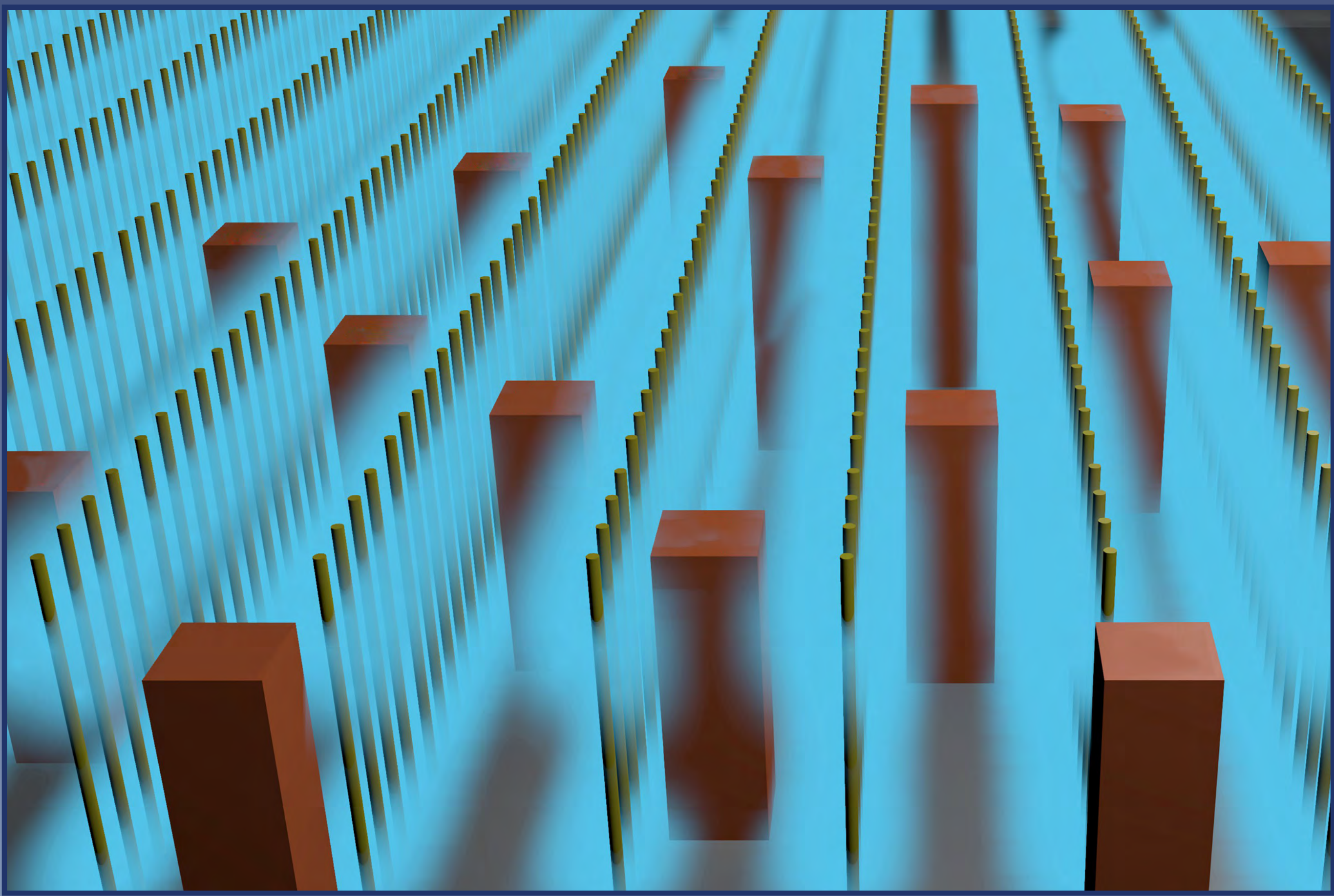
Management of spent nuclear fuel and its waste



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FOREWORD

This report aims to help policy makers develop national programmes for the future management of spent nuclear fuel and the waste generated by fuel treatment. In a concise but comprehensive way, it describes the options for spent fuel management.

The report is the result of the fruitful collaboration between the European Commission's Joint Research Centre (EC-JRC) and the European Academies' Science Advisory Council (EASAC).

To ensure that European policy making is informed by the best current scientific knowledge, a panel of experts from Europe and the US was consulted by EASAC and the JRC to assess the challenges associated with different strategies for managing spent nuclear fuel. This assessment covered open, partially-closed and fully-closed nuclear fuel cycles. The report captures these expert views and summarises the conclusions on the issues raised on sustainability, safety, non-proliferation and security, economics, public involvement and on the decision-making process.

EASAC and the JRC have prepared the present document to support the implementation of the Directive 2011/70/EURATOM on the responsible and safe management of spent fuel and radioactive waste.

The collaboration of the two organisations, endorsed by a letter of intent in 2011, has spanned the mandates of two JRC Directors-General and two EASAC Presidents.

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ABSTRACT

The spent nuclear fuel from the operation of nuclear power plants needs to be managed in a safe, responsible and effective way. Several possibilities exist to deal with the spent fuel. Within the so-called "open fuel cycle", it is disposed of without further use. When "closing the fuel cycle", the energetic component in the spent fuel, plutonium and uranium, is extracted (i.e. 'reprocessed') for reuse. Consequently, in fully closed cycles, up to 50 to 100 times more energy can potentially be generated from the uranium mined originally. In addition, comprehensive recycling and treatment of the used fuel components by anticipated advanced technologies would leave waste material that decays to low levels of radioactivity in less than 1 000 years. However, all of these steps involve additional dedicated facilities, and require substantial further research and development before they are commercially available.

The European Council Directive 2011/70/EURATOM on the "responsible and safe management of spent fuel and radioactive waste" requires EU Member States to establish a dedicated policy, including the implementation of national programmes for the management of spent fuel and radioactive waste. This report by the Joint Research Centre and European Academies' Science Advisory Council aims to inform policy makers on important issues to be taken into consideration for national programmes. It describes the options for spent fuel management, their present state of development and their consequences.

It concludes that the fuel cycle policy should take account of the following considerations:

- Given the long timeframes (more than 100 years) of all the fuel cycles, it is advantageous to generate robust technical solutions, covering the whole process, but keeping alternatives available to accommodate changes in future policies and plans.

- To ensure this flexibility in future choices, it is important that research is conducted on both open and closed fuel cycles. Cooperation bilaterally or at the European level is very useful for this purpose, including also the common development of fuel cycle and reactor facilities.

- The potential improvement in uranium utilisation from recycling in fast neutron reactors merits continuing their development.

- Further work on national or regional solutions for deep geological disposal is essential and urgent to ensure that spent fuel or high level waste can be safely disposed of at the appropriate time.

- Education and training are necessary to support the long term safe management of spent nuclear fuel and should be carefully considered. EU level initiatives to enable sharing of training materials and access to research facilities would be of value.

In the end the policy will not only be based on technical and organisational factors, but will also have to consider political aspects in general, and public acceptance issues in particular. It will thus be important to ensure sufficient public involvement and communication in the different steps of decision-making.

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1 INTRODUCTION

The spent (or used) nuclear fuel from the operation of nuclear power plants needs to be managed in a safe, responsible and effective way. Several possibilities exist to deal with the spent fuel. Within the so-called "open fuel cycle", it is disposed of without further use. When "closing the fuel cycle", the energetic component in the spent fuel, plutonium and uranium, is extracted (i.e. 'reprocessed') for reuse. Consequently, potentially up to 50 to 100 times more energy can be generated from the uranium mined originally. In addition, comprehensive recycling and treatment of the used fuel components by anticipated advanced technologies would leave waste material that decays within 'historical' timescales[1]. However, all of these steps involve additional dedicated facilities.

The strategy for the management of spent fuel adopted in different countries has changed over the years. In the early phase of nuclear power production (1960's and 1970's), it was generally agreed that all spent fuel should be reprocessed and the uranium and plutonium recycled in dedicated *fast neutron*[2] reactors, to avoid potential shortages in supplies of nuclear fuel. From the 1980's on, some countries have continued to reprocess spent fuel and recycle uranium and plutonium, but primarily as fuel for *thermal neutron* reactors. Other countries have changed their strategy and implemented an open fuel cycle. Currently, several countries are keeping both options open.

There are technical, economic and political reasons for the change in strategy. The high demand for nuclear fuel originally forecasted did not materialize, as expansion of nuclear power slowed down, and uranium is available on the world market from countries considered to be reliable in geopolitical terms. Hence, recycling of nuclear fuel in order to decrease the demand for uranium or achieve political independence has become less important, at least in Europe. Furthermore, the development of *fast neutron* reactor technology has been more difficult than expected. Finally, the prospect of a spreading of technology for plutonium extraction has led in some countries to increasing concerns about nuclear proliferation.

The factors to consider in making strategic choices between different fuel cycle options are changing with the evolution of nuclear technologies, the variable demand for uranium, the challenges encountered in the implementation of geological repositories, and developments in the geopolitical situation. For these reasons, national nuclear fuel cycle policies may benefit from being periodically reassessed. A further impetus to do so now comes from the recently adopted Council Directive 2011/70/EURATOM on the "responsible and safe management of spent fuel and radioactive waste" which requires EU Member States to establish a dedicated policy, including the implementation (and notification to the Commission) of "national programmes" for the management of spent fuel and radioactive waste.

More generally, decisions on the role of nuclear power are made within the context of national and European strategies and targets for climate change mitigation. These include the aim that Europe's electricity system achieve essentially zero emissions of greenhouse gases by 2050[3].

2 AIM AND SCOPE OF THE REPORT

The present report aims to inform policy makers on important issues to be taken into consideration for developing national programmes for the future management of spent fuel and the waste generated by fuel treatment.

The report has been prepared by the European Academies' Science Advisory Council (EASAC) (www.easac.eu) and the European Commission's Joint Research Centre (JRC) (https://ec.europa.eu/jrc/en), to ensure that European policy making is informed with the best current scientific knowledge.

1 *In this context, "historical timescales" refers to a period less than some 1 000 years until the disposed waste has decayed to radioactivity levels comparable with natural uranium ores.*

2 *Fast neutron reactors use high energy (high speed) neutrons, as distinct from present-day thermal neutron reactors where the neutrons are slowed down for the fission of the uranium in the fuel. In comparison with thermal neutron reactors, fast neutron reactors consume the uranium and plutonium in the fuel in a more efficient way.*

3 *"A roadmap for moving to a competitive low carbon economy by 2050", European Commission COM (2011) 112 final.*

The report discusses:

- the need for a national policy;
- the fuel cycles to consider;
- the decision factors in fuel cycle choice;
- experience with the involvement of stakeholders in decision-making; and
- the key decisions to be taken and their consequences.

To inform preparation of the report, a seminar was held in Brussels in February 2013 to get the views of a panel of experts from Europe and the US on the challenges associated with different strategies to manage spent nuclear fuel, in respect of both open cycles and various steps towards closing the nuclear fuel cycle. The report integrates the conclusions of the seminar, which considered issues of sustainability, non-proliferation, safety, organisational and economic factors, and public involvement.

3 THE NEED FOR A NATIONAL POLICY

The Council Directive 2011/70/EURATOM, of 19 July 2011, establishes a Community framework for the responsible and safe management of spent fuel and radioactive waste, and sets out the principles to be reflected in the national policies of EU Member States[4].

A Member State's decisions on spent fuel management will depend strongly on its overall energy strategy (including nuclear energy strategy) and, in particular, on its requirements for security of energy supplies at an affordable cost. However, defining a policy for the management of spent fuel and radioactive waste is an essential cornerstone to ensure continuity in the necessary technological developments and related investments, and the consolidation of knowledge and competence. Moreover, experiences in some EU Member States have shown that clear communication of policy can also facilitate public dialogue and involvement.

The Directive considers this by requiring that each Member State establish and implement a "national programme", for turning its national policy into practical actions and solutions. The *national programme* will include:

(a) the overall objectives of the national policy;

(b) milestones and timeframes for achieving the objectives;

(c) the inventory of the spent fuel and radioactive waste;

(d) concepts or plans and technical solutions from generation to disposal;

(e) concepts or plans for the post-closure period of the disposal facility;

(f) necessary research, development and demonstration activities;

(g) the responsibility for the implementation and performance indicators;

(h) an assessment of the cost of the programme;

(i) the financing scheme;

(j) a policy or processes for transparency; and

(k) if applicable, the concluded agreement(s) with a Member State or third country on management of spent fuel or radioactive waste, including on the use of disposal facilities.

The Directive does not specify the fuel cycle option to be chosen, but sets out requirements which are closely linked to the fuel cycle choice.

The Directive emphasises not only the requirement for safety, but also acting responsibly and consistently with the principle of not imposing undue burdens on future generations. The timeframes of nuclear fuel cycles require that responsibilities are allocated over the long term, including long after the waste has been produced for the benefit of generating electricity. This includes the particular need for funding schemes to be put in place: those who have

4 *The obligations for transposition and implementation of provisions related to spent fuel of this Directive do not apply to Cyprus, Denmark, Estonia, Ireland, Latvia, Luxembourg and Malta for as long as they decide not to develop any activity related to nuclear fuel.*

benefited also take responsibility for providing the financial resources to remediate the waste.

