices in the future if retrieval of the materials disposed of cannot be achieved technically and/or economically. Recycling fissile and fertile materials can increase significantly the energy content extracted from natural uranium and thorium, extend the lifetime of nuclear fuel resources and enhance the sustainability of nuclear energy.

The energy content of recyclable materials can be exploited to a certain extent with existing technologies. The retrievable energy content of depleted uranium inventories, using current technologies, is very high, exceeding the energy content retrievable from plutonium inventories used in nuclear energy systems of the present generation.

Nuclear energy systems in operation today could produce 50% more energy from the same amount of natural uranium initially mined if recycling options were implemented instead of the once through approach. With advanced technologies (reactors and fuel cycles) including fast neutron reactors the energy produced by unit of uranium mined could be multiplied by 50 or more and the amount of spent fuel arising reduced by a similar factor.

5.2 Main conclusions and recommendations

Countries and operators owning inventories of recyclable fissile and fertile materials have at their disposal today a choice of viable and safe management options. Choices between alternative options should be based on thorough analysis of their short- and long-term consequences, avoiding in so far as feasible irreversibility in the light of potential technology progress and breakthroughs that would open new opportunities.

The energy content that could be retrieved through recycling fissile and fertile materials is highly dependent on the technologies used and on the strategies adopted. The most efficient strategies are likely to involve nuclear systems capable of using various materials in a synergetic manner (e.g., plutonium and depleted uranium in fast neutron reactors).

It is essential to assess options for the management of recyclable material inventories in a long-term perspective integrating prospective views on the evolution of the role of nuclear systems in global energy supply and on expected technology progress.

At the national level, choices of options and strategies need to be integrated into long-term national energy policies, recognising that some options may foreclose other choices later on. Inventories of recyclable fissile and fertile materials represent a large potential energy resource which could help countries relying on nuclear energy in enhancing their security of supply and reducing greenhouse gas emissions from their energy sector at affordable costs.

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 size nuclear power programmes.

Key issues such as safety, proliferation resistance and physical protection raised by the implementation of strategies to manage fissile and fertile materials deserve policy-maker attention and may be addressed more effectively through international cooperation.

International endeavours including joint R&D, international fuel cycle facilities and international agreements on regulatory frameworks could facilitate the implementation of optimised options from a global viewpoint.

Appendix A

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OECD/Nuclear Energy Agency	
Evelyne BERTEL	Nuclear Development Division
David GROOM	Consultant (UK)

Appendix B

INVENTORY OF RECYCLABLE FISSILE AND FERTILE MATERIALS

Recyclable material inventory at end of 2005

Country	Mass of material in tonnes									
	Spent fuel				RepU	Pu	Thorium	HEU	Tails	Other
	LWR UOX	LWR MOX	FBR	Other						
OECD America	**54 205**	**0**	**56**	**35 557**	**0**	**39.30**	**106**	**67**	**739 000**	**0**
Canada*	0	0	0	35 557	0	0.00	0	0	0	0
Mexico	405									
United States	53 800	0	56	0	na	39.30	106	67	739 000	0
OECD Europe	**30 825**	**535.2**	**0.1**	**6 398.7**	**40 446.2**	**117.81**	**33 354.2**	**1.54**	***311 696***	**50.0234**
Belgium**	2 344	0	0	0	0	0.00	0	0	0	0
Czech Republic	960	0	0	0	0	0.00	0	0	0	0
Finland	1 443	0	0	0	0	0.00	0	0	0	0
France	10 350	520			18 000	48.00	33 300		240 000	
Germany	4 160								*4 500*	
Hungary	1 094									
Italy	215	15		1.7	14.2	0.01	2.2	0.04		50
Netherlands	47					0.00			6 456	0.0234
Slovak Republic	1 084									
Spain	3 370									
Sweden	4 356					0.80				
Switzerland**	1 133									
United Kingdom	269	0.2	0.1	6 397	22 432	69.00	52.0	1.5	60 740	
OECD Pacific	***19 530***	***0***	***0***	***0***	***348***	***119.89***	***2***	***0***	***0***	***0***
Japan***	11 570	0			348	119.89	2			
Korea	7 960	0	0	0	0	0.00			0	
Total OECD	**104 560**	**535.2**	**56.4**	**41 955.95**	**40 794.2**	**277.00**	**33 462.2**	**68.54**	**1 050 696**	**50.0234**
Non-OECD										
China										
India										
Russian Fed.						[2] 78.00		250	545,000	
Ukraine										
Total non-OECD	[1] ***53 000***				***4 000***	***78.00***		***250***	***545 000***	

* PHWR; ** LWR; *** Cumulated at the end of September 2005. RepU: Reprocessed uranium.

Numbers in italic are Secretariat estimates.

[1] RBMK+VVER+Other. [2] Including 38 t of ex-military Pu.

Appendix C

NUCLEAR ENERGY DEVELOPMENT SCENARIOS

At present nuclear energy provides some 6% of the world primary energy supply. The future development of this technology will depend on many factors, including policy issues, which cannot be predicted. Therefore, analysts usually rely on a scenario approach to investigate challenges and opportunities in various development schemes. In the context of the present study, the presentation of illustrative nuclear development scenarios serves as a backdrop to provide insights on the relevance of careful management of recyclable fissile and fertile materials in a long term perspective.

By 2030, the projections provided by the IEA *World Energy Outlook* (IEA, 2006) indicate a world nuclear capacity ranging form 415 to 520 GWe in 2030, which would lead to a share of nuclear energy in electricity supply ranging from 10% to nearly 14%. Recognising that in 2004 nuclear electricity represents 16% of the world supply these scenarios, which seem realistic, do not project a significant growth of the nuclear sector and would not raise any concern regarding fuel supply irrespective of the option adopted for the management of recyclable fissile and fertile materials. It might be noted, however, that such scenarios would not be compatible with the environmental and security of supply goals that most OECD countries are pursuing, as they imply, in spite of a significant penetration of renewable energy sources, a growing reliance on imported fossil fuels.

In the longer term, the projections for nuclear power indicate that the installed nuclear capacity could range in 2050 between 350 and 1 800 GWe (see Figure AC.1, drawn from the IIASA/WEC study), although more recent projections lead to a more narrow range from 700 to 1 200 GWe. Obviously factors such as fossil fuel price escalation rate and nuclear technology progress will have a drastic impact on the energy supply mixes prevailing. In particular, the development of hydrogen economy and of very high temperature reactors could offer opportunities for the penetration of nuclear energy on non-electricity markets.