Some further information on the provisions of the Directive is provided at Annex II.

4 THE FUEL CYCLES TO CONSIDER

4.1 THE MAIN TECHNOLOGICAL OPTIONS

OPEN FUEL CYCLE

With the open cycle, the spent nuclear fuel is not further used or recycled. Instead, all spent fuel is intended to be encapsulated and disposed of in a geological repository.

The steps and facilities of the open cycle can be summarised as:

- *interim storage* of the spent fuel in the reactor pools for some years to cool down the fuel;
- if needed, transfer to a dedicated store at the reactor site or to a centralised storage facility;
- *encapsulation* of the fuel in a disposal container; and
- *disposal* in a geological repository.

For the interim storage of the fuel, two possibilities exist: the spent fuel can be stored in pools ('wet storage') or can be enclosed in casks in a dedicated facility ('dry storage'). Both alternatives are currently implemented, or planned at a large scale, in several EU Member States.

The 'encapsulation' of the spent fuel has until now only been practiced with dummy fuel at a pilot scale, although in some countries encapsulation facilities and the related geological repositories are at an advanced design stage and applications to build have been submitted[5,6].

5 *"Environmental Impact Statement – Interim storage, encapsulation and final disposal of spent nuclear fuel", SKB, 2011.*
6 *"Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto", Posiva, 2012.*

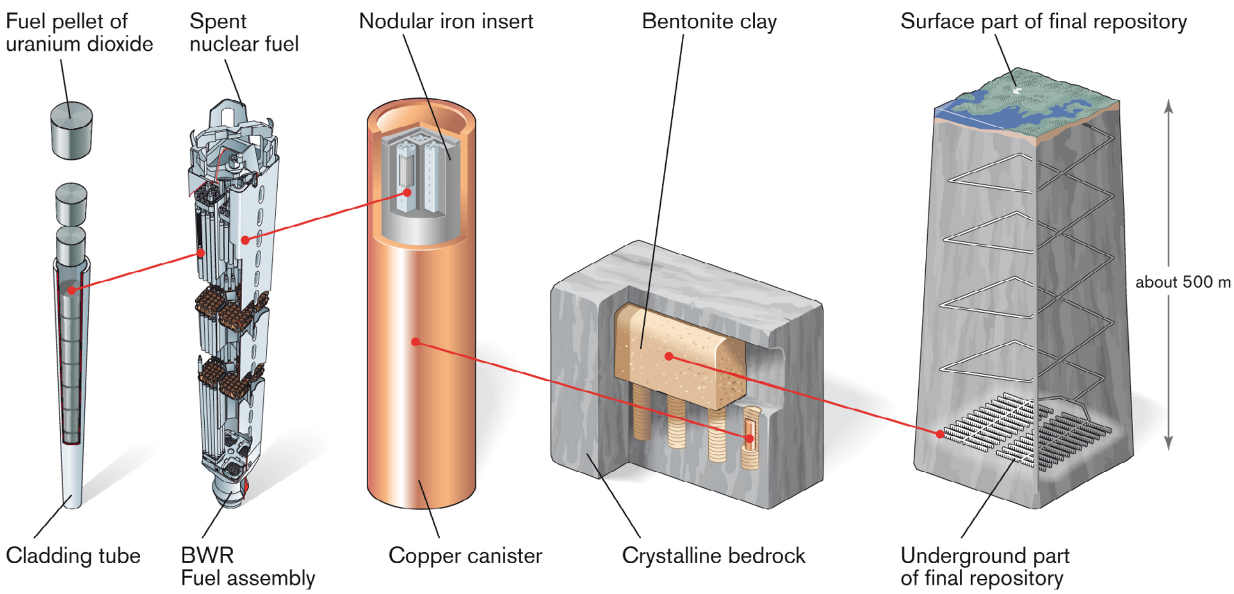

Figure 4.1: Disposal of spent fuel according to the Swedish/Finnish KBS-3 method (SKB)

Type of cycle	Type of reactor	Treatment of spent fuel	Re-use of spent fuel material	Waste requiring geological disposal
Open fuel cycle	thermal neutron reactors	Storage, encapsulation and disposal	none	all the spent fuel after one cycle
Partially closed cycle *(one cycle of extraction of uranium and plutonium)*	thermal neutron reactors	spent fuel is reprocessed for extraction of uranium and plutonium spent recycled fuel (MOX fuel) is stored for later disposal	first cycle: re-use of plutonium and depleted uranium for MOX fuel, re-use of reprocessed uranium no second cycle	conditioned high level waste and compacted fuel cladding spent MOX fuel
				waste from reprocessing and fuel fabrication
Fully closed cycle *(repeated extraction of uranium and plutonium)*	fast neutron reactors and thermal neutron reactors	repeated reprocessing (also of spent recycled fuel) for extraction of plutonium and uranium	plutonium and uranium from different re-use cycles and depleted uranium are mixed to allow fabrication of recycled fuel	conditioned high level waste and compacted fuel cladding
				waste from reprocessing and fuel fabrication
Fully closed cycle + Partitioning and Transmutation *(repeated cycles of partitioning, followed by transmutation of long-lived residues)*	fast neutron reactors or waste burners	repeated reprocessing including partitioning	full re-use of plutonium and uranium 'burning' of long-lived residues (transmutation)	residual conditioned high level waste and compacted fuel cladding
				waste from reprocessing and fuel fabrication

Table 4.1: Characteristics of the open fuel cycle and main different levels of closing the fuel cycle

CLOSING THE FUEL CYCLE

'*Closing the fuel cycle*' means that the spent fuel is not considered as waste but is treated in order to re-use the main fissile components, i.e. the plutonium and the uranium, by separating them from the unproductive and radioactive residues[7].

Closing the fuel cycle involves the following steps:

- *interim storage* of the spent fuel in the reactor pools for some years to cool down the fuel;
- transfer of the fuel to a *reprocessing plant* where the re-usable components are separated from the residual waste products;
- *conditioning* of the waste products ('high level waste' or 'HLW'), e.g. by vitrification, and transfer of the conditioned waste to a facility for interim storage, pending disposal;
- fabrication of *recycled fuel* with the separated energetic components in dedicated plants and re-use of these fuels in a *thermal neutron reactor* or in a *fast neutron reactor*; and
- *disposal* of all HLW and other long-lived waste in a geological repository.

There are many possible variants; some of them are summarised in Table 4.1.

7 *The residues in spent fuel consist of 'fission products', generated by the fission reactions in the reactor and 'activation products', generated by the interaction of materials with neutrons from the nuclear fission process. Some of these are described as 'short-lived', i.e. decaying in periods of less than a few hundred years, some as 'long-lived'.*

In the case of a '*partially closed cycle*', the plutonium and uranium components of the spent fuel are separated and recycled once (e.g. as 'MOX' fuel[8]) in thermal neutron reactors, but the remaining spent recycled fuel is then disposed of. In a '*fully closed cycle*', the recycling is repeated to totally consume the plutonium and uranium.

The partially closed cycle with a single recycling of the spent fuel in *thermal neutron* reactors has been practiced on an industrial scale for a few decades. Experiments have already been done with a second recycling step, but an iterative recycling and the steps towards the fully closed cycle are still under development. Full recycling remains for the moment only a long term prospect and is in principle only feasible with the use of *fast neutron* reactors, which can be optimised to consume the plutonium and uranium efficiently. Fast reactors are not yet commercially available in Europe, and the necessary development work is on-going.

A process complementary to the fully closed cycle is '*partitioning and transmutation*' in which not only plutonium and uranium, but also the other long-lived radiotoxic residues are extracted separately (i.e. 'partitioning'). Their transformation into short-lived products (i.e. 'transmutation') would generate

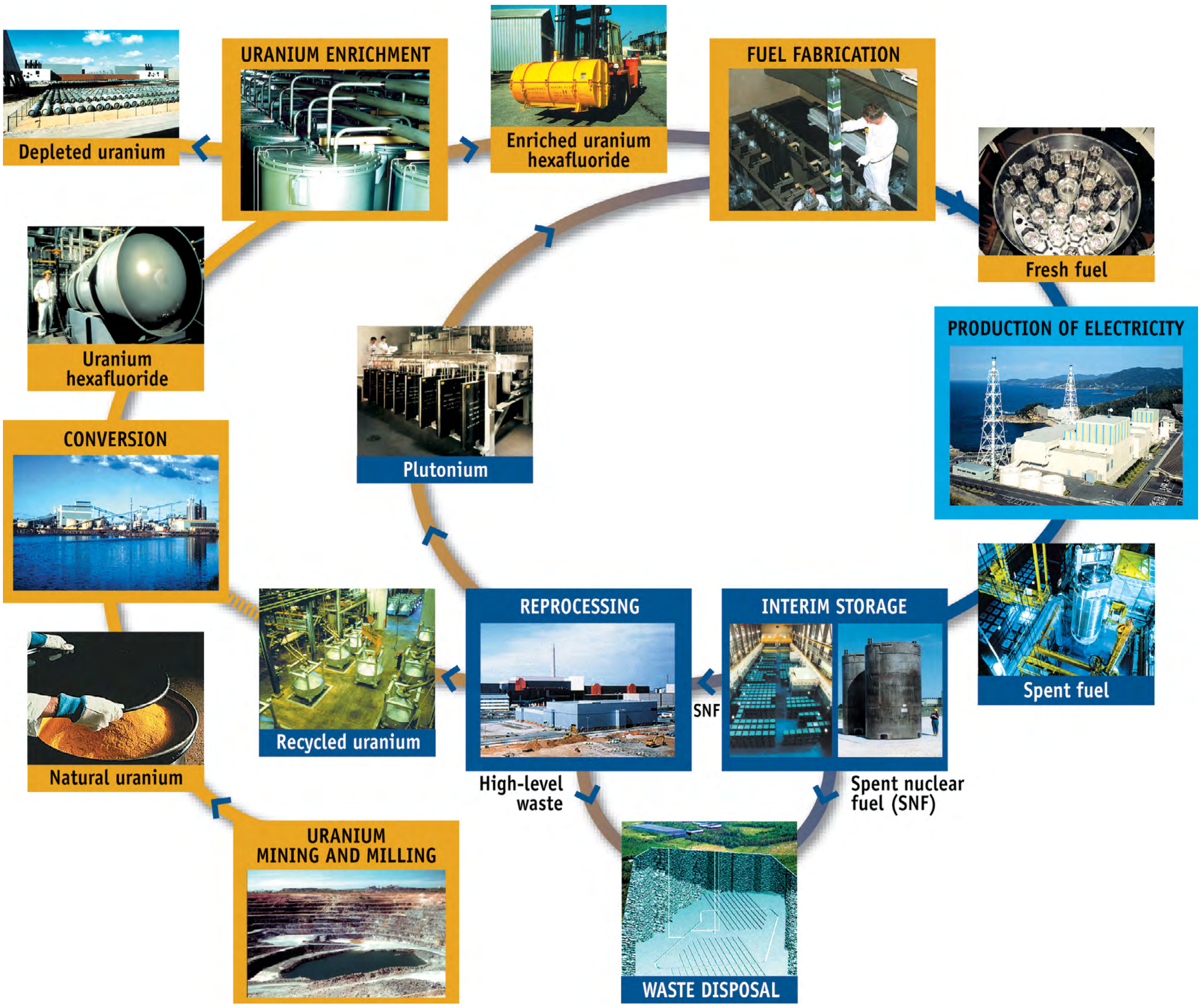

Figure 4.2: Fuel Cycle Steps (OECD/NEA, 2011, Trends towards Sustainability in the Nuclear Fuel Cycle, Nuclear Development, OECD Publishing http://dx.doi.org/10.1787/9789264168268-en

8 *MOX fuel (Mixed Oxide Fuel): fuel fabricated by mixing reprocessed plutonium with uranium oxides.*

only waste decaying in historical timeframes. This would be done by an adaptive design of *fast neutron* reactors or in dedicated '*waste burning*' reactors. Development of partitioning and transmutation is currently only at an experimental scale.

With the envisaged processes the quantity of long-lived waste can be significantly reduced. Nevertheless, there will always be a need for a deep geological repository: the recycling processes will inevitably generate waste containing the remains of long-lived radiotoxic products (although through advanced conditioning techniques the immobilisation of the waste can be enhanced). There are also long-lived wastes from other sources such as fuel from research reactors, legacy non-standard fuel from past activities, residual fuel or fuel components, long-lived decommissioning wastes, and vitrified waste from previous reprocessing.

4.2 THE TIMEFRAMES INVOLVED

A nuclear programme is a very long term commitment, which includes not only the operation of the nuclear power plants, but also the processing and/or disposal of the fuel. The programme inevitably extends to a century or more.

There are different timeframes associated with the various phases and/or processes (a summary of the steps to consider is presented in Table 4.2). Timeframes may overlap, because activities are not all implemented sequentially. But estimates of the actual timeframes should also include the necessary research and development to reach industrial maturity of new technologies. And timeframes can extend, if decisions are postponed.