Figure AC.1 Illustrative scenarios of world nuclear capacity (GWe) by 2050

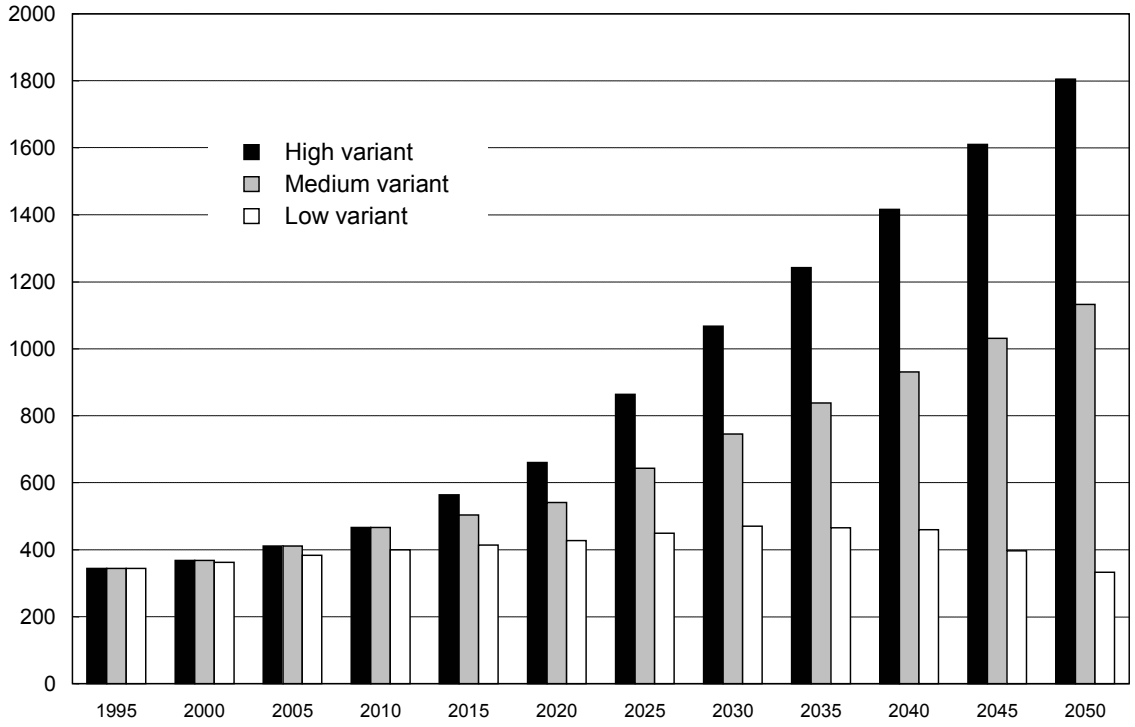
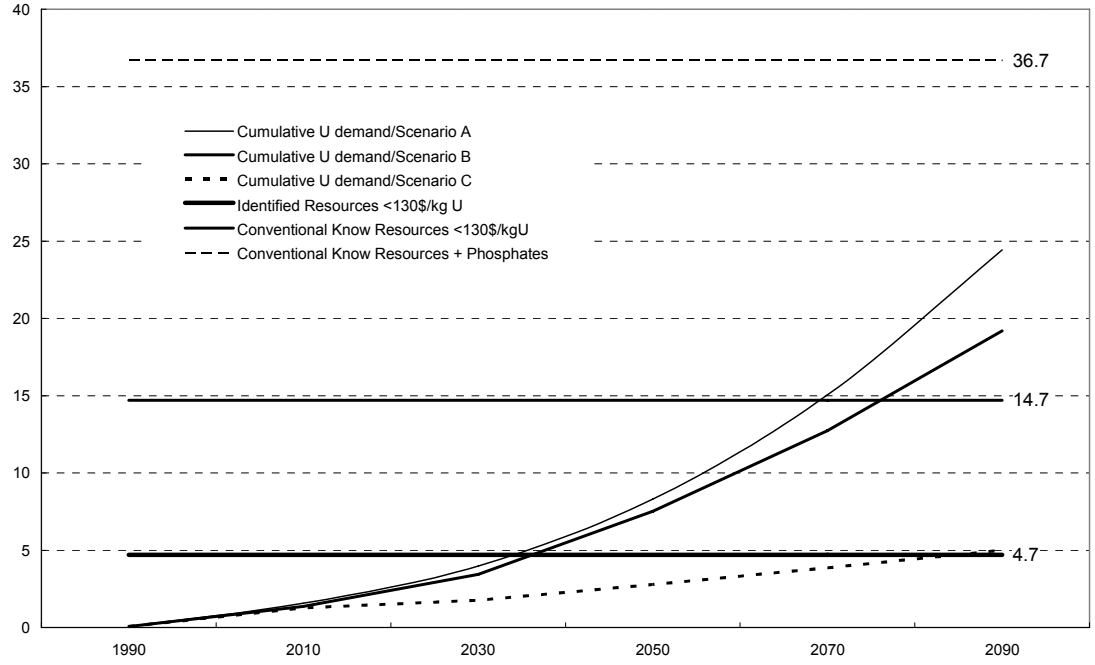


Figure AC.2 Cumulative uranium consumption scenarios and resource categories (million tU)



Scenario up to 2100 are highly speculative as within a century drastic changes may occur in energy production and consumption patterns as well as in technology preparedness levels of sources such as photovoltaic or thermonuclear fusion. Therefore, the objective of prospective studies at long-term horizons is merely to help investigating issues raised by alternative, contrasted possible futures.

Figure AC.2 is based on the IPCC report on emissions scenarios (IPCC, 1998) which offer a comprehensive set of scenarios for energy demand and supply, and associated greenhouse gas emissions up to 2100 based on a compilation of results from state-of-the-art models. The scenarios selected for illustrative purpose in the figure cover a broad range of possible from the implementation of ecologically driven policies (scenario C) to a future driven by economic and technology progress (scenario A) through a business as usual evolution (scenario B). The resulting nuclear electricity generation projections would vary by a factor of 5 by 2100.

The cumulated uranium consumptions have been estimated assuming a reactor fleet with characteristics similar to those of the current generation of nuclear power plants, i.e., some 170 tU/y per GWe in operation. Obviously, improvements in nuclear system performance should reduce progressively the average uranium consumption per unit of electricity generated. However, this conservative approach is adequate to illustrate the challenge may be raised by nuclear electricity generation growth by 2030 and beyond. Uranium resources levels are drawn from the latest Red Book (NEA and IAEA, 2006).

In all scenarios, there is a sharp increase of cumulated uranium consumption by 2040 and in the scenarios A and B the cumulative demand reaches the level of presently identified resources before 2040. Recognising that the cumulated uranium consumption does not take into account the "committed" demand corresponding to the amounts needed for fuelling the nuclear plants in operation during their entire lifetime, i.e., around 60 years, the relevance to assess the value of recyclable materials is obvious. The analysis should be carried out taking into account the progressive exhaustion of presently known uranium resources, the expected evolution of uranium prices and the potential discovery of additional resources.

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Appendix D

RECYCLING PLUTONIUM AND REPROCESSED URANIUM IN A PWR: A UTILITY'S EXPERIENCE

The recycling of the uranium and plutonium contained in the spent fuel could contribute to the conservation of the natural uranium resources by 10-20%. Such recycling is technically and economically feasible in LWRs that are currently operating. It has already been implemented on an industrial scale in several countries (e.g., Belgium, France, Germany and Switzerland).

Experience gained by the KKG utility in Switzerland has shown that the aspects discussed below have to be taken into account.

Recycling of existing plutonium inventories

The plutonium recovered from the reprocessing of LWR fuel at La Hague (France) and Sellafield (United Kingdom) is stored at the site of the reprocessing plant until its transfer to the MOX fabrication facilities located in Belgium, France, Japan and United Kingdom.

The plutonium in PuO_2 physical form is a very stable product, which could be stored if necessary for long periods of time. The storage costs are however very expensive, not only because of the radioactive properties of the material but mainly because of the security issues.

Once a quantity of plutonium has been allocated to a utility, it is in the interest of the utility to recycle it in the form of MOX fuel assemblies as soon as possible, not only to avoid the high storage charges but also because of the degradation over time of its isotopic quality.

The main isotopes present in the recovered plutonium are: ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu. Their relative concentration depends on the technical characteristics of the spent fuel from which they were derived and the length of time that elapsed prior to reprocessing and then subsequently during storage. In an LWR, the ^{239}Pu and ^{241}Pu isotopes are fissile and their concentration determines the reactivity of the MOX fuel assembly when it is inserted in the reactor core.

The ^{241}Pu decays quite rapidly (half-life of 14.4 years) to form ^{241}Am. If the separated plutonium is held in storage for a long period before being sent to the MOX fabricator then there is a loss in its fissile worth in the reactor and hence a decrease in its energy content. In addition, the ^{241}Am emits penetrating radiation which imposes radiological protection concerns for the workers at the MOX fabrication plant. Therefore, the MOX fuel fabricators have set an upper limit on acceptable ^{241}Am concentration in order to limit the radiation dose to their workers. In some facilities, this limit could be exceeded after 5 to 6 years storage of the separated plutonium. In the newer MOX fabrication plants the limit is higher and plutonium that has been stored for 10 years is still acceptable.

For these reasons, it is essential that the utility maintains strict control to co-ordinate the timing of the MOX manufacturing with the reprocessing of the spent fuel. It is also important to keep the pace

of the reprocessing in line with the quantities of plutonium which could be effectively recycled in the reactors, in order not to allow the build-up of stockpiles of plutonium which are ageing.