Type of fuel cycle	Phase or activity	Approximate minimum timeframe	Possible overlap
Common to all type of cycles	Siting, construction, commissioning of first reactor (from decision to enter a nuclear programme) construction, commissioning of first reactor (from decision to enter a nuclear programme)	10 years	In the past none. For new programmes: ideally overlapping with disposal programme[(a)]
Open fuel cycle	Operation	First reactor 40-60 years	Ideally overlapping with disposal programme
	Spent fuel storage	20-60 years after final removal from core, i.e. last fuel used becoming spent fuel	Until the last reactor is shut down: overlap with reactor operation.
	Siting and construction of spent fuel repository	30-40 years	Can overlap with reactor operation and spent fuel storage, and should at least overlap with end-phase of spent fuel storage
	Operation of spent fuel repository	Minimum 30 – 60 years	Overlap desired with later phase of reactor operation and storage
Total estimated timeframe		**Minimum some 100 years**	

(a) In several EU Member States new reactors cannot be licensed unless there is a credible disposal programme in place, including financial provisions.

Type of fuel cycle	Phase or activity	Approximate minimum time-frame	Possible overlap
	Thermal neutron reactor programme	First thermal reactor: 80 years	Ideally overlapping with disposal programme
	First generation spent fuel ready for partitioning	10 years	The time after starting operation of thermal neutron reactor programme
	Partitioning and fabrication of first generation of MOX fuel	10 years	Can be part of one-cycle reprocessing programme ahead of full partitioning and transmutation
	Development, testing and demonstration of fission product and minor actinide conditioning techniques	30 years	Should overlap with thermal and fast neutron reactor programmes
	Fast neutron reactor programme development	Development and start of commercial operation: Some 50 years	Will overlap with thermal neutron programme but still needs some 50 years from the present day
Fully closed fuel cycle including Partit-ioning and Trans-mutation	Operation of fast neutron reactor programme	First fast reactor: some 80 years	Operation will not start until MOX from the first cycle thermal neutron programme is available, in general only when the thermal neutron reactor programme has reached considerable maturity and the amount of plutonium from reprocessing available as MOX is substantial.
	Storage of conditioned waste	50 – 100 years	Until the last reactor is shut down: overlap with reactor operation.
	Siting and construction of waste repository	30 years	Will overlap with reactor operation and partitioning and transmutation, and should at least overlap with end-phase of waste storage
	Operation of waste repository	Minimum 80-100 years	Overlap desired with later phase of reactor operation, partitioning and transmutation
	Phase-out	50 years 100 – 150 years	If there are only fast neutron reactors in the fleet, or if the spent fuel from the thermal neutron reactors is disposed of without processing, and a repository for spent fuel is available, the phase-out could be implemented within some 50 years. It should however be noted that a fully closed cycle is implemented in the logic of long term operation of nuclear energy[(c)].
Total estimated timeframe		**Minimum some 150-200 years [(d)]**	

Table 4.2: Estimated timeframes for different phases of a nuclear programme – open cycle and fully closed cycle including partitioning and transmutation[(d)]

(b) To be noted however that a fully closed cycle is implemented in the logic of long term operation of nuclear energy.
(c) This does not include the technology developments necessary today to achieve full maturity for all steps of a closed cycle.
(d) Numbers are given as orientation values because they can vary widely as discussed in this section. Disposal is only considered for the waste with the longest half-life for the respective option.

In theory (this scenario is presented hypothetically), an open fuel cycle option may be implemented and closed within a timeframe of about 100 years. This assumes that a reactor is built in about 10 years and shut-down after 40 to 60 years of operation, without renewal of the reactor. The remaining time is associated with cooling/storing of the last batch of spent fuel from reactor operation, disposing of this spent fuel and associated wastes and closing the repos-itory, and in parallel, decommissioning the reactor and disposal of decommissioning wastes. The construction of more than one reactor, and operating them over a longer time period, will extend the overall timeframe.

When partially closing the cycle by reprocessing the spent fuel and re-using it in a *thermal neutron* reactor, the timeframe will still be of the order of a century. Introducing a national programme to fully close the fuel cycle using advanced technologies and multiple recycling of plutonium in *fast neutron* reactors, would require a commitment over a total timeframe which can be several hundred years for the elaboration, operation and finalisation of the programme, depending on the level of recycling pursued. In practice, use of internationally shared, existing facilities (e.g. reprocessing plants and in the future *fast neutron* reactors) may reduce the total timeframe.

Schedules for the implementation of the policy can vary widely, being strongly affected by, for example, delay of decisions, or decisions to extend plant lifetimes or conversely to phase out nuclear power.

In conclusion, the policy should be robust enough to accommodate political, social and economic changes over very long timescales.

4.3 PRESENT PRACTICES IN EUROPEAN AND NON-EUROPEAN COUNTRIES

Currently only a few countries worldwide have consistently committed to implementing either an open or closed fuel cycle.

In the EU, the open cycle strategy has been adopted by Sweden and Finland, where the encapsulated fuel is planned to be disposed of in a geological repository after 40 years interim storage. Sites have been chosen for a geological repository in each country, and licenses have been applied for. Also in Germany the open fuel cycle is currently used, resulting from a 2002 amendment of the nuclear energy act (subsequently, in 2011, a decision was taken to phase-out nuclear power).

France is working towards a fully closed fuel cycle with the development of *fast neutron* reactors and advanced reprocessing technology. A partially closed cycle has been implemented for several decades: spent fuel is reprocessed and MOX fuel is fabricated and recycled in light water (thermal neutron) reactors. Spent MOX fuel is stored for later reprocessing and recycling in fast reactors. The development of a geological repository for high level and long-lived waste is on-going.

In most of the other nuclear EU countries both strategies are considered, or the situation has varied over the years: fuel has been reprocessed and partially recycled and direct disposal is envisaged, at least for part of the fuel.

In the USA, the present policy, as set out in the U.S. Department of Energy's Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste, is to pursue centralised interim storage and ultimate disposal for the current inventory of spent nuclear fuel without further treatment. However, research on advanced fuel cycles and advanced reactors continues, thus keeping closed fuel cycles as an option for the future management of spent nuclear fuel.[9, 10]

In the main countries with a growing nuclear programme (China, India and Russia) the strategy is to develop a fully closed fuel cycle. This includes the development of reprocessing plants and the implementation of *fast neutron* reactors, which are currently in operation at a pilot scale or are at a planning phase. The same strategy applies in Japan, although after the Fukushima accident the way forward is linked to the future of the nuclear energy programme.

9 *"Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste", U.S. Department of Energy, 2013.*

10 *The situation in the USA and possible developments have been assessed by the Blue Ribbon Commission on America's Nuclear Future, see "Report to the Secretary of Energy", 2012.*

In most other nuclear countries worldwide both strategies are being considered, as in EU countries, and the situation has varied over the years[11].

4.4 THE DEVELOPMENT OF FUTURE REACTOR TECHNOLOGY

Fast neutron reactor technology has been developed since the 1950's and several prototype and more advanced reactors were in operation in the world in the 1970's and 1980's. Since then, their operation has stopped in most countries for technical, economic and political reasons, the main exceptions being Russia, Japan[12], China and India. However, since 2000 there has been renewed interest in the development of *fast neutron* reactors in several countries.

Although the front-end fuel cycle process (before entering the reactor) and back-end fuel cycle process (after removal from the reactor) are not as such part of the GIF scope, the new systems being developed will have direct implications for future fuel cycle strategies.

Three of the six reactor systems are *fast neutron* reactors (sodium-cooled, lead-cooled and gas-cooled reactors), in which the key aim is improved use of the uranium resource by the recycling of plutonium and uranium. Transmutation of separated long-lived components is also anticipated at a later stage. The most advanced system is the sodium-cooled fast reactor, with experience in several countries worldwide and new projects in the design or construction phase.

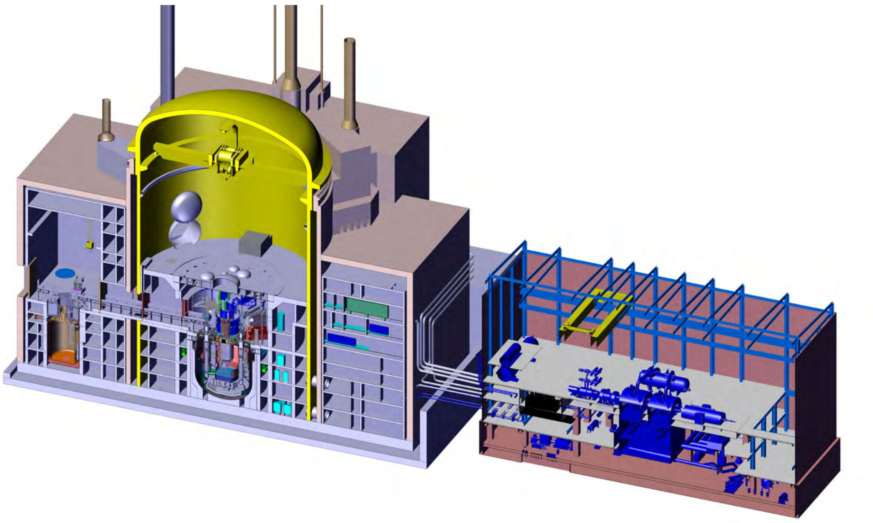

Figure 4.3: View of the ASTRID technological demonstration plant (fast neutron reactor) (©CEA)

Much of this on-going technological development of nuclear power and the associated fuel cycles is coordinated within the '*Generation IV International Forum*' ('GIF'), established in 2001. Within GIF, six favoured nuclear reactor systems have been selected. Collaborative research and development is under way, with the aim of starting the deployment of new systems within a few decades.

A fourth system, the *molten salt* reactor system, allows for continuous recycling on-line of the fuel dissolved in a salt. The present reference design is also a *fast neutron* reactor, using alternative fissile material: thorium. The system is in an early stage of development.

The two other systems (the *very high temperature* reactor and the *super-critical water* reactor) are not focused on recycling but on higher energy efficiency and alternative utilisation of heat for industrial processes. The fuel for the very high temperature reactor is not anticipated to be reprocessed.

11 See "Country Nuclear Fuel Cycle Pro-files", IAEA technical report Series n°425, 2005.

12 Though operation has been suspended following the Fukushima accident.

In Europe, the most advanced development work is performed in France. A prototype *fast neutron* reactor is planned to be in operation around 2025. This will subsequently be followed by commercial test reactors. A larger scale introduction of fast reactors and their fuel cycle facilities is expected to be possible in Europe around 2050. In Russia the development is further ahead and large scale utilisation could come some 10 years earlier.

Besides the GIF systems discussed here, which are power reactors producing electricity, research is also underway to develop '*waste burner*' systems: reactors mainly focused on the consumption of the long-lived waste products. They are at a very early stage of development and the most advanced designs are the *accelerator driven systems*[13], where a particle accelerator interacts with a target to induce the fission reactions in the reactor.

5 THE DECISION FACTORS IN FUEL CYCLE CHOICE

A holistic approach, considering the full set of issues and consequences ('from cradle to grave'), is a prerequisite for defining policy[14]. Many factors can indeed influence the choice of fuel cycle; for the purpose of this report, they are grouped in four sections:

- sustainability;
- safety;
- non-proliferation and security; and
- economics.

5.1 SUSTAINABILITY

With respect to the long timeframes of nuclear fuel cycles as discussed above, it is essential to have assurance that the choices made are sustainable, i.e. have the capacity to endure over the required time period.

Sustainability is considered in respect of:

- *the availability and use of natural resources*
- *the spent fuel handling and treatment process*
- *waste disposal*

Each issue merits being evaluated, as it is positively or negatively impacted by the fuel cycle option. Their relative importance can vary with time or place and with the evolution of the socio-economic environment. A synthesis is presented in Table 5.1.

SUSTAINABILITY RELATIVE TO THE AVAILABILITY AND USE OF NATURAL RESOURCES

The sustainability relative to natural resources is primarily concerned with the long-term availability of uranium in relation to its expected consumption.

With the open cycle, the average consumption of uranium is about 20 tonne/TWh, corresponding roughly to 200 tonnes per year of reactor operation.

One key advantage of the closed cycle is the better utilization of the uranium resource. For the partially closed fuel cycle with single recycling of plutonium in *thermal neutron* reactors as practiced today, about 11% more electricity is produced per tonne of natural uranium. If the reprocessed uranium is also recycled as nuclear fuel, an additional 10% electricity can be generated per tonne of natural uranium.

In a fully closed cycle with *fast neutron* reactors, the consumption of uranium and plutonium can be optimised in such a way that 50 to 100 times more electricity can be generated from the original natural uranium. This high efficiency is anticipated to be enabled by recycling of the depleted uranium arising from the current uranium enrichment process for *thermal neutron* reactor fuel, as well as the reprocessed uranium, in fast reactors where they are converted to plutonium[15, 16, 17].

However, uranium is at present not a scarce resource in relation to its current consumption. The availability of uranium corresponds to the amount of known uranium reserves accessible at a specific market price. The price is variable; at the end of the last

13 *For example, the proposed MYRRHA research reactor: http://myrrha.sckcen.be/.*

14 *"Trends towards Sustainability in the Nuclear fuel Cycle", OECD/NEA, 2011.*

15 *"The Sustainable Nuclear Energy Technology Platform – A Vision Report", European Commission Special Report, 2007.*

16 *"Transition from Thermal to Fast Neutron Nuclear Systems", NEA, 2010.*

17 *"Advanced Nuclear Fuel Cycles and radioactive waste Management", OECD/NEA, 2006.*

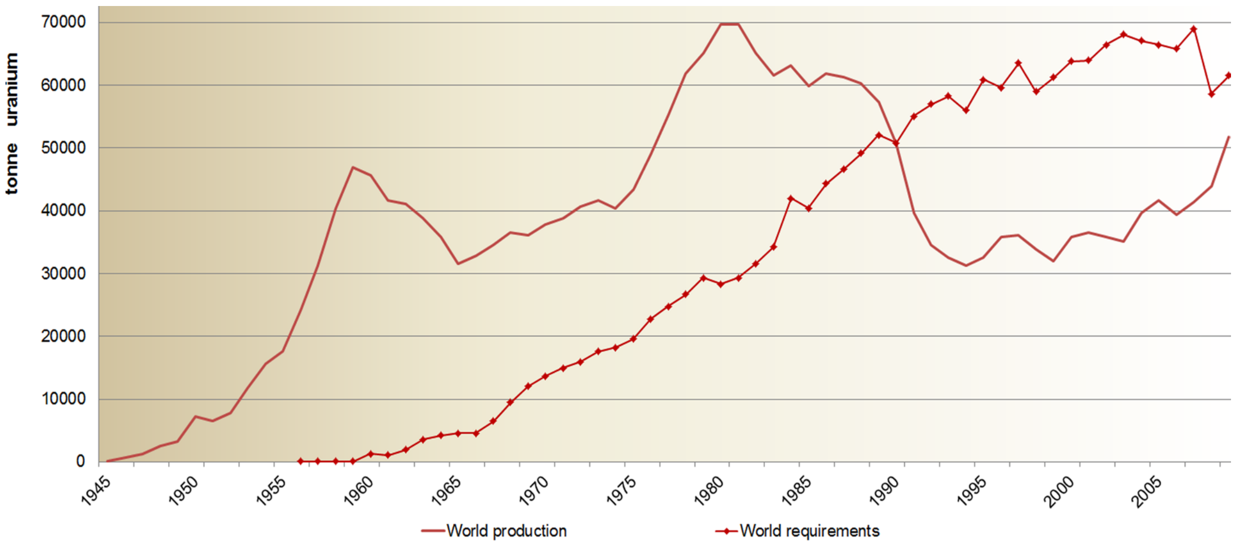

Figure 5.1: Evolution of uranium consumption (NEA)

century, the market price dropped to below 20 US $/pound (about € 40/kg). Reasons included the lower than expected expansion of nuclear power and the use of uranium extracted from recycled weapons for commercial power reactor fuel. In the last decade the price surged but decreased again, and is currently around 40 US $/pound (about € 80/kg).

At the current price, the identified reserves would allow about 100 years of operation at the present rate of consumption by nuclear reactors and without major recycling[18]. If fast neutron reactors are used with full recycling of plutonium and uranium, current uranium reserves would permit at least 5 000 years of operation at present global levels of nuclear power generation.

Besides undiscovered uranium ore reserves, large quantities of uranium could be extracted as a by-product of phosphate mining, which until now have only been utilised to a small extent. Development work is in progress to lower the cost of uranium extraction from phosphate residues. Additional alternative sources can be envisaged, such as extraction of uranium from sea water, but their use would require further technological developments and they are only economically viable at much higher market prices[19].

An alternative to uranium is the use of thorium, reserves of which are more widely available. However, a thorium cycle requires the availability of reprocessing capabilities. Industrial experience with thorium is at this stage very limited. Research on using thorium-based fuel is on-going for future new types of reactors (e.g. *molten salt* reactor)[20, 21].

SUSTAINABILITY OF THE SPENT FUEL HANDLING AND TREATMENT PROCESS

The storing, handling and treatment of spent fuel (the operations from retrieval from the reactor up to waste disposal) rely on a large spectrum of techniques, involving physical, material and chemical sciences, and mechanical and civil engineering. Whether these processes are sustainable over the long-term will depend on:

- the complexity of the techniques;
- the current maturity of the techniques and required developments;
- the long term feasibility, independent from internal and external factors; and
- the flexibility and reversibility of the process.

18 *"Uranium 2011: Resources, Production and Demand", A Joint Report by the OECD/NEA and the IAEA, 2012.*

19 *"Extracting Uranium from Seawater", Chemical & Engineering News, 2012.*

20 *"Thorium fuel cycle – Potential benefits and challenges", IAEA, 2005.*

21 *"Trends towards Sustainability in the Nuclear Fuel Cycle", OECD/NEA, 2011.*

The sustainability of all fuel cycle options depends also on the continuing availability of the necessary expertise, the nature and level of which will vary to some extent between the options.

For the *open fuel* cycle, the facilities involved are few (interim storage, encapsulation) and have a low degree of complexity, as they rely on relatively basic techniques. As mentioned, there is a substantial body of experience of interim storage ('wet' and 'dry' storage). However, some research is still needed to assess the effects of long duration dry storage, in particular the behaviour of the irradiated fuel and its long term inspectability, as well as the ageing of the facilities and equipment. The subsequent encapsulation process is for the moment only at the design phase, but should be implemented in some countries in the coming decade.

Fuel storage and handling within the open cycle requires investment on a scale that can in principle be managed by the utilities or at least at country level, making them rather independent from international political or economic changes. In the long term, the main issues to consider are the interim storage capacity and the ageing of the fuel and the installations.

As long as the spent fuel is in interim storage, a reversing of the process and implementation of a recycling strategy remains feasible as retrievability of the fuel from the storage facility must be ensured in any case.

Considering steps towards *closing the fuel cycle,* more facilities will be involved and more complex techniques will be needed for reprocessing, conditioning of high level wastes, and fabrication of recycled fuel. However, reprocessing and recycled fuel fabrication have been practiced for more than three decades on an industrial scale. The technology, including also the vitrification of the high level waste, can be considered as mature, although many developments are still on-going, which are mainly focused on optimising and further closing the fuel cycle[22]. The next step, being the 're-use and burning' of the recycled products in dedicated installations, is currently only at a pilot stage (for fast neutron reactors), or even only at a design stage (for dedicated 'waste burners' like accelerator driven systems). But in the future, fast neutron reactors should offer some flexibility, as the current design would allow some 'tuning' depending

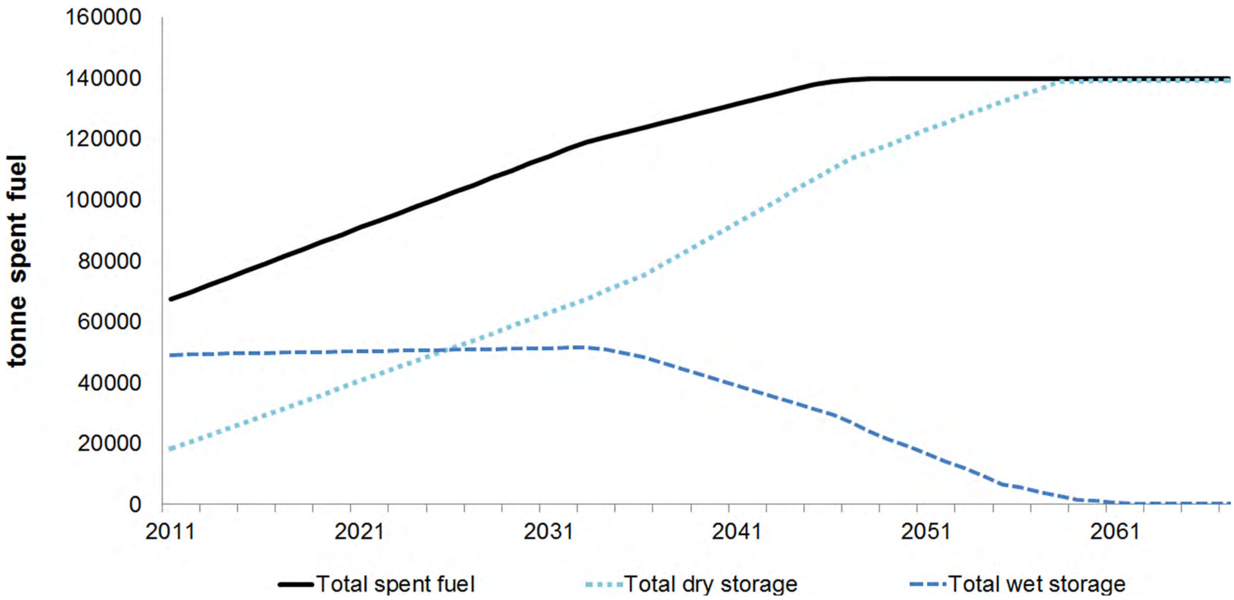

Figure 5.2: Evolution of interim storage of spent fuel in the U.S. (G.A.O.[21])

21 *"Spent Nuclear Fuel Accumulating Quantities at Commercial Reactors - Present Storage and Other Challenges", United States Government Accountability Office, Report to Congressional Requesters, 2012.*

22 *See synthesis of research and development in "Spent Fuel Reprocessing Options", IAEA TECDOC 1587, 2008.*

on the level of recycling pursued, and whether transmutation of residual wastes is used.

Implementing a closed fuel cycle decreases the need for investments in long-term interim storage capacity, the reduction depending on the achieved continuity and level of recycling pursued. But the more specialised techniques for reprocessing and fabrication of recycled fuel require large, and in most cases internationally shared investments, to benefit from the scale effect and enable cost-effective operation. In this way the process is more sensitive to external factors, like changes of the international political or economic configuration.

Reversing the strategy, abandoning the option of closing the fuel cycle, is from a technical point of view feasible and has been experienced already in some countries (for example, Germany). The decision has however significant cost implications if investments, which are only profitable in the long term, become obsolete and if additional resources are needed to undertake the decommissioning of the shutdown installations. Specific provisions are also needed to deal with the disposal of the intermediate products generated prior to the decision to abandon recycling.

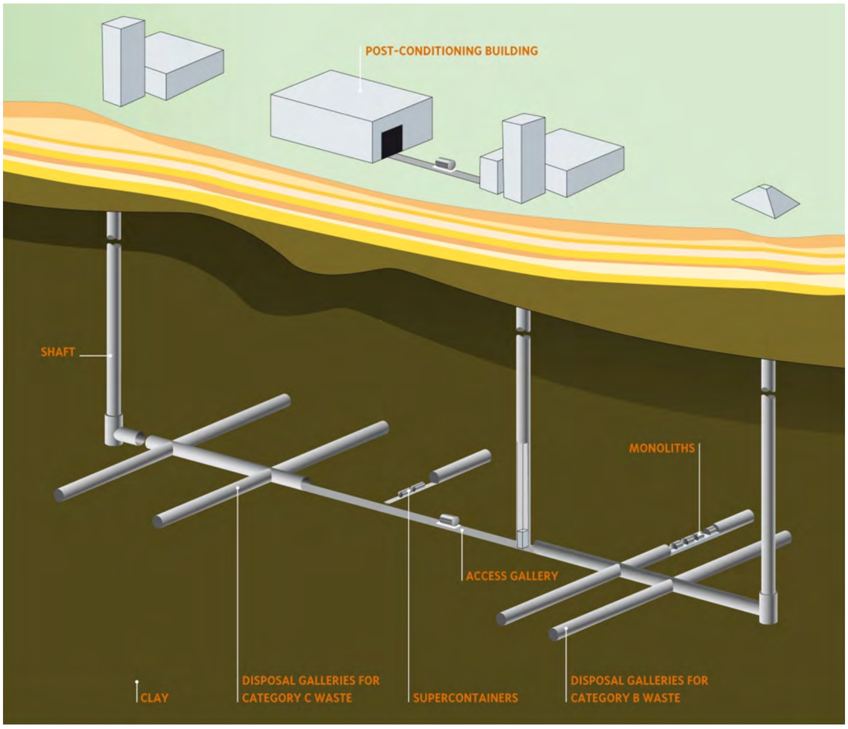

Figure 5.3: Illustration of geological repository concept (Courtesy NIRAS/ONDRAF)

SUSTAINABILITY RELATIVE TO WASTE DISPOSAL

Several types of geological waste repositories are currently being studied: burial in geological clay layers, hard rock (e.g. granite) formations or salt. The choice between the different types of geological formations for waste repositories depends on the national availability of suitable formations. The fuel cycle strategy will have an impact on the way this final stage of the cycle can be implemented in a sustainable way. Issues to consider are:

- the consequence on the repository *footprint*, i.e. the disposal area needed;
- the required *longevity* of the repository, i.e. the timescale over which the isolation function remains important;
- the *retrievability* and *recoverability* of the disposed waste.

The *footprint* of a geological repository is defined by the waste quantity, the heat emitted by the waste and the geo-mechanical structure. The dimensioning factor is mainly imposed by temperature constraints. High level waste and spent fuel generate heat to escape through the surrounding filling material and the geological formations. To respect temperature limitations of the repository, a preliminary cooling storage time of at least a few decades is needed before the waste is transferred to a geological repository, to allow part of the short lived components to decay. Furthermore, the underground gallery section of the disposal facility is designed such that the waste canisters are placed some meters apart to limit the amount of heat generated in a specific volume.