If, for political, technical or licensing reasons, the separated plutonium has to be stored for prolonged periods, then it is technically possible to treat the plutonium to remove the ^{241}Am before it is actually recycled. This operation can be performed at the reprocessing facilities. It is however a very expensive operation (basically an additional reprocessing operation), which, if required should be performed just before the plutonium is sent to the MOX fabrication plant.

In the current design of LWRs, up to one-third of the core can be taken up by MOX fuel assemblies, generating for the utility significant savings in uranium procurement and enrichment costs. However, these savings will be offset by higher MOX fuel fabrication and transport charges.

The Euratom Supply Agency has reported that at the end of the year 2005, almost 86 tPu had been incorporated into MOX fuel and loaded into LWRs operating in European Union countries. Using very conservative assumptions that 1 tPu in MOX fuel is equivalent to 120 tU and 80 tSWU, they attribute the savings achieved by this recycling as totalling over 10 000 tU and almost 7 000 tSWU.

However, the use of MOX fuel assemblies also carries some drawbacks, which can be summarised as follows:

- In comparison with a uranium fuel assembly, the fabrication cost of a MOX fuel assembly and its transport to the reactor site is currently considerably more expensive.

- A spent MOX fuel assembly emits much more heat compared with a spent uranium assembly which may increase the cost of their subsequent storage.

- Although it is technically possible to send spent MOX fuel assemblies for reprocessing, the lower quality of the recovered plutonium makes a second round of LWR recycling an unattractive option. One solution would be to have these MOX assemblies reprocessed in the same batch as spent uranium assemblies (in a ratio of 1 to 10) to produce an average plutonium quality compatible with further recycling in current LWRs. In addition, since depleted uranium is usually used in the U/Pu matrix in MOX fuel, the residual enrichment in ^{235}U of the reprocessed uranium (RepU) that would be recovered by a second round of reprocessing is extremely low, making it very difficult for re-enrichment even when mixed with other RepU.

- MOX fuel assemblies should not be inserted in the core during the approach to the end of life of the reactor. Because of their relatively higher heat load, at least a ten-year cooling period is needed before spent MOX assemblies can be transferred from the reactor pool into dry storage casks for longer term storage. To avoid high operation costs after the final shutdown, the reactor spent fuel pool should be emptied as soon as possible. The ability to transfer spent MOX fuel off-site for reprocessing or longer term wet storage would overcome this constraint.

Although the costs associated with the recycling of plutonium in form of MOX fuel assemblies lead to higher electricity generating costs compared with the use of uranium fuel, such a decision is only a part of the total strategy for the complete fuel cycle. A complete analysis of the total fuel cycle costs (front-end, back-end and final disposal) is required to determine the advantages and

disadvantages of a closed fuel cycle compared to an open (or once-through) cycle. Also the availability of RepU for recycle needs to be taken into account. This is dealt with in the next section.

The recycling of the plutonium in form of MOX fuel assemblies is currently the only credible option available for a utility that has chosen the closed fuel cycle. MOX recycling enables the plutonium recovered from reprocessing to be safely and advantageously managed by placing it free from any possible diversion and, in doing so, to also help to conserve the world's uranium resources. The recycling of plutonium as LWR MOX fuel is a proven industrial process that presents no technical or safety issues in the operation of the reactor. On this basis, if further conservation of uranium resources was desired, plutonium held by utilities that had no recycling ambitions could be traded and made available to utilities that were willing and able to use it.

Whilst not a technical issue, one factor might deter utilities from systematically recycling third party plutonium. A MOX assembly containing third party plutonium does not help to reduce the number of irradiated fuel assemblies to be disposed of (7 PWR fuel assemblies need to be reprocessed to produce the quantity of plutonium for one MOX fuel assembly). It simply replaces an equivalent uranium fuel assembly for the energy production but keeps all the technical and financial disadvantages specific to a MOX assembly without the advantages brought by the reprocessing.

The implementation of a strategy to utilise third party plutonium in the shorter term will require the establishment of a market which will have to provide the user utilities with adequate and attractive technical and financial solutions for the subsequent management of the spent MOX fuel assemblies.

It should be noted that spent LWR MOX assemblies contain valuable quantities of fissile materials that could be used to great advantage in a fast reactor system.

Recycling of existing RepU inventories

After the reprocessing operations, the RepU is in liquid form (UHN). It has to be converted into a solid form as either UO_3 or U_3O_8 or into a gaseous form as UF_6, depending on the timing of its recycle.

The UO_3 and U_3O_8 physical forms are very stable products and are therefore suitable for long-term storage. These physical forms are suitable to utilities with no immediate plans to recycle the RepU. The material can be easily stored in industrial drums for long periods of time, waiting for attractive technical or commercial conditions to re-use and recycle the material.

If prompt recycle is planned, the RepU has to be re-enriched. This can be achieved either by accepting the material in solid oxide form prior to blending it with HEU, or by taking the material in UF_6 form as feed for subsequent enrichment by conventional processes.

The oxide material can be easily transported in commercial containers. The UF_6 physical form is also a stable product but more prone to oxidation. The product is stored in standard 30B cylinders. Since these cylinders have to be regularly maintained, this physical form has drawbacks if the material is to be stored for extended periods prior to recycle

After irradiation in the reactor, additional uranium isotopes, including ^{232}U and ^{236}U are found in the RepU, in addition to the three isotopes – ^{234}U, ^{235}U, ^{238}U – contained in the natural uranium. The relative concentration of these uranium isotopes depends amongst other things on the type of reactor fuel, the initial ^{235}U enrichment, the burn-up achieved and the cooling time.

The ^{236}U is a neutron absorber and over-enrichment in ^{235}U will be required to compensate for its presence when the RepU is recycled in form of nuclear fuel assemblies in commercial reactors. In the centrifuge enrichment cascades, the isotopes lighter than ^{235}U become more enriched than ^{235}U. The relative concentration of the neutron absorbing isotope ^{234}U is therefore increased and this, together with the presence of ^{236}U requires the level of ^{235}U to be increased in order to ensure equivalent reactivity in the reactor core. This phenomenon has to be taken into account when designing the core loading pattern of the reactor and might reduce the flexibility of the in-core fuel management strategies.

The ^{232}U isotopes have basically no influence on the reactivity of the fuel assemblies but could lead to major radiological consequences for the subsequent re-enrichment and fabrication operations. Although it is present in very small quantities (parts per billion), some of its daughter products emit penetrating radiation. As soon as the reprocessing operations have been completed, the concentration of these daughter products will steadily increase and the radiation emitted will be eventually great enough to require additional shielding in the RepU recycling facilities. This is of particular concern to the fuel fabricators.

Because of the radiological impact of the ^{232}U in RepU, once it has been enriched in the UF_6 form it should be converted into UO_2 powder within a couple of months. Since they have not been specifically designed for the fabrication of RepU fuel assemblies, most of the current commercial fuel fabrication facilities have very strict limits on the acceptable concentration of ^{232}U in order to control the radiation dose to workers at acceptable levels.

It is necessary to carefully plan the timing of all the processes in the recycle of RepU; little flexibility exists to cope with external events which could lead to significant delays. However, if ^{232}U concentration limit is exceeded, it is possible to transfer the RepU from one cylinder to another and to filter the material to reduce the concentration of the ^{232}U daughter products. This would result in increased costs and project delays. This technique may also be applied to UF_6 that has been stored for a prolonged period prior to enrichment.

The management of tails material arising from the re-enrichment of RepU by centrifugation processes will have to take into account the need for greater radiological protection measures compared with tails from natural uranium feed. This is likely to involve higher costs. Nevertheless, this material should not be considered as nuclear waste. Rather it can be safely stored until it can be industrially recycled on a large scale in the new generation of nuclear reactors.

To avoid the disadvantages of using current enrichment technology, the enrichment of the RepU could also be performed by blending it with uranium of higher ^{235}U enrichment levels i.e. with MEU (around 36% ^{235}U) or HEU (over 90% ^{235}U).