The estimated repository footprints are typically the order of a few square kilometres which may, or may not, be an issue depending on the dimensions of suitable geological formations at preferred repository sites. The area depends, of course on the size and schedule of the national nuclear programme and the planned operational lifetime of the disposal site[23].

In comparison to the open cycle, a partially closed cycle is not expected to give a major reduction of the footprint, as there will be a need to also dispose of the spent recycled fuel. For a fully closed cycle with total recycling of the plutonium and uranium, the needed repository size for the high level waste is reduced by 40%. If in addition partitioning and transmutation is applied, the high level waste volumes could be significantly reduced, with vitrified waste containing mainly short-lived components (while the long-lived components are recycled or consumed)[24]. The necessary length of disposal galleries will be about one third of the length required for direct disposal of spent fuel[25, 26].

The required *longevity* of a repository is directly linked to the evolution of the *radiotoxicity* of the waste, an indicator of the long-term potential hazard. The indicator is often compared with the radiotoxicity present in the amount of natural uranium needed to generate the same amount of electricity.

The radiotoxicity, however, does not indicate the real potential for release from a repository. Most of the highly radiotoxic elements have a low solubility and mobility in the geological layers. But the radiotoxicity will impact on how long the isolation function of the repository will remain important.

In the case of the open fuel cycle it takes more than 200 000 years before the radiotoxicity in the spent fuel has dropped below the level present in the natural uranium that was needed to produce that fuel. For the partially closed fuel cycle with single recycling of plutonium a small reduction of the radiotoxicity of the waste is observed; the radiotoxicity level of natural uranium is reached after about 100 000 years. For a fully closed cycle the timescale is reduced to 30 000 years. Only for a fully closed fuel cycle with partitioning and transmutation and small process losses can a more significant reduction be achieved, as the radiotoxicity of the residual waste theoretically drops below that of natural uranium after about 400 years (although even in this case some wastes requiring very long term isolation will remain)[27, 28].

Retrievability of the waste is defined as the ability to remove emplaced packages from the repository. Retrievability may contribute to confidence and provides an insurance against future, currently unforeseen developments. Retrievability can be considered for various reasons[29]: in case of changes in policy, to allow the future *recovery* of valuable materials, or if in the future the safety of the repository is questioned (the latter should not, in practice, occur if the safety case of the repository is robust enough).

In the open fuel cycle the disposed waste, the spent fuel, still contains the energetic components uranium (93%) and plutonium (1%). It is possible that at some point in the future the spent fuel will be considered to be a resource and that recovery is envisaged. For the fully closed cycle the main disposed waste can be considered as ultimate waste, i.e. extraction of valuable components is unlikely ever to be viable. In this case, retrievability would only be considered for safety reasons.

The cost, ease and justification of retrieval will strongly depend on the stage of the sealing of the disposal cells and the closing of the repository. Current designs consider retrievability until the closing of the repository (in France, retrievability for 100 years is demanded by law). Research is underway to improve the ease of retrieval, but adaptations ensuring retrievability must not

23 The footprint of the repository planned in Sweden is estimated to be around 4 km² to accommodate some 12 000 tonnes of spent fuel, roughly corresponding to about 500 reactor years. According to the French national waste agency ANDRA, the estimated footprint of the deep geological repository operated for 100 years in France will be of the order of 15 km².

24 "Potential Benefits and Impacts of Advanced Nuclear Fuel Cycles with Actinide Partitioning and Transmutation", OECD/NEA, 2011.

25 "RED-Impact – Impact of Partitioning, Transmutation and Waste Reduction technologies on the Final Nuclear waste disposal", Jülich Forschungszentrum, 2008.

26 "Impact of Advanced Fuel Cycle Scenarios on Geological Disposal", Euradwaste 2008.

27 "Concept of Waste Management and Geological Disposal Incorporating Partitioning and Transmutation", 10th Information Exchange Meeting on Partitioning and Transmutation, OECD/NEA, 2008.

28 "An Assessment of the Impact of Advanced Fuel Cycles on Geological Disposal", Radioactive Waste (R. A. Rahman, Editor), 2012.

29 "International understanding of reversibility of decisions and retrievability of waste in geological disposal", OECD/NEA, 2011.

	OPEN CYCLE	CLOSING THE CYCLE PARTIALLY CLOSED CYCLE	 FULLY CLOSED CYCLE
SUSTAINABILITY RELATIVE TO AVAILABILITY AND USE OF NATURAL RESOURCES			
consumption and availability of uranium	- inefficient use of the uranium; availability for 100 years reactor operation	+ uranium consumption reduced by 10-20% ensuring some longer availability of resources for reactor operation	+ uranium consumption reduced by a factor of 50 to 100 ensuring more than 5 000 years of reactor operation
SUSTAINABILITY OF THE SPENT FUEL HANDLING AND TREATMENT PROCESS			
degree of complexity of techniques	+ relatively 'basic' techniques for interim storage of spent fuel and encapsulation	- more complex techniques for reprocessing, vitrification and fabrication of recycled fuel	- complexity increased by use of fast reactor system
maturity of the techniques, developments required	+ experience with interim storage - developments for long term storage - encapsulation at the design phase	+ experience with reprocessing, vitrification and fabrication of recycled fuel - developments for further reprocessing of spent recycled fuel	- limited experience with fast neutron reactors, reactors in design phase - developments for the spent fuel partitioning and transmutation techniques
long-term feasibility, independence from external factors	+ limited investments, no interdependence - need for sufficient interim storage capacity	+ reduced need for interim storage capacity - need for large, shared investments, increasing interdependence	+ limited need for interim storage capacity - need for large, shared investments, increasing interdependence
flexibility and reversibility of the fuel processing	+ no major constraints relative to reversibility, change of policy	- large investments requiring long term return - provisions to deal with the intermediate recycling products	- even larger investments requiring long term return - provisions to deal with the intermediate recycling products
SUSTAINABILITY RELATIVE TO WASTE DISPOSAL			
repository footprint	- repository footprint of few square km	- marginal reduction of the repository footprint	+ reduction of the footprint by 40%, or by 70% in the case of partitioning & transmutation
long-term radiotoxicity of the waste	- very long time scale to reach radiotoxicity of natural uranium (200 000 years)	- very long time scale to reach radiotoxicity of natural uranium (100 000 years)	+ reduced time scale to reach radiotoxicity of natural uranium (30 000 years, or 400 years in the case of partitioning & transmutation)
retrievability and recoverability of disposed waste	- retrievability (including recovery of the fuel) only until closure of the repository	- retrievability (including recovery of the fuel) only until closure of the repository	+ retrievability until closure of the repository; recovery is not needed

Table 5.1: Sustainability of the options

Summary of issues to consider: advantages (+) and disadvantages (-)

jeopardise the safety and security of the repository. After closure and sealing of the repository, retrieval will not be totally excluded (in a comparable way that ore can in principle always be extracted from underground deposits), but it is clear that costs will be substantial, and the techniques remain to be developed.

5.2 SAFETY

The *interim storage, handling* and *treatment, transport, recycling* and *disposal* of spent fuel and waste necessitate multiple and particular safety provisions, mainly to deal with the high radiation levels of the used fuel, the high and specific radiotoxicity of the components, and the risks of a criticality reaction. In addition, the occupational hazards for the workers as well as the impact on the environment have to be addressed.

For *interim storage,* the safety priority is to ensure the integrity of the spent fuel. Deterioration of the spent fuel must be prevented by continuous cooling in order to dissipate the decay heat. Wet storage pools require an active cooling system; the chemistry of the water must also be controlled over the whole storage term. Dry storage casks are cooled with natural circulation of the air. The radiation shielding and sub-criticality of the fuel is ensured by the design and setup of the storage facilities.

The safety provisions for interim storage are in principle the same for the open and closed cycles, although for closed cycles the spent fuel will on average be stored for shorter times. With the extension of storage durations that has been experienced in many countries (which is mainly a consequence of the unavailability of geological repositories), concerns have been raised about the long term behaviour and condition of the stored fuel elements and their retrievability, particularly in respect of fuel in dry storage casks (where handling and inspection of fuel elements is more complicated). The risk of having to re-pack the wastes increases over time and thus additional provisions will be needed to ensure safe long-term interim storage.

In the case of reprocessing, the interim storage of high level wastes has also to be considered; it requires rather standard safety provisions to ensure passive cooling, shielding and confinement.

For the *fuel handling and treatment operations*, the level of the safety provisions is mainly a reflection of the complexity of the technologies involved.

With the open cycle, the handling of the fuel is limited to transfer operations and the encapsulation process. The technology requires standard provisions for radiation shielding and contamination controls.

In reprocessing facilities and plants for the fabrication of recycled fuel, where radioactive material is handled as liquids and powders, a larger number of provisions are put in place to protect the workers and the environment from the radiological risks[30]. The whole process is carried out in a shielded and confined environment in order to limit the radiation exposure of the workers and to prevent any uncontrolled release of radiotoxic substances. Besides the radiological risks, specific measures are taken and very strict procedures are in place to guarantee that the handling of the material in all its forms is done within criticality safety margins.

Recycling involves opening the fuel cladding, with the consequent atmospheric or liquid potential for discharges to the environment of waste fractions which cannot be treated. Over the last decades, reprocessing plants have progressively implemented measures which have substantially reduced the environmental impact of such gaseous and liquid effluents.

The *transport* of spent fuel and other radioactive substances is undertaken in certified casks that comply with international regulations for transport of dangerous goods and there is now long standing experience in this field.

The open cycle typically requires that the spent fuel is transported from the reactor site to a central interim storage facility (if applicable) and from the storage facility to the encapsulation plant and disposal facility.

For closed fuel cycles, several types of transport have to be considered between different facilities, involving the spent fuel, the extracted plutonium and uranium, the recycled fuel and the high level waste. Depending on the country of origin, some

30 External exposure to radiation and risk for intake of radioactive particles (internal contamination).

of the shipments are international and even intercontinental.

In the case of *recycling* of fuel in *thermal neutron reactors*, specific safety provisions and procedures are implemented to deal with the different physical and radiological properties of the MOX fuel. The operation of *fast neutron reactors* or *waste burner facilities* will require dedicated safety provisions. Without detailing them in this report[31], they

complementary functions of the natural geological barrier and the engineered, man-made barriers. Releases from such a repository system would only be expected to occur many thousands of years after disposal, and to be very small due to the characteristics of the selected site and the design of the repository.

In almost all national regulations for geological repositories, the calculated radiation dose to the

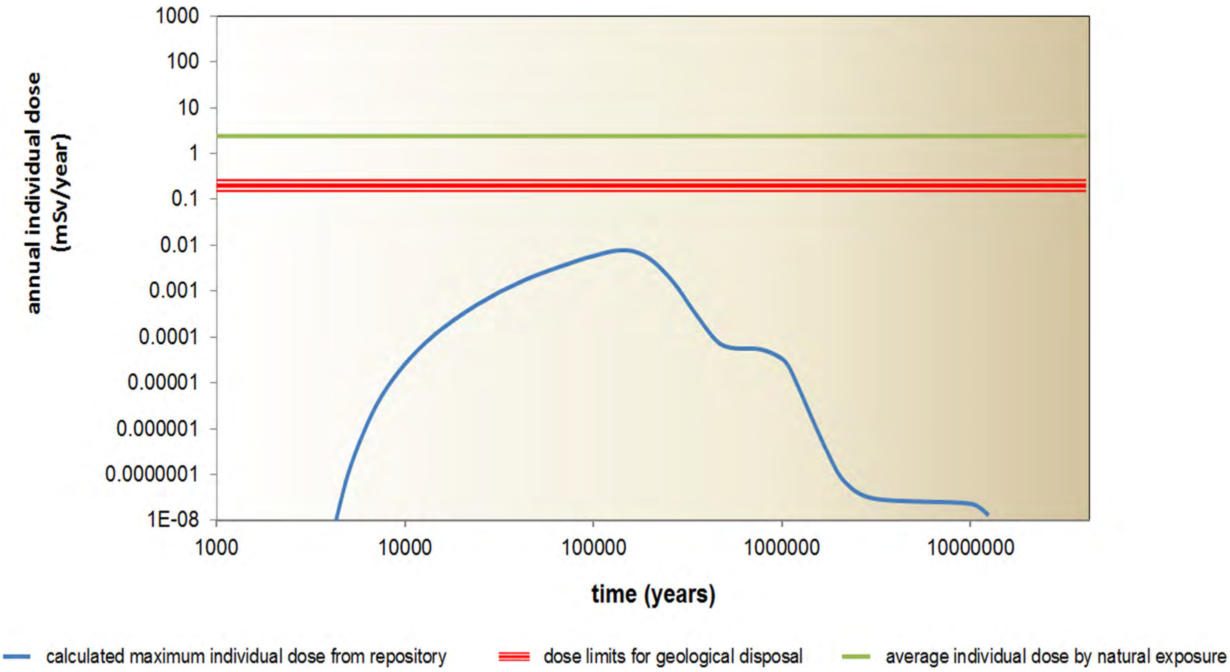

Figure 5.4: Example of modelling expected radiation dose to most exposed individual, compared to natural radiation dose (Courtesy NIRAS/ONDRAF)

are related to the particular physical and chemical properties of the coolant medium (sodium, lead or gas) and the reactor core and infrastructure.