The blending process has the advantage that all of the processed quantities are immediately available for recycling. The extra requirements linked to the enrichment tails do not exist. In addition, the fraction of neutron absorbing isotopes is reduced and relatively little over-enrichment of ^{235}U is needed to compensate for their presence. The concentration of ^{232}U is also reduced and hence the radiological impact of the daughter products is lessened. The fabrication and transport of the RepU fuel assemblies can take place in exactly the same way as for assemblies based on natural uranium.

Since the late 1990s, blending services have been offered by Russia on a commercial basis and the recycling of RepU in LWRs by European utilities (Germany, the Netherlands, Switzerland) has grown significantly. Besides the technical advantages, the commercial conditions for RepU recycle,

compared with the use of natural uranium, have been sufficiently attractive to stimulate demand. The steady increase of the uranium prices from 2004 onwards has increased the demand.

RepU is a valuable asset for the utilities who wait for the first attractive opportunity to recycle their inventories. It could play in the short term a significant role in the security of supply and in the saving of natural resources while waiting for the new generation of nuclear reactors. An industrial structure for the recycling of the RepU is already in place and there is no significant technical drawback to recycle RepU in existing LWRs. The main driver is that it is economically attractive. In addition, its use does not raise noticeable opposition from the political and environmental organisations.

In the current LWRs, annual reloads can comprise 100% RepU fuel assemblies, resulting in significant savings for the utilities in uranium procurement. Some Swiss utilities have long-term procurement contracts for RepU fuel assemblies which will cover their needs up to the end of the 2010s. Combined with the recycling of their plutonium inventories in the form of MOX fuel assemblies, these utilities will be using only recyclable materials to fuel their reactors over an extended period of time. They will not need to procure any further natural uranium supplies at a time when the price is rising significantly in real terms.

It is estimated that by the end of the year 2005, the recyle of RepU in reactors in the European countries had replaced the need for about 3 000 t of natural uranium. Over one third of this recycle has been achieved by the Swiss utilities.

Existing spent fuel inventories

Up to the point in time that spent fuel assemblies are packaged and disposed (without intent to retrieve), they constitute a stockpile of potentially recyclable materials, which could be recovered by reprocessing.

The decision to reprocess the spent fuel assemblies depends on several factors. The attractiveness of the closed fuel cycle versus the “once-through fuel cycle” can vary over the years depending on the evolution of the economical and industrial situation. Furthermore, the political context may impose a moratorium or a ban on reprocessing or on the associated transport operations.

The spent fuel assemblies which are not sent to reprocessing are stored at various locations waiting for their final disposal or for better conditions for later reprocessing. Storage may be:

- wet storage in spent fuel pools at the reactor site or at a centralised interim storage facility (i.e. CLAB in Sweden, Tihange in Belgium); or

- dry storage in transport/storage casks at the reactor site (e.g., German utilities, Doel in Belgium) or at a centralised interim storage facility (e.g., Gorleben in Germany, ZWILAG in Switzerland).

The spent fuel assemblies in storage worldwide represent a considerable source of valuable nuclear fuel for the next generation of reactors which could start a sustainable energy system on a global scale. In addition to the current stockpile, worldwide, about 10 000 t of spent fuel arises each year.

All this spent fuel has to be stored for an extended period of time before it could be eventually recycled. When considering the most appropriate method of storing this fuel the following issues have to be addressed:

- The spent fuel will have to be transported to the reprocessing facilities. All transport regulations in force at the time of the transport would have to be met. Little experience is currently available concerning the mechanical behaviour of the spent fuel after several decades of interim storage, especially in dry conditions. To ensure the safety of the transport, R&D studies are needed to evaluate the behaviour of such "old" fuel assemblies in normal and accidental transport conditions.

- Concerning the dry storage casks, although they were fully licensed for transport at the time of their loading, it would most probably not be the case at the time of transport of the spent fuel to reprocessing. Then, all the fuel assemblies would have to be transferred into up-to-date dedicated transport casks. Such operations would have to be performed in hot cells, which are currently not available at all the interim storage locations. For the dry storage casks located at a reactor site, it would also be possible to perform these operations in the reactor spent fuel pool. However, after an extended period of interim storage, there is no guarantee that the reactor will be still in operation and that the required fuel handling facilities would be available.

- Since the recovered fissile materials would most probably not be used in the reactors from which the spent fuel had originated, such long-term planning could only be done by utilities with a large and sustained programme of reactors.

- The utilities, which for industrial, economical or political reasons, do not plan to replace their reactors once they have reached their end of life, would generally prefer to close as soon as possible their obligations regarding the final disposal of their spent fuel. Transferring the spent fuel to another utility, especially abroad, would raise difficult political issues. The cost of storing the spent fuel while waiting for an uncertain renaissance of a domestic nuclear program could be prohibitive and face serious opposition from political and environmental bodies. Retrieving the spent fuel after final geological disposal, even if designed for, would be technically challenging and very expensive.

Although spent fuel from the present generation of LWRs constitutes a very large resource of nuclear material to fuel the next generation of reactors, very few countries have currently long-term strategies which would justify such long-term storage. The direct geological disposal of the spent fuel has been selected by many utilities in the world. Once these final disposal facilities enter into operation, the potentially recoverable fissile content of the disposed fuel will be lost forever.

Appendix E

ENVIRONMENTAL AND HEALTH IMPACTS OF NUCLEAR FUEL CYCLE FACILITIES

Introduction

The production of electricity from any form of primary energy has some environmental effect. In order to carry out a robust environmental assessment of the different energy chains, it is important that specialists doing similar work in other energy chains have a general knowledge of all parts of the nuclear fuel cycle. The present section intends to provide a generic description of the environmental releases from the nuclear fuel cycle and health effects on workers in the industry. In keeping with this general approach, only the releases from nuclear facilities are discussed since impacts from these releases are considered to be highly site and country specific. For example the definition of environment may differ from country to country, as may the end points used to define impacts.

In carrying out the comparative assessment of different energy chains, it is important that impacts from all parts of the fuel cycle be considered. This would include the extraction of the raw material, transportation of intermediate products and wastes, processing materials, storage of used fuel or reprocessing of used fuel, as well as the management of the wastes generated in all steps of the chain. Potential health and environmental impacts to workers, the public and the environment, due to radioactive and non-radioactive releases during routine operation should be assessed.

The present Appendix provides an overview on the main contaminants in the waste streams and effluents arising from nuclear facilities and their impacts.

At a uranium mine ordinary operating procedures normally ensure that there is no significant water or air pollution. The environmental effect of coal mining today is also small except that larger tracts may require subsequent rehabilitation, and in certain areas acid mine drainage can be a problem.

Small amounts of radioactivity are released to the atmosphere from both coal-fired and nuclear power stations. In the case of coal combustion small quantities of uranium, radium and thorium present in the coal cause the fly ash to be radioactive, the level varying considerably. Nuclear power stations and reprocessing plants release small quantities of radioactive gases. At present, neither constitutes a significant environmental problem.

Solid high-level waste from nuclear power stations is stored for 40-50 years while the radioactivity decays to less than one percent of its original level. Then it will be finally disposed of well isolated from the biosphere. Intermediate-level waste is placed in underground repositories. Low-level waste is generally buried more conventionally. Radioactive fly ash from coal-fired power stations has in the past had a much greater environmental impact largely because it was not perceived as a problem and appropriate action was not taken. Today, it is buried in dams; seepage and run-off need to be controlled.

Waste heat produced due to the intrinsic inefficiency of energy conversion, and hence as a by-product of power generation, is much the same whether coal or uranium is the primary fuel. The thermal efficiency of coal-fired power stations ranges from about 20% to a possible 40%, with newer ones typically giving better than 32%. That of nuclear stations mostly ranges from 29-38% with the common light water reactor today giving about 34%. There is no reason for preferring one fuel over the other on account of waste heat. This is the case whether power station cooling is by water from a stream or estuary, or using atmospheric cooling towers. In any case this heat need not always be "waste". District heating and agricultural uses are increasingly found for the released heat.