Finally, the future *geological disposal* must guarantee the very long term safety of long-lived and high level wastes. For this reason, the safety functions need to be passive (i.e. not depending on active maintenance) and robust (i.e. not sensitive to changes in the surrounding conditions). Geological repositories will fulfil these criteria through the

public is the main indicator to evaluate the risks and thus the safety of a repository. Safety assessments of planned geological repositories predict that these doses remain far below the regulatory constraints[32]. Model calculations of doses generally do not show a major difference between the open and closed fuel cycle options, despite the lower radiotoxicity

31 The safety of fast neutron reactors is addressed within 'SARGEN IV', a European Commission funded project that aims to prepare the future assessment of advanced nuclear reactors (Generation IV).

32 The International Commission on Radiological Protection recommends that the annual anticipated radiation dose would be lower 0,3 mSv per year, which is about 1/3 of the current dose limit for the public (and corresponds roughly to 1/8 of the average exposure of individuals to natural radiation). Some national regulators specify doses as low as 0,01 mSv per year as a design objective for various reasons, including leaving margins for future releases from long-term use of nuclear energy.

	OPEN CYCLE	CLOSING THE CYCLE	
		PARTIALLY CLOSED CYCLE	FULLY CLOSED CYCLE
FRONT-END OF THE CYCLE			
Safety of uranium extraction and fuel fabrication	– provisions for uranium mining (including also tailings); provisions linked to uranium fuel fabrication	– slightly reduced need for uranium: same provisions but reduced in amplitude	+ very limited need for uranium (becomes a nearly negligible issue)
BACK-END OF THE CYCLE			
Safety of interim storage of the spent fuel	– long term interim storage; provisions to cover continuity of cooling and ageing of the fuel	– provisions for long term interim storage of MOX fuel	+ provisions to cover interim storage duration limited to one/few decades
Safety of fuel handling and treatment	+ standard safety provisions for handling the spent fuel	– specific (enhanced) safety provisions for spent fuel treatment, recycled fuel fabrication and high level waste conditioning	
Safety of transport	+ provisions for limited number of transports of spent fuel	– provisions for several types of transport between different facilities and different countries	
Safety of fuel recycling in reactors	not applicable	– specific provision for recycling MOX fuel in thermal neutron reactors	– particular provisions applicable for fast neutron reactors and waste burners
Safety of geological disposal	– provisions ensured by engineered and geological barriers (must be guaranteed over 200 000 y)	– provisions ensured by engineered and geological barriers (must be guaranteed over 100 000 y)	+ provisions ensured by engineered and geological barriers

Table 5.2: Safety provisions
Summary of issues to consider: advantages (+) and disadvantages (-)

of the waste in the case of the fully closed cycle. The reason is that the chemical solubility of most of the long-lived waste components under the repository conditions is very low, and these elements are strongly retained in the repository near-field and in the path up through the geological layers. The long term safety of a repository is therefore determined by few, more mobile elements, which have a relatively low radiotoxicity, but which will migrate through geological layers.

These considerations prevail as long as there are no unexpected intrusive, disruptive or other unexpected events affecting the repository. It is clear that independently of the modelling, the safety of a repository, and in particular its isolation function in the long term, is more robustly established, with a higher certainty level, if there are less long-lived radiotoxic waste products, as in the case of the fully closed fuel cycle and partitioning and transmutation.

A summary of the safety provisions is given in Table 5.2. For completeness of a comparative overview not only the back-end but also the front-end of the fuel cycle has to be considered. For the open fuel cycle, more uranium ore extraction will be needed. Uranium mining activities also require workers' radiological and non-radiological safety provisions and have a significant impact on the environment. In particular, the remediation of the uranium tailings containing residues of radioactive ore is a significant issue of concern in many countries[33].

33 *"Radiological Impact of Spent Fuel Options – A Comparative Study", OECD/NEA, 2000.*

5.3 NON-PROLIFERATION AND NUCLEAR SECURITY

The use of nuclear materials for solely civil purposes is controlled worldwide by the application of IAEA *safeguards*, acting under the Non-Proliferation Treaty[34]. Within the EU, the control is complemented by the Euratom safeguards inspections. The inspectors verify the declared uses of nuclear materials, while the IAEA mandate also extends to verifying the absence of undeclared activities and diversion. In addition, the material and the facilities have to be secured from non-state sabotage or theft (i.e. physical protection of nuclear security).

While for the front-end of the fuel cycle the control is dedicated to uranium and the enrichment process, the safeguarding and physical protection measures on the back-end of the cycle are concentrated on plutonium, which is the main fissile component of spent fuel. It is of note that the plutonium discharged from commercial nuclear power plants is of poor quality in respect of fabrication of efficient atomic weapons[35]. The plutonium is nevertheless submitted to all applicable international control measures; the reasoning is that even low grade materials could be of interest.

Two *phases* of surveillance have to be considered:

- the *short term,* or the control of the fuel storage, handling and (if applicable) recycling; and

- the *long term*, or the control of the geological disposal.

A non-proliferation benefit of the *open cycle* in the short term is that the sensitive material, the plutonium, is not separated from the spent fuel. Moreover, the spent fuel is, to a certain extent, "self-protecting" over the first 100 years after discharge from a reactor. The radiation levels are so high[36] that it is practically impossible to manipulate fuel elements without specialised equipment. Nevertheless, the fuel assemblies in interim storage facilities are submitted to safeguards and physical protection measures to ensure that they are not diverted and that they remain intact.

In the long term however, spent fuel disposed of in geological formations will gradually lose its self-

34 "Treaty on the non-proliferation of nuclear weapons", IAEA INFCIRC 140, 1970.

35 In comparison with "weapons grade plutonium", the plutonium discharged from most of the civil reactors generates a relatively high neutron radiation and generates heat, linked to its composition.

36 For most of the reactors, the radiation of the fuel remains very high during about 100 years after discharge, at a level that would be lethal for operators in a few hours; for some type of reactors (e.g. CANDU Heavy Water Reactor) the discharged fuel will only exceed that radiation level for a few years.

	OPEN CYCLE	CLOSING THE CYCLE	
		PARTIALLY CLOSED CYCLE	FULLY CLOSED CYCLE
Short term – fuel storage and handling	+ no separation of fissile material (plutonium) + fuel is self-protecting + limited number of handling steps	- separation of the fissile material (plutonium) - variety of operations to secure	- separation of the fissile material (plutonium) - variety of operations to secure + no or nearly no uranium enrichment required
Long term - fuel geological disposal	- disposed fuel contains fissile material (safeguards required on the repository)	+ disposed fuel contains fissile material, although less attractive (safeguards required on the repository)	+ no fissile material disposed (no safeguards required on the repository)

Table 5.3: Proliferation Resistance and Nuclear Security provisions for open, partially closed and fully closed cycles.
Summary of issues to consider: comparative advantages (+) and disadvantages (-)

protection by the radioactive decay of its short-lived components. In addition, on an even longer term, the plutonium composition changes and becomes slightly more attractive for weapons use. Although it can be questioned whether in a far future a closed geological repository with disposed spent fuel at several hundred metres depth could be used as a source for clandestine purposes, appropriate safeguards and safeguards measures need to be developed, including also the long term continuity of knowledge about the repository and its contents, and the protection of this information.

For the *closed cycle* options, the short term safeguarding of fuel recycling facilities and their protection is much more demanding, especially from the moment the plutonium is separated from the rest of the fuel. Increased surveillance and verifications have to be implemented. Partially for this reason, alternative reprocessing techniques are under development, where the plutonium is not extracted separately from the spent fuel, but together with the uranium.

But in the case of a fully closed cycle, essentially all fissile material is, in the end, re-used and consumed, which is beneficial in respect of the long term proliferation risk. With full recycling, also the front-end uranium enrichment process, which is particularly sensitive, is reduced to a minimum. And at the back-end, geological repositories are mainly limited to the disposal of high-level waste, which will not require long term safeguards controls.

In the case of a partially closed cycle, in which fuel is recycled once and spent recycled (MOX) fuel would be disposed of, safeguards and physical protection considerations for the recycling is similar to the closed cycle and for disposal similar to the open cycle, except that the plutonium composition of spent MOX fuel is degraded and it is therefore less sensitive for proliferation.

While provisions for improving safeguards and physical protection can also serve nuclear safety, others may conflict with it. For this reason it is desirable that safeguards, physical protection and safety issues are considered jointly and managed in an integrated way.

5.4 ECONOMICS

When addressing the economics of nuclear energy it has to be kept in mind that the largest component of the cost is the capital cost of the nuclear power plants; most studies agree that the total fuel cycle expenditures (including front end and back end) typically account for about 10 to 20% of the overall energy production costs.

There are however uncertainties associated with the *cost estimates* and the elaboration of the respective *financing schemes*.

Current *costs estimates* generally favour the open fuel cycle. Closing the fuel cycle reduces the costs for the front end of the cycle (less uranium acquisition, processing and enrichment) but the savings are not totally balanced by the costs of the additional steps and facilities as mentioned in the previous sections. In this context, the assumed future uranium price is important and the impact of closing the fuel cycle is frequently presented in the form of a uranium break-even price.

Besides the (variable) uranium price, significant uncertainties affect the cost estimates for both open and closed cycles. They are related to the limited maturity or even unavailability of some of the involved technologies, which require further development.

The OECD Nuclear Energy Agency compared a variety of open, partially closed and closed cycles in 2006[37]. The results of this study, summarised in Figure 5.5 for some of the options considered, indicate a maximum increase in costs of 20% compared to the open cycle. The uncertainties, however, are in excess of this difference.

Several other studies and cost estimates can also be referred to[38, 39, 40, 41].

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37 *"Advanced Nuclear Fuel Cycles and Radioactive Waste Management", OECD-NEA No. 5990, 2006.*

38 *"The economics of reprocessing versus direct disposal of spent nuclear fuel", Harvard University, Report DE-FG26-99FT4028, 2003.*

39 *"The economics of reprocessing versus direct disposal of spent nuclear fuel", Nuclear Technology, 2005.*

40 *"The future of the nuclear fuel cycle", Massachusetts Institute of Technology, ISBN 978-0-9828008-4-3, 2011.*

41 *" Economic Analysis of Different Nuclear Fuel Cycle Options", Science and Technology of Nuclear Installations, Vol. 2012, Article ID 293467, 2012.*

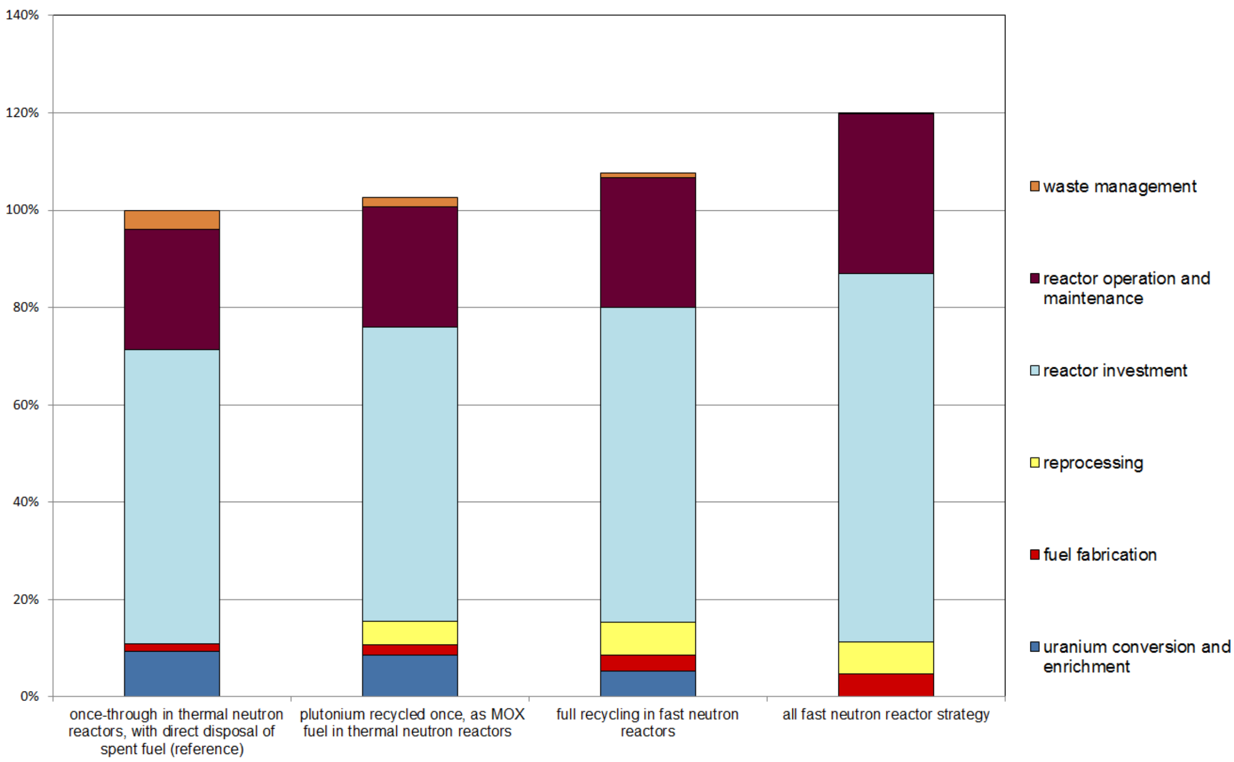

Figure 5.5: Relative cost estimates for alternative types of fuel cycles (courtesy NEA)

It should be stressed that factors which are a priori 'non-economic' may also end up playing a significant role in determining the economics of the fuel cycle. In particular, assurance of energy supply and stakeholder requirements or incentives are additional factors to consider in the budgets associated with the introduction of fuel cycle schemes. State subsidies, in turn, may be allocated, linked for example to strategic considerations.