The main environmental matter relevant to power generation is the production of carbon dioxide (CO_2) and sulfur dioxide (SO_2) as a result of coal-fired electricity generation (Hore-Lacy, 2003). CO_2 is also produced by the combustion of other fossil fuels such as oil and gas.

Sulphur dioxide and nitrogen oxides in large quantities released to the atmosphere can cause (sulphuric) "acid rains" and smog in areas downwind. In the northern hemisphere many millions of tonnes of SO_2 are released annually from electricity generation. It is possible to remove most of the SO_2 from coal stack gases, but the cost is considerable. On the other hand, between 1980 and 1986 SO_2 emissions in France were halved simply by replacing fossil fuel power stations with nuclear. At the same time electricity production increased 40% and France became a significant exporter of electricity.

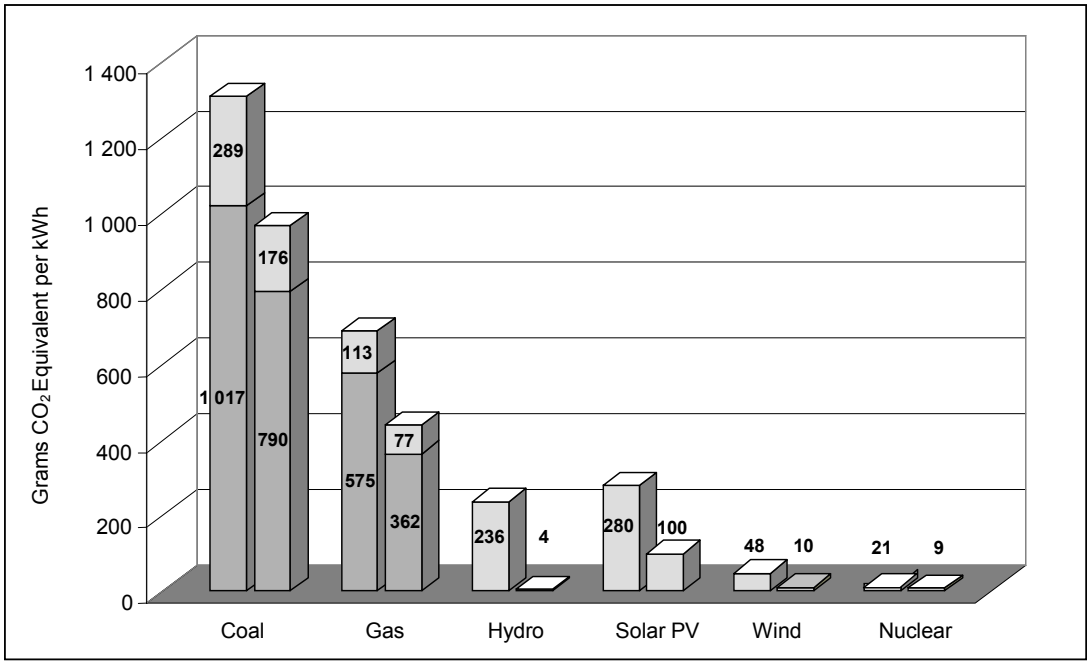
Oxides of nitrogen (NO_x) from fossil fuel power stations are also an environmental problem. If high levels of hydrocarbons are present in the air, nitrogen oxides react with these to form photochemical smog. Also, oxides of nitrogen have an adverse effect on the earth's ozone layer, thereby increasing the amount of ultra-violet light transmitted to the earth's surface. NO_x is not released from nuclear power plants.

The greenhouse effect refers to the effect of certain trace gases in the earth's atmosphere so that long-wave radiation such as heat from the earth's surface is trapped. A build-up of "greenhouse gases", notably CO_2, appears to be causing a warming of the climate in many parts of the world, which if continued will cause changes in weather patterns and other profound changes. Much of the greenhouse effect is due to carbon dioxide.

While the understanding of relevant processes is advancing, it is still unknown how much carbon dioxide the environment can absorb, or how the long-term global CO_2 balance is maintained. However, scientists are increasingly concerned about the slow worldwide build-up of CO_2 levels in the atmosphere. This is the result of the combustion of carbon-based fossil fuels. In addition, progressive clearing of the world's forests also contributes to the greenhouse effect by diminishing the removal of atmospheric CO_2 by photosynthesis. Presently, it is recognised that the global climatic effect of increasing CO_2 levels is now a very significant factor in the comparison of fossil fuels and nuclear power for producing electricity (see Figure AE.1).

Worldwide emissions of CO_2 from burning fossil fuels total about 25 billion tonnes per year. About 38% of this is from coal and about 43% from oil. Every 1 000 MWe power station running on black coal results in CO_2 emissions of about 7 million tonnes per year. If brown coal is used, that amount is about 9 million tonnes. If uranium is used in a nuclear power reactor, these emissions do not occur.

Figure AE.1 Every 22 tonnes of uranium (26 t U_3O_8) used saves about one million tonnes of CO_2 relative to coal (Hore-Lacy, 2003)

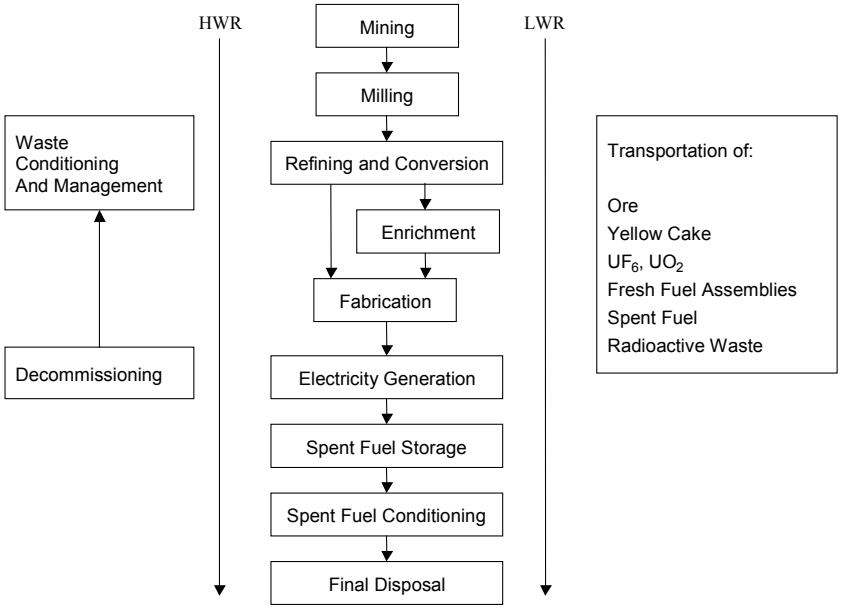


Nuclear fuel cycle description

The main activities in the nuclear fuel cycle include the following steps:

- mining;
- milling;
- refining and conversion;
- enrichment;
- fuel fabrication;
- spent fuel reprocessing;
- waste treatment; and
- disposal.

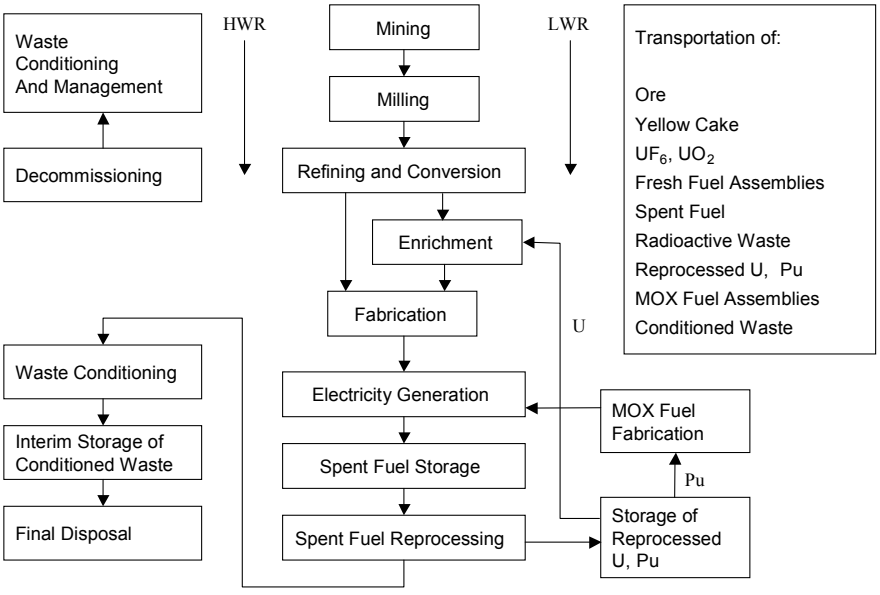
Figure AE.2 Once-through fuel cycle for LWR and HWR



In general, there are two possible configurations of the fuel cycle (IAEA, 1996):

- The once-through fuel cycle, in which the ore is made into fuel passed through the reactor once and then stored awaiting final disposal (Figure AE.2).
- The reprocessing cycle, in which the fuel is passed through the reactor, reprocessed and passed through the reactor again (Figure AE.3).

Figure AE.3 Example of reprocessing cycles for LWR and HWR



More complicated reprocessing cycles than illustrated in Figure AE.3 can include additional and/or modified stages as illustrated in Table AE.1 (Jansma, 2001). The difference between the once through cycle and the reprocessing cycle is that the reprocessing cycle makes more efficient use of the fuel through extraction of plutonium and recycling of ^{235}U. This recycling can decrease the demand for natural uranium in these reactors by up to 35%.

Table AE.1 Illustrative types of the nuclear fuel cycles

Fuel cycle stage	Once-through cycle	MOX-cycle	Cycle with advanced reprocessing
Front-end stages	• Uranium mining and milling • Conversion • Enrichment • Fuel fabrication	• Uranium mining and milling • Conversion • Enrichment • Fuel fabrication from reprocessed uranium	• Uranium mining and milling • Conversion • Enrichment • Fuel fabrication
Additional stages		• Reprocessing • MOX fuel fabrication	• (Traditional) reprocessing • Advanced reprocessing • Production of several types of fuel and targets
Electricity generation	• Nuclear power plant operation with UOX	• Nuclear power plant operation with UOX and MOX	• Nuclear power plant operation • Operation in heterogeneous NPP park • Optional application of accelerators
Back-end stages	• Interim storage • Final disposal	• Interim storage • Final disposal	• Interim storage • Final disposal

The supporting manufacturing operations to the nuclear fuel cycle and construction of facilities have been judged to be relatively remote, indirect and less significant contributors to the environmental impact. On the other hand, decommissioning of nuclear facilities is important due to the treatment and disposal of contaminated materials and the amount of waste (IAEA, 1994).

Impacts on humans and the environment

The general public is showing an increased concern with environmental protection and with the protection of species other than humans. In response to this increased concern, the IAEA proposed that environmental impact comprise three elements (IAEA, 1995):

- Impacts on humans;
- Impacts on resources (i.e. agricultural land, potable water etc); and
- Impacts on the ecology.

Concerning the protection of fauna and flora, recent analyses based on generalised information and conservative assumptions, have shown that radiation levels implied by current radiation protection standards for the public are generally adequate to protect the other species (plants and animals) and that only the combination of specific ecological conditions such as the presence of rare or endangered species and specific stresses may require site specific analyses (IAEA, 1992).

The environmental protection strategy for nuclear fuel cycle facilities is aimed at achieving national and international radiation standards for humans. As part of this strategy environmental monitoring and studies are carried out during all phases of the facility's operation.

Non-radiological impacts

Many different chemicals and equipment are used in nuclear fuel cycle facilities. They are the same in many instances as used in other industries. The effects of using these chemicals and equipment are also much the same. Similarly, the environmental protection strategy for non-radiological substances released to the environment by nuclear fuel cycle facilities will be the same as other non-nuclear industries. Mitigative measures consist of proper codes of practice, appropriate treatment systems, and a good safety culture.

Environmental monitoring and studies carried out for radiological contaminants will also include the monitoring and studies of non-radiological contaminants. Table AE.2 shows potential sources of environmental impacts and mitigation (IAEA, 1996).

Table AE.2 Potential sources of environmental impacts and mitigation

Factor	**Mitigation**
Mining and milling	
Temporary land disruption	reclamation/proper practices
SO_x emissions	scrubbers
Silica dust	ventilation/filters
Radon & radon daughters	ventilation, water or soil covers
Heavy metals	effluent treatment
NH_3	removal
Acid production	neutralisation/anoxic covers
Tailings	tailings management facility designed to retard migration of radionuclides and reduce radon emissions
Refining and conversion	
Temporary land disruption	reclamation
Low activity solid waste	disposal in waste management facility
NH_3	recovery
Acids	proper practices
$HF + F_2$	collectors + scrubbers/neutralisation
Organics TBP + kerosene	proper practices
CaF_2 residue	disposal in waste management facility

Table AE.2 Potential sources of environmental impacts and mitigation (continued)

Enrichment	
Temporary land disruption	reclamation
SO_X + NO_X from electricity generation	flue gas treatment
Contaminated water (anions and some metals)	dilute and discharge
Sludges	retention
UO_2 fuel fabrication	
Temporary land disruption	reclamation
HF	scrubbers and filters
Liquid effluents (lower negligible activity)	neutralised
NH_3 + nitrogen compounds	recovery
Strong acids	proper practices
Decommissioning	conventional techniques
MOX	
Temporary land disruption	reclamation
Atmospheric discharge	filters
Liquid effluents (low or negligible activity 1-5 kBq/m^3)	monitored and discharged
Liquid wastes of low or intermediate activity	conditioned to solid waste
Solid waste	incinerated or compacted then encapsulated in concrete for waste management
Spent fuel storage	
Temporary land disruption	reclamation
Waste effluents	concrete moulds
Atmospheric discharges	filters
Spent fuel disposal	
Future option	
Spent fuel reprocessing	
High level liquid waste	concentration and vitrification
Intermediate and low level waste	concentrated and converted to solids
Liquid effluent	Monitored filtered ion exchange
Atmospheric discharges	scrubbers and filters
Conventional chemicals and hazards	plant design and proper practices

Radiological impacts

During normal operation small amounts of radioactive materials may be released into the environment resulting in some radiological impact on the general public and the environment.

Adverse environmental effects may arise from any component and life cycle stage of the nuclear energy system. Moreover, the design and operation of one component of the system can have a major influence on the environmental effects of other components. Therefore, the environmental performance of a proposed system should be evaluated as an integrated whole.

The expected adverse environmental effects should be within the current regulatory guides, namely those prevailing at the time of the assessment. See, for example, the European Union ExternE study (EC, 1996), which has examined the impacts of alternative energy production systems and has shown that the existing nuclear generation has a low relative impact. It is expected that the environmental performance of innovative nuclear energy system will be better than that of an existing system.

For a nuclear facility, potential environmental effects include radioactive and non-radioactive chemical emissions, heat discharges and mechanical energy. The actual effects attributable to the stressors may differ significantly with geographical location and other site-specific and project-specific factors.

Impacts on humans

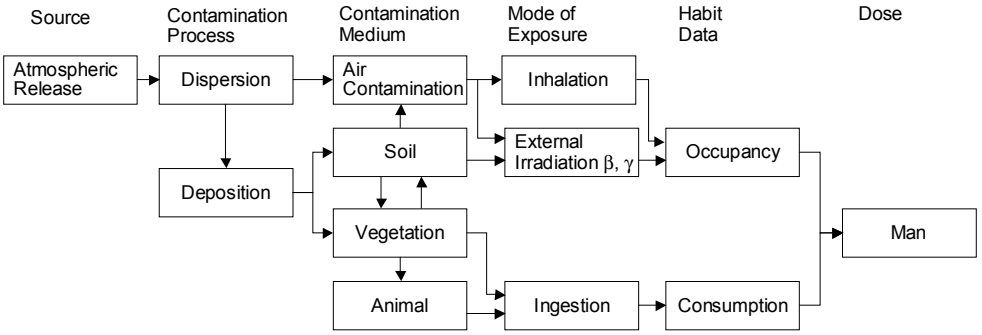
Nuclear fuel cycle impacts on humans in the area stated in terms of dose. Doses to the public may be calculated using a method known as pathway analysis. Figure AE.4 shows examples of a typical set of pathways that could be considered in such an analysis. In order to perform this assessment, knowledge of the transfer pathways in the human food chain and the transfer parameters between each compartment in that food chain are required.