The fuel cycle expenditures often occur several decades after the energy has been produced. Robust long term *financing schemes* must therefore be established to ensure that the costs are borne by the energy producer. The schemes build on cost forecasts and on the assumed operational time during which the collection of funds can take place. Consideration has to be given to additional uncertainties caused by:

- the interim storage timeframe: if very long-term storage of spent fuel is considered (for those countries without a fuel cycle strategy implemented or without a geological repository in sight), additional requirements (hence costs) could be incurred;
- the risk of premature shutdown and phase-out, when less financial resources have been gathered than estimated for the full operation time; and
- long term financial and economic instability.

6 THE INVOLVEMENT OF STAKEHOLDERS IN DECISION-MAKING

6.1 PUBLIC ACCEPTANCE

Public acceptance, as an issue, emerged when nuclear industrial programmes (and especially waste repository programmes) faced implementation difficulties due to resistance from the public, local communities, stakeholder organisations and political groups. There are different explanations for this phenomenon, but they reflect, at least in part, a stronger societal preoccupation with perceived risks, not only in the nuclear field. A key problem is that different actors have failed to communicate effectively with each other because they have different perspectives, and different ways of dealing with knowledge and interpreting (factual) information[42].

In order to bring different stakeholders together towards a common goal, the way of handling the overall process has changed. Various local or national actors are involved at an early stage, with the aim of broadening the decision-making basis and turning the input of different stakeholders into constructive contributions towards implementation.

6.2 STAKEHOLDER INVOLVEMENT

Currently, successful programmes are progressing with appropriate consideration being given to stakeholder involvement[43]. Decision-making is based upon stakeholders supporting, or at least tolerating, solutions. For this purpose it is important that stakeholders are well informed, preferably through a dialogue process where they can voice their concerns and questions and have them answered. Thus the decision making process needs to be transparent and well communicated. Several approaches have been followed, among them:

- national review processes involving stakeholders and the public through active forms of participation and engagement; and
- partnership with host communities.

The process is reflected in the preference for iterative planning and implementation, in contrast to what otherwise would be predetermined decision-making.

In general, there are two phases of decision making to consider for stakeholder involvement: on the policy and programme, and on the siting of the installations. Experience to date is that the first phase is generally less controversial, but effective dialogue at that early stage is advantageous as it will, to a certain extent, facilitate debate at the second phase.

One recurring issue is that the public is, in general, rather sceptical of scientific-technical solutions and predictions, and concerned about the controllability of technical processes. Good intentions are not always mirrored by reality; remedial actions are common in the average life experience. This can result in requests for additional assurance through design features allowing for direct observation, certain types of monitoring and the inclusion of retrievability in design and operation.

Figure 6.1: Consultation working group (Courtesy SKB) (Photographer: Lasse Modin)

Public engagement on, and acceptance of, choices between options may be enhanced through continuing involvement in research and development on a range of options, so that genuine choices are available, and decisions are better informed.

The public acceptance of geological repositories may be influenced by the timescales on which high levels of radioactivity decay. But if it extends over more than a few centuries, it will probably not make much difference to public perception compared to repositories with wastes decaying over tens to hundreds of thousand years or more. The horizon needs to be a few generations up to the lifetime of, for example, known historical constructions in order to make a difference.

42 *"Meaningful communication among experts and affected citizens on risk: Challenge or impossibility?", Journal of Risk Research, 2008.*

43 *An example is given by: "Consultations according to the Environmental Code 2009-2010", Svensk Kärnbränslehantering AB, 2011.*

6.3 IMPACT ON DECISION MAKING

As discussed before, decision-making on nuclear fuel cycles inevitably initiates long-term commitments exceeding the life span of an individual, irrespective of the option. Stakeholder involvement should not be seen as an obstacle, but rather, if implemented in a correct way, as a constructive contribution reflecting basic democratic principles and a pre-requisite for successful implementation of a decision.

Public participation and consultation have become part of the process of siting nuclear facilities and lead to a broadening of the objectives, beyond solely optimizing technical and safety criteria. They have been broadened to the more general decisions on the policy and strategies. It is important to accept that in this multi-dimensional decision-making process, different stakeholders use different criteria. If managed well and provided that sufficient time is allowed for them, such engagement processes can add substantial value, resulting in more robust decisions.

7 THE KEY DECISIONS AND IMPLEMENTATION OF THE STRATEGY

7.1 OVERVIEW OF THE MAIN DECISION MILESTONES AND CONSEQUENCES

From the moment a country has embarked on a nuclear programme, it is expected that a series of decisions will have to be taken in relation to the fuel cycle and the management of the spent fuel. Figure 7.1 summarises the key strategic decisions and their main consequences with respect to the spent fuel management process.

A decision to implement a nuclear energy programme also requires that a fuel management policy be established. This will include a strategy for the implementation of spent fuel interim storage capacity. It is expected that, in parallel, the development of suitable fuel cycle and geological repository options is supported. An appropriate funding scheme must be established.

The binding decisions on the fuel cycle option can be taken at a later stage and will have consequences for investments, contractual arrangements and orientations for research and development. These decisions should not only address the spent fuel and waste from operational activities, but also the many legacies from past industrial activities and the fuel from past and current research activities.

Decisions to adopt fast reactors or partitioning and transmutation presuppose that the extensive research, development and demonstration activities still required for these technologies prove to be successful.

The possibility exists, and it is experienced frequently, that a decision on the implementation of a fuel cycle option is not taken or is postponed. This has consequences, not only for the interim storage capacity needed, but also for the provisions and measures to be implemented to ensure safety and the continuity of knowledge over the long term. And an extended funding scheme has to be set up.

A spent fuel management system will be implemented over a century or more. The decision process needs to be considered as a ‘living issue’ over this period, during which the boundary conditions are likely to change. A periodic re-assessment of the decisions taken is desirable. In order to be able to accommodate such changes it will be advantageous to keep a certain level of flexibility. This includes participation in research on key options to reduce the uncertainties, and to provide a real and better informed basis for the choice of option when needed. Reversibility must be taken into consideration in order to manage the organisational and financial consequences of a change in strategy.

7.2 IMPLEMENTATION OF THE STRATEGY

As a result of the decisions taken, it is important to generate the resources for the development of robust *technical solutions*, covering the whole process and to allocate responsibilities to the utilities, national agencies, and local and national entities that will be involved. A strong safety case has to be established, which ensures that there is confidence in a reliable solution with limited sensitivity to potential future upgrading of criteria, considering the very long term safety, security and safeguards aspects of geological disposal.

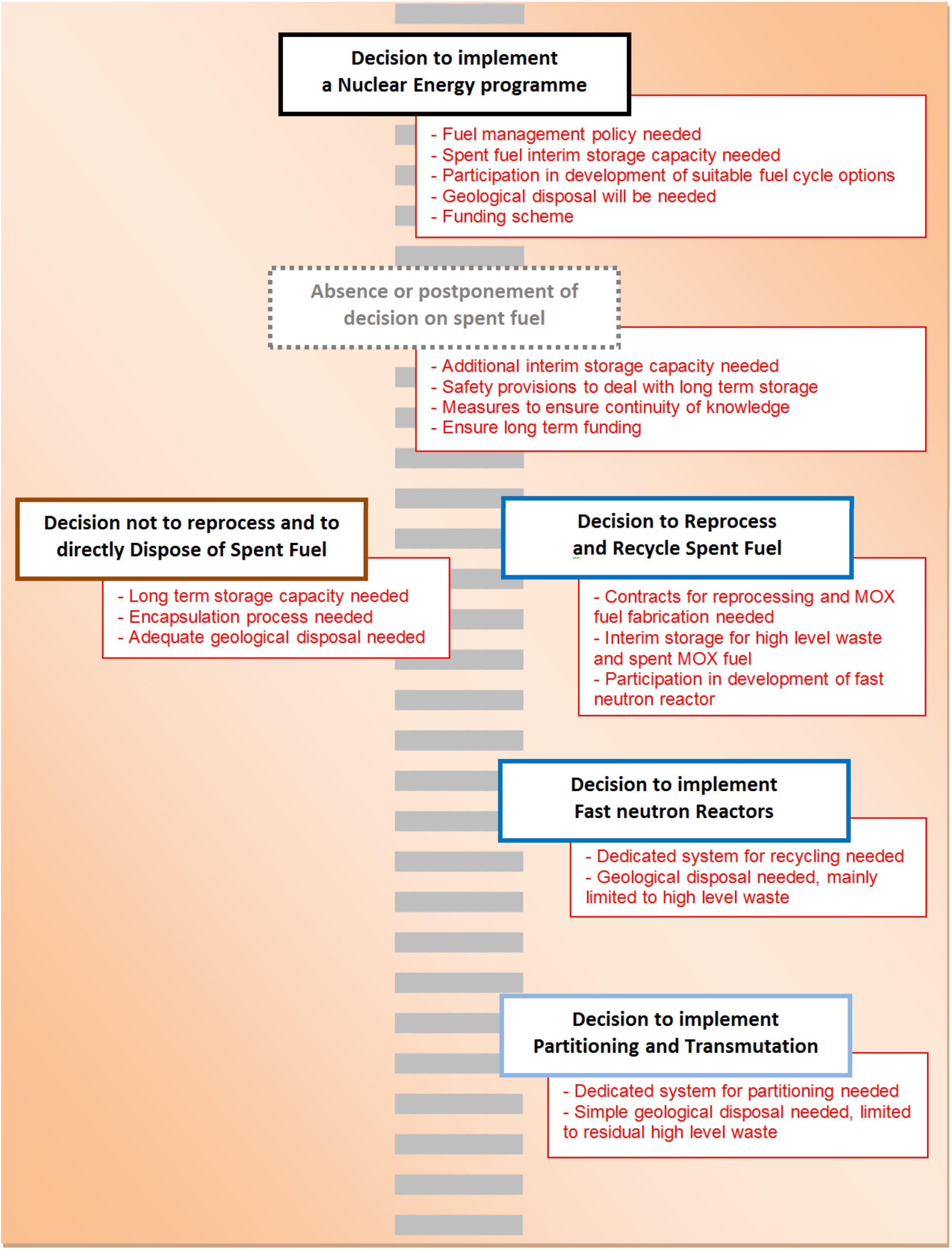

Figure 7.1: Key decisions and main consequences with respect to spent fuel

Capacity for interim storage must be ensured, taking planning uncertainties into account. Consideration has to be given to the experience so far that development of the closed fuel cycle and geological repositories have been slower than expected, and that such developments are on-going.

It is desirable to move ahead with developing technical solutions for fuel handling, treatment, storage and disposal to the stage of industrial implementation, in order to:

- build on practical experience and use the feedback to further strengthen the safety case and, if needed, implement changes. This may include changes in general expectations and developments, but also expectations by involved stakeholders;
- ensure the sustainability of the solutions, including also the long term availability of knowledge and competence;
- avoid undue delays in programme implementation, paying attention to the long lead-times, in particular for bringing geological disposal to industrial maturity, and the time needed for public participation in the decision processes; and
- align developments to possible evolutions of the spent fuel features.

Although the planning for spent fuel management should be based on a specific option and end-point, it will remain important to keep an appropriate level of flexibility and reversibility in light of potential policy changes (over decades) and developments in alternative technologies. In such a way, even if direct disposal of fuel is chosen by some countries as the reference option, there is a need to continue to support, at least at EU level, developments towards closing the fuel cycle, as a longer term strategy having the potential for a much better utilisation of the uranium energy resource and for waste reduction. In addition, it would provide a broader knowledge basis for possible future choices of spent fuel management strategies and insurance for the continuity of this knowledge. It will also ensure that stakeholders are not confronted with a situation that can be perceived as pre-empted decision making.

On the other hand, work on the development of the closed fuel cycle should not be interpreted as a justification for delaying the geological disposal programme. Such repository capacity is required also for the waste from the closed fuel cycle, even if some technical features of the repository may be less restrictive.

These considerations do not imply that each country needs a full advanced fuel cycle development programme. Countries with small nuclear programmes can rather be expected to participate in collaborative initiatives on a limited scale, at least in order to maintain and develop the competence and capability to assess the different options.