Occupational doses to workers on the other hand are usually assessed using direct measurements rather than modelling. International organisations such as UNSCEAR (UNSCEAR, 2000) have done much to systematically collect, analyse, and present information in this area. In its 2000 report to the General Assembly, the Committee evaluated the normalised collective doses to the public and annual occupational exposures to monitored workers from the various steps of the nuclear fuel cycle (Tables AE.3 and 4). The local and regional normalised collective effective doses – which are effectively received within one or two years of discharge – amount to 3 man Sv per GWe per annum and are principally due to routine atmospheric releases during reactor and mining operations.

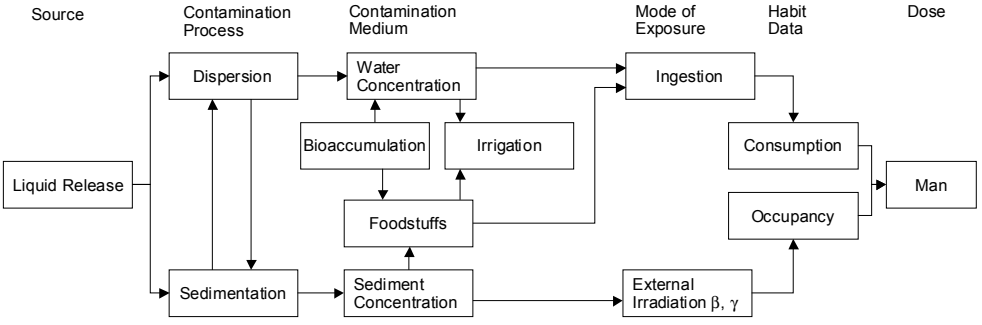
The annual effective doses range from 0.001-0.02 mSv to the most highly exposed members of the public for the principal types of power plants. The corresponding annual figures for modern fuel reprocessing plants are 0.01-0.05 mSv.

The impact of the nuclear fuel is also quantified by using the concept of collective dose. This allows consideration of the impact on a local or regional level and on a global level. Additional details of the calculation of these data can be found in (UNSCEAR, 2000).

Figure AE.4 Typical pathways in a nuclear environmental impact assessment



Schematic representation of atmospheric pathways



Schematic representation of aquatic pathways

Table AE.3 Normalised collective effective dose to the public from the nuclear fuel cycle (UNSCEAR, 2000, Annex C)

Source	Nomalised collective effective dose (manSv per GW(e).y)				
	1970-1979	1980-1984	1985-1989	1990-1994	1995-1997
Local and regional component					
Mining	0.190	0.190	0.190	0.190	0.190
Milling	0.008	0.008	0.008	0.008	0.008
Mine and mill tailing (release over 5 yrs)	0.040	0.040	0.040	0.040	0.040
Fuel fabrication	0.003	0.003	0.003	0.003	0.003
Reactor operation					
Atmospheric	2.800	0.700	0.4	0.400	0.400
Aquatic	0.400	0.200	0.06	0.050	0.040
Reprocessing					
Atmospheric	0.300	0.100	0.060	0.030	0.040
Aquatic	8.200	1.800	0.110	0.100	0.090
Transportation	< 0.100	< 0.100	< 0.100	< 0.100	< 0.100
Total (rounded)	12	3.1	0.970	0.920	0.910

Table AE.4 Occupational exposures to monitored workers – 1990-1994 (UNSCEAR, 2000, Annex E)

Fuel cycle step	Monitored workers (thousands)	Average annual collective effective dose (manSv)	Normalised collective effective dose (manSv per GW(e).y)	Annual effective dose per (mSv)	
				Monitored workers	Measurably exposed workers
Mining	69	310	1.72	4.50	5.0
Milling	6	20	0.11	3.30	
Enrichment	13	1	0.02	0.12	
Fabrication	21	22	0.10	1.03	2.0
Reactor operations	530	900	3.90	1.40	2.7
Reprocessing	45	67	3.00	1.50	2.8
Research	120	90	1.00	0.78	2.5
Total (rounded)	800	1 400	9.80	1.75	3.1

Environmental impact assessment (EIA)

In general, environmental impact assessments consider the environment to be composed of interacting systems which in turn comprise biological elements, fauna and flora, and physical elements, atmosphere, land and water. Impacts are considered to be those effects that alter the existing system either temporarily or permanently. However, the definition and measurement of impact is highly dependent on location, country, and social and economic factors.

Figure AE.5 illustrates the factors involved in an assessment of environmental effects of a nuclear energy system (IAEA, 2004). In particular the causal chain from source to effects is shown. Environmental effects generally include: physical, chemical or biological changes in the environment; health effects on people, plants and animals; effects on quality of life of people, plants and animals; effects on the economy; use/depletion of resources; and cumulative effects resulting from the influence of the system in conjunction with other influences on the environment.

For the environmental impact assessment, both radiological and non-radiological effects are relevant. A nuclear fuel cycle system potentially will have adverse environmental effects that must be considered in evaluating the system. At the same time, it must be recognised that such a system will have environmental benefits. For example, nuclear power is acknowledged as a key technology in meeting global emission targets of the Kyoto Protocol of the United Nations Framework Convention on Climate Change. Although it is adverse effects and their minimisation that are emphasised in assessing environmental performance, it is important that the existence of the benefits be always kept in mind.

Figure AE.6 illustrates the flow of materials and wastes in a generic case. Each nuclear fuel cycle facility produces a product from raw materials by using resources (energy, water, land) and reagents, producing solid waste and releasing effluent to air, water and the soil. These radiological and non-radiological releases may have impacts on both humans (workers and the general public) and non-humans and on the physical environment as in changes in water, sediment or air quality. Because of the long lived nature of some of the radionuclides released, concentration and bio-magnification in all food chains must be taken into account where appropriate when evaluating environmental impacts.