7.3 VALUE OF REGIONAL AND EU LEVEL INITIATIVES IN SUPPORT OF THE STRATEGY

Human, technical and financial resources can be more effectively used by joining forces. This is done at European level through so-called “Technology Platforms” for developing advanced nuclear fuel cycles (Technical Platform for Sustainable Nuclear Energy) and for geological disposal (Technical Platform for Implementing Geological Disposal). Also, sharing of European skills is supported through the European Commission’s Joint Research Centre and through other bi- or multilateral cooperation initiatives supported by the European Commission’s Directorate-General for Research and Innovation.

Further initiatives could be envisaged at EU level and at regional level (between neighbouring countries) in support of future strategies.

A particular topic is the development and maintenance of the appropriate level of *education and training*. A skills base needs to be in place capable of developing or supporting the technologies. This is an issue for nuclear energy in general, but more particularly for waste disposal, as competence has to be maintained over a long time frame. Initiatives coordinated at a European level, like educational partnerships or networks, would be helpful. Integration of interesting R&D on innovative solutions and enabling students to undertake related work on nuclear facilities would raise the interest of future generations[44].

44 “The UK’s Nuclear Future” , HM Government (UK), 2013.

Some of the steps of the fuel cycle, for example reprocessing, MOX fuel fabrication and fast neutron reactors, will require fairly large facilities to benefit from economies of scale. Some of these facilities will also be sensitive from a proliferation point of view. It could therefore be advantageous for several countries to cooperate on their development and construction[45].

With respect to geological repositories, each Member State with a nuclear programme should implement a programme for development of an adequate repository. In parallel, *regional geological disposal* solutions may be investigated, taking into account potential scientific, technical and economic advantages[46, 47]. Good communication of risks will be needed in view of the political sensitivity of regional shared facilities, for which national and international legal frameworks will need to make appropriate provision[48]. It should be kept in mind that regional solutions for other types of toxic waste disposal, as well as collaborations on other types of nuclear facilities, are already in place.

Finally, notwithstanding the responsibility and autonomy of individual Member States, *harmonisation of the regulatory frameworks* could support a progressive integration of activities and infrastructure across Europe.

45 Cooperation in a similar way to practiced when the La Hague and Sellafield reprocessing plants were built in the 1980s respectively in France and the UK.

46 For history and examples of multinational repository projects, see: "Management of Spent Fuel from Nuclear Power Reactors – Experience and Lessons Learnt around the World", International Panel of Fissile Materials IPFM, 2011.

47 "Developing Multinational Radioactive Waste Repositories – Infrastructural Framework and Scenarios of Cooperation", IAEA, 2004.

48 "Developing Multinational Radioactive Waste Repositories – Infrastructural Framework and Scenarios of Cooperation", IAEA, 2004.

8 CONCLUSIONS

The report has summarised the various issues that should be considered when developing and implementing policy to deal with spent fuel and its waste in order to manage it in a safe, responsible and effective way.

The nuclear fuel cycle options each have advantages and disadvantages: the choice between them may differ between countries depending on the national boundary conditions. Also, neither the open nor the closed fuel cycle is yet fully realised, although the open fuel cycle is closer to realisation in some countries. Closed fuel cycles have the potential for better uranium utilisation and possibly simplified waste disposal which warrants further research and development. With fast neutron reactors, 50 – 100 times more energy can be extracted from the originally mined uranium than in current light water reactors. Irrespective of which option is chosen, a deep geological repository will be needed for some waste products.

Although good progress has been made on geological disposal and development of fast neutron reactors, the management of spent nuclear fuel will spread out over more than 100 years irrespective of strategy chosen. To realise the benefits of the fully closed fuel cycle will require several hundred years. During such long periods the boundary conditions, e.g. technology development, energy policies, are likely to change. It will therefore be important that the strategy adopted be flexible enough to accommodate such changes.

The costs for spent fuel management are substantial and will occur to a large extent long after the fuel has produced energy and thus an income. It is therefore important that the funding system ensures that money be available when needed.

Key considerations for a fuel cycle policy

Defining a spent fuel management policy is an essential step. Each country must implement a programme and ensure that the necessary technical and financial resources are available now and in the future for the safe and responsible management of spent fuel.

The policy will support continuity in the necessary developments and in the related investments, and continuity of knowledge and competence.

The fuel cycle policy should take account of the following considerations:

- Given the long timeframes of all fuel cycles, it is advantageous to generate robust technical solutions, covering the whole process, but keeping alternatives available to accommodate changes in future policies and plans.
- To ensure this flexibility in future choices, it is important that research is conducted on both open and closed fuel cycles. Cooperation bilaterally or at the European level is very useful for this purpose, including also the common development of fuel cycle and reactor facilities.
- The potential improvement in uranium utilisation from recycling in fast neutron reactors merits continuing their development.
- Further work on national or regional solutions for deep geological disposal is essential and urgent to ensure that spent fuel or high level waste can be safely disposed of at the appropriate time.
- Education and training are necessary to support the long term safe management of spent nuclear fuel and should be carefully considered. EU level initiatives to enable sharing of training materials and access to research facilities would be of value.

In the end the policy will not only be based on technical and organisational factors, but will also have to consider political aspects in general, and public acceptance issues in particular. It will thus be important to ensure sufficient public involvement and communication in the different steps of decision-making.

ANNEX I
ATTENDANCE AT BRUSSELS SEMINAR 18-19 FEBRUARY 2013

CHAIRS OF THE SEMINAR

Hans Forsström, SKB International AB, Sweden
Jan Marivoet, Studie Centrum voor Kernenergie, SCK.CEN, Belgium
Yvan Pouleur, Agence Fédérale de Contrôle Nucléaire, AFCN, Belgium

ATTENDANCE TO THE SEMINAR AND EXPERTS CONSULTED

Anne Bergmans, Universiteit Antwerpen, UA, Belgium
Roger Cashmore, UK Atomic Energy Authority, UKAEA, United Kingdom
Miguel Angel Cuñado Peralta, Empresa Nacional de Residuos Radioactivos S.A., ENRESA, Spain
Concetta Fazio, Karlsruhe Institut für Technologie, KIT, Germany
Martin Freer, Birmingham University, United Kingdom
Paul Gilchrist, Jacobs Engineering, United Kingdom
Ingmar Grenthe, Kungliga Tekniska högskolan, Royal Institute for Technology, Sweden
Zoltan Hozer, Magyar Tudományos Akadémia, Academy of Sciences, Hungary
Yves Kaluzny, Commissariat à l'Energie Atomique, CEA, France
Joachim Knebel, Karlsruhe Institut für Technologie, KIT, Germany
Ben Koppelman, The Royal Society, United Kingdom
Mark Nutt, Argonne National Laboratory, United States
Eero Patrakka, Posiva Oy, Finland
Rainer Salomaa, Aalto-Yliopiston Perustieteiden Korkeakoulu, Aalto University School of Science, Finland
Michael Siemann, OECD Nuclear Energy Agency, NEA
Robin Taylor, National Nuclear Laboratory, NNL, United Kingdom
Claes Thegerström, Svensk Kärnbränslehantering AB, SKB, Sweden
Francesco Troiani, Agenzia Nationale per le Nuove Tecnologie, L'energia e lo Sviluppo Economico Sostenibile, ENEA, Italy
Eugenijus Uspuras, Lietuvos Energetikos Institutas, LEI, Lithuania
Maarten Van Geet, Nationaal Instelling voor Radioactief Afval en Verrijkte Splijtstoffen, NIRAS/ONDRAF, Belgium
Magnus Vesterlind, International Atomic Energy Agency, IAEA
Janne Wallenius, Kungliga Tekniska Högskolan, Royal Institute for Technology, Sweden
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Vladimír Šucha, Gunnar Buckau, Giacomo Cojazzi, Elisa Dalle Molle, Jean-Paul Glatz, Didier Haas, Pierre Kockerols, Christos Koutsoyannopoulos, Manuel Martin Ramos, Christina Necheva, Vesselina Ranguelova, Vincenzo Rondinella, Franck Wastin

ANNEX II
SUMMARY OF THE 2011 WASTE DIRECTIVE AND IMPLEMENTATION OF NATIONAL PROGRAMMES

The policy basis for Disposal in EU Member States is embedded in the Council Directive 2011/70/EURATOM, of 19 July 2011, establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste. The Directive provides the basic principle to be reflected in Member States'* National Policies. The Directive requires each Member State to establish and implement a National Programme for turning its National Policy into practical actions and solutions. The Directive makes no prescription with respect to the various types of fuel cycle options, and thus each Member State may decide for itself.

Content of National Programmes

The constituents of a National Programme are listed in Article 12.1 of the Directive, and are as follows:
- (a) The overall objectives of the national policy;
- (b) Milestones and timeframes for achieving the objectives;
- (c) The inventory of the spent fuel and radioactive waste;
- (d) Concepts or plans and technical solutions from generation to disposal;
- (e) Concepts or plans for the post-closure period of the disposal facility;
- (f) Necessary research, development and demonstration activities;
- (g) The responsibility for the implementation and performance indicators;
- (h) The assessment of the cost of the programme;
- (i) The financing scheme;
- (j) The transparency policy or processes;
- (k) If applicable, the concluded agreement(s) with a Member State or third country on management of spent fuel or radioactive waste, including on the use of disposal facilities.

The National Policy should define the fuel cycle option followed, unless this is left to be decided by the actors within the National Framework, especially organisations responsible for the spent fuel and radioactive waste. The National Programme should provide for milestones and timeframes for the implementation of the fuel cycle options, including disposal of the different types of waste. Milestones include decision points which support an open decision making process. The concepts or plans and technical solutions from generation to disposal need to define disposal endpoints for the National Programme to work towards. The end-points may change with time, but without encompassed end-points, the programme lacks orientation.

A national inventory is required where all spent fuel and radioactive waste are documented together with estimates of future arisings. This inventory is essential as it defines the actual basis for the programme, namely what it will manage in a responsible and safe manner. Previous experience points towards the benefit of inclusive characterisation of waste. The reason is that evolution of the National Programme, delays in implementation of repositories, and changes in disposal strategies can result in the need to re-define or re-verify classification and disposal end-points for existing waste. Exhaustive documentation of existing waste within the national inventory eases such re-definition or re-verification.

Concepts or plans and technical solutions need to be defined for all steps and activities from generation to disposal of the spent fuel and/or radioactive waste. Technical solutions need to be developed where they are not yet available. Concepts and plans for the post-closure phase also need to be defined for the repositories. The concepts and plans for activities scheduled to take place in the distant future will be of provisional character.

* *The obligations for transposition and implementation of provisions related to spent fuel of this Directive do not apply to Cyprus, Denmark, Estonia, Ireland, Latvia, Luxembourg and Malta for as long as they decide not to develop any activity related to nuclear fuel*

They may change as the programme evolves, but as is the case with milestones, they are needed in order to give orientation to the programme implementation.

Research, development and demonstration activities will be very intense during development of a given repository. As the experience with repositories of the same type increases, and as implementation of the specific repository is progressing, the need for research, development and demonstration will change in character and decrease in magnitude. The level of research and development required by the regulatory framework for continued improvement of evidence of safety also in later phases of repository development and operation needs to be defined.

Responsibilities of the different actors need to be clearly defined, and the implementation and regulatory functions clearly separated. Thereby, it needs to be ensured that responsibility is assigned for all wastes at all times, as well as for implementing overriding issues, such as the financing scheme. Cost assessments of the different types of waste and implementation steps are the basis for defining the need for financial resources, including their timely distribution. Correspondingly, a financing scheme is required to ensure that those who generate the waste provide the financial resources for its management, including disposal. The financing system should ensure that sufficient financial resources are available for the different steps and activities, when needed.

Transparency in decision-making, where it can be of concern for different stakeholders, will be implemented in accordance with good practices and requirements in other fields. Finally, Member States may have agreements with other countries on sharing resources and expertise through, for example, joint research, development and demonstration, and making common use of know-how and infrastructure.

Some Member States consider that the sharing of facilities for spent fuel and radioactive waste management, including disposal facilities, is a potentially beneficial, safe and cost-effective option when based on an agreement between the Member States concerned.

Implementation of the Directive and of National Programmes

The implementation of the Directive for a Member State is mainly built around the following steps and activities:

1. Transposition of the Directive into National Law before 23 August 2013.

2. Establishing, implementing, reviewing and updating a National Programme, and its Notification for the first time to the Commission as soon as possible, but not later than 23 August 2015, and any subsequent significant changes.

3. Reporting on progress on the implementation of the Directive for the first time by 23 August 2015, and every three years thereafter.

4. Arranging for self-assessments of their national framework, competent regulatory authority, national programme and its implementation, and inviting international peer review of their national framework, competent regulatory authority and/or national programme periodically, and at least every 10 years.

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As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new methods, tools and standards, and sharing its know-how with the Member States, the scientific community and international partners.

EASAC - the European Academies' Science Advisory Council - is formed by the national science academies of the EU Member States to enable them to collaborate with each other in providing advice to European policy-makers. It thus provides a means for the collective voice of European science to be heard. Its mission reflects the view of academies that science is central to many aspects of modern life and that an appreciation of the scientific dimension is a pre-requisite to wise policy-making. This view already underpins the work of many academies at national level. With the growing importance of the European Union as an arena for policy, academies recognise that the scope of their advisory functions needs to extend beyond the national to cover also the European level. Here it is often the case that a trans-European grouping can be more effective than a body from a single country.

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