Figure AE.5 Factors considered in an environmental assessment

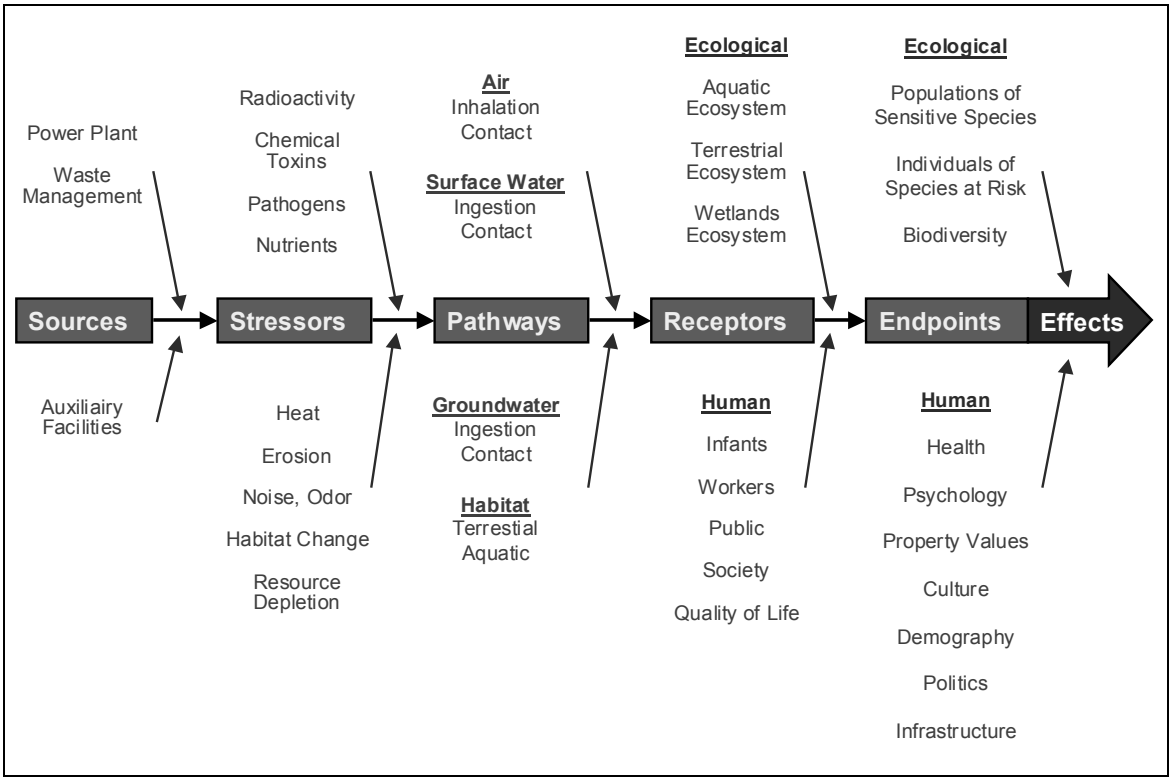
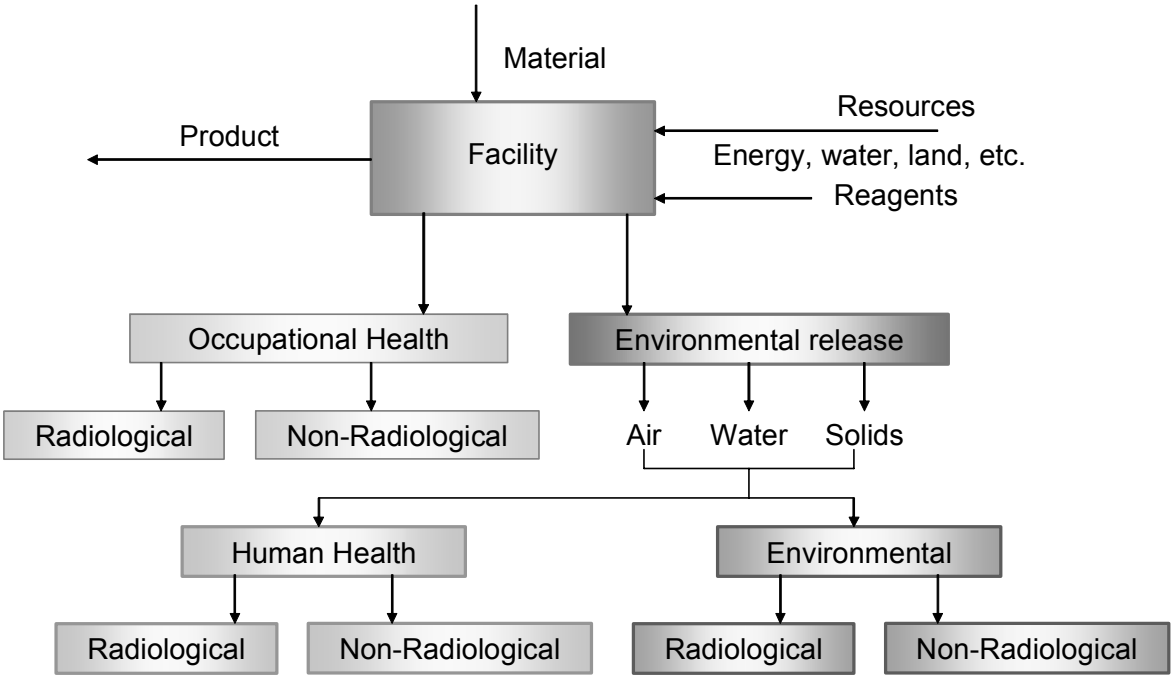


Figure AE.6 Health impacts – occupational and public



Environmental assessment is increasingly becoming mandatory in many countries as part of the regulatory practice. In the past, several reports have been published on the effects of the nuclear fuel cycle on the environment such as "Environmental Survey of the Uranium Fuel Cycle" (US-AEC, 1974). This study assesses the environmental considerations related to the nuclear fuel cycle for LWRs. The environmental considerations included natural resource use (land, water, and fossil fuel), effluent (chemical, radiological and thermal) and the effects on the environment. "The Environmental Impacts of Production and Use of Energy, Part II, Nuclear Energy" (UNEP, 1979) and "Nuclear Energy and the Environment" (UNEP, 1980) were published as part of the environmental impacts of different sources of energy. These reports deal with non-radiological and radiological impacts of each step of nuclear energy use. "Nuclear Power, the Environment and Man" (IAEA, 1982) is intended to present technical and other information on nuclear power and its health and environmental influences.

Information on radiological impact analysis may be obtained from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) report (UNSCEAR, 2000).

Within the nuclear fuel cycle the concept of nuclear safety analysis can also be used in environmental assessment in addressing accident conditions. Nuclear safety analysis is a means of analysing and evaluating the probability of accident occurrences, and identifying the measures that are necessary to reduce the probability and consequences of accidents. The release of hazardous materials is minimised by appropriate countermeasures, and health and environmental impacts are reduced. The NEA published a review of the safety of the nuclear fuel cycle facilities in 1993 (NEA, 1993).

Summary

The production of electricity from any form of primary energy has some environmental effect.

In the case of nuclear energy, environmental aspects are related to specific characteristics of nuclear reactors and fuel cycle facilities. The environmental performance of the nuclear energy system is vital to its future acceptability and is an important aspect of the evaluation of present and future nuclear technologies.

Environmental requirements can be divided into two classes: requirements imposed on the nuclear energy system itself, and requirements imposed on the methods used to assess its environmental performance.

For nuclear fuel cycle facilities, the main aspect to consider is the radiological impact of the different stages of the fuel cycle on the environment. However, there are various potential sources of non-radiological impacts in the different stages of the nuclear fuel cycle that need proper assessment. These impacts also include positive effects such as the minimal release of greenhouse gases.

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Appendix F

ACRONYMS

A

AGR	Advanced gas-cooled reactors

C

COEX	Co-extraction of actinides

E

EIA	Environmental impact assessment

F

FR	Fast reactor

G

GANEX	Grouped extraction of actinides
GNEP	Global Nuclear Energy Partnership

H

HEU	Highly enriched uranium
HLW	High-level waste

I

IAEA	International Atomic Energy Agency
IEA	International Energy Agency
ILW	Intermediate-level waste

J

JAEA	Japan Atomic Energy Agency

L

LEU	Low enriched uranium
LLFP	Long-lived fission product
LLW	Low-level waste
LWR	Light water reactor

M

MEU	Medium enriched uranium
MEXT	Ministry of Education, Culture, Science and Technology
MIMAS	Micronised masterblend
MOX	Mixed-oxide fuel

N

NEA	OECD Nuclear Energy Agency
NDC	NEA Nuclear Development Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle

O

OECD	Organisation for Economic Co-operation and Development

P

PHWR	Pressurised heavy water reactor (CANDU)
PWR	Pressurised water reactor

R

RepU	Reprocessed uranium

U

UOX	Uranium oxide

S

SWU	Separative work units

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Management of Recyclable Fissile and Fertile Materials

Interest in nuclear energy continues to grow in many countries as a means to ensure security of energy supply and to limit greenhouse gas emissions from the power sector. In this context, recyclable materials constitute an asset for broadening the resource base for nuclear fuel supply, especially in medium- and long-term perspectives.

This report provides an overview of recyclable fissile and fertile materials inventories which can be reused as nuclear fuel. It reviews the options available for managing those materials, through recycling and/or disposal. The potential energetic value of recyclable materials is assessed, taking into account the variability of retrievable energy contents of various materials according to technology and strategy choices made by the owners of the materials.

The analyses contained in this report will be of particular interest to energy policy makers and to nuclear fuel cycle experts.

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